

EMI 2022

**Book
of
Abstracts**

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Enabling Uncertainty Quantification Across SimCenter Modules for Simulation in Natural Hazards Engineering

Author(s): *Aakash Bangalore Satish, *University of California Berkeley*; Sang-ri Yi, *University of California Berkeley*; Joel P Conte, *University of California San Diego*; Alexandros Taflanidis, *University of Notre Dame*;

The NHERI SimCenter at UC Berkeley is developing a software framework to support the computational modeling and simulation of civil infrastructure from the material scale to the regional scale. Uncertainty quantification (UQ) is a critical component of SimCenter's workflows, where the scope of the modeling efforts could range from asset and hazard characterization to estimation of risk, encompassing all the intermediate analytical steps of performance-based engineering. This presentation highlights some of the challenges and opportunities presented by the task of UQ in computational simulations of interest to the natural hazards engineering community and showcases some of the ongoing efforts at the SimCenter to develop a framework supporting the breadth of the UQ activities across the SimCenter applications suite. The UQ module is being developed with two objectives in view – to facilitate ease of use by the non-expert end users, and to facilitate ease of addition of new features/algorithms/capabilities by contributors who are typically UQ experts. The presentation will give a brief overview of the design features of the UQ module meant to support these two objectives.

The SimCenter conducts training sessions which showcase new features and capabilities whenever a new version of the applications is released to demonstrate how the features and capabilities can be used through application examples. In addition to these regular training sessions, educational modules that can be used in a classroom setting are being developed to highlight the importance of UQ in the natural hazards engineering community and to promote a more widespread application of UQ methods in research and practice. These modules deliver an introduction to specific topics in UQ to a graduate-level audience that is not familiar with the concepts of UQ, while also teaching the students how to use the SimCenter's tools to perform UQ analyses related to the topic of the course. During this presentation, an overview of the SimCenter's UQ educational module developments so far will also be provided.

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Baltimore, MD, May 31 - June 3, 2022

Title: A Thermomechanical Framework for Modeling Fluid-Saturated, Brittle Granular Materials in Dynamic Flows with High Strain-Rates

Author(s): *Aaron Baumgarten, *Johns Hopkins University*; Nilanjan Mitra, *Johns Hopkins University*; Ryan Hurley, *Johns Hopkins University*; K.T. Ramesh, *Johns Hopkins University*;

Understanding and modeling the behavior of brittle granular materials in dynamic flows at high strain-rates is important for many industrial, civil, and geotechnical engineering problems, including applications in defense, mining, and construction. In these types of flows, it is necessary to consider how the deformation of individual particles affects the behavior of the bulk solid. Grain-scale elastic deformations determine the rate at which effective stresses and shocks are propagated through the material, and inelastic deformations (e.g., grain-scale fracture) affect how the grains organize themselves (i.e., the grain-scale microstructure). Additionally, the presence of a fluid saturating the pore space between grains can change the mechanics of grain–grain interactions (e.g., lubrication forces) and admissible granular motions (e.g., pore compaction or dilation).

Significant research in recent years has been devoted to developing models for dry, brittle granular materials that incorporate particle fracture and breakage; pore collapse and dilation; and shock loading into unified descriptions of these materials (e.g., see Cil et al., 2020, and Herbold et al., 2020). However, there has not been substantial analysis of the fully-saturated condition outside of quasi-steady or dilute granular flows (e.g., see Baumgarten & Kamrin, 2019). In this presentation, we discuss a thermomechanical framework for modeling fluid-saturated, brittle granular materials that considers the coupled influence of particle breakage, pore evolution, shock loading, and pore fluid motion. A general form of this framework is presented alongside convenient simplifying assumptions, which allow the equations of motion to be simulated computationally. Simulated results are shown to qualitatively predict the different responses of dry and fully-saturated granular materials under impact loading events.

Baumgarten, A. S., & Kamrin, K. (2019). A general fluid–sediment mixture model and constitutive theory validated in many flow regimes. *Journal of Fluid Mechanics*, 861, 721-764.

Cil, M. B., Hurley, R. C., & Graham-Brady, L. (2020). Constitutive model for brittle granular materials considering competition between breakage and dilation. *Journal of Engineering Mechanics*, 146(1), 04019110.

Herbold, E. B., Homel, M. A., & Rubin, M. B. (2020). A thermomechanical breakage model for shock-loaded granular media. *Journal of the Mechanics and Physics of Solids*, 137, 103813.

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Title: Lateral-Torsional Buckling of Thin-Walled Anisotropic Laminated Composite I-Beam Under Pure Bending

Author(s): *Abdul Halim Halim, VAA LLC; Hayder Rasheed, *Kansas State University*;

Lateral-torsional buckling is one of the most common failure modes that thin-walled members experience prior to reaching their full strength. In this study, analytical solution based on classical lamination theory is presented for composite I-beams with lateral-torsional buckling as the dominant mode of failure. The solution considers both in-plane and out-of-plane shear deformation in addition to warping deformations for orthotropic and symmetric beams. The solution could be adopted for I-beams with arbitrary layups in which case a modified term for warping deformations shall be used. Buckling expression is formulated using kinematics, constitutive and equilibrium equations and solved using infinite series method. The solution is verified using finite element analysis. It is also validated against Timoshenko's classical solution for isotropic I-beam. In general, the solution gives conservative results and consistently follow the finite element results. Deviations from finite element analysis range between 0.5-12%. However, larger deviations were observed for beams with different buckling modes in which case the present solution is not applicable. A parametric study is performed to investigate length-depth ratio and flange-web thickness effects on the critical buckling moment.

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Title: Fire and Explosion Testing of a Lithium-Ion Energy Storage System Mockup

Author(s): *Adam Barowy, *Underwriters Laboratories*;

In 2020, UL conducted three UL 9540A “installation level” tests on mockup walk-in containerized lithium-ion (li-ion) ESS to address concerns from the fire protection/explosion safety engineering industry, authorities having jurisdiction and the fire service. Representative ESS Units were installed within an ISO container outfitted with deflagration pressure relief vents. The first test provided a baseline data on hazards developed in the absence of active fire protection system intervention. The second test included a Novec 1230 system and the third test incorporated a dry pipe water suppression system. All tests were instrumented to characterize the thermal and gaseous conditions inside the ISO container. A limited selection of gas detection technologies was deployed in all three tests to evaluate the viability of different types of sensors in responding to initial and ongoing gaseous hazards.

This presentation will cover the findings of the three tests as related to the interests of AHJs, the fire service and the fire and explosion protection engineering industries.

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Title: An Approximate Bayesian Perspective on Model Falsification with Applications to Parameter Inference and Model Selection of Dynamical Systems

Author(s): *Agnimitra Dasgupta, *University of Southern California*; Erik Johnson, *University of Southern California*;

Model falsification, with roots in frequentist statistics, is used to solve inverse problems wherein the feasibility of an hypothesis is assessed by comparing the predictions from it with the observations. Hypotheses that remain unfalsified are considered candidate solutions to the inverse problem. In contrast, Bayesian inference makes use of observations to update prior beliefs about hypotheses with the help of a likelihood to yield a posterior that probabilistically represents the solution to an inverse problem. Bayesian inference and model falsification have developed independently as inference approaches. The key difference between the two approaches lies in the fact that falsification does not require a prior and, in most cases, a likelihood to be specified. However, in practice, model falsification is implemented by sampling models from a prior density and then subjecting these samples to falsification. As a result, the process of falsification bears resemblance to approximate Bayesian computation (ABC) wherein the falsifier plays the role of a discrepancy measure. This provides an opportunity for the Bayesian re-interpretation of model falsification. More formally, as shown in this work, the set of unfalsified models can be considered realizations drawn from an approximate posterior. Further, we show how different model falsifiers can be embedded within ABC methods — as discrepancy metrics and density kernels — to carry out different inference tasks. Predictions computed using kernel regression with model falsifiers are also introduced. ABC using model falsifiers are used to tackle two practical applications albeit with synthetic measurements. The first example concerns the identification of a cubic-quintic dynamical system. The second example involves model selection for a base isolated structure. The results are compared against Bayesian inference. The results show that model falsification can be used with ABC to solve inverse problems in a computationally efficient manner. The results are also used to compare the various falsifiers in their capability of approximating the posterior and some of its important statistics.

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Title: Modeling Fracture in Rate-Dependent Polymer Networks: A Quasicontinuum Approach

Author(s): *Ahmed Elbanna, *University of Illinois Urbana Champaign*; Ahmed Ghareeb, *University of Illinois Urbana Champaign*;

Soft materials, such as rubber and gels, exhibit rate-dependent response where the stiffness, strength, and fracture patterns depend largely on loading rates. Thus, accurate modeling of the mechanical behavior requires accounting for different sources of rate dependence such as the intrinsic viscoelastic behavior of the polymer chains and the dynamic bond breakage and formation mechanism. In this talk, we extend the QC approach presented in Ghareeb and Elbanna (2020, *An Adaptive Quasi-Continuum Approach for Modeling Fracture in Networked Materials: Application to Modeling of Polymer Networks*, *J. Mech. Phys. Solids*, 137, p. 103819) to include rate-dependent behavior of polymer networks. We propose a homogenization rule for the viscous forces in the polymer chains and update the adaptive mesh refinement algorithm to account for dynamic bond breakage. Then, we use nonlinear finite element framework with predictor–corrector scheme to solve for the nodal displacements and velocities. We demonstrate the accuracy of the method by verifying it against fully discrete simulations for different examples of network structures and loading conditions. We further use the method to investigate the effects of the loading rates on the fracture characteristics of networks with different rate-dependent parameters.

Our results for fracture and damage of rate-dependent disordered networks suggest that stretch rates have significant effects on the network strength, toughness, and fracture patterns. For networks with viscoelasticity in the polymer chain behavior and link stretch based damage criterion, the network strength and toughness scale with the network stretch rate. For networks with dynamic bond breakage, the network strength and toughness have a logarithmic dependence on the stretch rate. The trade-off between viscous damping and dynamic bond breakage parameters has a direct effect on the damage and fracture pattern of polymer networks. Modeled networks were found to follow one of four failure patterns: Crack blunting followed by bulk damage, steady-state crack propagation, crack arrest followed by bulk damage, and non-steady-state crack propagation were sharp cracks, and crack-in-crack patterns were observed. These results provide insights on design of tough polymer networks through direct control of the microstructure characteristics.

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Title: Interpreting Ground Penetrating Radar Scans with Semi-Supervised Learning for Building Pathology and Diagnostics

Author(s): *Ahmed Nirjhar Alam, *Pennsylvania State University*; Wesley Reinhart, *Pennsylvania State University*; Rebecca Napolitano, *Pennsylvania State University*;

Ground Penetrating Radar (GPR) is a pervasive technology in the field of Structural Health Monitoring (SHM) for garnering quantitative information about damage, material conditions, and geometric measurements in a non-destructive manner. This information is vital when converting sensor readings into action as it can provide data about critical SHM stages. GPR can also aid in quantifying damages or irregularities such as changes in tensile strength or changes in porosity of concrete and enables intelligent diagnosis and repair by providing true boundary conditions for finite element models used during load forecasting simulations.

While GPR has a great deal of potential for the field of SHM, analysis of radar scans has traditionally relied on extensive human interpretation which reduces the amount of quantitative information that can be gleaned about structure, damages, and loads while increasing bias that can interfere with diagnostic and repair decisions. More recently, pattern recognition with machine learning as well as machine learning techniques based on neural networks (NNs) have been employed for classification and detection problems in GPR.

A general problem with automating the process GPR scan interpretation is that labeled training data is hard to come by. While there can be a wide array of GPR scans available for a given structural layout, the corresponding geometry information detailing the electromagnetic properties (such as conductivity and dielectric permittivity) of the different objects present, as well as their shape, are rarely available. Semi-supervised learning methods are suitable for this case since information available from sparse labels can provide quantitative characterization of vast amounts of unlabeled data. In this work, a semi-supervised learning method based on dimensionality reduction is developed for the interpretation of GPR scans. The proposed methodology is tested in the laboratory on structural materials commonly found in building envelopes.

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Title: State-Space Representation of Radiation Damping of an Oscillating Surge Wave Energy Converter

Author(s): *Alaa Ahmed, *Stevens Institute of Technology*; Muhammad Hajj, *Stevens Institute of Technology*; Raju Datla, *Stevens Institute of Technology*; Jia Mi, *Virginia Polytechnic Institute and State University*; Lei Zuo, *Virginia Polytechnic Institute and State University*;

Given complexities of the design of wave energy converters, the expense of testing them in open waters, and variations in operational conditions, their performance analysis and optimization must depend on numerical modeling and simulations. High-fidelity numerical models require significant computational power and are time-consuming. In contrast, low-fidelity models offer an effective alternative especially in the early stages of the design of the prime mover and PTO to estimate the capture width ratio or levelized cost of electricity for specific wave conditions. One significant impediment in implementing low-fidelity models for wave energy converters is the convolution integral that models the radiation damping. Integrating this term in time is computationally inefficient. Alternatively, replacing this term by a parametric model in the form of a state-space formulation will reduce the computational burden. We implement and discuss two approaches to identify the coefficients of the state-space model representing radiation damping of an oscillating surge wave energy converter is considered for the analysis. The validity of this representation is assessed using data generated from radiation tests conducted in Davidson Laboratory and simulations performed using AQWA over a broad range of operational parameters.

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Title: A Stochastic Lattice Discrete Particle Modeling Approach for Fracture Simulations in Porous Media

Author(s): *Alessandro Fascetti, *University of Pittsburgh*; John E. Bolander, *University of California, Davis*;

We will presents a stochastic modeling approach for simulating the mechanical behavior of porous media, based on novel extensions of the lattice discrete particle model. The method is applied to the simulation of fracture in highly permeable concrete. Selected digital images of the internal mesostructure, obtained from physical specimens, are used to survey material features and produce statistically representative descriptions of the pore networks. A procedure for estimating the statistical features of the mesostructure is proposed, and samples of spatially correlated random fields are utilized to numerically reproduce the distribution of the porosity in the material. The novel techniques are presented to link the numerical samples to the topology of the lattice network: 1) a random placement procedure for the poly-sized spheres representing coarse aggregate; and 2) a ray tracing technique, which is used to evaluate the effective distributions of mass, stiffness, and strength of each lattice element according to the local distribution of porosity. Numerical results demonstrate how the proposed model is capable of simulating both the large scatter in strength and the variety of failure modes that are observed when testing physical specimens of pervious concrete. The proposed procedure is generally applicable to different types of materials with varying porosity, opening up new possibilities for the simulation of porous media by means of lattice discrete particle modeling techniques.

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Title: Data- and Physics-Based Modeling of Backward Erosion Piping in Flood Protection Infrastructure

Author(s): *Alessandro Fascetti, *University of Pittsburgh*;

This talk will present research conducted in the context of the assessment of Flood Protection Infrastructure (FPI) against the progressive evolution of internal damage caused by erosion mechanisms, with emphasis on Backward Erosion Piping (BEP) induced failures. A novel approach, encompassing both deterministic physics-based numerical simulations and probabilistic data-based techniques, is presented and validated through experimental data obtained at multiple length scales. The deterministic simulations are used to train a multilayer machine learning model that is capable of quantifying the state of the infrastructure in quasi-real-time and is inherently capable of accepting live data from embedded and remote sensors. The significant reduction in computational cost obtained through the adoption of ML techniques allows for the investigation of the hyperparameters space in an efficient fashion, allowing for meaningful sensitivity analyses and physics discovery. The results of a simulated real-life case study will also be presented, where a selected FPI system is simulated at the system scale

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Title: Modular Architecture for Origami-Inspired Flat-Folding Robots

Author(s): *Alexandra Haraszti, *California Institute of Technology*; Manan Arya, *Jet Propulsion Laboratory, Caltech*; Sarah Hovsepian, *Jet Propulsion Laboratory, Caltech*;

Previously, the Pop-Up Flat-Folding Robot (PUFFER) effort demonstrated a flat-folding robot that could package into small volumes [1]. PUFFER could enable multi-robot exploration of planetary bodies since many such robots could be packaged into a small spacecraft volume. However, PUFFER's folding structure is challenging to modify, expand, and adapt to different space mission scenarios. Here, we present a system for designing flat-folding robots using a modular approach; this approach allows the robot design to be adapted in a straightforward manner. This system, called Modular Origami Flat-Folding Explorer Robot (MORFFER), is based on existing zippered Miura-ori tube structures [2]. Each module is realized as a Miura tube, allowing the modules to be arranged together to produce a robot body that is globally flat-foldable. The Miura tubes provide stiffness through deployment and reconfigurability. We present the design of these modular robotic bodies, the design of different modules (e.g. photovoltaic modules, wheel-and-suspension modules, etc.), and the design and testing of preliminary prototypes. An example design of a wheeled Lunar rover robot is presented to illustrate the proposed MORFFER system.

[1] J. T. Karras et al., "Pop-up mars rover with textile-enhanced rigid-flex PCB body," 2017 IEEE International Conference on Robotics and Automation (ICRA), Singapore, 2017, pp. 5459-5466

[2] Filipov, E. T., Tachi, T. & Paulino, G. H. "Origami tubes assembled into stiff, yet reconfigurable structures and metamaterials", PNAS 112, 12321–12326 (2015)

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Title: Implications of Large-Scale Lithium-ion Indoor Energy Storage for Fire Safety in Urban Areas

Author(s): *Ali Ashrafi, *Thornton Tomasetti*; Mahesh Bailakanavar, *ThorntonTomasetti.com*; Nezar Abraham, *Thornton Tomasetti*;

Large-scale energy storage is an essential part of any solution for decarbonization since it allows for clean energy to be produced at the optimal time and place and be used at a different time and place. Lithium-ion batteries, themselves a family of different designs and technologies, have become the dominant technology for reliable high-density energy storage. As the need for energy storage increases exponentially, these battery energy storage systems (BESS) are coming into dense urban areas and indoor spaces at larger scales. We will discuss potential safety hazards associated with these applications and potential risk mitigation approaches.

Lithium-ion batteries have different designs and chemistries and these variations impact the associated risks. For fire, the risks are typically associated with the thermal runaway process in which an unstable process results in production of ever more heat, release of combustible gases, and fire and/or explosion. The released gases are also highly toxic. These risks have meaningful differences compared to typical building fires, with implications for safety and design. There are important differences in explosive potential of released gases, toxicity of gases, initial rate of fire growth, fire dynamics, production of oxygen, fire extinguishing requirements, and detection by smoke detectors, among other factors. While each of these differences could impact fire safety and the appropriate mitigation approach, their interactions and collective impact have the potential to substantially change the risk profile.

For example, fire department operations could be more difficult and risky because of the explosive potential, toxicity of gases, and harder fire extinguishing procedures. The same concerns could also impact evacuation operations adversely. Furthermore, high amounts of stored energy combined with sudden onset of fire at thermal runaway and its jet fire component could mean faster fire spread and longer fires. To the extent that energy storage might be spread throughout a building, that could make it harder to devise appropriate mitigation approaches compared to similar risks from electric vehicles that will nonetheless be in known areas of buildings. We will discuss various aspects of fire safety and explore some potential design and emergency response approaches to risk mitigation.

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Baltimore, MD, May 31 - June 3, 2022

Title: Implications of Electric Vehicles for Fire Safety of Indoor Parking Spaces

Author(s): *Ali Ashrafi, *Thornton Tomasetti*; Mahesh Bailakanavar, *Thornton Tomasetti*; Nezar Abraham, *Thornton Tomasetti*;

With accelerating increases in production and use of electric vehicles (EVs), they are starting to represent a large share of cars in parking spaces and could be the majority of cars in a few years. Different fire hazards of EVs and internal combustion engine vehicles (ICEV) can change the risk profile of parking structures and buildings with parking spaces, whether new or existing.

This abstract will discuss the nature of EV hazards and their implications for design, with particular emphasis on indoor spaces. There are potentially important differences in explosive potential of released gases, toxicity of gases, initial rate of fire growth, fire dynamics, production of oxygen, fire extinguishing requirements, and detection by smoke detectors, among other factors. While each of these differences could impact fire safety and the appropriate mitigation approach, their interactions and collective impact have the potential to substantially change the risk profile. For example, the explosive potential could make fire department response more difficult and risky, leading to longer fires. Larger required quantities of water to extinguish the fire could have a similar impact. The combination of explosion potential and toxicity may also impact evacuation operations. The sudden onset of fire at thermal runaway and its jet fire component could mean faster fire spread to other cars, changing the heat growth in a group of cars parked close to each other. Challenges in detecting the onset of thermal runaway by traditional smoke detectors could also make successful fire suppression less likely. Further complicating the matter, mitigating some risks might exacerbate others. For example, more burned gases would create more heat while more unburned gases could increase the explosion potential. We will discuss the various aspects of fire safety and also explore some potential design and emergency response approaches to risk mitigation.

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Title: Contact Creep and Friction of Nickel-Based Inconel 617 Superalloy at Elevated Temperatures: Indentation Experiments and Finite Element Analysis

Author(s): Sepehr Salari, *George Mason University*; MdSaifur Rahman, *ATSP Innovations*; Andreas Polycarpou, *Texas A & M University*; *Ali Beheshti, *George Mason University*;

Surface friction, wear, and contact properties of the contacting pairs are highly influenced by the surface oxides especially at high temperatures which in turn impacts the durability and performance of the tribo-components. This study investigates the influence of high temperature and helium aging on the mechanical and contact properties of Inconel 617 up to 600 °C using nanoindentation along with complementary finite element analysis. The mechanical properties of the oxide layer are obtained through high temperature nanoindentations and consequently are utilized to study temperature and dwell time effects on contact area and friction coefficient variation using a spherical asperity contact. Friction coefficient and contact area sensitivity on load, temperature, and holding time are determined and consequently a model at asperity level is obtained. The findings show high dependency of the oxide friction coefficient on creep of the material during dwell time especially at higher loads.

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Title: Biomolecule-Microstructure-Property Relationships Towards Rational Design of Admixtures in Cementitious Materials

Author(s): Sadegh Tale Masoule, *University of Miami*; Elvis Baffoe, *University of Miami*; *Ali Ghahremaninezhad, *University of Miami*;

Nature has mastered creation of nanocomposite materials, including nacre of abalone shell, bone, and sea urchin, with properties far exceeding those of the traditional engineering materials. The superior properties of these biological nanocomposites are known to be due to the effect of certain biomolecules derived, as a result of the evolutionary selection. These biomolecules govern bio-mineralization and microstructure formation leading to enhanced properties at the macroscale.

In this study, the interaction between the biomolecules and cement environment and the effect of biomolecules on the microstructure and properties of cementitious materials are evaluated. Several biomolecules with different molecular structures and physicochemical characteristics were used to allow the investigation of a large number of interaction pathways with cementitious materials. Due to the presence of hydrophobic functional groups in the molecular structure of the biomolecules, they can act as a surfactant reducing the surface tension of the pore solution and potentially generate a stable void system in the microstructure of the cementitious materials. The creation of a properly designed void system is critical to the freeze-thaw resistance of cementitious materials. The results are used to establish biomolecule-microstructure-property relationships in cementitious materials.

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Baltimore, MD, May 31 - June 3, 2022

Title: A Topology Optimization Framework for Multi-Material Design

Author(s): *Alireza Asadpoure, *University of Massachusetts Dartmouth*; Mohammad Minhajur Rahman, *University of Massachusetts Dartmouth*; Seyed Ardalan Nejat, *University of Massachusetts Dartmouth*; Navid Changizi, *University of Massachusetts Dartmouth*; Mazdak Tootkaboni, *University of Massachusetts Dartmouth*;

With the advancement of different manufacturing techniques, the multi-material design has gained significant interest in recent years due to the potential for achieving unprecedented performance. For such designs, topology optimization (TO) is among the most powerful approaches due to its “free-form” capability without a need for prior knowledge on optimal material layout. One of the most common TO approaches is the density-based design in which each material layout is identified by binary values of an associated material design variable in a way that allows for enforcing a minimum length-scale using different filters. In density-based methods, we often relax the binary requirement, which allows for the usage of efficient gradient-based optimizers, and employ a penalization technique for avoiding emergence of non-binary values of design variables. The penalization technique, such as the Solid Isotropic Material with Penalization (SIMP), is formulated to interpolate (and penalize) the material properties for non-binary values often in a restrictive way that it does allow for emergence of more than one material in each region. However, such a restriction may lead to some challenges including freely emergence of different material phases in each phase and violation of the minimum length-scale when more than two constituent materials exist in the design space. In this work, we develop a TO framework for the multi-material design using a relaxed SIMP formulation combined with the Heaviside projection method (HPM) as the filter such that each material phase can easily emerge in each region without violation of the minimum-length scale. We demonstrate the performance of the proposed framework through a few examples with four constituent materials.

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Baltimore, MD, May 31 - June 3, 2022

Title: Lab-Scale Characterization of Micro-Structured Mechanical Metamaterials via Phase Separation of Overlapped Waves

Author(s): Joshua Morris, *University of Massachusetts Lowell*; Darshil Shah, *University of Massachusetts Lowell*; Thomas A. Plaisted, *CCDC US Army Research Laboratory*; Christopher Hansen, *University of Massachusetts Lowell*; *Alireza V. Amirkhizi, *University of Massachusetts Lowell*;

Micro-structured metamaterials with dispersive response at low frequency (acoustic/ultrasonic) have effective properties not found in nature that are inherently challenging to characterize in a physical experiment. Long wavelengths traditionally required extended measurement media with low wave speed, such as fluids, and clear time domain distinction between incident and reflected wave components. Collection and careful processing of signal phase angles provides the opportunity to separate overlapping wave components from a steady state frequency domain response, reducing the scale of the experiment and permitting the use of high wave speed structural materials. A characterization experiment has been constructed that monitors strain amplitude and phase response along 4 meters of aluminum at four locations, two before and two after the sample. The pseudo-steady state response is realized with an extended duty cycle ultrasonic transducer whose response is measured using sensitive semiconductor strain gauges. The amplitude and phase information are sufficient for separating overlapping waveforms, constructing the sample's transfer matrix, and extracting the effective properties for the metamaterial. This method only requires knowledge of the metamaterial thickness and is unaffected by the composition. Validation of the characterization technique is performed using several 3D printed mechanical metamaterials with different resonator shapes and materials, all designed to have wide band of attenuated frequency. Comparison with finite element solutions confirms that the expected transmission performance and effective properties can be achieved practically. Regions of diminished phase velocity are apparent in the experimental results, credited to the anticipated metamaterial effect. Practical lab-scale characterization methods advance engineered mechanical metamaterials towards applications for lenses, pressure/blast attenuation, passive vibration filtering, and sound proofing.

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Title: Reduced Order Modeling of Mechanical Metamaterials Under Dynamic Loading

Author(s): Weidi Wang, *University of Massachusetts Lowell*; Willoughby Cheney, *University of Massachusetts Lowell*; Reza Abedi, *The University of Tennessee Space Institute*; *Alireza V. Amirkhizi, *University of Massachusetts Lowell*;

Wave propagation in microstructured media has been studied extensively due to the potential exciting dynamic features. Most such studies focus on band structures derived from eigen-frequency analysis or similar steady state/frequency domain models. In impact and dynamic loading situations, such an approach is a good initial step to predict the behaviour of various designs, but more accurate determination of unsteady wave propagation requires a suitable time domain analysis. However modeling and design of these structures is hindered by the geometric complexity and the inherent computational burden, especially in the time domain finite element models. In this work, we propose a reduced order model (ROM) of low-frequency resonant metamaterial cells for predicting time domain response of finite specimens. These models may be utilized for optimization on a cell-by-cell basis in single and multi-dimensional arrays. The ROMs are first constructed for periodic unit cells based on an assembly of beam models, in which the effective parameters are determined through the eigen-analysis of the model. The ROMs are optimized to preserve the dynamic features of the eigenmodes in the low frequency range and only model the active degrees of freedom in the frequency range of interest. The ROMs are further fine-tuned for the finite array through adjustments in the boundary elements. The time dependent analysis of the reduced order systems shows good accuracy compared with the conventional finite element approach, while the computational cost is reduced significantly. The proposed ROM method therefore affords a concise description of the microstructural dynamics and is a robust tool to facilitate the design optimization of metamaterials for applications including (but not limited to) the management of energy from impact loading.

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Title: Large-Scale Open-Jet Testing: A New Frontier in Structural Wind Engineering

Author(s): *Aly Mousaad Aly, *Louisiana State University*; Md. Faiaz Khaled, *Louisiana State University*;

This study aims to meet the widely reported challenges associated with building aerodynamics by testing large-scale models at high Reynolds numbers. We tested 1:5 and 1:10 scale models of the Silsoe cube at multiple locations in the Louisiana State University (LSU) open-jet facility. The paper investigates the velocity-related parameters and the statistical quantities of roof pressures to yield a suitable scale and testing location in the facility. Moreover, we compare measured surface pressures with those from Tokyo Polytechnic University's (TPU) wind tunnel and the Silsoe full-scale data to validate the results. We attempt to generate both small- and large-scale turbulence by employing the concept of flow without boundaries. The paper reveals the open-jet facility's promising capabilities to produce mean and peak pressures on buildings, which reasonably conform with the full-scale counterparts. The results suggest that the open-jet facility can generate realistic wind loads on low-rise buildings.

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Title: Bond Behavior of Irradiated Concrete with Reinforcing Rebars

Author(s): *Amani Cheniour, *Oak Ridge National Laboratory*; Mohammed Alnaggar, *Oak Ridge National Laboratory*;

Reinforced concrete containment structures play an essential role in maintaining nuclear facilities safe operation. These structures are exposed to harsh operating conditions and must satisfy accident tolerance requirements over their prolonged life spans. As the Nuclear Power Plants (NPPs) fleet keeps aging, these structures accumulate more radiation. In general, radiation causes degradation to the concrete in the form of aggregate minerals Radiation Induced Volumetric Expansion (RIVE) and paste hydrolysis. The result is a very fine scale cracking and loss of stiffness within the aggregate that propagates in the material. The extent of this degradation is not well known but is expected to reach the reinforcing rebars layers as NPPs operate for long periods. If this degradation reaches the rebars area, it is expected that the bond between rebars and concrete can be affected and that may degrade the ability of the containment structure to perform during accidental scenarios like under earthquakes or even external attacks.

Experiments to evaluate such effects are very difficult and expensive. Simply because the exposure to radiation in test facilities requires stringent precautions and the exposure as well as the test cells are small in size. Aside from size limitations, radiations induce heating, and it is both hard and costly to maintain temperatures as low as room temperature during irradiation so that drying and thermal conditions do not interfere with radiation effects. Finally, after exposing samples to radiation in a suitable test reactor, they become radioactive, therefore, experiments are to be performed in so called "Hot Cells" which are radiation shielded. These hot cells are also small in size with limited manipulation capabilities and are very costly to use.

Therefore, accurate modeling is needed to understand and predict the full structural behavior by using limited small scale experiments. In this presentation, details of an ongoing experimental campaign will be outlined and then, multi-scale multi-physics modeling approach will be presented. The approach links a microscale model called "MOSAIC" for modeling the RIVE effects with a mesoscale model called "LDPM" to represent the concrete mesoscale behavior during rebar pullout. Then, the LDPM model will be linked to a continuum scale FE model to simulate a large scale containment structure.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Johansen Cointegration for Structural Condition Monitoring Under Environmental and Operational Variations Effect

Author(s): Mohsen Mousavi, *University of Technology Sydney*; *Amir H Gandomi, *University of Technology Sydney*;

Condition monitoring of civil infrastructures is influenced by the environmental and operational variations (EOV) effects. The main reason is that the key structural parameters such as natural frequencies are prone to changes by some environmental factors such as temperature variations. These parameters, however, are sensitive to damage in the structure as well. Therefore, when these parameters are monitored for assessing the structural integrity, it is likely that changes due to temperature be mistakenly interpreted as damage. Therefore, new strategies have been developed to tackle the problem through devising techniques that mitigates the effect of the EOV on the structural features, while maintaining information about damage. Generally, the effect of damage on the structural natural frequencies is mostly stationary, when of course the progression of damage through time prior its identification is neglected. On the other hand, there are two trends can be found in the structural natural frequency signals that can be correlated with the temperature variations. These are short term fluctuations of the frequency signals due to the temporal variations of temperature. The second trend is correlated with long term variations of temperature. As such, the former trend cannot be deemed to include any effect of damage and can be excluded from further analysis. This will facilitate the process of condition monitoring by reducing the fluctuation of the variance in the frequency signal in long term. In this study, the Variational Mode Decomposition algorithm is employed to extract these two different trends in the frequency signals. Then, the mode corresponding to the short term fluctuations of temperature is removed. The resulting frequency signals are then used in Johansen Cointegration algorithm to obtain a stationary representation of a couple of cleansed lowest natural frequencies of the structure. The obtained stationary representation of the signals is used as the target in a machine learning framework to be trained for the prediction of such stationary representation of those signals in the future. The prediction results are then compared against the obtained values using the Johansen Cointegration algorithm from upcoming recorded data. The resulting error signal plays the role of an R-chart that can be monitored for damage. To this end, an upper control limit is obtained for the R-chart to be set as a threshold based on the historical data obtained from the healthy structure. The capability of the proposed algorithm is demonstrated by solving the benchmark problem of the Z24 bridge.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: A Machine Learning Approach to Predict the Glass Transition Temperature of Conjugated Polymers from Chemical Structure

Author(s): *Amirhadi Alesadi, *North Dakota State University*; Zhiqiang Cao, *The University of Southern Mississippi*; Zhaofan Li, *North Dakota State University*; Xiaodan Gu, *The University of Southern Mississippi*; Wenjie Xia, *North Dakota State University*;

Glass transition temperature (T_g) is a key property that governs the chain dynamics and thermomechanical properties of the conjugated polymers (CPs). Despite its vital role in the applicability of the CPs, it still remains challenging to predict T_g of CPs due to the heterogeneous chain architectures along with diverse chemical building blocks. In this study, we present a predictive modeling framework to predict T_g for a wide range of CPs through the integration of machine learning (ML), molecular dynamics simulations, and experiments. With nearly 154 T_g data collected from experiments and simulations, a predictive model based on ML is developed by taking simplified geometry of six chemical structures (i.e., side-chain fraction, isolated rings, fused rings, bridged rings, double/triple bonds, and halogen atoms) as input molecular features. Among those features, we point out that side-chain fraction, isolated rings, fused rings, and bridged rings features as the dominant factors for T_g . Molecular dynamics (MD) simulations are implemented to unravel the fundamental roles of those chemical building blocks in dynamical heterogeneity and local mobility of CP chains at a molecular level, which is supported by the quasielastic neutron scattering (QENS) experiment. Interestingly, the developed ML model is demonstrated for its capability of predicting T_g 's of several new high-performance solar cell materials to a good approximation. The established predictive framework would be an important milestone for the design and prediction of T_g of the next generation of CPs, hence paving the way for addressing device stability issues that have restricted the field from developing stable organic electronics.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Weak Enforcement of Essential Boundary Conditions Using the Variational Multiscale Method

Author(s): *Andrew Groeneveld, *U.S. Army Engineer Research and Development Center*, Michael Hillman, *The Pennsylvania State University*,

Meshfree shape functions generally do not possess the Kronecker delta property, so enforcing essential boundary conditions (EBCs) is not as straightforward as it is in the finite element method. There are three classical methods for weak enforcement of EBCs: the penalty method, the Lagrange multiplier method, and Nitsche's method. This work explores an alternative, the variational multiscale (VMS) method. The core concept of VMS is the use of a coarse-scale/fine-scale decomposition. The fine scale can then be localized and solved for, either analytically, numerically, or approximately.

The VMS approach to enforcing EBCs (VMS-EBC) is derived starting from the Lagrange multiplier method. The fine scale is then condensed out of the system, resulting in a system containing the coarse scale and Lagrange multipliers only. At this intermediate stage, the VMS-EBC approach can be viewed as a stabilized Lagrange multiplier method. The Lagrange multipliers can also be eliminated from the system, yielding a primal formulation. Choosing fine scale basis functions with disjoint support and piecewise constant Lagrange multipliers results in a formulation that is very similar to Nitsche's method. Unlike Nitsche's method, in which a single stability parameter is used to ensure positive definiteness of the system, in VMS-EBC a stability parameter is determined separately for each node on the boundary. In the general case, the stability parameter is a matrix. The VMS-EBC stability parameters arise naturally from the choice of the fine scale and Lagrange multiplier basis functions rather than numerically selected as in Nitsche's method.

The VMS-EBC method is compared to the Lagrange multiplier method and Nitsche's method in several 2D problems. The Lagrange multiplier method is unstable when the Lagrange multiplier nodes are more finely spaced than the nodes in the rest of the domain. VMS-EBC does not suffer from the same instability. VMS-EBC and Nitsche's method generally give comparable performance. VMS-EBC does have lower error for a linear basis and uniformly-spaced nodes. The condition number of the stiffness matrix resulting from VMS-EBC and Nitsche's method was also investigated. For both methods, the condition number increases as the discretization is refined. For a given discretization, VMS-EBC has a lower condition number. The VMS-EBC approach described here offers an alternate view on weak enforcement of EBCs and the determination of stabilization parameters.

Title: Topology Optimization of Dynamic Structures Using a State Space Representation

Author(s): *Andrew H. Fletcher, *University of Illinois at Urbana–Champaign*; Philip M. Renkert, *University of Illinois at Urbana–Champaign*; Andrew G. Alleyne, *University of Illinois at Urbana–Champaign*; Kai A. James, *University of Illinois at Urbana–Champaign*;

Traditionally, multidisciplinary dynamic system optimizations are performed as shape or sizing optimizations. While very useful and efficient, these optimizations restrict the design space to only improve the existing design features. On the other hand, topology optimization allows for the creation of new features therefore making it a promising direction for dynamic system design optimization [1]. This work proposes a modular and easily extendable approach to performing dynamic system topology optimization. This paper first presents a flexible method for constructing finite element models that seamlessly interfaces with a centralized design tool. Then, a state space representation [2] is proposed for modeling structural and rigid body dynamics. To form the state space representation, the finite element stiffness matrix is used to model the stiffness of the structural displacements. The mass matrix is constructed using a diagonal lumped representation, and the damping matrix is computed using Rayleigh damping. After simulating the dynamics, the stresses are computed in one operation using a linear map. Additionally, the state space representation facilitates the easy calculation of additional system characteristics such as the eigenvalues. Finally, the dynamics model is used to create a gradient-based topology optimization with analytic sensitivities. The sensitivities are derived using a transient adjoint formulation and validated using finite differences. The optimization is then applied to a simplified quad-rotor optimization problem. The quad-rotor mesh is generated using a centralized design tool which is integrated with the dynamics solver. Additionally, control inputs are generated by a separate simplified quad-rotor optimization of the control inputs and component selection. Preliminary results show that the framework is able to accurately capture dynamic effects and reduce the mass of the quad-rotor structure.

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Using Scratch Tests to Investigate the Rate-Dependence of the Fracture Response of Carbon Nanofiber-Reinforced Cement

Author(s): *Ange-Therese Akono, *Northwestern University*;

Carbon nanofiber-reinforced (CNF) cement is appealing as a means to yield multifunctional construction materials that are electrically conductive, magnetic, and self-sensing. Despite many studies focused on the mechanical properties and the durability of CNF-cement, a fundamental understanding of the role of CNF on the fracture response is still needed. In prior studies, we showed that CNFs toughen Portland cement matrices, by refining the pore size, linking cement hydration products, and by bridging air voids. In this study, we investigate the influence of mechanical loading rate on the fracture response of CNF cement. To this end, we synthesize cement reinforced with 0.1 wt% CNF, 0.2 wt% CNF, and 0.5 wt% CNF. We employ a multistep approach to disperse CNF in Portland cement: after pre-dispersing carbon nanofibers using ultrasonic energy, the carbon nanofibers are further dispersed using un-hydrated cement particles in high shear mixing and mechanical stirring steps. Furthermore, we employ microscopic scratch tests where a sphero-conical probe pushes against the surface of the material under a prescribed linearly increasing vertical force. In our tests, the maximum vertical force is 2.5 N and three loading rates are considered: 2.5 N/min, 5 N/min, and 10 N/min. Meanwhile, the scratching speed varies from 1 mm/min to 10 mm/min. We formulate a nonlinear visco-plastic-fracture model to capture the influence of viscous behavior on the scratch test scaling. We study the influence of CNF content on the scratch rate master curve. This study is important to understand how nanomaterials influence the coupling of creep and fracture in cement. This work is supported by the National Science Foundation.

Carbon nanofiber-reinforced (CNF) cement is appealing as a means to yield multifunctional construction materials that are electrically conductive, magnetic, and self-sensing. Despite many studies focused on the mechanical properties and the durability of CNF-cement, a fundamental understanding of the role of CNF on the fracture response is still needed. In prior studies, we showed that CNFs toughen Portland cement matrices, by refining the pore size, linking cement hydration products, and by bridging air voids. In this study, we investigate the influence of mechanical loading rate on the fracture response of CNF cement. To this end, we synthesize cement reinforced with 0.1 wt% CNF, 0.2 wt% CNF, and 0.5 wt% CNF. We employ a multistep approach to disperse CNF in Portland cement: after pre-dispersing carbon nanofibers using ultrasonic energy, the carbon nanofibers are further dispersed using un-hydrated cement particles in high shear mixing and mechanical stirring steps. Furthermore, we employ microscopic scratch tests where a sphero-conical probe pushes against the surface of the material under a prescribed linearly increasing vertical force. In our tests, the maximum vertical force is 2.5 N and three loading rates are considered: 2.5 N/min, 5 N/min, and 10 N/min. Meanwhile, the scratching speed varies from 1 mm/min to 10 mm/min. We formulate a nonlinear visco-plastic-fracture model to capture the influence of viscous behavior on the scratch test scaling. We study the influence of CNF content on the scratch rate master curve. This study is important to understand how nanomaterials influence the coupling of creep and fracture in cement. This work is supported by the National Science Foundation.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Fatigue Response of Metakaolin-Based Geopolymer

Author(s): *Ange-Therese Akono, *Northwestern University*;

Fatigue is the propagation of fractures in a material under an applied repetitive loading at loads well below the catastrophic level. Fatigue failure occurs in three stages: crack nucleation or regime I, crack propagation or regime II, and catastrophic fracture or regime III. Our research objective is to understand the intrinsic fracture response of metakaolin-based geopolymer. To this end, we employ depth-based sensing methods. First, we rely on cyclic indentation, where a load is periodically applied using a Berkovich indenter. A decrease in the indentation hardness is observed as a function of the number of loading cycles, maximum vertical load, and load increment. Compared to homogenous materials such as glasses and polymers, a higher decrease in indentation hardness is observed in metakaolin-based geopolymers. Using fatigue mechanics modeling, we then calculate the cycles to failures as a function of the maximum applied load. In future studies, we will apply Paris fatigue's law to characterize the fatigue crack propagation law of geopolymers. These studies are important to understand the durability of geopolymer composites. This research was supported by the National Science Foundation under Grant No. DMR 1928702.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Biocompatibility of Geopolymer Scaffolds for Bone Tissue Regenerative Engineering

Author(s): *Ange-Therese Akono, *Northwestern University*; Xinlong Wang, *Northwestern University*; Chongwen Duan, *Northwestern University*; Guillermo Ameer, *Northwestern University*;

Musculoskeletal diseases affect 1 in 2 adults in the United States and result in an annual loss of 5% of the Nation Gross Domestic Product in both direct and indirect costs. An important subset is musculoskeletal trauma that creates a major challenge for restoring full function and appearance. The problem is crucial for patients who have endured massive injuries as well as for elders following an osteoporosis-induced hip fracture. Due to a reliance on titanium-based, polymer-based, and ceramic-based orthopaedic implants, standard tissue engineering methods often result in complications such as infection or bone degeneration due to a mismatch in both geometry and physical properties between the implant and the surrounding natural bone structure. Therefore, there is a gap of knowledge in novel functionally-graded materials for tissue regenerative engineering that are patient-specific, can mitigate bone loss, and promote bone proliferation around the host bone structure. We focus on a new class of materials, geopolymers that are X-ray and alkali-bonded amorphous inorganic polymers, and investigate their biocompatibility. We show that geopolymers are bioinductive. Specifically, we observed the formation of calcium phosphate crystals on the surface of pure geopolymer after incubation in simulated body fluid. We show that geopolymers are biodegradable using accelerated biodegradation tests. We show that geopolymers are biocompatible using mouse fibroblast cells. Finally, the mechanical properties of geopolymers are shown to be close to that of cortical bone. These results suggest that geopolymer materials can be used to replicate bone tissue behavior and induce bone regeneration. This work was supported by the National Institutes of Health under Grant NCATS 3UL1TR001422-06S2.

Title: Damage Detection of Cable-Actuated Origami Structure Using Dynamic Relaxation

Author(s): *Angshuman C. Baruah, *University of Illinois at Urbana-Champaign*; Ann C. Sychterz, *University of Illinois at Urbana-Champaign*;

Adaptive structures can alter their geometry and characteristics for a given application. A powerful tool for the development of adaptive structures is the art of origami. Origami-enabled adaptive structures can be enhanced with biomimetics, the development of synthetic mechanisms that mimic the structure or functionality of biological systems. The origami structure presented in this paper draws inspiration from pill bugs that can alter their shape between a flat and a rolled configuration. The paper aims to characterize the dynamic behavior of the Origami Pill Bug (OPB) structure in both healthy and damaged states along the rolling process. The study attempts to rank various elements of the structure based on their potential to damage.

The application of classical finite element approach for civil engineering-scale structures that are geometrically nonlinear becomes challenging due to high degree of modeling uncertainty associated with scale effects. The study, therefore, utilizes the dynamic relaxation (DR) method with the new module developed for the actuated Miura Ori origami structure [1]. Comparison of the DR method with the experimental model validates its applicability towards form-finding of origami structures [2].

The OPB structure is modeled as bars, hinges, and actuation elements. The model accounts for panel bending and uses a similar topology method as an energy-based approach [3]. The structure is self-stresses in DR by varying the length of the actuation cable. The study also presents an approximation of the cumulative energy per unit cross-sectional area of bar elements for both healthy and damaged cases. The normalized energy value provides a useful indicative measure of the extent of the effect damaging a specific element can have on the OPB structure. The energy produced by activation of folding and bending stiffness of the origami structure is a useful measure to rank elements in terms of their potential to damage. The research also has the potential to contribute towards understanding the origami mechanics and control techniques of adaptive structures.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Rapid Generation of Numerical Models for Cultural Heritage Structures Conservation

Author(s): *Antonio Maria D'Altri, *University of Bologna*; Branko Glisic, *Princeton University*; Stefano de Miranda, *University of Bologna*; Rebecca Napolitano, *The Pennsylvania State University*;

The structural analysis of cultural heritage structures is generally pursued through numerical modelling strategies, given the complex geometrical and mechanical features that distinguish historic buildings. In this framework, even the generation of the numerical model is a challenging task.

In this contribution, advanced possibilities for the rapid numerical model generation of cultural heritage structures are explored and discussed. Particularly, an existing point cloud-to-numerical model procedure previously developed by the authors is herein extended also for non-comprehensive point cloud data of historical buildings, where the lacking information in the point cloud is deduced through off-site virtual tours.

The effectiveness of this procedure for the rapid numerical model generation of cultural heritage structures is investigated by means of a real-scale structure application, and likely damage scenarios are eventually investigated through nonlinear numerical analyses.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Dynamic Deep Learning-Based Power Restoration in Distribution Systems

Author(s): *Ashkan Bagheri Jeddi, *The Ohio State University*; Abdollah Shafieezadeh, *The Ohio State University*;

The optimal feeder reconfiguration (OFR) problem involves finding the optimal distribution system topology through switch operations in order to minimize a certain cost such as the load shedding cost associated with power loss after extreme weather events. Through solving the OFR problem in real-time, the utility operators have access to a power restoration strategy that minimizes the power outages in the distribution system and therefore enhances the resilience of the grid. OFR is a combinatorial optimization problem with power flow equations as the constraints. This problem can generally be NP-hard and is commonly formulated as a mixed-integer nonlinear program. However, for large-scale three-phase unbalanced distribution systems, the number of integer variables significantly increases and therefore it is extremely difficult to solve the mixed-integer model in a timely manner. The plethora of approaches that are commonly employed in the existing literature for solving the OFR problem can be categorized into two classes, namely, formal and heuristic methods. In this study, we propose using temporal graph networks (TGNs) trained under the imitation learning framework to approximate a given optimal OFR solution obtained through formal methods. The efficacy of the proposed method in prediction of the OFR solution is demonstrated for multiple IEEE testbeds.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: End-to-End Deep Learning Method to Predict Stress Tensor Field for Composites with Application in Multiscale

Author(s): *Ashwini Gupta, *Johns Hopkins University*; Anindya Bhaduri, *Johns Hopkins University*; Lori Graham-Brady, *Johns Hopkins University*;

The microscale features control the macroscopic response of materials which are, in succession, affected by the loading at the macroscale structure. These structure-property coupling are often simulated using multiscale approaches such as the finite element method (FEM). However, multiscale FEM requires many calculations at the local scale which are often computationally intractable. Here, we report a significantly faster data-driven machine learning based approach in multiscale materials modeling. In this work, we develop a deep learning model to predict stress tensor field at the local level in a fiber-reinforced composite material. A U-Net convolutional neural network (CNN) is employed to develop a mapping between the spatial arrangement of fibers and the corresponding 2D stress tensor field. The machine learning model is trained using a set of input and output image data obtained from running the FEM model for a series of random microstructures under uniaxial tension and shear loading. We use our model in a multiscale simulation framework and demonstrate excellent accuracy in homogenization of elastic material properties and localization of stress tensor field. We observe that the predicted stress from our deep learning model show excellent convergence with the stress obtained from concurrent multiscale model using FEM, the latter being computationally very expensive. Also, the numerical example of multiscale modeling of L-shaped plate shows the uncertainty introduced due to the spatial arrangement of fibers. Our approach shows tremendous potential in the efficient multiscale simulations of materials and uncertainty quantification in multiscale.

Title: On the Use of Principal Component Analysis for ATR-FTIR Spectra, Obtained from Bitumen During Oxidation as a Tool for Differentiate Asphalt Binders

Author(s): Michalina Makowska, *Aalto University*; *Augusto Cannone Falchetto, *Aalto University*; Mika Kögäs, *Aalto University*; Leena Korkiala-Tanttu, *Aalto University*;

The composition of bitumen is known to affect the performance in the field. However, current European regulations behind the CE-marking, do not require the producers to evaluate the mixture's performance parameters upon the change of bitumen constitution. The infrared analysis of fresh binders was previously suggested to aid in recognition of the bitumen products containing different polymer contents [1] and linking the binder's chemical composition to performance [2]. Additionally, it was observed that differing binder origins influenced the oxidation reaction, providing the possibility to recognize the bitumen products [3]. Building on these observations, an attempt to create a two-step analytical procedure for the recognition of bitumen composition was pursued hereby. Four asphalt producers and three binder producers supplied the samples to the project, resulting in a unique database of 54 products of various compositions and grades.

The samples were tested using infrared spectroscopy performed on the fresh binder at room temperature and during the oxidative reaction performed in-situ on the infrared spectrometer for the period of 2 hours. The fresh samples were each tested 9 times, providing over 500 spectra entries for analysis. During the oxidation reaction, spectra were collected every four minutes, creating additional 31 spectral entries per sample. To process this relatively large database of spectra, a Machine Learning Algorithm, namely Principal Component Analysis (PCA), was applied to the generated database to evaluate its applicability to this problem.

The Machine Learning Algorithms applied to ATR-FTIR analysis are promising for the differentiation of the bitumen samples in a faster manner than the current Quality Control tests. The PCA algorithm was applied to the unoxidized spectra, and first-level differentiation between soft and non-soft binders was plausible. Unfortunately, the PCA was unable to differentiate between smaller grade differences in unoxidized bitumens.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: A Data-Driven Model for Master Curves of Viscoelastic Materials

Author(s): *Babak Asadi, *University of Illinois at Urbana-Champaign*; Ramez Hajj, *University of Illinois at Urbana-Champaign*;

Latest developments in machine learning have led to new capabilities to predict the properties of materials. The viscoelastic behavior of bituminous materials is frequently defined using a master curve developed based on employing the time-temperature superposition principle. However, the constitutive model used to fit the master curve is typically chosen arbitrarily among a previously established model to work for similar materials. Given recent advances in asphalt materials, including high amounts of polymer additives and the increased use of recycled binders in conjunction with recycling agents, the validity of the time-temperature superposition principle can no longer be taken for granted. In addition, it is much harder to know the appropriate model for delineating distinct patterns in the master curve of different binders. In this work, the authors propose a novel data-driven approach for predicting the master curve of asphalt binders and subsequently viscoelastic materials. To this end, isotherms were freely shifted to generate master curves. This approach was adopted since the commonly used constrained shifting method forces master curve or shift factors to fit a predefined function. Afterward, having performed hyperparameter tuning for artificial neural networks by considering a wide range of experimental results, we developed an optimum unified deep network architect, which prevailed over both simpler and more complex structures. The adopted activation function also plays a crucial role in finding the superior model. Graphical comparisons and goodness-of-fit statistics revealed that the ML-based model for fitting master curves of both complex shear models and phase angle considerably outperformed existing mathematical and mechanical models. Similar superiority of the model was observed for asphalt mastics and different kinds of polymers. It is worth mentioning that the derived smooth ML-based model catches any pattern in the master curves, and does not overfit, nor is it negatively affected by some intentionally added outliers in test results.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: A Comparative Study on Life-Cycle Cost of a Tall Concrete Core-Wall Building Using Prescriptive and Performance-Based Wind Designs

Author(s): *Baichuan Deng, *University at Buffalo*; Teng Wu, *University at Buffalo*;

The wind engineering of tall buildings is moving toward the performance-based wind design methodology. Compared with the conventional prescriptive wind design method (e.g., ASCE-7), the performance-based wind design (PBWD) can clearly articulate stakeholder's expectations and explicitly satisfy performance objectives. Moreover, it shows potential to improve the structural economy since the controlled inelastic behavior of the designed structure is allowed. Currently, there are very limited buildings designed with performance-based wind engineering approach. To quantify the benefits of PBWD, systematic case study on the life-cycle cost of tall buildings designed with prescriptive and performance-based methods is needed. In this study, two design plans for the main wind force resisting system of a tall concrete core-wall building are generated based on ASCE-7 and performance-based procedures. The essential difference between the two design processes for tall buildings is highlighted. A thorough evaluation of the wind resistant capacity of the buildings associated with the two design plans using the performance objectives described in the ASCE pre-standard for PBWD is developed. Finally, a detailed comparison on life-cycle cost considering the initial cost and repair cost for the two design plans is also carried out.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Glulam Beams with Finger-Joints – Numerical and Analytical Model

Author(s): *Barbara Fortuna, *University of Ljubljana*; Goran Turk, *University of Ljubljana*; Simon Schnabl, *University of Ljubljana*;

Multilayer structural elements are very common in modern engineering, and this is also true for timber components. In our research, the numerical model of a two-layer beam was developed. The model takes into account the heterogeneity of the material properties of wood and includes finger-joints, which have been shown to be crucial for the load-bearing capacity of glulam beams. In general, the model allows for any number of layers. However, the beam model is defined with two layers connected with the weakest of all interlayer connections. The novelty of the model is the implementation of an arbitrary number of finger joints which can be positioned in the lower or/and the upper lamella.

The model is based on the Timoshenko beam theory and therefore also takes into account the shear deformation of the lamellae. It is assumed that shear deformation between the two layers is identical. The model allows the interlayer slip but the uplift is restrained. These assumptions are consistent with the expected failure modes, which in most cases are related to either material failure and/or finger-joint failure in the tension zone of the beam or shear failure of the adhesive joint parallel to the laminations, in the zone of maximum shear stress above the supports of the beam, where maximum sliding between the layers is also expected. The numerical model can be loaded with distributed or point loads in any direction.

To validate the numerical model, an exact analytical solution was obtained. The analytical model considers the same assumptions as the numerical one. Since the complexity of the exact solution increases with the number of finger-joints, the validation is performed for the beam model with one finger-joint. Comparisons of the internal forces, displacements and slips under load are made. The comparison of the results of the two models shows a very good agreement.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Why Gannets Survive Repeated Plunges at High Velocity

Author(s): *Bart Boom, *University of Washington*; Anthony Nguyen, *University of Washington*; Andrew Duim, *University of Washington*; Aidan Sleavin, *University of Washington*; Simon Shimel, *University of Washington*; Frank E. Fish, *West Chester University*; Tadd Truscott, *King Abdullah University of Science and Technology*; Ed Habtour, *University of Washington*;

The body of a gannet, deep-diving bird, is designed to plunge repeatedly into water at dangerously high velocities to search for food up to a 60 ft depth. The presentation will provide experimental insights into why the gannet vertebrae can withstand high rate extreme compression loads without damage. The object of the experiment is to reveal which mechanisms is more important for the impact survivability of diving birds, their aerodynamics [1] or biomechanics. Simplified segmented structures inspired by the gannet vertebrae are tested at various velocities in an aquatic tank. The bio-inspired vertebrae structure is compared to (i) structural systems that consist of bones with various cross sectional shapes; and (ii) vertebrae with heads that have different beak geometries. While the aerodynamic design of gannet bodies play an important role in their ability to safely perform dangerous plunges[1], our preliminary findings suggest that the internal segmentation and morphology of their vertebrae design provide improvement in dissipating the impulse energy due to impact.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Nonlinear Lattices Violating A Thermodynamic Law

Author(s): *Bart Boom, *University of Washington*; Ed Habtour, *University of Washington*;

Both classical mechanics and statistical thermodynamics tell us when a single mode (or state) energy is injected into a system of nonlinear lattices, the energy will diffuse into other modes (or states) until an equipartition is reached. Surprisingly, for a system of lattices with weakly nonlinear interactions, almost all but 3% of mode 1 energy will return to its initial state, which is in contradiction with the equipartition law of thermodynamics. This contradiction is referred to as the energy recurrence paradox— not well understood phenomenon since its discovery in nonlinear lattices by Fermi, Pasta, Ulam and Tsingou in 1956. This discovery continues to raise many scientific questions and challenges for researchers until this day. This presentation provides computational insights into the behaviors of the energy recurrence in a nonlinear structural system with weakly quadratic and cubic nonlinear interactions. The numerical results indicates that the energy recurrences are more stable for high quadratic than cubic non-linearity. Furthermore, the outcomes also show that the amount of energy return back into a quadratic system's initial state is higher than for lattices with cubic interactions.

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: An Equivalent D50 to Predict the Erodibility of Cohesive Riverbed Soils in Nebraska

Author(s): *Basil Abualshar, *Department of Civil and Environmental Engineering, University of Nebraska-Lincoln*; Chung Song, *Department of Civil and Environmental Engineering, University of Nebraska Lincoln*;

One of the commonly used methods to predict the erosion rate of soils is the excess shear stress method that is based on the parameters such as the erodibility coefficient and the critical shear stress. In addition, studies showed that the mean grain size diameter D50 could be correlated to the erosion resistance of soils on the river bed, particularly for sandy soils. If the same technique can be used for cohesive soils, the prediction of river bed erosion may be conveniently conducted even for cohesive soils. However, cohesive soils may have different shapes from those for cohesionless soils, and therefore they may have different hydrodynamic characteristics such as Froude number and Reynold's number. Consequently, the D50 of cohesive soils may not accurately represent the erosion characteristics of the soils. This study aimed to find equivalent sand particle diameter (D50) for the cohesive soils experimentally for soils in Nebraska. To achieve this goal, 16 soil samples from four different rivers in Nebraska were tested using the Mini Jet device (Hanson type) to obtain the erodibility coefficient and the critical shear stress. After the tests, the erosion depth was simulated using FLOW3D, which incorporated the effect of the particle diameter and other hydrodynamics parameters. This study found that the equivalent D50 appeared substantially different from the D50 from the gradation analysis, showing that the revised D50 needs to be used to predict the riverbed erosion more realistically.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Beyond Elastocapillary: The Elastic Plateau-Rayleigh Instability in Polymeric Gels

Author(s): *Berkin Dortdivanlioglu, *The University of Texas at Austin*;

To date, the mechanics of interfaces of soft solids, e.g., polymeric gels, remain elusive. In particular, the mechanical properties of the bulk gel can differ from its boundary due to the fundamental role of surface tension and other lower-dimensional energetics at length scales of nanometers to millimeters. From a theoretical perspective, classical continuum mechanics is size-independent and lacks a physical length scale. A characteristic length scale and size-dependent material response can be captured in continuum models by accounting for the energetic competition between the bulk gel and its boundary. This energetic competition, referred to as the elastocapillary effect, plays a vital role in cavitation, soft composites, wetting on soft substrates, adhesive failure, and pattern formations in polymeric gels.

A fundamental challenge in understanding the behaviors of soft materials at small scales is the emergent mechanical instabilities due to dominating elastocapillary stresses, e.g., the recently observed Plateau-Rayleigh (P-R) instability at soft gels. In liquid P-R instabilities, the surface tension overwhelms cylindrical liquid columns and breaks up the cylindrical column into spherical droplets. However, in solid P-R instabilities, the bulk elasticity will resist the capillary forces, limiting the break-up. The competition between capillary and bulk energies results in cylinders-on-a-string morphology in soft gels compared to spherical bead formations in liquid columns. This contribution quantifies solid-surface competition and assesses the highly nonlinear post-instability regime in soft solids at small scales.

The key focus of this presentation is to develop a computational framework modeling solid P-R instabilities using a surface-enhanced isogeometric finite element technique. First, we will show that the solid P-R instability is mainly a subcritical (discontinuous) bifurcation, which requires the development of path-following methods to track stable and unstable equilibrium paths. Next, equipped with an arc-length-type nonlinear solution methodology, we study both the onset and the post-instability behaviors. We present numerical results illustrating the entire evolution of P-R instability. Our findings show that the soft cylinders form two distinct radii connected by a transition region with a finite width. Importantly, we show that the cylinders-on-string formations in hydrogels are highly tunable by controlling the applied stretch, residual stresses, compressibility, and the characteristic length scale. The proposed methodology provides a robust computational foundation to elucidate elastocapillary instabilities in soft hydrogel fibers.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Coupled Artificial Intelligence and Classical Constitutive Model to Predict the Concrete Response Under the Extreme Loading

Author(s): Taehyo Park, *Hanyang University*; *Bilal Ahmed, *Hanyang University*; Jong-Su Jeon, *Hanyang University*;

In the proposed work, the material modeling for each phenomenon (stress wave propagation, refraction, negative pressure, debris formulation, temperature variations, etc.) that happens under loading (static, earthquake, impact, blast loading) will be developed and framework will be proposed for the coupling of various phenomena, by different techniques of machine learning (Artificial neural networks, Convolution neural networks, long short-term memory, etc.). The constitutive model developed at the material level is extended to the structural level using machine learning techniques. We are intended to develop an Artificial intelligence network using FEM coupled for various phenomena under complex static, dynamic, and impact loading. To achieve the necessary goals, starting from the basics, the simplest constitutive model will be developed or adopted from the literature to capture each phenomenon (stress wave propagation, refraction, negative pressure, debris formulation, temperature variations, strain variations, irreversible deformation, damage propagation, etc.), and the dataset will be generated at the material level, which will be used by machine learning in future. In the presented scope, a small dataset will be used to test the machine learning framework. In the future, it can be extended by adding more and more data. Once the different uncoupled constitutive models will be developed and the uncoupled results are obtained, few experimental works will be obtained from the literature to produce coupled results. The coupled results from the experiment and uncoupled results from the constitutive model will be bridged using a machine learning framework. This trained machine learning will be the main goal to obtain coupled constitutive models for all the phenomena happening under complex and extreme loading. As, theoretically, and mathematically, these phenomena are difficult to be coupled and they will be computationally expensive. Therefore, this work will be performed by the machine learning method. The benefit of using machine learning is that more addition conditions can be added simply and can be further extended to most severe cases (hypervelocity impact, extreme temperature, and extreme pressure).
Keywords: Extreme Loading, Machine Learning, Constitutive Modeling, Damage Propagation.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Research on Multi-Gas Three-Dimensional Development and Carbon Storage Technology of Deep Coal-Bearing Rock System

Author(s): *Bing Hou, *China University of Petroleum;*

The complex ground stress, non-homogeneity and anisotropy are significant when the deep coal-bearing system is developed with multiple lithologies and multiple deserts superimposed, thus leading to the engineering problems of short seam-making distance and low flow-conducting capacity in the horizontal and height directions. Supercritical CO₂ fracturing is the key to solve the above problems, which can enhance the capacity release of deep coal gas and increase CO₂ sequestration. The fracture propagation mechanism of supercritical CO₂ fracturing in coal-bearing rock systems is not clear, so it is urgent to study the propagation mechanism of non-planar supercritical CO₂ fracturing through layers and the method of fracture height control. The mechanical properties, deformation damage and fracture characteristics of different lithologies under the action of supercritical CO₂ are studied to reveal the non-linear deformation damage and anisotropic characteristics of rocks from the microscopic perspective. The elastic-plastic fracture damage constitutive model is established to study the tension-shear slip damage mechanism, damage characteristics of fractured rock mass and fracture initiation and evolution process of lithologic transition zone. The non-planar propagation of fractures in transition zones and the formation mechanism of complex fracture bodies are revealed. Based on the supercritical CO₂ true triaxial fracturing experiment, the theoretical model and criterion of artificial fracture penetration through the lithologic interface are verified, so as to form the control technology to improve the scale of fracture network reconstruction. Combined with the heterogeneous in-situ geological conditions of the deep coal measure strata and different construction conditions, the numerical model of heat-fluid-solid-chemical multi-field coupling CO₂ fracturing-displacement-storage is established and verified. Study the integration technology of supercritical CO₂ fracturing-displacement-burial storage, and establish the process optimization method of the integration technology of supercritical CO₂ fracturing, displacement and effective carbon storage to improve the production capacity and CO₂ storage capacity of coal measure gas.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Molecular Interaction of Asphalt-Aggregate Interface Modified by Silane Coupling Agents at Dry and Wet Conditions

Author(s): *Bingyan Cui, *Rutgers University*;

This study investigated interfacial behavior between asphalt binder and aggregate through Molecular dynamics (MD) simulations. Asphalt-aggregate systems were constructed at dry and wet conditions to observe the effects of silane coupling agent (SCA) on adhesion and moisture susceptibility of asphalt mixtures.

It was found that the SCA modification could improve the adhesion between asphalt and aggregate at dry condition. The asphalt molecules can penetrate the SCA film on aggregate surface and form a compact transition zone between asphalt and aggregate. The transition zone helps enhance the compatibility and improve the force transfer between asphalt and aggregate since the thickness and compactness of transition zone became greater after the SCA modification.

The static contact angle simulation of asphalt droplet on aggregate surface showed that wetting behavior of asphalt binder on aggregate changed from non-wetting to partial wetting after using SCA. During the wetting simulation, asphaltenes and resins are distributed closer to aggregate surface than aromatics and saturates.

At wet conditions, the decreasing percentage of interaction energy for the SCA modified interface was much lower than that of non-modified one. The SCA grafted on aggregate surface mitigates the attraction of hydroxyl groups to water and reduce the formation of hydrogen bonds. Also, fewer water molecules would agglomerate on the SCA-modified surface.

Although all three types of SCAs had positive benefits on interfacial bonding of asphalt-aggregate systems, the SCA with amino group showed superior performance.

The SCA has been widely used in practice since its bi-functional nature in enhancing the interfacial bonding between asphalt binder and aggregates. However, not each type of SCA can reach the same performance.

Incorrect modifications can be counterproductive. Traditional experimental tests, including contact angle test, tensile test, and boiling test can be used to evaluate the performance of different SCAs. But it is time-and-cost consuming to screen the optimum SCA from various agents. Through this study, we have found that MD simulations can also obtain comparable results with experiments in evaluating the performances of different types of SCAs.

Therefore, it turns out that MD simulations can not only be applied to pure asphalt binder and aggregate, but also to functionalized interface modification, which could be a promising research topic in the future.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Identification of Dam Leakage Using Hydrothermal Coupled Analysis and Distributed Temperature Sensing

Author(s): *Binyam Bekele, *University of Nebraska-Lincoln*; Chung Song, *University of Nebraska-Lincoln*;

Seepage-related structural health monitoring is a critical task to address dam safety concerns. The advent of fiber optics Distributed Temperature Sensing (DTS) technology presented growing potential in the hydrothermal coupled (HTC) approach for monitoring the seepage condition of earthen dams. However, the method is still not well developed and needs more research. This study disseminated fundamental aspects of the HTC approach based on a well-controlled laboratory test and numerical simulation of a homogenous dam subjected to artificial leakage. The temperature variability of the dam arising from the boundary heat flux and internal advection-conduction mechanisms was instrumented using a high-resolution DTS. The leakage zone showed a distinct temperature pattern and profile compared to healthy zones due to substantial advection-driven heat flow. In addition, the temperature anomaly was magnified, and defects were easily exposed for a considerable leakage or higher thermal gradient. Computational Multiphysics modeling of the dam confirmed DTS findings and showed that the temperature contains clear and vital information about the integrity of earthen dams.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Asymptotic Analysis of Berry Phase Governed by the Scalar Wave Equation

Author(s): *Bojan Guzina, *University of Minnesota*; Othman Oudghiri-Idrissi, *University of Minnesota*; Shixu Meng, *Chinese Academy of Sciences*;

We deploy an asymptotic model for the interaction between nearby dispersion surfaces and respective eigenstates toward explicit evaluation of the Berry phase governed by the scalar wave equation in 2D periodic continua. The model, featuring a pair of coupled Dirac equations, endows the interacting Bloch eigenstates with an explicit gauge that caters for analytical integration in the wavenumber domain. Among the featured parameters, the one ($s \in [0, 1/2]$) that synthesizes the phase information on the coupling term is shown to decide whether the Berry connection round the loop is singular ($s = 0$) or analytic ($s > 0$). We show that the Berry phase is π -quantal and topological when $s = 0$, equaling π when the contour encloses the apex of a Dirac cone and zero otherwise. The analogous result is obtained when $s \in (0, 1/2]$ and similarly for $s \in [0, 1/2)$. In the interior of the s -domain, we find that the Berry phase either equals π or is not quantal. Beyond shedding light on the anatomy of the Berry phase for 2D periodic continua, the featured analysis carries a practical benefit for it permits single-wavenumber evaluation of this geometrical phase quantity.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Low-Cycle Fatigue Performance of Cu-Al-Mn Superelastic Alloys Under Different Temperatures

Author(s): Huanpeng Hong, *University of Southern California*; *Bora Gencturk, *University of Southern California*; Hadi Aryan, *University of Southern California*; Amit Jain, *University of Southern California*;

The large strain recovery and excellent energy dissipation capability render shape memory alloys (SMA) a preferable material for seismic applications. The commonly used SMA in earthquake engineering are Ni-Ti based. However, the Ni-Ti based SMA are very expensive and hard to machine, which prevent them from being widely used as a construction material. As an alternative to Ni-Ti based SMA, the Cu-Al-Mn (CAM) superelastic alloys (SEA), which show excellent strain recovery behavior under a wide-range of operating temperatures, have attracted attention recently. The authors' previous research has shown that the CAM SEA have comparable superelastic strain recovery and better temperature/frequency stability compared to Ni-Ti SMA. However, the previous research was limited to few specimens and only conducted to a few hundred cycles without considering the full deterioration in the material properties. The testing was also only limited to room temperature, which is not sufficient to validate the use of CAM SEA for engineering applications. To fill this knowledge gap, in this research, the low-cycle fatigue behavior of CAM SEA in comparison to Ni-Ti based SMA is studied at -45°C, 25°C and 50°C. Strain cycles exceeding 10,000 have been applied at a tensile strain of 5%. These parameters cover most civil engineering conditions. Variations in superelastic properties are observed and analyzed, including the stress-strain curve, recovery strain, elastic modulus, transformation stresses and the damping ratio. The large number of fatigue cycles and the temperature range considered in this study verifies the feasibility of using CAM SEA in earthquake-prone regions.

Title: An Active Noise Cancellation Method for Ultrasonic Signals on Metal Cylindrical Containers

Author(s): Bozhou Zhuang, *University of Southern California*; *Bora Gencturk, *University of Southern California*; Iman Asareh, *University of Southern California*; Assad Oberai, *University of Southern California*; Ryan Meyer, *Pacific Northwest National Laboratory*;

Abstract

Detecting gas composition using ultrasonic acoustic sensing is of great significance for cylindrical steel structures. For example, the dry storage canisters (DSC) are sealed cylindrical structures containing spent nuclear fuels (SNFs) assemblies, and they are filled with an inert gas such as helium. During storage, the gas properties may change, and this change could indicate potential abnormalities in the stored high-level waste[1]. Since it is a tedious task to open and investigate these packages, non-destructive testing (NDT) methods using ultrasonic signals are being investigated[2]. Ultrasonic signal can be coupled into the gas through the cylinder wall and picked up by a receiver on the other side. However, a stronger signal (i.e., "noise") propagates through the structure because the acoustic impedance of steel and gas is greatly different. In this study, to minimize the structural noise, an active noise cancellation method is proposed by assuming that the wave propagation is linear and time-Invariant (LTI). Subsequently, the LTI assumption is verified on a 3-D model of a physical cylinder chamber through numerical analysis. It is shown that the noise can be minimized by optimizing the excitation of multiple transducers. Specifically, the peak-to-peak amplitude in the interested time window could be significantly reduced by optimal placement of transducers and with proper scaling and time shift. Besides, the cancellation performance using more transducers with different layouts are also investigated and evaluated. This reduction in the noise could enable the detection of the signal propagating through the gas and allows for monitoring gas composition. The proposed noise cancellation method in this presented study is meant to be applied on the canister for SNFs, yet it can be extended to all cylindrical steel structures such as gas fuel storage tanks, and natural gas pipelines, among others.

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Bayesian Model Updating of Spent Nuclear Fuel Assemblies with Experimental Data Considering Uncertainties in the Modeling and Experiments

Author(s): Mehrdad Aghagholizadeh, *University of Southern California*; *Bora Gencturk, *University of Southern California*; Roger Ghanem, *University of Southern California*; Anna Arcaro, *University of Southern California*; Nidhi Thanki, *University of Southern California*;

Nuclear fuel assemblies need to be stored permanently at the end of their lifecycle. Due to the hazardous nature of the radioactive material, a safe storage of the spent nuclear fuel (SNF) assemblies is crucial. The Nuclear Waste Policy Act of 1982 requires that the United States Department of Energy takes custody of the SNF from commercial power plants in the United States. This creates a need for a swift plan to transport the SNF to an interim or long-term storage location. To carry out a safe transportation program, it is crucial to understand the dynamics of the SNF packages and identify any abnormality or damage to the system prior to transportation. This study introduces a methodology to perform Bayesian model updating of high-fidelity finite element models that employ dynamic model reduction techniques using experimental data. Uncertainties related to modeling (i.e., simplifying assumptions, lack of understanding of the real structural system such as boundary conditions, material models, etc.), and experimental measurements are taken into consideration. This results in an accurate model to predict the possible damage scenarios and prevent such failures. Particularly, finite element model updating of mock-up SNF assemblies under dynamic loading is performed. The physical models are 2/3 scale mock-up of fuel assemblies made of structural steel. In the first stage of the study, a comprehensive experimental modal analysis is conducted. In the second stage, high-fidelity finite element models of the fuel assemblies are developed in LS-DYNA. A nested Craig-Bampton method is implemented to reduce the computational time associated with the solution. Finally, a Bayesian model updating is performed to construct probabilistic distribution of the parameters of the model.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Engineered Aggregates for Self-Healing Concrete

Author(s): Xiaoying Pan, *University of Southern California*; *Bora Gencturk, *University of Southern California*;

Self-healing concrete incorporating brittle macrocapsules faces challenges in terms of survivability of the brittle capsules during the mixing, placing and consolidating of concrete. This study presents the preparation and application of engineered aggregates (EA), which is a novel encapsulation method for randomly embedded self-healing inclusions in concrete in the same way of natural aggregates. EA are made of glass capsules coated with a cementitious material. The performance of EA during mixing and influence on fresh and harden concrete are investigated. The results showed that EA are capable of resisting the harsh conditions of concrete mixing and sufficiently weak to break once cracks appear in concrete. The reduction of the concrete strength due to embedded EA is about 10%. Concrete samples containing EA with different healing agents are pre-cracked and healed in a high humidity condition. Self-healing effect of EA is investigated in terms of recovery in the tensile strength, visual observation on crack healing, and improvement in durability based on water permeability and absorption tests. After seven days of healing, the split tensile strength of cracked concrete with a specific healing agent was up to 80% of the uncracked concrete. The durability of healed samples also reached almost to those of the uncracked samples in terms of water absorption. This study presents the findings on self-healing efficiency with cost-effective and easy to apply engineered aggregates.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Damage Identification of a Spent Nuclear Fuel Canister Structure with an Accurate Multi-Level Nested Substructuring Model

Author(s): Xiaoshu Zeng, *University of Southern California*; *Bora Gencturk, *University of Southern California*; Roger Ghanem, *University of Southern California*; Olivier Ezvan, *Université Gustave Eiffel*;

In this study, nondestructive identification of internal damage for complex systems through linear dynamic signals is investigated. The structure of particular interest is a fully-loaded spent nuclear fuel canister (FLSNFC). The fuel pellets are placed in slender fuel rods bundled by spacer grids along their height into fuel assemblies (FA). In a typical boiling water reactor spent nuclear fuel storage configuration, 68 FAs are inserted into a honeycomb basket structure and placed in a cylindrical canister. In this study, the dynamic responses are measured on the exterior surface of the canister bottom plate and are used for structural integrity assessment of the internal components. The dynamics effects of the fuel rods are first transmitted to the FA through the spacer grids. Next, these effects are transmitted to the canister bottom plate via two routes: i) directly through the point connection between the FA and the bottom plate; ii) first to the basket structure through the connection between the FA and the basket at the top, then to the bottom plate. To detect the change of dynamic signals at the canister bottom plate before and after damage, the computational model must be able to describe relevant structural levels. This is achieved by a multi-level nested Craig-Bampton substructuring technique proposed by the authors, in which an accurate computational model is constructed with a manageable cost. Damage localization for different scenarios is investigated: i) misloading of FAs; ii) severe damage to the FAs; iii) severe damage to the fuel rods. With observation and excitation points underneath each of the 68 FAs on the canister bottom plate, an accurate computational model can detect the location of the damaged FAs for each of these scenarios.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Investigating Lost Heritage Structures: Digital Reconstruction of Vezir's Great Bridge

Author(s): Andronira Burda, *Polytechnic University of Tirana (Universiteti Politeknik i Tiranës)*; James McDonagh, *Princeton University*; Moriah Hughes, *Princeton University*; *Branko Glisic, *Princeton University*;

Lost heritage structures represent a loss of cultural values and at the same time a loss of knowledge. Therefore, while preservation and restoration initiatives utilize extant, physical case studies for investigation and analysis, lost heritage requires the exploration and development of different and innovative analyses tools in the absence of the physical object of study. This research project for the digital reconstruction of Vezir's Great Bridge develops methods for visualizing in-absentia architecture and providing researchers with the necessary digital dataset for future scientific investigations.

The Ottoman Vezir's Great Bridge, built in the early 19th century and located along the possible ancient Roman route Via Lissus-Naissus – which connected the Adriatic coast with the Central Balkans – conceived a dramatic, yet elegant shape that blended harmoniously with the surrounding mountainous environment of the Drin Valley in Albania. It represented one of the first slender and light-weight masonry structures in this region, but was destroyed during war times in the early decades of the 20th century and its remains inundated by the waters of the Fierza Hydropower Plant built in the mid-70's.

This lost heritage constitutes an interesting imprint to be further studied and analyzed in the architectural, engineering, and construction fields. Therefore, the research team performed archival investigations to collect the (limited) available quantitative and qualitative information necessary to produce a visual dataset to be further used for scientific investigations. A photogrammetric digital reconstruction to generate the necessary 3-dimensional model dataset was unachievable due to lack of images. Lack of project design drawings or surveying documentation also made it challenging to produce accurate orthogonal projections based on which a 3D model could be further elaborated.

Ultimately, the team identified an integrated method through historical and archival research combined with CAD tools and aided by the theoretical background of descriptive geometry to elaborate a digital reconstruction of this lost heritage. A method which can be further used for extrapolating digital visual datasets for other lost heritage structures with very limited documentation.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Elasto-Plastic Hourglass Control for Physically Stabilized Non-Linear Finite Elements with Reduced Integration

Author(s): *Brian Giffin, *Lawrence Livermore National Laboratory*;

A physically stabilized hourglass control scheme is proposed for low-order finite elements with reduced integration, specialized to the case of elasto-plastic material behavior. Conventional hourglass stabilization techniques necessitate an ad hoc reduction of the element's stabilization stiffness parameters to prevent artificially stiff behavior under large plastic deformations. In contrast, the proposed approach circumvents this difficulty by instead enabling plastic deformation in the element's hourglass modes. The method employs an elasto-plastic model order reduction strategy over a given finite element domain to effect a non-linear form of hourglass stabilization, bearing similarity to a resultant plasticity model. Specifically, a mixed discretization of the element's hourglass stress/strain fields is established within a co-rotational frame, and supplemented by a stabilizing plastic strain field to characterize the plastic deformations associated with the hourglass modes. An L_p measure of the hourglass stress field is integrated over the element domain to obtain an element-averaged representation of the stabilizing effective stress. By exploiting the mixed representation of the hourglass stress field, the resulting integrals can be efficiently evaluated without recourse to quadrature. The chosen effective stress measure is then used to generalize an element-based yield criterion, which is designed to inherit the same yield stress and hardening parameters from the constitutive model associated with the element's single integration point. Within this framework, a generalization of the classical radial return algorithm for continuum plasticity is proposed to facilitate a convenient and computationally efficient evolution of the stabilizing plastic strains. The method is formulated to satisfy an element-averaged dissipation inequality, and the resulting stabilization scheme is demonstrated to exhibit energetic consistency. The proposed technique is applied to low-order hexahedral elements, and may be viewed as an elasto-plastic extension of the physically stabilized element formulation introduced by Puso (2000). The efficacy and computational efficiency of the method are explored through a variety of large deformation elasto-plastic problems in explicit dynamics, and compared against conventional hourglass stabilization approaches.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: One-Shot Methods for Topology Optimization of Flow Problems

Author(s): *Bruno Barroca, *KU Leuven*; Maarten Blommaert, *KU Leuven*; Mattias Schevenels, *KU Leuven*; Martine Baelmans, *KU Leuven*;

Following the recent advances in manufacturing technologies, topology optimization has become a valuable tool for the design of mechanical components. Increasing the component complexity for industrial applications motivates the use of three-dimensional domains with high resolution. This calls for low-memory solvers for the state and adjoint problems, which are known to be the bottleneck in terms of problem size.

Typically, topology optimization is done using a nested approach, by decoupling the state, adjoint, and design equations. Consequently, there is the need to solve a set of PDE's numerous times before there is convergence of the design, meaning that ideally, wall clock time of state and adjoint solutions should be kept low. This led to its widespread application on problems that can quickly be solved numerically, and to the selection of fast, memory-hungry solution methods whenever there is a choice to be made. In flow problems, conversely, so-called segregated solvers that iteratively solve the coupling between mass and momentum conservation are often preferred for their lower memory usage. These segregated solvers, however, tend to come at a high computational cost, thus strongly limiting their use in large-scale topology optimization.

In the context of aerodynamic shape optimization, one-shot optimization was pioneered for solving unconstrained optimization problems, by exploiting the fixed-point nature of iterative solvers to converge the state, adjoint and design variables simultaneously. In this contribution, a one-shot optimization algorithm is presented that copes with the high dimensionality that is intrinsic to topology optimization, while also handling the constraints.

The proposed one-shot approach was applied to two benchmark laminar flow problems. The developed algorithm was shown to be robust with regards to its tuning parameters. When compared to a nested approach using the same state and adjoint solver, the one-shot approach results in a speedup of between 7 to 12. This is in line with results reported for one-shot shape optimization of flow problems. Furthermore, the one-shot method is also compared to a nested approach using a Newton method for the state solution, showing to be maximally about two times slower.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Full-Waveform Inversion of Seismic Input Motions at a Domain Reduction Method Boundary in a Domain Truncated by PML

Author(s): *Bruno Guidio, *Central Michigan University*; Heedong Goh, *The University of Texas at Austin*; Chanseok Jeong, *Central Michigan University*;

A new inversion approach is developed for estimating seismic ground motions in an interior domain surrounded by a domain reduction method (DRM) boundary from sparsely-measured seismic motion data by identifying seismic input motions at the DRM boundary. A 2D solid domain of the plane-strain setting truncated by non-convolutional second-order complex-frequency-shifted perfectly matched layers (CFS-PML) is considered, and the DRM is utilized to propagate incident waves into the domain. We attempt to identify an effective seismic force at the DRM boundary and reconstruct the ground motions and structural responses in an interior domain. To this end, a gradient-based optimization method minimizes a misfit between measured motions induced by targeted incident waves (or equivalent effective forces on a DRM boundary) and their estimated counterparts induced by reconstructed effective forces. The presented method includes the discretize-then-optimize (DTO) approach, the finite element method (FEM), which is used for solving state and adjoint problems, and the conjugate-gradient scheme, determining the desired search path throughout a minimization process. The numerical results show that (1) targeted effective forces are in good agreement with their reconstructed counterparts at the DRM boundary and (2) the targeted ground motions in an interior domain surrounded by the DRM boundary can be accurately reconstructed. Therefore, the presented inversion method can help decision-makers and engineers to analyze the impact of earthquake motions on built environments and soils.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Short-Term Heat-Induced Risk Assessment of Urban Scale Energy Systems

Author(s): *Byeongseong Choi, *Carnegie Mellon University*; Mario Berges, *Carnegie Mellon University*; Matteo Pozzi, *Carnegie Mellon University*;

Urban heat significantly influences human comfort, and subsequent indoor air-cooling increases energy consumption in the built environment. As extreme temperature causes extra energy consumption, weather forecasting is essential to reliably operate power grid systems. Forecast and operation is needed at urban and sub-urban scales, as power systems currently integrate renewable sources and they evolve toward a set of locally controllable systems.

This research proposes a probabilistic approach to assess the short-term energy reliability of urban scale power systems. The proposed approach exploits two data-driven models: (1) probabilistic spatio-temporal model for near-surface temperature and (2) local load forecasting models. The probabilistic spatio-temporal temperature forecast is based on a linear gaussian state-space model, approximating a numerical weather prediction model (i.e. the Weather Research and Forecasting model, coupled with Princeton Urban Canopy Model: WRF-PUCM) at the reduced computational cost. The load forecasting models are calibrated using data of simulated building energy systems, which represent typical commercial and residential buildings. In the numerical application, we assess the energy reliability of urban scale systems in New York City and the City of Pittsburgh.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: A Literature Review on Deep Learning-Based Pavement Crack Segmentation

Author(s): Shanglian Zhou, *University of Hawaii at Manoa*; *Carlos Canchila, *The University of Alabama*; Wei Song, *The University of Alabama*;

In recent years, with rapid advancements in high-performance computing devices and computer vision algorithms, deep learning-based methodologies such as deep convolutional neural networks (DCNNs) have been extensively explored and developed for pavement crack detection. Compared to traditional handcrafted feature extraction methods for crack detection, the deep learning-based methodologies have shown superior performance under real-world complexities, due to their ability to directly learn from data and make self-adaptations. In this paper, the most recent developments and technological advancements in deep learning-based crack detection are reviewed and categorized. Furthermore, an experimental study was performed to evaluate the crack segmentation performance of a series of established DCNNs regarding multiple evaluation metrics and efficiency. This study also demonstrates the challenges and issues in the existing methodologies. Besides, investigations on the optimal choice of image data for network training and testing provide are performed to provide insights for future applications.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Optimized DCNN for Crack Segmentation Using Bayesian Optimization

Author(s): *Carlos Canchila, *The University of Alabama*; Shanglian Zhou, *University of Hawaii at Manoa*; Wei Song, *The University of Alabama*;

In recent years, deep convolutional neural networks (DCNNs) have gained popularity for image-based crack segmentation due to their outstanding performance, self-adaptability, and reduced subjectivity. Despite the many advantages offered by DCNNs, their development is a complex and time-consuming task that requires expertise to select hyperparameters for implementation or adaptation. A non-optimal or simply heuristic choice of hyperparameters can negatively reflect on the performance of the final model. In this paper, a DCNN crack segmentation model obtained using an optimal hyperparameter configuration is presented. A Bayesian optimization technique is applied to determine an optimal set of hyperparameters to obtain a DCNN crack segmentation model that offers better crack segmentation performance compared to non-optimized counterparts. The performance of the DCNN models is evaluated based on different metrics for semantic segmentation. Furthermore, this study offers insights on the relations between the DCNN model performance and the selected hyperparameters.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: A Numerical Investigation of Well Plugging Scenarios Using the Lattice Boltzmann Method

Author(s): *Carlos Garcia, *University of Pittsburgh*; Eilis Rosenbaum, *National Energy Technology Laboratory*; Julie Vandebossche, *University of Pittsburgh*; Anthony Iannacchione, *University of Pittsburgh*; Naser Sharifi, *University of Pittsburgh*; John Brigham, *University of Pittsburgh*;

Plugging abandoned wells with bentonite gel and cement is an efficient and economic method to prevent migration of unwanted fluids and achieve zonal isolation. In a typical plugging process, bentonite and cement slurry are used to fill the annulus of different zones in the wellbore, ideally sealing the zones completely. The particular use of bentonite as a plugging material was introduced to address some of the drawbacks of using cement alone, such as unsealing issues, cracking problems, and high prices. However, there have been issues with some applications of this plugging technique, such as loss of the bentonite component of the plug. As such, the present research goal is to establish an approach to simulate the placement of a bentonite-cement wellbore plug, so that potential causes of plug failure can be investigated. The Lattice Boltzmann Method (LBM) was chosen as the approach to simulate the multicomponent non-Newtonian fluid interaction occurring during plug placement, due to LBMs' capability to capture the behavior of such complex systems with relative computational efficiency and flexibility. More specifically, LBM has been applied with the multicomponent model presented by Shan and Chen (1993), because of its efficiency to capture fluid interaction. To simulate non-Newtonian behavior, an approximation of the Bingham Plastic model has been implemented. Results will be presented that examine the rheological behavior of cement slurry and bentonite during realistic plug placement scenarios. In particular, scenarios to be explored include the conditions (i.e., viscosity and yield stress of the materials, pumping velocity, etc.) in which the cement slurry will flow through bentonite or not, and the conditions that could potentially lead to bentonite and cement slurry fully or partially mixing during placement processes.

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Impact of Inflow Turbulence on Validation of Large-Eddy Simulations of Wind-Induced Pressures on Buildings

Author(s): Lup Wai Chew, *Stanford University*; *Catherine Gorré, *Stanford University*;

Accurate prediction of wind-induced pressures on building surfaces is important for design and risk assessment of high-rise buildings. Computational fluid dynamics (CFD) simulations can provide the detailed pressure distribution on building surfaces, but validation studies are needed before employing simulation results for design purposes. Such validation studies require representative inflow turbulence parameters, which are often subject to uncertainties that can have significant impact on the predicted turbulent wind pressures. Therefore, this study aims to quantify the effect of uncertainties in the inflow turbulence parameters when validating large eddy simulations (LESs) against experiments available from the Tokyo Polytechnic University experiment database (http://www.wind.arch.t-kougei.ac.jp/info_center/windpressure/highrise/Homepage/homepageHDF.htm). The test case considers wind flow across a 120 m by 40 m by 80 m (height by width by length) high-rise building with a scale-down ratio of 1:400. The database includes the inflow mean velocity profiles and streamwise turbulence intensities recorded in the wind tunnel. The Turbulence Inflow Tool (<https://simcenter.designsafe-ci.org/backend-components/tinf>) developed by SimCenter is used to generate spatially and temporally correlated turbulence at the inlet of the CFD domain. In addition to the mean velocity profile and streamwise turbulence intensities, the inflow generator requires spanwise and wall-normal turbulence intensities and length scales as inputs. Since these parameters are not reported in the database, they are estimated based on similarity relationships. A mesh sensitivity study reveals that a mesh resolution of about $H/200$ (where H is the building height) is needed to resolve flow separations induced by the building. This mesh resolution corresponds to 27.4 million cells and an average y^+ of about 30 (the minimum y^+ to employ wall functions) on the building surfaces. The mean pressure coefficient on the building surfaces is well predicted and is insensitive to the inflow turbulence. However, the root-mean-square pressure coefficient (C_{p_rms}) on the building surfaces are sensitive to both Reynolds stresses and turbulence length scales prescribed at the inlet. The initial estimated set of inflow turbulence parameters under-predicts C_{p_rms} compared to the experiment. After incorporating uncertainties in the inflow turbulence, a range of C_{p_rms} that encompasses the experimental results is obtained. In general, higher Reynolds stresses and larger turbulence length scales increase C_{p_rms} . Our study shows that freestream turbulence parameters, including the Reynolds stresses and turbulence length scales, can significantly affect C_{p_rms} on building surfaces. Therefore, these parameters should be measured and reported accurately when performing experiments for validation of computational predictions of pressure distributions on building surfaces.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Evaluation of Distributed Temperature Sensing to Improve Scour Predictions at Bridge Crossings

Author(s): *Celso Castro-Bolinaga, *North Carolina State University*; Rebecca Hatley, *North Carolina State University*; Chadi Sayde, *North Carolina State University*; Mahmoud Shehata, *North Carolina State University*;

Accurate predictions of maximum scour depths are of paramount importance for bridge crossing design and assessment. Despite major advances in our quantitative understanding of these phenomena, bridge failure due to hydraulically induced scour still represents a major technical, economical, and societal challenge. Fiber-optic distributed temperature sensing (FO-DTS) has the potential to enhance our ability to measure scour hole development. With high temporal and spatial resolutions, FO-DTS scour monitoring devices can dynamically locate and track the interface between the sediment and the water phases, providing new insights that in turn can improve the predictive capabilities of empirical and physics-based numerical methods. In this presentation, the results of a series of laboratory flume experiments of a FO-DTS scour monitoring device that was constructed to monitor scour in the field are presented. Results indicated that the FO-DTS scour monitoring device was able to locate the aforementioned interface for various flow conditions, ranging from standing water to flow velocities of 2.8 cm/s. Moreover, when scour was mimicked by rapidly pulling the device out of the sediment bed, results indicated that the FO-DTS device was able to accurately track the rapid change in the location of the sediment-water interface. Finally, the potential of the FO-DTS scour monitoring device to advance our understanding of the spatial and temporal scales associated with scour phenomena is also discussed.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Stochastic Optimization of Risk-Constrained Management Policies for Deteriorating Systems Under State and Model Uncertainties

Author(s): *Charalampos Andriotis, *Delft University of Technology*; Konstantinos Papakonstantinou, *Penn State University*;

Management of deteriorating engineering systems is a stochastic sequential decision-making problem that entails several modeling and computational intricacies. Multiple interconnected system components result in complex state definitions and solution spaces, thus encumbering probabilistic inference and optimized selection of possible Inspection and Maintenance (I&M;) action combinations. Long horizons and temporal dependencies of optimal decisions on past actions and observations further create a vast number of admissible policies. Moreover, uncertainties in state and/or model variables combined with noisy observations make failure probability estimates, and therefore risk, a stochastic process in time. Establishing I&M; policies based on fixed deterministic risk thresholds at every time step may, therefore, be inadequate, as these thresholds can be arbitrarily violated at all times. This work discusses how risk targets can be viewed and imposed as multi-step stochastic constraints. To this end, in this work the stochastic optimization problem is mathematically formulated as a constrained Partially Observable Markov Decision Process (POMDP) and solved using Deep Reinforcement Learning (DRL). More specifically, the Deep Decentralized Multi-agent Actor Critic (DDMAC) algorithm is utilized [1], which belongs to the general family of off-policy actor-critic DRL methods with experience replay, enabling advanced sampling efficacy compared to on-policy approaches. Various architectures are devised and discussed, ranging from fully parametrically centralized multi-actor networks to decoupled inspection and maintenance networks that can make explicit use of the conditional value-of-information and value-of-maintenance, respectively [1-3]. Different types of life-cycle risk-based constraints are discussed as well, such as expectation and value-at-risk probabilistic constraints, which are mathematically incorporated in the stochastic optimization problem via dual variables. The framework is tested in various multi-component deteriorating engineering system settings, featuring state and model uncertainties that are propagated and updated with the aid of dynamic Bayesian networks. Results showcase unmatched performance of the presented framework in terms of life-cycle cost and policy sophistication when compared with conventional and state-of-the-art I&M; decision rules.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Interrogating the Configuration Space of an Axially-Loaded Frame Structure

Author(s): Lawrence Virgin, *Duke University*, *Charles Cervi, *Duke University*,

This paper considers the global buckling behavior of a right-angled planar frame structure. A specific asymmetric frame, sometimes referred to as Timoshenko frame, is made up of a slender horizontal rigidly connected to a slender vertical member. When subject to a compressive axial force applied to its corner, where the two members meet, buckling occurs. The post-buckling is characterized by a trans-critical bifurcation, and as such, the frame exhibits a degree of imperfection sensitivity. In various states of post-buckling the frame is then subject to a torque also applied at the corner. The magnitude of the torque, as a function of the angle, provides considerable information about the potential energy landscape in which the axially-loaded system operates. The applied torque can be thought of as a probing mechanism whereby various equilibrium configurations are revealed, together with information regarding their robustness. In addition to analysis, which is primarily based on FEA, a number of experiments are conducted exploiting the geometric versatility of 3D-printing, with experimental data generally supporting the behavior predicted theoretically.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: A Novel Multiphysics Multiscale Multiporosity Shale Gas Transport Model for Geomechanics/Flow Coupling in Steady and Transient States

Author(s): Zihao Li, *Cornell University*; Yuntian Teng, *Stevens Institute of Technology*; Ming Fan, *Oak Ridge National Laboratory*; Nino Ripepi, *Virginia Polytechnic Institute and State University*; *Cheng Chen, *Stevens Institute of Technology*;

A novel multiphysics multiscale multiporosity shale gas transport (M3ST) model was developed to investigate shale gas transport in both transient and steady states. The microscale model component contains a kerogen domain and an inorganic matrix domain, and each domain has its own geomechanical and gas transport properties. Permeabilities of various shale cores were measured in the laboratory using a pulse decay permeameter (PDP) with different pore pressure and confining stress combinations. The PDP-measured apparent permeability as a function of pore pressure under two effective stresses was fitted using the microscale M3ST model component based on nonlinear least squares fitting (NLSF), and the fitted model parameters were able to provide accurate model predictions for another effective stress. The parameters and petrophysical properties determined in the steady state were then used in the transient state, continuum-scale M3ST model component, which performed history matching of the evolutions of the upstream and downstream gas pressures. In addition, a double-exponential empirical model was developed as a powerful alternative to the M3ST model to fit laboratory-measured apparent permeability under various effective stresses and pore pressures. The developed M3ST model and the research findings in this study provided critical insights into the role of the multiphysics mechanisms, including geomechanics, fluid dynamics and transport, and the Klinkenberg effect on shale gas transport across different spatial scales in both steady and transient states.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Experimental Investigation of Non-Monotonic Fracture Conductivity Evolution in Energy Georeservoirs

Author(s): Zihao Li, *Cornell University*; Qingqi Zhao, *Stevens Institute of Technology*; Yuntian Teng, *Stevens Institute of Technology*; Ming Fan, *Oak Ridge National Laboratory*; Nino Ripepi, *Virginia Polytechnic Institute and State University*; Xiaolong Yin, *Colorado School of Mines*; *Cheng Chen, *Stevens Institute of Technology*;

Significant fracture conductivity can be achieved using a much lower material cost based on the optimal partial monolayer proppant concentration (OPPC) theory. However, experimental validation and investigation of the OPPC theory have been extremely rare in the literature. In this study, we used a laboratory fracture conductivity cell to conduct well-controlled fracture conductivity experiments to comprehensively study the role of effective stress, proppant size, rock type, and water soaking on the evolution of fracture conductivity as a function of increasing proppant concentration. With seven proppant concentrations (up to 2 lb/ft²) and seven effective stresses (up to 6000 psi) used in the conductivity measurements, we experimentally confirmed that the correlation between fracture conductivity and proppant concentration was non-monotonic because of a competing process between fracture permeability and fracture width. We also investigated the influence of the abovementioned experimental conditions on the OPPC and the corresponding optimal fracture conductivity (OFC). This is the first study that uses well-controlled laboratory experiments to comprehensively investigate nonmonotonic fracture conductivity evolutions. The existence of the OPPC indicates that a relatively low proppant amount can be used to form a partial-monolayer proppant pack in the fracture space, which has similar or higher fracture conductivity compared to a multilayer proppant structure. This finding has important economic implications because high-strength, ultralight-weight proppant particles can be used to form partial-monolayer proppant packs in fractures, leading to sufficiently high fracture conductivity using a much lower material cost compared to multilayer proppant structures. Our experiments illustrated that proppant embedment is the primary mechanism that causes the competing process between fracture width and fracture permeability and consequently the non-monotonic fracture conductivity evolution as a function of increasing proppant concentration. Without proppant embedment, there will not be such a competing process, and the non-monotonic fracture conductivity evolution will not be observed.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Semi-Active Control for Seismic Protection of Buildings Using Magnetorheological Dampers with Control-Structure Interaction Included

Author(s): *Chia-Ming Chang, *National Taiwan University*; Chung-Chen Liu, *National Taiwan University*;

High control performance has been verified to be achievable for active control if the interaction between the active control devices and structure is considered. Similarly, when implementing semi-active control using magnetorheological (MR) dampers, the dynamics of these dampers should be interactively included in the controller. In this study, the objective is to develop and experimentally verify a semi-active control algorithm that accounts for the MR damper-structure interaction in the designed controller. Moreover, this control algorithm can straightforwardly calculate the required input voltage (or current) to MR damper(s) at each time step and avoid the two-step approach that computes the required control force first and then converts the force into the input voltage. In this study, the control-structure system is realized by the first-order approximation of ordinary differential equations in accordance with the current state, and the MR damper is modeled by a simplified model which employs a bilinear model to describe the force-velocity relationship in terms of input voltage. Two numerical examples including single and multiple degree-of-freedom structures with a single MR damper are provided, while an experimental study is carried out to verify the proposed semi-active control method through hybrid simulation. As seen in the numerical and experimental results, the proposed semi-active control method can drive MR dampers with appropriate input voltages being adaptive to ground motions. Moreover, the control performance of the proposed semi-active control method is still comparable between numerical and experimental studies and even superior to the clipped-optimal control method.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Hybrid Crowd-AI Framework to Reduce Uncertainty in Automated Post-Disaster Damage Assessment

Author(s): *Chih-Shen Cheng, *Texas A&M; University*; Amir Behzadan, *Texas A&M; University*; Arash Noshadravan, *Texas A&M; University*;

We present an uncertainty-aware crowd-AI teaming system that reinforces the power of AI with human intelligence to improve accuracy and reduce the uncertainty in rapid and automated damage assessment using aerial imagery.

Advancements in remote sensing technology, computer vision techniques, and social network platforms provide transformative opportunities for more rapid, efficient, and effective disaster damage assessment practices. However, AI-assisted post-disaster damage assessment is subjected to uncertainty and lack of reliability due to the high complexity of post-disaster scenes, making the refined classification of damage states challenging. In such scenarios, humans usually perform more reliably since humans often have background knowledge and a certain understanding of the complicated scenes in disaster-affected areas. On the other hand, the fully human-based damage assessment is resource-intensive and costly due to the large number of information required to be processed during disaster events.

The present research is motivated by collaboratively utilizing human and AI capacity to enhance disaster impact practices. Our proposed hybrid crowd-AI framework consists of two modules: (i) the Deep-PDA module, an AI-assisted building damage classification model based on computer vision and convolutional neural network, and (ii) the Crowd-PDA, a crowdsourcing-based module for participatory damage assessment. The Deep-PDA uses a Bayesian deep learning model to predict the probabilistic descriptions of building damage severity. The quantified uncertainty will then be used to measure the value of information and identify the tasks that go into the Crowd-PDA module for improved assessment with reduced uncertainty. Moreover, to achieve a more reliable inference of crowd assessment, the crowdsourcing module uses a maximum posterior estimation where the AI predictions are utilized as the prior in a Bayesian setting. The outcome of this study will enable leveraging the collective strength of both machine and human intelligence to achieve a more accurate disaster damage assessment, which is instrumental in post-disaster response and management.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: A Study on the Bond Between GFRP Bars and Concrete: Fracture Tests of Notched Beams

Author(s): Mohammad Minhajur Rahman, *Case Western Reserve University*, Xudong Zhao, *Case Western Reserve University*, *Christian Carloni, *Case Western Reserve University*,

The use of glass fiber reinforced polymer (GFRP) bars to reinforce concrete is growing as an alternative to the use of steel rebar. The most important feature of the GFRP bar is its corrosion resistance. Few studies have been conducted till now to understand the fracture behavior of GFRP reinforced concrete notched beams. This study presents three point bending tests of GFRP reinforced concrete notched beams. The depth of the specimens is 150 mm. Two different widths i.e., 150 mm and 75 mm are tested to explore possible effects owing to different restraining effect of concrete around the GFRP bar. The length of the notch is half of the depth of the specimen. A GFRP bar is placed in the middle of the width and at 37 mm from the bottom of the specimen. All specimens are cast with the GFRP bar protruding at both ends by 50 mm. For some specimens, the protruded GFRP bar is cut at the ends before the test to investigate possible anchoring effects. Plain concrete specimens with the same sizes are also cast from the same batch of concrete as a reference. The fracture tests are run to obtain the peak load, crack mouth opening displacement (CMOD), GFRP bar slip at the two ends of the beam, and load point displacement. Digital image correlation is used to identify the fracture process zone and to observe if smaller width specimens show any stress concentration on the surface of the concrete. The test results don't show any stress concentration detectable on the concrete surface. A cone effect is observed for the 75 mm-wide specimens. No clear trend that distinguishes the specimens with the protruding part of the bar cut from those with the protruding part can be identified. Finally, an analytical model based on the cohesive hinge approach is to simulate the response of the three-point bending tests of plain concrete. The parameters of the stress-crack opening curve are then optimized to best fit the responses of the actual three point bending tests. This analysis is then used for the GFRP bar reinforced concrete specimens to determine the tension force in the GFRP bar at any given load. A comparison of the force in the bar at peak load with the peak load from pull-out tests of the same GFRP bar embedded in concrete cylinders (with the same bonded length) is carried out.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Complex Biomechanics: from Atoms to Patients

Author(s): *Christian Hellmich, *TU Wien*; Stefan Scheiner, *TU Wien*; Johannes Kalliauer, *TU Wien*; Niketa Ukaj, *TU Wien*;

Complex systems are characterized by an overall behavior which is different from that of the components making up the systems - hence, (nonlinear) interactions between the components play a very important role. Taking an interdisciplinary approach rooted in theoretical and applied mechanics and engineering mechanics, we report on two types of recently studied systems where individual system components (atoms and patients) interact in a way which unfolds very interesting emerging patterns that can be mathematically quantified through concepts arising from (bio-)mechanics: (i) the interaction of atoms within a short thread of DNA, which, as a compound, result in a family of a highly nonlinear beam structures with varying, but always coupled torsion-stretching modes [1]; (ii) the compliance of sets of patients to the lethal effect of SARS-COV-2 [2,3], which follows integro-differential equations reminiscent of those introduced by Boltzmann in the context of creep (or hereditary) mechanics [4]. We conclude that smart classical concepts of applied mechanics and physics continue to show an unparalleled potential for solving pressing global problems in the context of computational modelling of living systems.

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Adaptive Multi-Fidelity Gaussian Process Model for Efficient Bayesian Inference

Author(s): *Christopher Hurst, *Colorado State University*; Min Li, *University of Michigan*; Xinfeng Gao, *Colorado State University*; Gaofeng Jia, *Colorado State University*;

Based on measurement data, Bayesian inference can be used to infer properties of the underlying model. However, Bayesian inference typically requires many runs of the forward model. This could become challenging when the forward model is expensive to run. To address such computational challenges, this study proposes an adaptive multi-fidelity Gaussian Process (MFGP) model for efficient Bayesian inference. The overall idea is to replace the original expensive numerical model with the efficient MFGP for use in the Bayesian inference. Considering that many numerical models can be run at different fidelity levels, instead of only relying on training data from high-fidelity numerical model to build the GP model, MFGP integrates information from a small number of high-fidelity training data (e.g., from high-fidelity simulations) with a large amount of low-fidelity training data (e.g., from low-fidelity simulations) to efficiently establish an accurate Gaussian process model that can be used for prediction at new inputs in place of the high-fidelity model. Then the established MFGP can be used for Bayesian inference (e.g., in sampling from the posterior distribution). Since the posterior distribution typically has peak in a local region of the entire domain, and this is even more so when point estimates are used (e.g., MAP or MLE); therefore, in the context of Bayesian inference the accuracy of the MFGP in such local regions are of more interest rather than good accuracy over the entire domain. Therefore, an adaptive process is proposed to iteratively improve the accuracy of MFGP in interested regions and improve the accuracy of the Bayesian inference. In particular, an initial MFGP is trained based on a small number of runs of low-fidelity and high-fidelity models, then the established MFGP is used in Bayesian inference to identify the MAP or MLE point estimates. The locations of these point estimates correspond to locations of interest. Then the low-fidelity and high-fidelity models are run at these points and the results are added to the training set to train an improved MFGP model, which is then used in Bayesian inference to update the posterior distribution. The above process is repeated until some convergence criteria are reached. The efficiency and accuracy of the proposed approach are demonstrated in the 2D heat diffusion problem with a reacting source where the goal is to identify the location of the source.

EMI 2022
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Title: Cross-Section Instability of Advanced High Strength Steel Thin-Walled Members

Author(s): *Chu Ding, *Johns Hopkins University*, Benjamin Schafer, *Johns Hopkins University*,

The objective of this research is to advance the understanding of thin-walled structure instability failures of advanced high strength steel (AHSS). AHSS, a new class of high-strength steel with the yield strength of up to 1,000 MPa for some grades (e.g., martensitic), has the potential to be adopted as the next-generation steel for the cold-formed steel construction industry, for better performance and lower carbon footprint. However, the unique characteristics of AHSS, high slenderness (due to high strength), high nonlinearity with no clear yield plateau, and limited material ductility, challenge the conventional understanding of thin-walled structure instability, which is underpinned by previous studies on conventional mild steel. It is for these unique characteristics that this research on AHSS thin-walled members has been conducted. The project consists of both experimental and numerical studies. The experimental research includes a large testing matrix of both AHSS beam bending tests and AHSS column compression tests conducted at Johns Hopkins University. The numerical studies are conducted through collapse analysis of AHSS members under typical use cases of cold-formed steel members, e.g., wall studs and floor joists, considering both geometric and material nonlinearity. Differences are found between AHSS thin-walled members and conventional mild steel members in strengths and buckling behaviors. Proposals to adjust current design specifications to account for AHSS are also discussed. It is hoped that this research marks the initial step towards incorporating a new class of steel (AHSS) into the realm of cold-formed construction steel.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Predicting the Yield Behavior of Polycrystalline Aggregates Using a Generalized Schmid Factor Approach

Author(s): *Coleman Alleman, *Sandia National Laboratories*;

The prediction of the yield behavior of polycrystalline aggregates from single crystal properties is an important open problem in the study of crystal plasticity. To solve this problem requires understanding how macroscopic stresses are experienced by the single crystal constituents, and how the constituent deformation contributes to that of the aggregate. Speaking to the first requirement, the classical Schmid factors relate the applied stress to the driving forces for dislocation glide for crystals of a particular orientation. In this study, it is shown that the classical formulation can be extended to treat crystal viscoplasticity, and that this extension allows single crystal yield behavior to be predicted accurately.

Next, it is demonstrated that a suitable volume averaging scheme allows the single crystal results to be applied in predicting the yield behavior of polycrystalline aggregates. There is significant variability in the accuracy of these predictions owing to violations of the assumption that the macroscopic stress is experienced uniformly by the constituent crystals; nevertheless, the predictions can be scaled in a regular way that takes account of this variability in an average sense.

Last, it is shown how the polycrystalline scheme can be used to derive an equivalent stress measure and viscosity model that can be used to simulate the viscoplasticity of aggregates in a traditional model formulation. The results of this study provide a framework by which such models can be informed by microstructural features such as orientation distribution and the micromechanics of rate-dependent single crystal plasticity.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Expert Knowledge Informed Bayesian Networks for weld Condition Monitoring

Author(s): *Cyprien Hoelzl, *ETH Zurich*; Vasilis Dertimanis, *ETH Zurich*; Eleni Chatzi, *ETH Zurich*;

The early detection of defects on railway infrastructure components, on the basis of on-board acceleration measurements, forms a challenging problem due to the mobile nature of the assessment task and the multiple sources of uncertainty that are involved. These relate to the imprecisely known excitation sources (track, rail and wheel irregularities, parameter and self excitation), the uncertainty of the rail-wheel contact dynamics and the variability of the environmental and operational conditions.

Amongst critical railway components, welds form an essential element of the track, where high response amplitudes occur. Their monitoring still largely relies on human assessment. In attempting to investigate the diagnosis of the condition of welds, we here propose to use Machine-Learning based outlier detection, via use of extreme value analysis and bayesian networks, to provide experts with samples of potentially faulty welds. The in-office and on-site inspection of these potentially damaged welds is then used as a source of expert knowledge to build informed bayesian networks for weld condition monitoring. We compare our results against naive outliers and conclude that Bayesian networks are capable of offering a good degree of efficacy in classifying condition. This in turn renders the integration of the acceleration based weld condition rating into the monitoring process quite open for further research and practical implementation.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Probabilistic Life-Cycle Multi-Objective Optimization and Decision Making for Managing Deteriorating Bridges and Bridge Networks

Author(s): *Dan M. Frangopol, *Lehigh University*; Sunyong Kim, *Wonkwang University*;

Life-cycle performance of deteriorating individual bridges and bridge networks should be managed cost-effectively. In order to integrate various demands to manage the performance and service life of deteriorating bridges and bridge networks under uncertainty, probabilistic multi-objective optimization and decision making have to be used. This study presents (a) probabilistic objectives for performance and service life management of deteriorating individual bridges and bridge networks, (b) integration of these objectives through single- and multi-objective optimization, and (c) decision making to select the best-balanced solution. The probabilistic objectives for bridge management are based on performance, cost, service life, risk, resilience, and sustainability. The estimations to formulate the objectives and the relations among the objectives are provided. The representative Pareto sets of multi-objective optimization formulated by considering two, three, four, and more than four objectives are presented. The decision making process consists of identifying the essential objectives, estimating the weight of objectives, and determining the best-balanced solution. Furthermore, recent investigations of the multi-objective optimization for managing the performance and service life of individual bridges and bridge networks and applications are presented.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Optimizing 3D Fabric Tensor Calculation from 2D Images Using Artificial Neural Networks

Author(s): *Daniel Chou, *Georgia Institute of Technology*; Chloe Arson, *Georgia Institute of Technology*;

Fabric tensors are often used in mechanics to describe the statistical distribution of microscopic geometric features, such as the volume fraction, aspect ratio or orientation of defects, inclusions or minerals. Fabric tensors are defined as convolutions of moments of probability density functions of geometric descriptors and can be used as internal variables in thermodynamically consistent constitutive models of damage mechanics. The main challenge is to choose the descriptors that should be included in the definition of the fabric tensors in order to predict and explain the macroscopic mechanical behavior. This choice is restricted by the instruments that are used to measure fabric. A common way to obtain fabric descriptors is to use micro-computed tomography (micro-CT) scanning and generate slice images of 3D specimens, which are viewed as Representative Elementary Volumes (REV). This study aims at recommending best practices when using sets of 2D images or different orientations to calculate 3D fabric tensors. Specifically, a method is proposed to optimize the number and relative positioning of 2D slices in a 3D volume to achieve a targeted accuracy of 3D fabric tensor estimates in cemented aggregates. We first calculate 3D fabric tensors of six hundreds of virtual specimens made of smooth and/or angular aggregates generated with the Finite Element Method (FEM). Several sets of 2D slices are then positioned through the virtual REV (in the (x-y, y-z and x-z planes) to calculate 2D fabric tensors. A Deep-Learning (DL) approach is then used to establish correlations between the 3D fabric tensors (considered as ground truth) and the 2D images. The fabric tensors are reformatted in the form of row vectors, and the pixel values of the 2D images are converted to gray values, normalized and stored in the form of tensors. The registration of the images (plane and position) is also encoded. The image matrices are given as input to an Artificial Neural Network (ANN) made of a convolution neural network (CNN) layer extracted from the pre-trained Video Geometry Group (VGG), and fully connected layers. This ANN is trained, validated and tested with 60%, 20% and 20% of the data respectively to predict the 3D fabric tensors. We compare the accuracy of the results and the computational time for several numbers of images per direction (1, 3, 5 and 10 images per plane). Lastly, we explore the transferrability of the knowledge gained by the ANN by predicting 3D fabric tensors that the ANN was not trained for (i.e., for fabric tensors that are not part of the ground truth data). Eventually, we expect that the ANN will be an efficient tool to calculate/predict 3D fabric tensors from an optimally minimal number of 2D images.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Improving the Buckling Performance of Topology-Optimized Structures for Everyday Design

Author(s): *Dat Ha, *Massachusetts Institute of Technology*; Josephine Carstensen, *Massachusetts Institute of Technology*;

Key Words: Topology Optimization, MATLAB, Buckling optimization, Minimum length scale

Technological development in computation and manufacturing have enabled engineers to pursue solutions to increasingly sophisticated design problems using topology optimization. As a consequence, the last few decades have seen a significant increase in endeavors to advance the field. The first presented algorithms find an optimal distribution of linear elastic material in a design domain to minimize a single objective (usually compliance) subject to a single constraint (usually material volume). Since then, suggested extensions e.g. include multiple objectives, phases, loading and/or support conditions. Algorithms have also been suggested to design for nonlinear mechanics such as plasticity, large deformations, contact, and buckling. While these research efforts seek to generate new high performing solutions to more realistic design problems, they have also made the process of setting up and solving some topology optimization problems more complex. Most of the works that go beyond simple compliance minimization typically require sufficiently powerful computational resources and introduce parameters that often demand tuning (at least to some extent). For many design scenarios the performance gain is worth using all conceivable resources both in terms of computation and engineering hours. This is e.g. the case for many aerospace and automotive applications. However, there are also numerous everyday design situations for one-of-a-kind parts or structures, where design engineers do not have access to such resources.

This work proposes a new interactive topology optimization approach to improve the buckling performance, where a simple problem is solved with guidance from the user. The presented algorithm is based on solving a simple compliance minimization problem, however the user is enabled to interrupt the optimization loop and make changes based on their engineering judgement. More specifically, the user has the option to select areas of the design domain in which different minimum length scale requirements can be prescribed, after which the optimization loop proceeds. The presented algorithm is based on the 88-line code (Andreassen et al. 2010) and demonstrated on several 2D benchmark examples. The buckling performance is compared to results obtained for maximized buckling loads using the 250-line code (Ferrari et al. 2021).

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Comparative Study of Optimal Sensor Placement Methods for Structural Health Monitoring of a Hybrid CLT-Steel Building

Author(s): *David Caballero-Russi, *Pennsylvania State University*; Alejandro Palacio-Betancur, *Pennsylvania State University*; Mariantonieta Gutierrez Soto, *Pennsylvania State University*;

Data-driven modeling and simulation techniques implemented for developing a digital representation about physical systems, known as a digital twin, have empowered Structural Health Monitoring (SHM) to accomplish insightful life cycle assessment and long-term risk analysis and failure predictions on engineering structures. For this purpose, instrumentation and data collection by SHM systems are highly relevant components for digital twin modeling. The quantity and placement of sensors required in SHM systems are critical to the efficiency and accuracy of SHM strategies for correctly identifying and keeping track of the structural properties and building operations. In this regard, it is important to conduct cost-efficient procedures to reduce installation time, energy consumption, and computational costs. Thus, by ensuring the Optimal Sensor Placement (OSP) in SHM applications, the structural identification and health assessment may imply a low-cost, accurate, and practical approach that is affordable for engineering structures. This research studies model-based OSP methodologies for SHM and digital twin modeling of the College of Engineering West 2 building, currently under construction at Pennsylvania State University. It is a rectangular 4-story building consisting of steel frames and composite floors of reinforced concrete layer and Cross-Laminated Timber (CLT) panels. For this case, the sensor placement of the SHM system is a sensitive factor in measuring due to the unsymmetrical distribution of lateral resisting structural systems that generates structural irregularities of the building. Two different algorithms are considered in this study: Sequential Sensor Placement (SSP) using four different criteria (Effective Independence, Effective Independence Driving-Point Residue, Eigenvalue Vector Product, and Non-optimal Driving Point), and Genetic Algorithm (GA) using different objective functions based on the Fisher Information Matrix (FIM) and the Modal Assurance Criterion (MAC). The OSP procedure is conducted in two different ways: using single-channel accelerometers that evaluate each Degree of Freedom (DOF) independently, and using tri-axial accelerometers that evaluate the DOFs of the nodes in the structure. The latter adds an additional constraint to the OSP procedure but reflects a realistic scenario that would reduce installation costs without compromising the accuracy of the SHM system. This proposal highlights GA algorithms for OSP methodologies as an effective, easy-to-use approach to streamline data collection, track building operations, enhance structural identification and health assessment, and preserve the life cycle of the structure.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Long-Term Dynamic Strain Monitoring of a 110-Years-Old Steel Railway Bridge: Influence of Damage vs. Temperature

Author(s): *Dimitrios Anastasopoulos, *KU Leuven*; Guido De Roeck, *KU Leuven*; Edwin Reynders, *KU Leuven*;

Among the multitude of SHM methodologies, Vibration-based Monitoring or VBM is arguably the most extensively explored. VBM is a non-destructive method that can provide with both local and global structural information. Despite its advantages, VBM faces also some challenges. Natural frequencies, which are the most widely used modal characteristic for VBM purposes, are mainly sensitive to global stiffness modifications and not so much to local ones. Therefore, local damage of small or moderate severity has a small influence on natural frequencies, while the global stiffness is often influenced by variations in environmental factors such as temperature. That influence can be high enough to completely mask the presence of even severe damage, necessitating data normalization. Displacement mode shapes are less sensitive to temperature and more sensitive to local damage than natural frequencies but obtaining them in dense grids, necessary for detecting and localizing damage, can be cumbersome due to the large number of required accelerometers. Another modal characteristic are modal strains, which are obtained from dynamic strain time histories and have proved to be more sensitive to local damage and less sensitive to temperature than natural frequencies [1]. Recent research has resulted in techniques based on fiber-Bragg grating (FBG) technology that enable to capture dynamic strains of sub-microstrain amplitude with a sufficient accuracy and precision and in a dense grid, allowing for accurate identification of modal strains [2,3]. In this study, a 110-years-old steel railway bridge is monitored for one year with 80 FBGs. Its modal strains and natural frequencies are automatically identified from ambient and operational dynamic strains. Before the scheduled decommissioning of the bridge, artificial damage is introduced by means of local cuts, roughly simulating fatigue cracks, in order to investigate the damage detection and localization capabilities of modal strains on a full-size civil structure for the first time. The influence of temperature on modal characteristics is also investigated during the monitoring period and is compared with this of damage.

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Assessment of Seismic Risk of Structures Using Manifold Learning-Based Surrogate Modeling

Author(s): *Dimitris Giovanis, *Johns Hopkins University*; Michael Shields, *Johns Hopkins University*; Alexandros Taflanidis, *University of Notre Dame*;

We propose a low-dimensional manifold-based surrogate modeling framework to facilitate quantification of seismic risk of structural systems in performance-based earthquake engineering. The method utilizes Grassmannian diffusion maps, a recently introduced nonlinear dimension reduction technique and a set of special functions called Geometric harmonics to construct a mapping from the input parameter space (e.g., uncertainties in the structure) to a reduced-dimensional solution space. Geometric harmonics is also employed to locally map points on the diffusion manifold onto the tangent space of a Grassmann manifold and back onto the Grassmann manifold through the exponential mapping for inversion and reconstruction of the full solution. A nine-story steel moment-resisting frame with stochastic structural properties is used as a testbed. We select the seismic fragility surface as a measure of the structure's seismic performance, since it provides an estimate of the probability of entering specified damage states for given levels of ground shaking. To assess the seismic risk of the model, we employ Incremental Dynamic Analysis (IDA) to evaluate the variability in the seismic demand and capacity of the non-deterministic structural model.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Seismic Fragility Estimates of RC Columns via Sequence-Based Deep Learning Using LSTM and GRU neural networks

Author(s): *Do-Eun Choe, *New Mexico State University*;

The research proposes and tests sequence-based modeling of deep learning (DL) for the fragility estimates of reinforced concrete (RC) bridge columns using Long Short-Term Memory (LSTM) and Gated Recurrent Unit (GRU) neural networks. These neural networks, specifically developed to learn long-term and short-term dependencies within sequential information such as time-series data, are successfully trained with the failure and censored data of RC columns to predict the conditional seismic fragility. The complete framework is presented with various designs of deep networks using unidirectional or bidirectional layers of LSTM and GRU networks. A total of 132 column testing data are used to train the networks to predict the failure of the column. The networks are trained to maximize the likelihood function and the probabilities are estimated using the Bayesian rule. The conditional probabilities of the failure are estimated given the demands of deformation and shear. The results of fragility obtained through the deep learning methods are compared to those obtained from the traditional probabilistic models. During the presentation, the determination of the model complexity and effects of the number of the data, as well as the model validation methods are discussed. The K-fold cross-validation accuracy of the selected network is estimated to be 94.6 % for drift failure and 93.2% for shear failure. The framework can be applied to various types of civil structures and infrastructures and contributes to improving the safety of structures.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Load Sharing In Accidental Hybrid Structures

Author(s): *Donald Friedman, *Old Structures Engineering, PC*;

Early skeleton frame buildings typically had thick exterior masonry walls, partly because of backward-looking building code requirements and partly because of the standards of building-envelope technology at the end of the nineteenth century and the beginning of the twentieth. In addition, these buildings did not have expansion joints in their exterior walls because the need for such joints was not yet understood. As a result, the buildings are de facto structural hybrids, with the masonry walls carrying far more load than was intended by their designers.

This issue has most often been studied with regard to steel-frame buildings but also occurs at low-rise nominally-concrete-frame industrial buildings if those buildings do not have strip or full-bay windows. Many American concrete-frame industrial buildings, from roughly 1910 onwards, have little curtain wall other than brick knee-walls at each floor with windows above, and so do not have inadvertent load sharing; earlier concrete buildings have more masonry in their walls, usually with isolated windows, and so are subject to load sharing.

Further complicating the issue is that columns in early concrete-frame buildings, particularly before 1909, may be under- or un-reinforced. There was no generally-accepted concrete code in the United States at that time, with the 1909 first draft of the report of the "Joint Committee" (composed of members representing the American Society of Civil Engineers, the American Society for Testing Materials, the American Railway Engineering Association, and the Association of American Portland Cement Manufacturers) being the first in wide use. Even the Joint Committee continued to provide recommendations for columns with only longitudinal reinforcing or only lateral ties as late as 1916.

This presentation will examine the mechanisms of inadvertent load sharing in early-1900s concrete-frame buildings, based on differential stiffness in axial deformation and lateral drift. Those mechanisms will be compared against observed conditions in a case-study building: a 1905 warehouse, seven stories tall, with one-way concrete joist floors, concrete columns, and solid brick exterior and partition walls.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Gaussian Process Regression with Bayesian Optimization for Mapping Between Modal Parameters and Environmental and Operational Variations

Author(s): *Doyun Hwang, *Seoul National University*; Sunjoong Kim, *University of Seoul*; Ho-Kyung Kim, *Seoul National University*;

In output-only modal analysis (OMA) based structural health monitoring, fluctuations in modal parameters (MP) from environmental and operational variations (EOV) prevent accurate decision-making, as changes in EOV may have a greater contribution to the variation of MP than structural damage. In particular, damping estimates have not been understood well in the context of EOV because of its 1) inherent uncertainty, 2) scattering from analytical errors (e.g., parameter selection), and 3) highly non-linear relationship with respect to EOV. For large civil infrastructure systems such as cable-supported bridges, damping is critical in assessing susceptibility against various wind-induced phenomena. To resolve the challenges associated with damping and gain a clearer understanding of its relationship with EOV, a reliable long-term damping database is first constructed from long-term continuous monitoring data of a cable-stayed bridge via an automated OMA process. Gaussian process regression (GPR) is applied to the database to examine the complex relationship between EOV and damping estimates. Bayesian optimization, widely used for tuning GPR models, is employed to improve the model accuracy of the model. One-to-one mapping between EOV and MP from the mapping model is examined to clarify known phenomena in previous literature. It is concluded that level of amplitude is, as it was known in literature, the principal predictor in explaining the variance of damping estimates in changing EOV.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Shrinking Fibers for Enhanced Durability of Concrete

Author(s): *Dryver Huston, *University of Vermont*, Diarmuid Gregory, *University of Vermont*, Joshua Allen, *University of Vermont*, Robert Worley II, *University of Vermont*, Zhuang Liu, *University of Vermont*,

This presentation describes the underlying principles and experimental results from using active fibers dispersed in concrete mixes that enhance durability by shrinking during and after cure. Conventional passive non-shrinking fibers are increasingly being used as admixtures to enhance concrete performance. Passive polymer fibers can mitigate shrinkage cracks. Passive steel fibers play an important role in ultra-high-performance mixes. The dispersal and mechanical action of these fibers tends to be random and nominally isotropic. Prestressing and post-tensioning with macro-scale strands are alternative methods of enhancing concrete performance. The strands generally induce anisotropic compressive stresses that prevent tension cracks. Active shrinking fibers hold out the hope of combining the convenience and isotropic action of using fibers as admixtures with the positive effects of an isotropic compressive prestress. Developing active shrinking fibers is a technical challenge. One approach is to use the biopolymer chitosan that derives from crustacean shells. Chitosan shrinks in high pH environments, such as fresh Portland cement concrete. Based on preliminary results on small cement samples with embedded chitosan fibers that show increased compression and bending strengths, a study was undertaken to determine if positive performance effects appear in larger samples that include aggregate. Durability testing in the form of cyclic freeze-thaw testing and cyclic chloride penetration testing indicated that the addition of shrinking chitosan fibers can extend freeze-thaw durability by a factor of at least two and reduce chloride penetration by a factor of up to three. A hypothesis explaining this increased durability is that the shrinking fibers exert an action late in the cure cycle to alter the microstructure and reduce porosity, thereby limiting the amount of water that penetrates in freeze-thaw testing and saline water penetration in chloride tests. Additional tests using steel fibers that exert post-cure compressive stresses through a water-activated mechanical release process indicate interesting results in terms of altered acoustic emission behavior and extended post-cracking strength versus passive non-stressing fibers. These results, as well as potential future research directions will be presented.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: An Elasto-Plastic Damage Model for the Jellyroll with Nonlinear Mechanical Behavior

Author(s): George Z. Voyiadjis, *Louisiana State University*; *Edris Akbari, *Louisiana State University*; Peter I. Kattan, *Petra Research*;

Commercial lithium ion battery cylindrical cells encounter severe mechanical abuse conditions that can trigger damage in cells and cause fires and explosion. Many attempts are made to enhance the safety of lithium ion battery cells, which contain a shell casing and a Jellyroll. In this study, the mechanical behavior and damage mechanisms of the Jellyroll has been studied in the three-point bending test. The constitutive model can simulate the damage characteristics of the jellyroll under the point of loading. An elasto-plastic damage model is proposed to predict the damage onset and propagation in the continuum damage mechanics framework. The proposed algorithm has been implemented in ABAQUS/Explicit via user-defined material subroutine (VUMAT). For the Jellyroll under the three-point bending, the force-displacement curve is studied and compared with the previously reported data from literature. The numerical results can precisely predict the location of the plastic flow strain localization and the damage onset.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Physics Guided Deep Learning Manifold Linearization of Porous Media Flow Equations

Author(s): Marcelo Dall'Aqua, *Texas A&M; University*; Emilio Coutinho, *Texas A&M; University*; *Eduardo Gildin, *Texas A&M; University*;

Meeting the net-zero emission paradigm will require a realignment of hydrocarbon production strategies with other forms of energy production (e.g., CCUS, H2, geothermal). Profiting from all these energy sources is only possible if accurate and timely prediction of behavior of fluids, including geomechanics issues in the subsurface, can be attained. Integrated reservoir studies are computationally expensive, especially for performance prediction and decision-making processes. Although powerful reservoir simulators exist in the market, a single forward simulation can still demand complex high-performance infrastructure. Reduced-order modeling (ROM) alleviates the computational burden of such large-scaled simulations by running cheaper and faster models while preserving a high level of accuracy.

This talk will show the developments of physics-based and Data-driven based proxy models for coupled flow and geomechanics in porous media. We have implemented the Proper-Orthogonal Decomposition with The Discrete Interpolation Method (POD-DEIM) for flow and mechanics with speedups of 50X. Although promising performance, it has proven not robust as it depends on many parameters' selection. On the other hand, to build our reliable proxy, we recognize that reservoir simulators execute several expensive Newton-Rapson iterations after each timestep to solve the nonlinearities of the physical model. Thus, we propose "lifting" the physics to a more amenable manifold where the model behaves close to linear, similar to the Koopman theory. An extra benefit of this framework is to enable the plethora of well-developed tools for MOR of linear systems (e.g., balance truncation).

We use autoencoder deep neural networks with specific loss functions and extra features to transform the nonlinear equation into a bilinear or quadratic bilinear form. We work with flow only at this stage. Such features force the states (pressures and saturations) to evolve in time by simple matrices multiplications in the lifted manifold. We also adopt a "physical driven" training approach: we use the basic reservoir equations at the early stages to guide the neural net to achieve physical output, even in the test set. However, it is worth noting that this method is a non-intrusive data-driven method since it does not need access to the reservoir simulation internal structure. Therefore, it is easily applied to commercial reservoir simulators. I will show the performance of this method for a two-dimensional two-phase (oi and water) reservoir subject to a waterflooding plan with three wells (one injector and two producers). I will also note that our framework is extendable to other studies.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Impact of FE Modelling Approach in the Long-Term Assessment of Prestressed Structures Based on Probabilistic Outcomes – Case Studies on T-Girder Beams

Author(s): *Emanuele Canestro, *Cresco Civil and Structural Engineers*; Alfred Strauss, *Universität für Bodenkultur Wien*; Helder Sousa, *HS Consulting*;

Nowadays, the evolution towards sustainable infrastructure networks is a priority where demands for a technical lifetime, in some cases for more than 100 years, are an important issue. For the particular case of prestressed concrete structures, the long-term assessment has an important role with the aim of planning the maintenance requirements under future demands. This can be done supported by advanced FE modelling, where the time history, the construction phases, the availability of monitoring data, the mechanical properties of concrete, and the effective loads applied are crucial inputs for deeper, better, and more precise assessments, i.e., predictions over the structure lifetime.

This work introduces a novel bottom-up approach for the long-term analysis of T-girder prestressed beams. A case study is considered to support the approach – a small-scale beam tested under laboratory conditions. An exhaustive discussion is made based on the quantification of displacements, strains, and stresses in both concrete and tendons taking into account lab-tested monitoring data. A throughout discussion is made to better understand the selection of the finite element type to model the long-term performance of the structure. This will be made with special attention to the stochastic parameters related to material properties and the attainment of the Serviceability Limit States.

Further to this a comprehensive discussion is made to better understand the essential requirements in the context of life-cycle analysis, with special attention to time investment vs. accuracy.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: On the Compressive Strength of Brittle Cellular Materials

Author(s): *Enze Chen, *Johns Hopkins University*; Shengzhi Luan, *Johns Hopkins University*; Stavros Gaitanaros, *Johns Hopkins University*;

Cellular solids are excellent candidates in numerous engineering applications because of their outstanding mechanical, thermal, and acoustic properties. Lattice materials made of brittle parent solid, such as carbon or ceramics, are widely used as thermal insulators in space structures, filters in exhaust systems, and electrode materials in batteries. This work aims to study the failure mechanism of brittle lattices and uncover the intrinsic relationship between lattice microstructure, the fracture strength of the parent solid, and the resulting macroscopic strength. We focus on three lattices with increasing topological rigidity based on the Kelvin cell, the cuboctahedron, and the octet lattice. Finite size cubic specimens are synthesized by additive manufacturing and tested to failure. An increasing fracture strength is observed as the stretching-to-bending loading ratio within the struts of each lattice increases. High-fidelity micromechanical models are used to elucidate the experimental measurements and further examine the effect of node connectivity, stress concentrations around the node, and the fracture strength of the parent solid under tensile and bending loads. The results are compared with corresponding ones on stochastic brittle foams with uniform and gradient-densities. Finally, we estimate an accurate representation for the scaling of strength with density for each lattice, and compare them with the classical Gibson-Ashby formulas.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Innovative Method for Progressive Crack Growth Analysis

Author(s): *Eric Cheifet, *SOCOTEC Engineering, Inc.*; Joseph Cluever, *SOCOTEC Engineering, Inc.*; Evan Schickel, *SOCOTEC Engineering, Inc.*; Robert Vecchio, *SOCOTEC Engineering, Inc.*;

In the Civil Engineering industry, understanding the mechanics of the propagation of an existing or assumed structural crack is critical when performing a root cause analysis, predictive crack growth analysis, or fitness-for-service (FFS) evaluation. This paper presents an industry application of a comprehensive analysis technique for crack propagation under static loading using Ansys's integrated ACT scripting capability and MATLAB. Inputs for the fracture mechanics analysis must first be determined, such as size, shape, and location of cracks, and the mechanical properties and fracture toughness of the affected material. Then, a three-dimensional finite element analysis is performed within Ansys, which is utilized to generate the primary and residual stress states, spatially-varying fracture toughness distribution, and stress intensity factors for each iteration of crack growth. Automated Python scripting within Ansys facilitates the quasi-static iterative progressive crack growth analysis, which works in conjunction with MATLAB to calculate, generate, and import incrementally grown crack surfaces. For each iteration, crack growth distance and direction are determined using a spatially-varying fracture toughness distribution and stress field. Crack growth can obey either SIF-based fracture criteria or the codified Failure Assessment Diagram, thereby extending the capability over other commercial software. Additional smoothing features are implemented within MATLAB to improve the numerical stability of generated crack surface geometry and subsequent stress intensity factor calculations. This technique can analyze growth of multiple cracks of arbitrary shapes, incorporate explicit or closed-form residual stress distributions, and account for dynamic and arrest toughness.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: The Effects of Heating Duration on Post-Fire Structural Steel Mechanical Properties

Author(s): James Gordon, *Oregon State University*, *Erica Fischer, *Oregon State University*;

For buildings and communities to be fire resilient, they must recover quickly after a fire such that buildings can be functional after a fire. This includes understanding the post-fire capacity of structural materials. Replacing structural components is costly and time consuming. To re-use members and still have the required strength and stiffness to resist loads imposed on the structural components, the post-fire mechanical properties of steel must be quantified. The experimental study presented in this paper investigates the effects of heating duration on post-fire steel mechanical properties. Previous research shows that the factors influencing post-fire steel mechanical properties include the maximum temperature of exposure, cooling rate, and heating duration. While the effects of cooling rate and temperature of exposure have been researched in depth, the available data demonstrating the effects of heating duration is not comprehensive. The experimental work summarized in this paper involves heating steel tensile test coupons to a range of 600-1000 oC for durations of 30 min, 1 hour, and 2 hours. The heated specimens are cooled and then subjected to tensile testing in accordance with ASTM E8/E8M. The resulting stress strain relationships are presented and used to calculate the retention factors for Elastic Modulus, Yield Strength and Ultimate Strength. The findings of the experimental testing suggest that heating duration has a notable influence on the post-fire mechanical properties of steel. Furthermore, when evaluating steel members for re-use after fire, the temperature of the fire, the duration of the fire, and the rate of cooling of the member should all be considered.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Hurricane Wind and Freshwater Flood Risk Assessment Considering Climate Change

Author(s): Chi-Ying Lin, *National Yang Ming Chiao Tung University*; *Eun Jeong Cha, *University of Illinois at Urbana-Champaign*;

Hurricane causes severe damage along the U.S. coastal regions, which may be aggravated as a result of increasing hurricane intensity in changing climate conditions. With the potential increase in hurricane intensity, the impacts of hurricanes are expected to be severer. Current hurricane risk management practices are based on the hurricane risk assessment with stationary hurricane occurrence assumption and not considering climate change impact. The design wind load specified in ASCE 7-16 was derived based on long-term averaged hurricane statistics and did not consider possible future climate conditions. Similarly, the National Flood Insurance Program assesses flood risk and delineates flood boundaries based on its Flood Insurance Rates Maps without considering the impact of climate change. Such practice might underestimate the future hurricane risk in the changing climate conditions and put the built environment of the nation at risk. For the development of proper hurricane risk management strategies, it is crucial to investigate the climate change impact on hurricane risk. However, investigation of future hurricane risk can be very time-consuming because of the high resolution of the models for climate-dependent hazard simulation and regional loss assessment.

This study investigates the climate change impact on hurricane wind and freshwater flood risks on residential buildings across the southeastern U.S. coastal states. To address the challenge of high computation time, surrogate statistical models using artificial neural networks are developed for evaluating wind and freshwater flood losses of simulated climate-dependent hurricane scenarios as well as simulating climate-dependent hurricanes. The change of hurricane wind and freshwater flood losses under the projected IPCC climate scenarios is investigated by using the developed surrogate models. The result of this study suggests the necessity of considering climate change scenarios to update design wind speed and flood maps in hurricane risk management.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Harnessing Pre-Stress for Continuous Equilibrium Under Gravity

Author(s): Maria Redoutey, *University of Michigan*; *Evgueni Filipov, *University of Michigan*;

Structures designed to deploy and reconfigure undergo large shape changes as they move through their kinematic paths. During motion, the effect of gravity changes the potential energy of the system, and active actuation is typically required to maintain equilibrium. In contrast, if gravity is counterbalanced or intentionally counteracted, the potential energy of the system stays constant and the structure remains in continuous equilibrium. In this talk, we introduce a method to optimize the properties and placement of pre-stressed springs to convert deployable and reconfigurable structures into systems with continuous equilibrium. We apply this method to the design of practical structures ranging from conventional four-bar linkages to three-dimensional origami-inspired systems. We investigate how different types of pre-stressed springs influence the overall behavior and contribute to counteracting gravity. We verify the new continuous equilibrium designs with traditional structural analysis methods and with physical proof-of-concept experiments. Enabling continuous equilibrium for deployable and reconfigurable structures would minimize the need for actuation and would ensure safe and stable motion throughout the kinematic path. These structures can offer novel applications in infrastructure, robotics, architecture, consumer devices, metamaterials, and more.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Genetic Algorithm-Based Frameworks for Optimized Design of Seismic Retrofitting of Masonry and Reinforced Concrete Frame Structures

Author(s): *Fabio Di Trapani, *Politecnico di Torino (Italy)*; Antono Pio Sberna, *Politecnico di Torino (Italy)*; Marco Martino Rosso, *Politecnico di Torino (Italy)*; Giuseppe Carlo Marano, *Politecnico di Torino (Italy)*;

Seismic events have a dramatic impact on communities belonging to earthquake-prone areas in terms of loss of human lives, disaggregation of social tissue, and massive financial commitments required to repair and rebuild. For these reasons, seismic retrofitting of existing structures emerges nowadays as a major priority of governments to increment the resilience of communities toward seismic risk.

Retrofitting interventions are generally associated with noticeable costs, significant invasiveness, and relevant downtime. Despite the vast type of efficient technical solutions available on the market, nowadays retrofitting design phases are mainly entrusted to the engineers' intuition and experience, and this requires several trial-and-error attempts with noticeable time consumption. Furthermore, this empirical design approach may also entail an overestimation of the extent of retrofitting interventions.

In this frame of reference, artificial intelligence applications emerge as efficient computational tool for the appropriate employment of funds allocated for the seismic retrofitting of existing structures. Their applications on structural optimization allow engineers to obtain cost-effective designs. In the last years, the scientific interest in this discipline was mainly focused on sizing and shape optimization of new structures. On the contrary, the issue of the optimization of seismic retrofitting of existing structures has not been investigated many times in the past, while noticeable interest is emerging in the last years.

Different AI-based frameworks for the optimal design of retrofitting interventions will be presented. The problem of finding efficient retrofitting configurations was tackled by developing genetic algorithms that are aimed to provide the optimal position (topological optimization) and design (sizing optimization) of retrofitting interventions so that their implementation costs are minimized. The novel genetic algorithm routines are defined by developing modified genetic operators capable of addressing retrofitting optimization for both masonry and reinforced concrete frame structures.

The outcomes of the proposed frameworks represent a valid support for engineers and technicians in identifying the best configuration of structural reinforcements in existing structures.

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Di Trapani F, Malavisi M, Marano GC, Sberna AP, Greco R. Optimal seismic retrofitting of reinforced concrete buildings by steel-jacketing using a genetic algorithm-based framework. *Engineering Structures*. 2020;219:110864.
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Title: A Novel Identification Procedure of Mass-in-Mass Metamaterials Endowed with Cubic Oscillators

Author(s): *Fabrizio Aloschi, *University of Trento*; Oreste Salvatore Bursi, *University of Trento*;

In this work, we propose a novel procedure for the identification of dispersion laws and mechanical characteristics of nonlinear locally resonant metamaterials, whose unit-cells are connected by cubic springs. We adopt the Floquet-Bloch theorem as input to identify the periodic chain from the output of a reference subsystem which includes the unit-cell. The advantage is threefold: 1) the computational effort is reduced to the integration of the system of equations of motion of a simple 2-DoF system; 2) the reflection of waves is avoided because we impose boundary conditions at any time and treat a forced problem without free vibrations; 3) the numerical dispersion law takes into account the imaginary part of the wavenumber.

Floquet-Bloch boundary conditions are imposed to the bounds of the n th unit-cell. The amplitude of excitation and the circular frequency are selected for the input; hence the dispersion law is only dependent on the complex wavenumber, target of the identification process. A Levenberg – Marquardt algorithm is then employed for solving a minimization problem including the Frequency Response Function of the unit-cell, which is calculated as ratio between the output and the input. Therefore, the identified complex wavenumber is associated to the input frequency, and the numerical dispersion curve is found for the given amplitude.

Once the numerical dispersion curve of the nonlinear periodic lattice is identified, we adopt the subspace method for the parametric identification of the linear and the nonlinear stiffnesses. Gaussian white noise as well as harmonic inputs are applied to identify the state space matrices of the periodic system by the output of the reference subsystem. Finally, we derive the unknown mechanical characteristics from the relevant estimated transfer function.

Keywords: Nonlinear cubic metamaterials; Floquet – Bloch theorem; Unit-cell; Subspace identification

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EMI 2022

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Title: Multi-Fidelity Parallel Sequential Design Strategy Under Classification Constraints with CFD Applications

Author(s): *Fei Ding, *University of Notre Dame*; Jize Zhang, *Hong Kong University of Science and Technology*; Ahsan Kareem, *University of Notre Dame*;

Surrogate modeling has been widely used to understand complex engineering systems involving intensive simulations. Simulations can often feature both high-fidelity simulations which are accurate yet costly, and low-fidelity ones that are computationally less extensive but potentially lack accuracy. For instance, CFD analyses can be conducted either through low-fidelity Reynolds-averaged Navier-Stokes (RANS), or through high-fidelity Large Eddy Simulation (LES). Developing a multi-fidelity surrogate model allows using simulations of varying fidelities to enhance model accuracy while maintaining computational efficiency.

A major challenge in multi-fidelity surrogate modeling is the sequential design of simulation data. In such a framework, simulation samples are sequentially generated based on certain infill criteria. In this study, we focus on a global sequential model updating scheme with the commonly used integrated mean squared error (IMSE) criteria. To improve such global sequential design approaches in the multi-fidelity setting, a parallel model updating scheme is proposed, which allows for generating multiple sequential samples at different model fidelities simultaneously, which enhances the computational efficiency as the numerical simulations can be carried out in parallel to meet the full computational capacity.

Another challenge is that the low-fidelity numerical simulations could bring non-physical or ill-conditioned evaluations. For instance, in RANS, violating modeling assumptions involving scale separation or empirical Reynolds stress modeling could result in simulation failure. To take into account such simulation failures, this study considers a probabilistic classification approach to identify the viable areas for the low-fidelity simulation and avoid the low-fidelity samples being casted into the erroneous regions where the low-fidelity observations significantly deviate from their high-fidelity observations. This classifier is then integrated with the sequential design in search of the locations and fidelity levels of the sequential samples.

Finally, the proposed parallel sequential model updating scheme with the embedded classification approach is applied to the CFD-enabled aerodynamic evaluation of civil structures with different profiles. To promptly predict the aerodynamic quantities of various building forms, a multi-fidelity surrogate model has been employed to take advantage of low-fidelity RANS and high-fidelity LES simulations. To resolve the aforementioned simulation failure issue induced by the low-fidelity model, the proposed multi-fidelity sequential design approach is applied, which aims at effectively identifying the feasible regions for RANS model sampling using the probabilistic classifier and conducting iteratively parallel updating to reach the satisfactory predictive accuracy, and ultimately facilitating the aerodynamic shape design of structures.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Discrete Element Modeling of Granular Hopper Flow Using Hysteretic Nonlinear Contact Models

Author(s): *Feiyang Chen, *Clemson University*; Qiushi Chen, *Clemson University*; Yidong Xia, *Idaho National Laboratory*;

Granular biomass materials such as woodchips feature irregular particle shapes and relatively low stiffness. These features result in unique bulk flow characteristics and could pose great challenges for the operation of handling equipment. In this work, we present a class of generalized strain-hardening hysteretic contact models for the discrete element method (DEM), which can capture the bulk behavior of flexible biomass particles. DEM simulations of a wedge-shaped hopper discharge of loblolly pine chips are conducted, and the results are compared and validated with experimental data. The flow behaviors, including the discharging profile, mass flow rate, and critical arching distance are investigated. The characterizations of the flow behavior affected by the two material attributes (moisture content and rolling friction) and the three operational parameters (hopper outlet width, hopper inclination, and pre-consolidation stress) are conducted. The results show that the mass flow rate increases linearly with the increase of the hopper outlet width while it decreases with the increase of all other material attributes and processing parameters. The materials' inter-particle motion resistance demonstrates the significant impacts on the critical arching distance of the hopper discharging. These findings provide guidelines for hopper operation in the material handling industry and the construction of design methods for material handling equipment in biorefineries.

Title: A Stochastic Peridynamic Model for Quasi-Brittle Fracture in Heterogeneous Materials

Author(s): *Florin Bobaru, *University of Nebraska-Lincoln*; Jiangming Zhao, *University of Nebraska-Lincoln*; Ziguang Chen, *Huazhong University of Science and Technology*;

Material microstructure affects initiation and propagation of failure in heterogeneous materials (fiber-reinforced composites, concrete, etc.). Due to differences in scale between material microstructure and the structure itself, predicting damage and fracture in such materials is difficult. The main approach for simulating this type of problems has been using multiscale models, for example those that employ two types of calculations: one at a representative element of the microstructure, the other at the structure level, and passing information between these two scales. Some promising results have been obtained using these approaches, however, they are still a long way from becoming predictive and able to validate experimental observations.

Here, we discuss a new class of models that side-step the separate scale simulations in favor of a single-scale, nonlocal modeling that uses some minimal microstructural information. To accomplish this, for materials with microstructure that are homogeneous at the larger scale, the Intermediately-Homogenized Peridynamic (IH-PD) model uses stochastic generation of PD bond properties to match the phases volume fractions in the heterogeneous material. In a sense, the IH-PD model contains some material microstructure information in the nonlocal interactions, while being able to simulate structural-scale samples. This allows us to side-step simulations at each separate scale and have a single-scale simulation, albeit a nonlocal one, to account for the multiscale problem. We show that this model leads to efficient computations, having a cost similar to that of modeling homogeneous/homogenized materials, but with the advantage that quasi-brittle failure initiation and propagation match the observed experimental behavior of heterogeneous materials. Examples are shown from porous rock [1], corrosion-induced quasi-brittle fracture in concrete [2], transverse failure in fiber-reinforced composites [3], static three-point bending and anchor pull-up from concrete structures [4], and dynamic loading of concrete [5]. The evolution of damage in such samples is shown to closely match experimental observations. The model is robust to small changes in input data that mimic the expected material variability and randomness of the microstructure.

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: A Vision of Engineering Education Inspired by the Career of Ahsan Kareem

Author(s): *Fred Haan, *Calvin University*,

Does success require specializing as early as possible and then practicing hard in one specialty? Recent research in education and in how research breakthroughs happen highlight the importance of breadth in a person or team's experience. While early specialization and the well-known 10,000 hours of practice might work in certain domains—for example, chess, golf, playing the violin, etc., these are relatively well-behaved domains. That is, the rules are very clear and always the same, the feedback on performance is nearly instantaneous, and the skills you acquire by immense amounts of repetition are very useful for the next performance.

Many engineering problems and many of our most critical social problems, however, are in domains that Epstein (2019) would call “wicked.” These are domains where no clear rules exist, repetitive patterns do not exist or are unclear, and feedback takes a long time and may be misleading. What worked in the past might not work in the future. What is required for such problems is less specialization and greater breadth that enables discovery of solutions from disparate sources.

When we specialize, it is natural for all problems to look like what we know well. If you have a hammer, all problems look like nails. For wind engineering, we must avoid training people to think every problem looks like a 3-sec gust or like a flutter derivative.

Ahsan Kareem's career illustrates how breadth of experience and breadth of engagement can frequently generate innovative solutions. By engaging in a broad range of engineering problems and in a variety of settings, Ahsan has shown that breakthrough concepts and breakthrough methods often come across domains and across disciplines. He has made use of concepts from electrical engineering and controls and stochastic methods to apply to offshore structures and wave loading and wind engineering and CFD.

Transfer of ideas from one domain to another is not at all easy, and it is typically not practiced explicitly in engineering education. However, the ability to transfer that Ahsan has consistently exemplified will be vital as engineers tackle future problems. Machine learning will increasingly handle well-behaved domains while the wicked problems can only be tackled by those who can make connections across domains and across knowledge categories. This talk explores how education can and should be helping us all think in more Kareem-like ways about the wicked problems we face.

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EMI 2022
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Title: Heat Transfer Enhancement for Nanofluid Flows over a Microscale Backward-Facing Step

Author(s): *Gabriella Bogнар, *University of Miskolc*;

In this talk, we present a numerical study of laminar flow in a micro-sized backward-facing step channel for water-based nanofluids containing Al₂O₃ and TiO₂ nanoparticles and investigate the impact of the temperature differences between the inlet and the downward wall temperatures. The present work is the first study to introduce a temperature-dependent separation flow model. The velocity increases with the increasing concentration of nanoparticles. However, when comparing Al₂O₃ and TiO₂ nanofluids, Al₂O₃ has a velocity and shear stress higher than TiO₂ for 0.04 volume fraction. Increasing the volume fraction of nanofluid led to an increase in the rate of heat transfer from the wall to the fluid, as the thermal properties improved as the volume ratio increased. The performance efficiency index (PEI) decreases as the volume fraction of the particle increases after a certain amount of nanoparticles. The simulation results of the nanofluid separation flow in the recirculation and reattachment show that the velocity increases as the temperature difference increases, the size of the primary and secondary recirculation regions behind the step is significantly influenced by the temperature difference, a larger temperature difference means a larger recirculation zone.

Keywords:

Nanofluid; single-phase; laminar; numerical; backward-facing step; temperature-dependent thermo-physical properties; performance efficiency index

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Baltimore, MD, May 31 - June 3, 2022

Title: Decoupled Adaptive Model-Based Compensation for Multi-Axial Real-Time Hybrid Simulation

Author(s): Cristobal Galmez, *Universidad Tecnica Federico Santa Maria*; *Gaston Fermandois, *Universidad Tecnica Federico Santa Maria*;

Real-time hybrid simulation (RTHS) is a promising technique that combines experimental testing and numerical modeling to provide structural assessment for critical components under seismic loadings. This technique aims to test the components of interest and their interaction with the structural system as realistic as possible. Consequently, multiple actuators are needed in the loading platform to emulate realistic multi-axial boundary conditions at the cyber-physical interface. Additionally, it is fundamental to minimize the experimental errors produced by the loading system to guarantee stability and accuracy. But, the dynamic compensation of multiple actuators in RTHS is still a complex challenge, and robustness is not always guaranteed.

In this study, adaptive dynamic compensation is implemented in a virtual RTHS problem where multi-axial loading (displacement and rotation) are imposed on the experimental specimen using two actuators. The experimental setup is modeled to consider realistic conditions such as transfer system dynamics, actuator-specimen interaction, and actuator-actuator interaction. The target displacements and rotations are transformed into actuator coordinates, and decoupled (independent) adaptive compensators control each actuator to minimize the synchronization errors. The compensators are based on a model of each actuator without considering specimen or actuator interaction. Then, through adaptive laws during the test, the interaction is captured, and each actuator's control parameters are updated in real-time. The adaptation capacity allows maintaining excellent compensation against uncertainty in the experimental substructure properties, providing robustness for the experimental setup. Furthermore, compensators designed independently from the specimen interaction can avoid identification tests that may cause premature damage to the physical specimens before the primary RTHS test.

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Baltimore, MD, May 31 - June 3, 2022

Title: Model Order Reduction Using Proper Generalized Decomposition for the Prediction of Railway Induced Vibration

Author(s): Thomas Alexiou, *KU Leuven*; Geertrui Herremans, *KU Leuven*; Pieter Reumers, *KU Leuven*; *Geert Degrande, *KU Leuven*; Stijn François, *KU Leuven*;

A novel methodology is presented to efficiently assess free field response for railway induced vibrations. The goal is the construction of a computational vademecum of the response, including both soil and track parameters, allowing for fast parametric studies on vibration mitigation. Current solution strategies for dynamic soil-structure interaction (SSI) problems use 2.5D and 3D coupled finite element – boundary elements formulations. These remain however computationally demanding. This is tackled by means of an a priori model order reduction technique, namely the Proper Generalized Decomposition (PGD) [1]. The potential of PGD is studied for the modelling of the source as well as for the propagation of waves.

The PGD formulation is based on the assumption of a separable form of the multidimensional field [1]. Each contribution therefore consists of a rank-1 tensor and is computed in a greedy manner. To this end, the PGD formalism is introduced into the weak form and the resulting non-linear problem is solved using fixed point iterations. Moreover, alternative solution strategies, like Petrov-Galerkin based solvers, are considered [2].

Firstly, a simplified source model is elaborated consisting of a beam connected to a Winkler foundation. An analytical Euler-Bernoulli formulation and a finite element model are used for the beam. Apart from the frequency and longitudinal wavenumber, model parameters as the rail pad stiffness are included in the formulation.

Regarding the elastodynamic wave propagation, Green's functions for the in-plane (P-SV) and out-of-plane (SH) problems are approximated for the cases of a (layered) halfspace, and of a layer on rigid bedrock. First, convergence of the PGD solvers and the separability of the variables are explored at a fixed frequency. Then, the discussion extends to the more complex case of decomposing the solution in the frequency domain.

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Title: Monte Carlo Simulation in Civil Engineering and Engineering Mechanics

Author(s): *George Deodatis, *Columbia University*,

Monte Carlo Simulation (MCS) techniques were introduced in the field of Civil Engineering & Engineering Mechanics in the early 1970's to deal with excitation as well as system uncertainties. Until that point, exact solutions were available only for a limited number of stochastic problems, mainly linear elastic ones involving stationary and Gaussian stochastic processes. Some approximate solutions were also available for more complex problems, but had various limitations related to their range of applicability and accuracy. MCS techniques revolutionized the field and enabled the accurate solution of complex nonlinear stochastic problems involving non-stationary and non-Gaussian stochastic processes, whose solutions were unavailable before. One of the most critical parts of MCS techniques is the simulation of stochastic processes, fields and waves involved in the problem under consideration. Usually, stochastic processes and waves are used to model stochastic system excitations and stochastic fields to model stochastic system properties. These processes, waves and fields can be scalar or vector, one-dimensional or multi-dimensional, Gaussian or non-Gaussian, stationary or non-stationary, homogeneous or non-homogeneous, or any combination of the above. Extensive work has been done over the last four decades in developing simulation algorithms for this purpose. This presentation will provide some general reflections on this field, and then highlight some of the groundbreaking contributions of Professor Ahsan Kareem in this area: (i) simulation of non-Gaussian processes, waves and fields, (ii) simulation of non-stationary processes, waves and fields, (iii) simulation using wavelets, and (iv) simulation of stochastic waves in lieu of stochastic vector processes of large size.

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Title: Longitudinal Impact into Micropolar Bodies

Author(s): *George Gazonas, *CCDC US Army Research Laboratory*; Charles Randow, *CCDC US Army Research Laboratory*;

We revisit the problem of wave propagation in micropolar media [1] and present new one-dimensional (1-D) impact solutions for the direct impact Hopkinson pressure bar (DIHPB) [2] test configuration in which an elastic flyer impacts a micropolar target (specimen) backed by an elastic transmission bar. Micropolar theories are often used in the study of polycrystalline and granular media due to their ability to capture behavior not described using classical continuum approaches [3]. Micropolar media possess additional degrees of freedom (microstructure) that are associated with rotation and described with an additional vector field when compared with classical continuum mechanics. Herein, a 1-D micropolar body is kinematically described with two displacement fields: one field associated with longitudinal displacement and one associated with rotation. The rotation is in the same direction as longitudinal displacement, leading to a non-centrosymmetric 1-D micropolar medium.

Two second-order partial differential equations result from the application of the balance of linear and angular momentum, yielding a mixed initial-boundary value problem consisting of initial conditions, and boundary conditions at the interface between the flyer, target and transmission bar. The impact generates multiple reflected fast and slow shock waves in the target.

The Laplace transform, together with a novel impact boundary condition derived elsewhere by us, are used to develop analytical solutions for the stress and particle velocity in the Laplace transform domain at any point of the pressure bar system; a modified Dubner-Abate-Crump (DAC) algorithm is used to numerically invert those solutions to the time domain.

The final value theorem for Laplace transforms is used to show that the asymptotic (long observation time) stress and particle velocity is independent of target properties in micropolar media, but depend only on the impedance of the flyer (striker bar) and transmission bar; we have obtained the same asymptotic results for other classes of materials. Our findings aid in determining whether impact induced stress waves are mitigated in structures in which a micropolar solid is bonded between dissimilar materials; the results are also useful for verification of impact simulations into micropolar media taken to long observation times.

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Baltimore, MD, May 31 - June 3, 2022

Title: A Novel Physics-Informed General Convolutional Network Framework for the Computational Modeling of Material Damage

Author(s): *Ghadir Haikal, *Southwest Research Institute*; Michael Hartnett, *Southwest Research Institute*; Matthew Kirby, *Southwest Research Institute*; Jake Janssen, *Southwest Research Institute*; Erin DeCarlo, *Southwest Research Institute*; Fassett Hickey, *Southwest Research Institute*;

Machine Learning (ML) methods have had a tremendous impact in advancing modeling techniques in data-rich applications such as computer vision, medical diagnostics, and climate modeling. ML models enable the discovery of complex patterns that are otherwise elusive, hard to quantify, and/or cannot be modeled using first-principle numerical formulations due to computational cost or complexity. ML methods, however, require a substantial volume of training data to produce a predictive model, and are not capable of generalizable and out-of-sample predictions. These disadvantages have historically limited the application of ML approaches in areas where data is limited, such as materials engineering.

Recent research efforts have explored improving ML prediction accuracy by “informing” the ML training process with governing physics equations. This approach, referred to as physics informed ML, enforces the governing equations explicitly at training locations, substantially reducing the amount of data needed for training and increasing computational efficiency. Physics-Informed ML is well-suited for assisting in material modeling and characterization, particularly in the context of modeling damage propagation and material degradation, an area where traditional physics-based methods have struggled with numerical discretization, stability and convergence at locations of singularities and stress concentrations.

This work investigates a novel Physics-Informed General Convolutional Network (PIGCN) framework for the numerical modeling of materials with damage. We propose a constrained optimization framework where the governing equations of equilibrium, deformations, and boundary conditions are incorporated into a deep ML process using convolutional networks. The network is designed to model multiple physical responses of the system (displacement, strain and stress) via multi-task learning to predict stresses, strains and deformations at all points within a material sample with pre-existing damage (e.g., cracks, holes, notches, etc.), given the problem geometry, loading, boundary conditions and initial flaws. We implement the techniques of algorithmic differentiation to integrate the governing Partial Differential Equations (PDE)s as constraints in the training process.

A key advantage of the PIGCN approach is that the underlying framework is based on ML, which eliminates the computational burdens of physics-based modeling. The proposed approach addresses key concerns that have handicapped ML implementations in computational material modeling. This presentation discusses the formulation and implementation of the proposed framework, including the generation of training data, constraint implementation, validation with experimental testing and comparison with traditional physics-based finite element simulations. The goal is to show that PIGCN balances the computational efficiency and speed of ML algorithms with the generality and accuracy of physics-based numerical formulations.

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Baltimore, MD, May 31 - June 3, 2022

Title: Linear and Fracture Response of an Elastodynamic Metamaterial to Impact Loading

Author(s): Reza Abedi, *The University of Tennessee Space Institute*; *Giang Huynh, *The University of Tennessee Space Institute*; Willoughby Cheney, *University of Massachusetts Lowell*; Weidi Wang, *University of Massachusetts Lowell*; Alireza V. Amirkhizi, *University of Massachusetts Lowell*;

Keywords: Microstructured Media, Impact, Continuum Damage, Phase Field

Metamaterials are defined as microstructured media, which demonstrate overall properties that are not normally observed in nature. Novel metamaterial designs can break the limitations of conventional materials, e.g., difficulty of being simultaneously wave attenuating and stiff. We analyze the time domain response of a low-frequency resonant ceramic metamaterial design to high strain loading conditions. The asynchronous spacetime discontinuous Galerkin (aSDG) method is used for continuum solutions. We compare the response of metamaterial with monolithic slabs and other microstructured designs (e.g. hollow unit cells) in terms of stress wave mitigation, peak load retardation, and suitable energy transfer metrics. The advantages of the metamaterial design will be demonstrated for different geometry (number of cells) and loading. Furthermore, we extend the comparison beyond linear regime by considering material failure as high amplitude stress wave passes through the slab. Continuum damage and phase field models are used to computationally represent material failure. Overall, metamaterial slabs show better response in delaying and reducing the peak of stress wave compared to other designs considered. We observe a distributed failure response, as opposed to spall fracture reported for monolithic designs. Furthermore, the stress wave amplitude decreases even further for the metamaterial design when material failure is considered. Finally, the uses of this accurate but computationally expensive continuum model for fine-tuning the parameters of a very reduced order model (ROM), based on discrete representation of a grid of metamaterial cells will be briefly discussed.

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Title: Homogenization of Coupled Discrete Models for Mass Transport and Fracture in Concrete

Author(s): *Gianluca Cusatis, *Northwestern University*; Jan Elias, *Brno University of Technology*;

Computational homogenization became classical approach delivering a substantial reduction of computational cost for models with direct representation of material internal structure. The contribution derives, using a rigorous mathematical procedure via asymptotic expansion, a homogenized solution for discrete models of coupled phenomena of mechanics and mass transport in concrete. The coupling is twofold: via the Biot's theory and via the cracks that create channels for the fluid. Discrete model at hand is a mesoscale model where each rigid body represent larger mineral aggregate and surrounding matrix. Transport model uses dual tessellation enable to effectively account for cracks in the conduit elements. The mesoscale part of the solution is solved with a help of representative volume elements (RVE). The RVEs are heterogeneous and represented by the discrete model. There are two RVEs at each macroscopic location, the mechanical one and the transport one. They are both loaded by projection of macroscopic strain-like tensors that are transferred into eigen strains, eigen curvatures and eigen pressure gradients, respectively. Both RVEs are steady state problems, resulting stresses, couple stresses and fluxes are evaluated by formulas derived by the homogenization. The mechanical RVE is independent on the transport one, while the transport RVE requires on its input an information about crack openings from the mechanical RVE. The macroscopic level is described by homogeneous continuous transient differential equation of transport and mechanics with coupling terms along with boundary and initial conditions. The differential equations come directly from the homogenization. The mechanical part corresponds to Cosserat (micropolar) continuum. The macroscale model is transferred to the weak form and solved by the finite element method. At each integration point, the RVE couple is placed and solved at every iteration. The homogenized model is verified by several simple examples including Terzaghi's consolidation, flow through a compressed cylinder, constrained tension of a sealed prism and hydraulic fracturing of a hollow cylinder. Significant savings of computational time are reported and there is an excellent correspondence between the full and homogenized model in all the cases unless strain localization takes place. The homogenization does not apply in the case of strain localization because the fundamental assumption of existence of the RVE does not hold. RVE response becomes size dependent then.

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Baltimore, MD, May 31 - June 3, 2022

Title: Large-Eddy Simulation of Wind Loads on a Tall Building Located in a City Center: Validation with Experimental Data

Author(s): Abiy Melaku, *Western University*; Jeroen Janssen, *Thornton Tomasetti*; Peter McDonald, *Thornton Tomasetti*; Nickolaus Sundholm, *Thornton Tomasetti*; *Girma Bitsuamlak, *Western University*;

In 2050 it is estimated that more than twice as many people will be urban dwellers compared to those living in rural areas. To accommodate this ever-growing urban population, designing cost-effective tall buildings satisfying structural strength and serviceability requirements is crucial. For tall buildings, wind is often the governing lateral load, and wind tunnel testing has traditionally been used to determine the wind loads. However, the testing typically comes at the end of the design process once major design decisions are finalized. As a result, buildings are typically not optimized for wind performance.

Properly validated CFD models offer the designers the ability to generate preliminary design loads early for various iterations of their design and seamlessly integrate them into the design optimization process. Several CFD-based wind load evaluation studies have been conducted in recent years, albeit most of these studies mainly focus on the CFD simulation of wind loads on an isolated building. In the current study, wind load on a 278m tall building located in a city center with a realistic urban setup is studied using large-eddy simulation (LES). The approaching wind characteristics were reproduced using a synthetic inflow turbulence generation method coupled with rough wall boundary conditions on the ground. The numerical simulations were conducted using OpenFOAM on an unstructured grid generated utilizing several refinement regions. Initial validation of the LES results against experimental data measured in boundary layer wind tunnel generally showed a promising agreement. The incident wind profiles were separately validated in an empty domain simulation, which compare well with the profiles reported in the experimental study. Comparison of the mean and root-mean-square base loads from LES with the experimental measurement reveals that the differences are well within a 15% limit.

The challenges, recommendations, and future directions for more accurate wind load simulation in complex urban environments using LES are highlighted based on the findings from the current study. The highly integrated implementation of the synthetic inflow turbulence generation method presented here and its ease of use shows incredible potential to be implemented within common and iterative design workflows. Furthermore, the proposed methodology gives structural engineers and architects a versatile tool at their disposal to incorporate wind-informed decisions early in the project life cycle.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Performance Evaluation of a Coupled Fire-Atmosphere Wildfire Simulation Platform: The 2018 Camp Fire Case Study

Author(s): Kasra Shamsaei, *University of Nevada, Reno*; Timothy W. Juliano, *National Center for Atmospheric Research*; Matthew Roberts, *University of Nevada, Reno*; *Hamed Ebrahimian, *University of Nevada, Reno*; Branko Kosovic, *National Center for Atmospheric Research*; Neil P. Lareau, *University of Nevada, Reno*; Ertugrul Taciroglu, *University of California, Los Angeles*;

This study investigates the performance and limitations of the Weather Research and Forecasting – Fire (WRF-Fire) model, a coupled atmosphere - wildland fire behavior simulation platform, in simulating the 2018 Camp Fire. The fire behavior model in WRF-Fire is a semi-empirical fire propagation model fully coupled with the WRF-ARW atmospheric simulation model. The coupling of the fire behavior model with WRF-ARW allows the fire model to ingest simulated weather conditions, and “create its own weather” by disturbing the atmosphere as a result of releasing fire heat fluxes to the atmospheric model. First, a baseline simulation of the Camp Fire is run using a typical setup found in WRF-Fire operational applications. Next, the results are compared to semi-continuous, high-temporal-resolution fire perimeters derived from NEXRAD radar observations and show non-negligible discrepancies between simulated fire boundary and observations. Lastly, a sensitivity analysis is performed on several modeling parameters and assumptions governing the simulated wind field, one of the possible sources of error, to further evaluate WRF-Fire performance and limitations. The sensitivity analysis results show that the simulated fire is highly sensitive to the modeling parameters and assumptions controlling the wind field, and refining the atmospheric grid domain of the Camp Fire complex terrain improves the fire prediction capabilities.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Modeling of 3D printing Concrete Using the Reproducing Kernel Particle Method

Author(s): Aleksandra Radlinska, *The Pennsylvania State University*; *Hanbin Cheng, *The Pennsylvania State University*; Feihong Liu, *The Pennsylvania State University*; Michael Hillman, *The Pennsylvania State University*;

In this study, the reproducing kernel particle method (RKPM) [1,2] was used to perform numerical investigation of the effects of printing speed and nozzle height on the geometry of printed concrete, as well as failure prediction for multi-layer concrete deposition. The RKPM modeling was verified through parametric experiments by using two concrete mix designs for 3D printing. The Bingham constitutive law was adopted to model the rheological properties of fresh concrete during 3D printing. The parameters of cement-based mortar used in the experiments were measured first with rotational rheology tests. As to the modeling of one-layer deposition printing, the dynamic rheological parameters, dynamic yield stress and viscosity, were determined through calibration method based on the Krieger-Dougherty and the Chateau-Ovarlez-Trung models, respectively. The printing failure prediction was conducted by using static yield stress and viscosity. These RKPM simulations investigated the effects of the fresh properties of printed concrete and related printing parameters on the performance of 3D printed concrete which provided insights for the toolpath design and printing strategy.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Numerical Simulation of 3D Printed Concrete Walls Under Mechanical Loads

Author(s): *Hao Chen, *Texas A&M; University*; Mohammad Aghajani Delavar, *Texas A&M; University*; Petros Sideris, *Texas A&M; University*;

Three-dimensional printed concrete (3DPC) structures present an attractive alternative to conventional construction by offering construction rapidity and potentially lower construction costs through automation, i.e. the use of 3D printers. It also offers environmental benefits by eliminating the need for formwork and by producing and using concrete only as needed during the construction process. However, there are no accepted 3DPC structural designs and no design guidelines, codes or provisions. The most common 3DPC element in proposed designs for residential construction is the 3DPC wall. Thus, appropriate numerical simulation strategies for 3DPC walls subjected to different loading conditions is essential for designing and understanding the performance of this new type of structures.

In this study, the numerical simulation of 3DPC walls is investigated. Multiple 3DPC wall designs adopting a proposed reinforcing strategy with integrated RC elements and ladder mesh are simulated under different axial loads and considering different infill patterns. For computational efficiency, the printed concrete was modeled via thick shell elements, the RC elements were modeled using fiber-based beam elements, and the ladder mesh is modeled via truss elements. A geometrically nonlinear thick 4-noded shell element adopting an element-independent corotational formulation was investigated. The material behavior of the shell elements was simulated using a new damage plastic 3D concrete material model, which was developed and implemented in OpenSees as part of this study. Results from pushover analyses demonstrate good agreement between the numerical and theoretical predictions. Cyclic analyses are also compared with data from large-scale tests of an ongoing parallel study.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Evolution of Bending Failure Mode and Bearing Capacity of RC Beams with Corrosion Propagation of Steel Reinforcements

Author(s): Chao Jiang, *Tongji University*; *Hao Ding, *Tongji University*; Xiang-Lin Gu, *Tongji University*; Wei-Ping Zhang, *Tongji University*;

In order to rapidly and accurately evaluate the influence of steel reinforcement corrosion on the flexural behavior of the normal cross-section of reinforced concrete (RC) beams, the stress and strain distributions over the normal cross-section of corroded RC beams at flexural failure were analyzed. According to the stress states of corroded tensile steel reinforcements at bending failure of an RC beam, three bound corrosion ratios and four bending failure modes for the corroded RC beam were identified and defined. Then, a failure mode-based calculation method for the bending bearing capacity of the normal cross-section of corroded RC beams was proposed that enables to predetermine failure mode first and calculate bearing capacity later. Subsequently, the proposed calculation method, as well as modified conventional methods, was compared with tested ultimate bending moments of 421 corroded and 96 non-corroded control RC beams. The comparisons and analyses showed that the bending bearing capacities predicted by the proposed method had good match with the test results in the full range of corrosion ratios of tensile steel bars, but the modified conventional methods theoretically remained valid only in partial ranges of corrosion ratios. Finally, several examples were designed to investigate the evolution of flexural failure mode and bearing capacity of the normal cross-section of an initially over-reinforced or under-reinforced RC beam with the corrosion propagation of tensile steel reinforcements. The results showed that as the corrosion ratio of tensile longitudinal steel reinforcements increases: 1) the flexural failure mode of the normal cross-section of an initially over-reinforced RC beam changes in order of "over-reinforced similar mode", "under-reinforced similar mode", "over-reinforced similar mode" and "slightly-reinforced similar mode"; 2) the flexural failure mode of the normal cross-section of an initially under-reinforced RC beam changes in order of "under-reinforced similar mode", "over-reinforced similar mode" and "slightly-reinforced similar mode"; 3) the flexural bearing capacity of the normal cross-section of an RC beam decreases in an approximately multi-linear way and finally reduces to the cracking moment of a plain concrete beam, in which the turning point positions locate at the bound and critical corrosion ratios.

Title: SPH+FEM Analysis of Anchoring Capacity in Dry Silica Sand

Author(s): *Haozhou He, *Georgia Institute of Technology*; Andras Karsai, *Georgia Institute of Technology*; Bangyuan Liu, *Georgia Institute of Technology*; Frank Hammond, *Georgia Institute of Technology*; Daniel Goldman, *Georgia Institute of Technology*; Chloe Arson, *Georgia Institute of Technology*;

In this study, a 3D hybrid continuum numerical approach that couples the Smoothed Particle Hydrodynamics (SPH) method and the Finite Element (FE) method is developed to analyze the local anchoring mechanisms and the ultimate capacity of different anchor systems that intrude into a bed of dry slightly polydisperse silica sand (450-800 micron) at controlled speed. The SPH method is less efficient than the FE method in terms of computational cost. But the meshfree nature of SPH enables accurate simulation of large deformation problems such as the intrusion of granular media by deformable solid bodies, which are difficult to solve with traditional FE methods. In the developed hybrid model, the soil subject to large deformation, close to the penetration zone, is modeled with SPH. To save computational cost, the deformable anchor and the granular medium in the far field, where only small deformation is expected, are modeled with the FE method. A MATLAB script is developed to merge the nodes at the interface of the FE and SPH discretization domains in the granular medium, so as to apply a tie-condition. The soil domain is thus modeled as a single deformable unit.

A frictional contact law is used at the anchor/soil interface. The behavior of the granular medium is represented by a Drucker-Prager constitutive model, in agreement with previous studies¹. The constitutive parameters of the granular medium are determined experimentally and the numerical parameters of the hybrid SPH+FEM model are calibrated against physical experiments conducted with anchors made of a variable number of fan-shaped or spike-shaped blades (convex hull of radius 40mm) attached to a bar of circular cross-section (radius: 2.5mm). Using a symmetry boundary condition, the numerical model is designed to represent half of the sand box ($L \times W \times H = 30 \times 20 \times 20$ cm). To simulate shallow penetration (up to 40mm), satisfactory results are found with a half - domain of dimensions $L \times W \times H = 32 \times 16 \times 14$ cm including a SPH domain of dimensions $L \times W \times H = 16 \times 8 \times 9$ cm. The sensitivity of the anchoring capacity to the shape and the number of blades is analyzed. The failure mechanisms are highlighted and the benefits of arching effects are discussed. With the long-term goal to design a self-propelled robot capable of exploring the subsurface, anchor deployment is then simulated, and the work input is calculated for various deployment sequences.

The hybrid modeling approach presented provides key insights on granular flow, anchoring mechanisms and soil/anchor interactions. This study shows that SPH+FEM hybrid continuum modeling approaches can be used for simulating intrusion of granular media and provides useful information for engineering design.

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EMI 2022
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Title: Inverse-Designed Nonlocal Scattering for Analog Computing

Author(s): *Heedong Goh, *The University of Texas at Austin*; Andrea Alu, *City University of New York*;

Analog computing is drawing significant interest as a fast and energy-efficient alternative to its digital counterpart. In particular, a wave-based analog computer exploits wave-matter interactions, either in acoustics, elastodynamics, or electromagnetics, where a solution to a given mathematical problem is encoded in the reflected or refracted waves by a precisely designed metamaterial device.

However, such devices generally require large areas to interact as special mirrors or lenses, limiting their scalability. Recently, we proposed a new compact platform of analog computing using a single scatterer to solve integro-differential equations [1]. By tailoring the nonlocality of a scatterer, an object of a size of a wavelength approximates the inverse operator of a given mathematical problem, realizing an analog solver to arbitrary input data.

In this presentation, we introduce the general concept of a scattering-type analog computer and its inverse-design framework. The Domain Reduction Method and the Perfectly Matched Layers are used to model the scattering problem. We use the Inexact Newton Method to find the optima of an objective functional, which measures the inverse relation of the scattering matrix and the target mathematical operator.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Reduced-Order Modeling with Time-Dependent Bases for Stochastic PDEs with Random Boundary Conditions

Author(s): *Hessam Babaee, *University of Pittsburgh*; Prerna Patil, *University of Pittsburgh*;

Low-rank approximation using time-dependent bases (TDBs) has proven effective for reduced-order modeling of stochastic partial differential equations (SPDEs). In these techniques, the random field is decomposed to a set of deterministic TDBs and time-dependent stochastic coefficients. When applied to SPDEs with non-homogeneous stochastic boundary conditions (BCs), appropriate BC must be specified for each of the TDBs. However, determining BCs for TDB is not trivial because: (i) the dimension of the random BCs is different than the rank of the TDB subspace; (ii) TDB in most formulations must preserve orthonormality or orthogonality constraints and specifying BCs for TDB should not violate these constraints in the space-discretized form. In this work, we present a methodology for determining the boundary conditions for TDBs at no additional computational cost beyond that of solving the same SPDE with homogeneous BCs. Our methodology is informed by the fact the TDB evolution equations are the optimality conditions of a variational principle. We show that the presented methodology can be applied to stochastic Dirichlet, Neumann, and Robin boundary conditions. We assess the performance of the presented method for linear advection-diffusion equation, Burgers' equation, and two-dimensional advection-diffusion equation with constant and temperature-dependent conduction coefficient.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: A Multilevel Sampling Approach for Uncertainty Quantification of Large-Scale Subsurface Flow

Author(s): *Hillary Fairbanks, *Lawrence Livermore National Laboratory*; Umberto Villa, *Washington University in St. Louis*; Panayot Vassilevski, *Portland State University*;

Model-based simulations are an important aspect of predicting physical phenomena. In the presence of uncertain physical parameters, which describe the physical system, accurately assessing confidence in these results, i.e., performing uncertainty quantification (UQ), can become computationally expensive. This is the case in subsurface flow modeling, where the uncertain permeability field is heterogeneous and can be described with multiple scales of resolution. Not only are the corresponding high-fidelity (fine-scale) simulations expensive, but popular statistical approaches, such as Markov chain Monte Carlo (MCMC), require an exceedingly high number of simulations.

In this work, we develop a new scalable sampling method which complements the algorithmic framework of multilevel MCMC, where coarse grid simulations are used to inform the fine level proposal distribution, thereby accelerating MCMC. Specifically, using tools from algebraic multigrid, we form a (scalable) fine grid Gaussian random field realization from a fine grid proposal by combining Gaussian random fields sampled across multiple levels of discretization. In this talk, we describe this new approach, corresponding theory, and numerical results when applied to a 3D subsurface flow application.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Fracture of 2D Materials – In situ Experiments and ML Parameterized Force Fields

Author(s): *Horacio D. Espinosa, *Northwestern University*; Xu Zhang, *Northwestern University*; Hoang Nguyen, *Northwestern University*;

2D materials are being employed in the development of next-generation electronics, optical, and sensor technologies, as well as in energy production and storage techniques, e.g., supercapacitors, solar cells, and battery electrodes. Such applications involve frequent mechanical deformations such as stretching and bending, so the lifespan (integrity and reliability) of the material is a critical feature. In this context, the abrupt and brittle failure of 2D materials require particular attention. In this presentation, I will discuss strategies for the in-situ electron microscopy fracture testing of 2D materials as well as advances in the parameterization of interatomic potentials (force fields) [1-2] for accurate description of crack tips' atomic lattice reconstructions and bond dissociations. Experimentally, I will present two approaches: i) e-beam assisted crack propagation with measurement of crack tip deformation fields, based on atomic images, and ii) MEMS-based displacement-controlled fracture testing. The parameterization of force fields is based on a multi-objective genetic algorithm and machine-learning-inspired protocols, with training and screening data sets involving both equilibrium and far from equilibrium pathways such as phase transitions, vacancy formation energies, and bond dissociation energy landscapes. Using monolayer MoSe₂ as a testbed, I will illustrate the effectiveness of the combined experimental-computational approach in measuring and predicting the toughness of the material, demonstrating in the process the advantages of ML-inspired force field parameterization in developing computational approaches with predictive capabilities.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Effects of Excitation Parameters and Material Flexibility on Performance of Fish Tails Forced by a Combination of Pitching and Heaving Motions

Author(s): *Hossam Aboalela, *Department of Civil, Environmental and Ocean Engineering Stevens Institute of Technology, Hoboken, NJ*; Muhammad Hajj, *Department of Civil, Environmental and Ocean Engineering Stevens Institute of Technology, Hoboken, NJ*;

Fish species belonging to caudal or trunk swimmers propel themselves by undulating their entire body or oscillating their posterior. Because of its efficiency and high maneuvering capability, fish-like propulsion has inspired the design of stable, efficient and quiet low-speed underwater robots. In these designs flapping a foil that mimics a fish tail can be achieved through a pitching excitation by pivoting it around a fixed point, by moving it in the transverse direction, or by a combination of the two excitations. Different geometric and material properties can impact the efficiency of the design, which can be optimized thorough analysis of the impact of these properties on the propulsion performance.

We perform a numerical investigation of the propulsion efficiency of flapping foils with particular attention on the effects of material flexibility. The flapping combines transverse and pitching motions that mimic tail oscillations of thunniform swimmers. The tail is modeled as a thin rectangular panel using the Euler-Bernoulli beam theory. The three-dimensional unsteady vortex lattice method is used to calculate the hydrodynamic loads generated by the combined excitation. The finite element method is implemented to solve the coupled time-dependent equations of motion with an implicit solver for time integration. The fluid-structure interaction is modeled through passing the hydrodynamic loads to the coupled equations of motion and solving for structural deformation of the tail at each time step. The deformation of the beam is assumed to be in the bending direction only. The performance metrics include thrust generation and propulsive efficiency. The results are validated with previously published experimental data.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Coupling 3D Solid and Shell Models with a Non-Intrusive Iterative Global-Local Algorithm

Author(s): *Javier Avecillas Leon, *University of Illinois at Urbana-Champaign*; Haoyang Li, *University of Illinois at Urbana-Champaign*; Nathan Shauer, *University of Illinois at Urbana-Champaign*; Armando Duarte, *University of Illinois at Urbana-Champaign*;

This paper presents a non-intrusive coupling algorithm able to accurately capture fine-scale phenomena on structural-scale finite element models. The structural model that captures the coarse-scale/global response of a problem adopts shell elements and is solved with commercial finite element software. Fine-scale phenomena such as geometry details, localized material nonlinearity, or cracks are simulated using the Generalized Finite Element Method with global-local enrichments (GFEMgl). Coupling the models with an iterative global-local (IGL) algorithm enables capturing localized 3D effects while keeping the computational efficiency and simplicity of the structural model [1]. Nevertheless, without an adequate acceleration technique, the IGL algorithm may require several iterations or even diverge. Therefore, the robustness of an acceleration algorithm based on dynamic relaxation is investigated for various representative problems.

The accuracy of the IGL-GFEMgl is compared against a reference solution provided by a Direct Generalized Finite Element Analysis. The results show that the proposed framework is able to capture the structural scale response as well as 3D localized phenomena.

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Physics-Informed Neural Networks for Network Analysis and Reliability Assessment of Lifeline Infrastructures

Author(s): *Ji-Eun Byun, *Technical University of Munich*; Daniel Straub, *Technical University of Munich*;

Lifeline infrastructures such as pipeline networks, transportation networks, and telecommunication systems play a pivotal role in today's societies. In extreme hazardous events, these systems may fail to fulfill their functionality (e.g., a disconnection from power generation to consumers or interrupted traffic flows to essential services). Accordingly, it is crucial to accurately assess the reliability of those systems so that risk-informed decisions can be made to prevent such adverse consequences.

Infrastructure networks are often represented as a graph, consisting of edges and nodes; and their functionality is evaluated by applying maximum flow or connectivity analysis over given realizations of the states of fragile components (which are limited to edges in this study). Since an exhaustive enumeration of the joint states of components is often infeasible, the most common approach for reliability assessment is to apply Monte Carlo Simulation (MCS). However, MCS becomes computationally demanding as a failure probability decreases, in which case a larger number of samples are required to achieve a satisfactory accuracy. This is an issue in particular for larger systems with many components.

To address this issue, we investigate whether network analysis algorithms can be partially replaced by artificial neural networks (ANNs) to evaluate system functionality. Since ANNs are particularly efficient in making predictions in batch over a large number of input datasets, they can facilitate an MCS-based reliability analysis by rapidly evaluating a large number of samples. To make the training of ANNs more efficient, we develop a physics-informed neural network to predict maximum flow from a source node to a terminal node. To this end, we incorporate equations and constraints used in maximum flow analysis into loss functions of ANNs, i.e., the functions used to measure prediction accuracy during a training phase. The accuracy and efficiency of the proposed ANNs and the MCS-based reliability analysis are evaluated by numerical examples.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: A Multiscale Finite Element Modeling Framework for Aluminum-Polyester Composite Abradable Coating in Gas Turbine Engines

Author(s): *Jiahao Cheng, *Oak Ridge National Laboratory*; Xiaohua Hu, *Oak Ridge National Laboratory*; Drew Lancaster, *Pratt & Whitney*; Xin Sun, *Oak Ridge National Laboratory*; William Joost, *Formerly Pratt & Whitney*;

Aluminum-polyester composites are applied as abradable sealcoating in gas turbine engines where they experience extreme strain rates “rub” from the engine rotating blade tip in a high temperature-pressure environment. Due to the difficulty in direct measurements, predictive computational models are important for analyzing the deformation and failure of the abradable material to help meet the design target of avoiding damage to blade-tip and maintaining high fuel efficiency. However, current rub models are phenomenological and cannot be relied on to reduce the testing required for certification. In this work, we describe a multiscale framework that captures microstructure-dependence of the composite material under “rub” condition. First, a microstructure-based finite element (FE) computational model is developed to capture the complex mechanical behavior of AlSi/polyester microstructure. The model is based on virtual representative-volume-element (RVE) of metal-polymer microstructure reconstructed from the x-ray computed tomography and models the plastic deformation and damage in each AlSi and polyester constituents as well as the failure at their interface, respectively. The model is calibrated and validated with uniaxial tension and compression experiments conducted at two temperatures of 300K and 533K at an applied strain rate of 10^3 - 10^4 s^{-1} . Then, a reduced order model (ROM) is developed for component level finite element simulations. This ROM incorporates the tension-compression asymmetry in the both plastic yield surface and damage evolution, and captures the temperature and rate dependency in the material properties. By validating with experiments, this multiscale model reveals mechanisms of rub response that are extremely difficult to access experimentally while opening routes toward design of improved coatings. Favorable comparisons to experimental results provide model validation while encouraging further application of this method.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Mixing kinetics of Ultra-High-Performance Concrete (UHPC)

Author(s): *Jiang Du, *Stevens Institute of Technology*; Soroush Mahjoubi, *Stevens Institute of Technology*; Yi Bao, *Stevens Institute of Technology*; Weina Meng, *Stevens Institute of Technology*;

The mixing of ultra-high-performance concrete (UHPC) featuring low water-to-binder ratios involves different evolution of microstructures and mixing torques from conventional concrete. This paper investigates the mixing kinetics of UHPC in the mixing process, presents a mixing kinetics model to predict the mixing torque at an arbitrary time instant, and develops a multi-batching method to reduce the mixing torque for large-volume production of UHPC. The presented mixing kinetics model considers the effects of mixing temperature, mixing volume, and mixing methods. The mixing kinetics model is calibrated using experimental data, and the calibrated model shows high prediction accuracy. The multi-batching method enables large-volume mixing of UHPC by reducing the mixing torque while retaining desired flowability and hardened properties of UHPC. Specifically, when the number of sub-batches is two, the peak mixing torque of the multi-batching method was approximately reduced to half of the peak mixing torque of the mono-batching method. Besides, the differences in workability, compressive strength, and autogenous shrinkage by using the multi-batching method and mono-batching method are within 5%. Finally, the mixing kinetics model and multi-batching method are validated using different types of UHPC. This study will advance understandings of the mixing kinetics for UHPC and promote large-volume UHPC production.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Data-Driven Microstructure Evolution Using Physics Regularized Interpretable Machine Learning
Microstructure Evolution (PRIMME)

Author(s): Joseph Melville, *University of Florida*; Weishi Yan, *University of Florida*; Kristien Everett, *University of Florida*; Lin Yang, *University of Florida*; Vishal Yadav, *University of Florida*; Amanda Krause, *University of Florida*; Michael Tonks, *University of Florida*; *Joel B. Harley, *University of Florida*;

Microstructural grain growth simulations are used to predict grain boundary evolution behavior of manufactured materials, such as metals and ceramics. The microscale character of these boundaries has a significant effect on the macroscale properties of these materials. Common techniques for simulating microstructural grain growth include phase field, cellular automata, and Monte-Carlo-Potts methods. However, these methods are often based on simplistic physical laws and do not easily incorporate experimental data to refine model behavior. As a result, the methods do not accurately model many real world grain growth behaviors, such as abnormal grain growth.

To address this limitation, this presentation discusses a data-driven and physics-informed deep learning framework for microstructural grain growth simulation called Physics Regularized Interpretable Machine learning Microstructure Evolution (PRIMME). This model enables us to train microstructure evolution based on a combination of physical laws and data (from simulations and/or experiments). Due to our integration of physics, this adaptive process does not require huge amounts of new data. In addition, the output of the PRIMME model provides an interpretable “action likelihood” that indicates which neighbors a site is likely to flip to and lends insight into the decisions made by the model.

In this presentation, we demonstrate the use of PRIMME to simulate polycrystalline microstructure evolution as trained on data from Stochastic Parallel PARTicle Kinetic Simulator (SPPARKS) for isotropic grain growth. We validate PRIMME results against simulations run in SPPARKS and Multiphysics Object-Oriented Simulation Environment (MOOSE). And we also investigate how the PRIMME “action likelihood” can be interpreted. Finally, we introduce updates to the publicly available PRIMME code, now implemented in PyTorch, which runs about twice as fast as similar simulations in SPPARKS and ten times faster than MOOSE.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Stochastic Modeling and Experimental Identification of Anisotropic Elasticity-Plasticity Constitutive Laws for Additively Manufactured Materials

Author(s): Shanshan Chu, *Duke University*; *Johann Guilleminot, *Duke University*; Athanasios Illiopoulos, *US Naval Research Laboratory*; John Michopoulos, *US Naval Research Laboratory*;

We present a stochastic modeling framework for the anisotropic elasticity and plasticity constitutive laws describing 3D-printed materials. We specifically consider the case of powder-bed manufactured 316L stainless steel. This material was experimentally characterized at the micro- and macro-structural levels. Information-theoretic models are developed to represent the observed spatially-dependent variability in the constitutive parameters, and statistical inverse identification is performed based on the aforementioned experiments. Uncertainty propagation is finally conducted in the linear and plastic regimes to investigate the impact of subscale material stochasticity on the structural response.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Nature Inspired Microvascular Active Cooling Network Design Using Steady State and Transient Topology Optimization

Author(s): *Jonathan Gorman, *Drexel University*; Reza Pejman, *Drexel University*; Ahmad Najafi, *Drexel University*;

We propose a gradient-based topology optimization framework using the Finite Element Method (FEM) to design a microvascular composite cooling network by applying a steady state and transient analysis. Microvascular composites are a novel class of fiber-reinforced polymer structures that employ internal vascularization to augment the performance of characteristics such as self-healing, thermal regulation, or electromagnetic modulation. The focus of this study is placed on the optimization of an actively cooled microvascular composite, which has an application in the thermal management of batteries and microelectronics.

Rapid cooling of electronic devices is an essential factor in increasing their applicability and longevity. Therefore, the concentration of this study is on designing the cooling network to convect heat out of the device as quickly as possible to facilitate an efficient return to the cold steady-state. In the transient method presented, a semi-discretization scheme in time is adopted to obtain the time-dependent thermal response. A Topology Optimization (TO) method is utilized for both steady state and transient analyses, which has the ability to change the topology of the network by creating/removing microchannels during the shape optimization process. This task has been carried out by introducing a set of design parameters that act analogous to the design parameters in the Solid Isotropic Material with Penalization (SIMP) method. Fully analytical sensitivity analyses of both the transient and steady state scheme have been developed and their accuracy verified against the finite difference method.

Several application problems have been solved to demonstrate the capability of using the proposed nature inspired TO schemes for the thermal design of microvascular materials.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Physics-Informed Neural Network Enhanced Reproducing Kernel Particle Method for Modeling Grain Refinement

Author(s): Jiun-Shyan Chen, *University of California, San Diego*; *Jonghyuk Baek, *University of California, San Diego*; Kristen Susuki, *University of California, San Diego*;

The microscopic behaviors of materials under large deformation often entail complicated localized phenomena, such as plastic slip, grain boundary evolution/migration, micro-shearband, and micro-damage. Modeling of such localizations requires highly refined discretization for accurate prediction, which significantly increases the computational cost. While adaptive model refinement can be employed for enhanced effectiveness, it is cumbersome for the traditional mesh-based methods to perform adaptive model refinement. In this work, neural network-enhanced reproducing kernel particle method (NN-RKPM) is proposed, where the location, orientation, and the shape of the solution transition is automatically captured by the NN approximation by the minimization of total potential energy. The standard RK approximation is then utilized to approximate the smooth part of the solution to permit a much coarser discretization than the high-resolution discretization needed to capture sharp solution transition with the conventional methods. The proposed neural network approximation is regularized by introducing a length scale related to the objective dissipation energy. The proposed NN-RKPM is first verified by solving the standard damage evolution problems. The proposed computational framework is then applied to modeling grain refinement mechanisms by coupling the proposed NN-RKPM with phase field and Cosserat crystal plasticity [1], including the migration of grain boundaries at a triple junction and sub-grain formation of a material with activated slip systems, for validating the effectiveness of the proposed methods.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: RKPM for Duality-Based Coupling of Cosserat Crystal Plasticity and Phase Field Theories for Modeling Grain Refinement

Author(s): *Jonghyuk Baek, *University of California, San Diego*; J. S. Chen, *University of California, San Diego*; Michael Tupek, *Sandia National Laboratories*; Frank Beckwith, *Sandia National Laboratories*; H. Eliot Fang, *Sandia National Laboratories*;

High-rate deformation processes of metals entail intense grain refinement and special attention needs to be paid to capture the evolution of microstructure. In this work, a new formulation for coupling Cosserat crystal plasticity and phase field is developed [1]. A common approach is to penalize kinematic incompatibility between lattice orientation and displacement-based elastic rotation [2]. However, this can lead to significant solution sensitivity to the penalty parameter, resulting in low accuracy and convergence rates. To address these issues, a duality-based formulation is developed which directly imposes the rotational kinematic compatibility. A weak inf-sup-based skew-symmetric stress projection is introduced to suppress instabilities present in the dual formulation. An additional least squares stabilization is introduced to suppress the spurious lattice rotation with a suitable parameter range derived analytically and validated numerically. The required high-order continuity is attained by the reproducing kernel approximation. It is observed that equal order displacement-rotation-phase field approximations are stable, which allows efficient employment of the same set of shape functions for all independent variables. The proposed formulation is shown to yield superior accuracy and convergence with marginal parameter sensitivity compared to the penalty-based approach and successfully captures the dominant rotational recrystallization mechanism including block dislocation structures and grain boundary migration.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: A Frame-Element Based Topology Optimization Framework for Low-Density Designs

Author(s): *Josephine Carstensen, *Massachusetts Institute of Technology*;

Topology optimization is often presented as a powerful freeform design tool with the potential to leverage the possibilities afforded by advances in manufacturing. The rapid development of fabrication technologies, including additive manufacturing (AM) techniques, have revolutionized the fabrication-related cost of design complexity by nearly eliminating it. Although fabrication possibilities have been dramatically changed, there are still limitations. Within the last decade, tailoring topology optimization algorithms to AM constraints has received considerable attention. Most work has focused on incorporating AM related manufacturing constraints and possibilities into continuum-based design frameworks. This includes efforts to address the need for support material and/or the so-called overhang constraint, infill design, and designing with multiple base materials.

A new thrust within the development of manufacturing technologies is the emersion of Large Scale AM methods, including technologies such as Wire-and-Arch AM, Big Area AM, and concrete 3D printing. These AM technologies will allow fabrication of complex full-scale structures as opposed to the current component-level size restriction imposed by most conventional AM machinery. In addition to the technology-specific behavioral and fabrication constraints, a design problem posed for Large Scale AM will differ from a conventional design problem for AM, in that the design domain typically will be much larger and require a small amount of material. While an efficient design with 50% material volume within the design domain may be well suited for conventional AM, it has an unreasonably high material use for many Large Scale AM applications.

Designs obtained with continuum-based topology optimization frameworks typically do not perform well for very low material volumes. This leads us to explore a design approach based on discrete elements. Whereas the few existing topology optimization approaches for AM with discrete elements use a truss discretization, this work will focus on frame elements. The design problem will be formulated as a mixed integer linear program and solved using Gurobi. The algorithm will be demonstrated on 2D benchmark design problems. Designs will be fabricated, experimentally tested, and compared to equivalent continuum density-based topology-optimized designs.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Autonomous Robotic Defect Tracking for Infrastructure Maintenance

Author(s): *Joshua Genova, *University of Houston*; Vedhus Hoskere, *University of Houston*;

Wind energy generated through wind turbines is a critical contributor towards realizing a renewable energy economy. Maximizing the efficiency of power generation from wind turbines is required to meet target generation capacities. The leading edge of wind turbine's blade is designed such that its smooth, aerodynamic surface will produce maximum power given the size specification of the turbine. As these blades age, they typically suffer from leading edge erosion, or LEE, which is the gradual erosion of the blade's leading edge. Not only does LEE shorten a blade's lifespan, but it also negatively affects performance, reducing annual energy production. Application of wind blade protection tape is a frequently used solution for LEE on the damaged area. Tape application requires a crew of technicians with a lift and is considered high-risk where one mistake can lead to fatal injury. The focus of this paper is to present a deep reinforcement learning approach of automating the wind blade protection tape application by using a UAV with a 7 degree-of-freedom robotic arm. The UAV learns suitable dynamic motions while the robotic arm follows a taping trajectory on a wind turbine blade. Given a UAV pose, we check if a set of joint angles is kinematically feasible for a robot arm trajectory by using a dense reward function that penalizes if the robot path is not achievable. In stochastic environments, such as high-towering wind turbines, this is beneficial in compensating for abrupt changes like wind speeds for UAV poses and robotic arm end-effector kinematics. The end-effector of the robotic arm is an automatic taping mechanism that will apply wind blade protection tape to the damaged area. Using deep reinforcement learning in navigation of the UAV and motion of the robotic arm accounts for changing dynamics of the aerial robotic system. The developed end-effector demonstrates the effectiveness of the automation of the taping operation, ultimately conserving the wind blade's lifespan and decreasing the risk of human injury.

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: A New Regularization Approach for Topology Optimization with Discrete Objects

Author(s): *Julia Carroll, *Johns Hopkins University*; James Guest, *Johns Hopkins University*;

Density-based topology optimization discretizes a structure using a spatial mesh and the goal is to determine whether each element is solid or void. Due to the large design space, topology optimization typically relies on gradient-based optimization, requiring discrete outcomes (each element of the mesh is either solid or void) to be achieved using continuous variables (elements may be semi-solid, between solid and void). Approaches such as SIMP or RAMP can be combined with approaches such as projection methods to achieve this goal at the finite element level. This talk will present a novel regularization technique that maps a field of continuous decision variables onto a discrete set of physical variables in order to enable the use of gradient-based algorithms in the topology optimization of components for fabrication by additive manufacturing. The technique was motivated by the capabilities of Electron Beam Freeform Fabrication (EBF3), a wire-fed AM process. We demonstrate the proposed approach on the design of lightweight structural components, using a manufacturing primitive tailored to the EBF3 process, employing the regularization technique to control geometry. Extension of the approach to other discrete topology optimization problems is explored, and applicability to more general engineering optimization problems is also discussed.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Reliability-Based Topology Optimization Using a Virtual Element Method

Author(s): *Junho Chun, *Syracuse University*;

The paper presents a virtual element method-based topology optimization under uncertainties. Along with a growing demand to improve the scientific approach and accountability behind risk quantification and failure prediction, the field of reliability-based topology optimization (RBTO) has progressed substantially in recent years. The objective of this research is to integrate reliability analysis approaches including the first/second-order reliability method, and single-loop method into topology optimization (Bendsøe and Sigmund 2004) employing the virtual element method (Beirão Da Veiga et al. 2013). The virtual element method, a discretization scheme for irregular meshes with the arbitrary number of nodes is utilized to solve RBTO problems in which design domains are discretized with convex and non-convex polygons. The utilization of the virtual element method for the construction of the discrete bilinear form, known as the stiffness matrix, and the force vector required to solve RBTO problems are discussed. This paper presents the geometry processing and tessellation algorithms to mesh design domains of RBTO problems and a system reliability method to estimate the probabilities of system events. For computational efficiency in a gradient-based optimization procedure, sensitivity analysis of the component and system failure probability is developed. Numerical examples and applications are presented to demonstrate the performance of the proposed method.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Assessing the Current and Future Probability of Hurricane Ida's Blackout-Heatwave Compound Hazard

Author(s): *Kairui Feng, *Princeton University*; Ning Lin, *Princeton University*; Avantika Gori, *Princeton University*; Dazhi Xi, *Princeton University*; Min Ouyang, *Huazhong University of Science and Technology*; Michael Oppenheimer, *Princeton University*;

The compound hazard of blackout-and-heatwave following hurricanes varies in response to changes in tropical cyclone (TC) climatology, sea level, and global warming. To assess the temporal evolution of blackout-heatwave compound hazard in the state of Louisiana, we combine probabilistic estimates of TC climatology, sea level, and temperature projection with a physical power resilience model. Between 2000 and 2100, the return period of Hurricane Ida's compound hazard is estimated to decrease by a factor of ~6x due to global warming under the SSP 5 RCP 8.5. When potential changes in TC climatology and sea level rise over the next century are taken into consideration, Ida's compound hazard return period is estimated to drop by a factor of ~24x between 2000 and 2100.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Effect of Partitioning Geometry on Inhomogeneous and Anisotropic Apparent Properties of Statistical Volume Elements

Author(s): *Katherine Acton, *University of Saint Thomas*; Reza Abedi, *University of Tennessee*; Justin Garrard, *University of Tennessee*;

Stochastic fracture applications require the availability of local constitutive information describing a material microstructure, which is naturally heterogeneous and anisotropic at a small scale. Constitutive information is non-unique at a scale below the Representative Volume Element (RVE), and depends upon the boundary conditions imposed on the smaller-scale Statistical Volume Element (SVE). When a microstructure can be partitioned into SVE whose boundaries avoid intersections between material phases, this approach is shown to reduce spurious stress concentrations on SVE boundaries, and thereby significantly improve convergence of SVE properties to the RVE limit.

In addition to avoiding phase discontinuity intersections with SVE boundaries, other modeling choices, such as the length scale, boundary conditions applied, and boundary shape chosen, may introduce modeling error and bias. In particular, directional modeling bias must be separated from the actual prediction of anisotropy at the SVE level, in order to provide an accurate basis for fracture simulation. In this work, material heterogeneity and anisotropy will be studied. Models will be tested on a material that is isotropic at the macroscale, as well as a material that contains slight directional bias. Properties will be evaluated at multiple scales, with SVEs of different geometry, including square, circular, regular and "irregular" or Voronoi-based geometries. Results for different SVE geometries will show the effect of these geometric SVE partitioning choices on material characterization at the meso- and macro-scale.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Investigation of Brucite Utilization as a Potential Sustainable Building Material

Author(s): Inderjeet Singh, *New York University Abu Dhabi*; Rotana Hay, *New York University Abu Dhabi*;
*Kemal Celik, *New York University Abu Dhabi*;

Reactive magnesium oxide (MgO) cement (RMC) has emerged as a potential alternative to ordinary Portland cement (OPC). However, life cycle analyses show that the magnesium carbonate decomposition to MgO is carbon-intensive. Besides, magnesite deposits are not widely available globally, adversely affecting global access and overall cost. Therefore, MgO recovery from desalination waste brine is considered a promising alternative technique to produce MgO and brucite ($\text{Mg}(\text{OH})_2$) to reduce the environmental impacts of the current MgO manufacturing method. In this study, brucite was synthesized from desalination brine using calcium oxide, and its direct carbonation was explored using compacted cylindrical pellets. The results verify that brucite acquired from desalination brine is capable of creating minerals with firm linking properties and sequestering CO_2 .

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Investigation of the Buckling Instability in Free-Floating Thin-Shell Domes

Author(s): *Kieran Barvenik, *University of Maryland*; Zachary Coogan, *University of Maryland*; Eleonora Tubaldi, *University of Maryland*; Matteo Pezulla, *Aarhus University*;

Shell buckling represents a promising avenue to enable fast, reversible, and controllable reconfigurations in multifunctional devices. Complex deformation characteristics typical of shell buckling mode shapes can facilitate the design of soft actuators, systems for locomotion, biomedical devices and prostheses. Here, we explore the design and buckling characteristics of soft thin-shell domes with free boundary conditions to inform a novel soft gripper design. Controlling the buckling mode and pressure could improve actuation speed and energy input characteristics of the soft device. Analytical and numerical models will be presented for determining the critical buckling pressure of the free-floating shell dome as a function of shell geometrical parameters, such as slenderness ratio and spherical cap angle. The quasi-static response of the shell upon pressurization is conducted with finite element (FE) analyses using the commercial package ABAQUS 2020/Standard. Good agreement between the predictions of the FE results and the corresponding analytical model will be discussed. For experimental validation, experiments on a hemispherical soft shell with a thin film covering the leading edge will be presented. This film creates an isolated fluid cavity, which can be used to pressurize the shell and analyze the resulting deformation and buckling characteristics. The fluid cavity is also modeled with numerical FE analyses, which will yield comparable characteristics for the experimental scenario as well as provide knowledge about the pressure-volume curves and force output of the shell throughout the deformation cycle. This research aims to advance the understanding of buckling of soft thin-shell domes and to provide insights into the use of hemispherical shells as soft grippers. This design strategy has the potential to set a path forward for future research into soft devices with buckling controlled actuation.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Symplectic Encoders for Variational Dynamics Inference

Author(s): *Kiran Bacsá, *ETH Zurich*; Zhilu Liu, *ETH Zurich*; Wei Liu, *Singapore-ETH Centre*; Eleni Chatzi, *ETH Zurich*;

We propose a new variational autoencoder with physical priors capable of learning the dynamics of a Multiple Degree of Freedom (MDOF) system. Standard variational autoencoders place greater emphasis on compression than interpretability regarding the learned latent space. We propose a new type of encoder, based the novel Hamiltonian Neural Networks, to impose symplectic constraints on the inferred a posteriori distribution. In addition to making robust trajectory predictions under noisy conditions, our model is capable of learning an energy-preserving latent representation of the system. This gives new perspectives for the application of physics-informed neural networks for engineering problems.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Full-Scale Deformation Field Measurements of a Highway Bridge via Photogrammetric Remote Sensing

Author(s): *Kiyarash Aminfar, *George Mason University*; William Graves, *George Mason University*; David Lattanzi, *George Mason University*;

3D remote sensing technologies have improved dramatically over the past five years. Methods such as laser scanning and photogrammetry are now capable of reliably resolving geometric details on the order of one millimeter or less. This has significant impacts for the structural health monitoring community, as it has expanded the range of mechanics-driven problems that these methods can be employed on. This work explores how 3D geometric measurements extracted from photogrammetric point clouds can be leveraged for structural analysis and measurement of structural deformations without physically contacting the target structure. Here we present a non-destructive evaluation technique for extracting and quantifying structural deformations as applied to a load test on a highway bridge in Delaware. Structural 3D reconstruction depends on the quality of images, and since there are some limitations on the data acquisition process during field experiments, preprocessing of input data and a series of image enhancement algorithms boost the performance. On the other hand, the challenging nature of 3D point cloud data means that statistical methods must be employed to evaluate the deformation field of the bridge adequately. Overall, the results show a direct pathway from 3D imaging to fundamental mechanical analysis with measurements that capture the true deformation values typically within one standard deviation. These results are promising given that the mid-span deformation of the bridge for the given load test is on the scale of only a few millimeters. Future work for this method will also investigate using these results for updating finite element models.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Computational Fluid Dynamics with Multiphysics Applied on Removal of Charged Particles by Electrophoresis in a Fluid Environment

Author(s): *Kun Gou, *Texas A&M; University-San Antonio*; Walter Deng, *Texas A&M; University-San Antonio*;

We work on a computational fluid dynamics project for charged particles separation by electrophoresis in aqueous solutions. The problem is highly coupled involving multiphysics in the area of fluid dynamics, transport of diluted species, and electrochemistry. The geometry of the flow field is mainly of a cylindrical shape. In the center of the cylinder is the smaller cylindrical cathode pole, and the outer surface is the anode pole. The flow enters from one side of the cylinder (inlet) and flows away from the other side of the cylinder (outlet). The chemicals in the fluid will be attracted to the poles by the electrochemical effect to reduce the concentration of the chemicals, reaching the water purification purpose. Laminar flow with no turbulence is considered. The computation is conducted on the commercial software COMSOL Multiphysics using finite element techniques with tetrahedral meshes. The fluid velocity field and pressure field, chemical concentration field, potential distribution field, and charge density distribution are obtained after the simulation to analyze how the purification geometry and physical parameters can be chosen for the maximal effect of water purification under a fluid dynamics environment.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Experimental Analysis of Desiccation Cracking Phenomenon of Clays Related to the Initial Imposed Suction Using DIC Method

Author(s): *Lamine Ighil Ameer, *Cerema*; Mahdia Hattab, *Universite de Lorraine*;

This research presents a comprehensive investigation on the impact of initial imposed suction both on the applied tensile force and the cracking phenomenon of unsaturated clayey soil samples. The proposed experimental approach is based on using a new developed apparatus for testing the indirect tensile force on small-beam bending. Several sets of bending tests have been carried out on small clay beams initially submitted to different levels of suction (361 MPa, 110 MPa and 38 MPa).

The approach consisted first to study the global behaviour by estimating the maximum tensile force F_{max} which controls the initiation of tensile cracks. The results show that F_{max} varies with the initial imposed suction level as well as the consolidation stress direction representing the initial loading applied to the sample during the stage of clay core preparation.

Then, unload-reload cycles allowed to describe the reversibility of beam's behaviour versus the initial imposed suction.

Finally, by using digital image correlation (DIC) technique, the formation and propagation of cracks were precisely captured through the measurement of the local strain variations, especially close the crack tip.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Estimation on the Initial Imperfection of a Thin-Walled Copper Shell Structure

Author(s): *Le Cao, *University of Kentucky*;

The mechanical behavior of a thin-walled copper shell is affected by the structural properties, which are often described before fabricated or placed in-service conditions. However, the initial imperfection may lead to a disproportionate failure due to the loss of load-carrying capacity of a relatively small portion of the structure. The earlier studies proposed the MLE method and the posteriori discovery method, to identify the initial imperfection field; and researchers developed the numerical procedures for the proposed methodologies, which showed promising results, compared to the initial geometric imperfection approximation by using the first modal shape. The proposed methodologies enhanced the description of uncertainty in the estimated quantity, which subsequently enriched the access to the variability in the predicted strength of imperfect structures for instability problems. This study reconstructs a spatially parameterized initial imperfection field of a thin-walled copper shell structure for a posteriori determination, and applies with the dependent sampling approach over the posterior distribution, to solve the marginal posterior distribution numerically. By introducing the Hasting ratio term, the sampling approach allows an asymmetric transitional kernel, in contrast to selecting a symmetric proposal distribution. Using an acceptance-rejection scheme, the sampling approach facilitates the posterior distribution to converge from an arbitrarily chosen initial state toward a target invariant distribution, with retaining the last candidate information. The initial imperfection field of a thin-walled copper shell structure is characterized under in-service loading conditions, in which the material exhibits heterogeneous microscopic behavior.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Markov-Transformable Processes to Model Deteriorating Engineering Systems

Author(s): *Leandro Iannacone, *University of Illinois at Urbana-Champaign*; Armin Tabandeh, *University of Illinois at Urbana-Champaign*; Paolo Gardoni, *University of Illinois at Urbana-Champaign*;

Time-variant systems are ubiquitous in science and engineering. State variables characterizing the behavior of such systems evolve with time under the effects of gradual and shock events, like corrosion and earthquakes. The physical laws that govern the evolution of the state variables are often rigorously represented by differential equations. The solution of these differential equations is influenced by uncertainties in system characteristics, exposure conditions, initial and boundary conditions, and model parameters. This paper develops a general approach to model the time-varying probability distribution of the state variables and presents a novel numerical method to solve the governing equations. Our starting point is a set of Stochastic Differential Equations (SDEs) that govern the physical evolution of the state variables. The formulated SDEs consist of a source term that models the gradual and shock events. A mathematical approach is then presented to transform the physical SDEs into the standard Ito? SDEs, i.e., a Markovian representation of the state variables. Associated with the formulated Ito? SDEs is the Fokker-Planck equation that governs the time-varying probability distribution of the state variables. A novel numerical method is then presented to solve the Fokker-Planck equation via optimization. The paper illustrates the proposed approach to model the deterioration of engineering systems. Engineering systems deteriorate over their service lives due to routine use, aggressive operating environments, and extreme events. Deterioration is a significant concern in complex systems like buried civil infrastructure since it is highly uncertain and not easily detectable. Quantifying the deterioration of engineering systems is essential for realistic performance modeling and accurate reliability analysis.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Stochastic Differential Equations for the Modeling of the Deterioration of Engineering Systems

Author(s): *Leandro Iannacone, *University of Illinois at Urbana-Champaign*; Paolo Gardoni, *University of Illinois at Urbana-Champaign*;

Modeling the evolution of engineering systems subject to multiple deterioration processes in a multi-hazard environment requires the development of models that can integrate the gradual and shock processes acting on the system. Recent studies in this field (Iannacone and Gardoni 2019, 2022) use a system of Stochastic Differential Equations (SDEs) to investigate the evolution of the state variables of a system subject to multiple, interacting processes. However, the form of these models, as well as the value of their unknown parameters, need to be adapted and calibrated based on the value of the state variables observed over time. Non-Destructive Testing (NDT) and Structural Health Monitoring (SHM) can provide a wealth of data that can be used to inform such calibration. This presentation focuses on the calibration of SDE models based on periodical monitoring of the state variables, performed either via NDT or SHM. We propose different calibration procedures for several scenarios that could be encountered in practice. In particular, we separate the case when data are collected preserving information on the deterioration paths from the case when information on the deterioration paths is not preserved. We propose an improved version of the Euler-Maruyama method that allows to account for the presence of shocks during the life-cycle of the system. The proposed formulation is also applicable when the time of occurrence of the shocks is not known, combining prior knowledge on the shock features with the collected data, in a Bayesian framework. In this scenario, we also propose a method to back-calculate the intensity and the time of occurrence of shocks that might have characterized the evolution of the state variables. Finally, the variation in the uncertainty of the estimated coefficients is investigated as a function of the inspection frequency.

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Real-Time Hybrid Simulation of a Novel Tuned Mass Friction Damper on a Tall Building for Wind Hazard Mitigation

Author(s): *Liang Cao, *Lehigh University*; Safwan Al-Subaihawi, *Lehigh University*; Thomas Marullo, *Lehigh University*; James Ricles, *Lehigh University*; Austin Downey, *University of South Carolina*; Simon Laflamme, *Iowa State University*;

A new semi-active friction device using band brake technology, termed the Banded Rotary Friction Damper (BRFD), has been fabricated at the NHERI Lehigh experimental facility. The device is a second-generation BRFD where its semi-active mechanism is achieved using two electric actuators. The BRFD generates a variable damping force as a linear function of the input force provided by the electric actuators, where the force amplification ratio (FAR) is equal to about 70. The FAR is defined as the ratio of BRFD damping force output-to-electric actuator force input.

The presentation will present the results of a study using real-time hybrid simulation (RTHS) to investigate the performance of the BRFD's in mitigating wind vibrations on a forty-story building. The building consists of steel braced frames that are augmented by outrigger systems about the minor axis of the floor plan. Nonlinear viscous dampers are placed in the outriggers to control floor accelerations about the minor axis of the building. In the orthogonal direction only braced frames exist, consequently, the structure's response is susceptible to increased floor accelerations and inter-story drift. A Tuned Mass Friction Damper (TMFD) is therefore placed at the roof and positioned in order to suppress the building's response in the orthogonal direction to the outrigger system.

First, the details of the prototype of the BRFD are presented. Second, details relating to the TMFD consisting of a moving mass, a stiffness element, and the BRFD are introduced. Lastly, details of the RTHS study and the results are presented. The building, the moving mass, and the stiffness element in the TMFD are part of the analytical substructure while the BRFD and large-scale nonlinear viscous dampers form multiple experimental substructures for the RTHS. The creation of the analytical model involved discretely modeling each of the members of the building using nonlinear elements, with the combined analytical and experimental substructures representing about 2000 degrees of freedom. The explicit, unconditionally stable dissipative Modified KR-Alpha integration algorithm is used to accurately integrate the equations of motion. Real-time online model updating is used to update parameters of some of the nonlinear viscous dampers that are modeled via the analytical substructure. The building's accelerations and inter-story drift from RTHS from controlled and uncontrolled cases are compared, where these cases correspond to the structure with and without the TMFD, respectively. Results show that the TMFD produces significant wind vibration reduction on both maximum lateral floor accelerations and inter-story drift.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Real-Time Hybrid Simulation of Wind-Induced Aerodynamic Vibrations on a Tall Building

Author(s): *Liang Cao, *Lehigh University*; Haitham Ibrahima, *Florida International University*; Thomas Marullo, *Lehigh University*; James Erwin, *Florida International University*; James Ricles, *Lehigh University*; Amal Elawady, *Florida International University*; Arindam Chowdhury, *Florida International University*;

Wind-induced vibrations, particularly in tall buildings, can produce considerable nonstructural damage and excessive acceleration. An accurate assessment of wind-induced dynamic response is critical to ensure the safety and functionality of such buildings. Numerical simulations of structural behavior under aerodynamic wind forces are challenged by the proper representation of such forces. Physical testing of scaled building models in the wind tunnels also has limitations in evaluating wind-induced response due to many challenges such as scaling errors and inaccurate modeling of complex structural properties (e.g., mass, stiffness, damping) and nonlinearities (e.g., geometric, material). Therefore, a new real-time hybrid simulation (RTHS) method developed by the NHERI facilities at Lehigh and Florida International University (FIU) is proposed to evaluate the wind-induced responses of structural systems in buildings.

The presentation will discuss the results of a study using RTHS to investigate wind-induced vibrations of a forty-story building with a rooftop monopole. First, the details of the building are presented. Second, the proposed RTHS approach is introduced. The analytical substructure in the RTHS contains the numerical model of the building, while a physical 1:150 scaled aeroelastic building and monopole model forms the experimental substructure. The experimental substructure is placed in the NSF-supported NHERI Wall of Wind Experimental Facility (WOW EF) at FIU. It is used to measure real-time multi-directional aerodynamic pressures through distributed pressure taps on the model's surface. The two substructures are kinematically linked via a simulation coordinator. For each time step, the displaced configuration obtained from the integration of the equations of motion for the numerical model is imposed onto the experimental substructure. The measured real-time aerodynamic pressures in the along-wind and cross-wind directions are then integrated over the skin of the building to obtain the aeroelastic force vector for the equations of motion. The force vector is then used to determine the response of the structure for the current time step. Finally, the RTHS results are presented. Two different analytical substructure cases are considered involving modeling structural members with linear and nonlinear elements, along with three wind load cases with different mean roof height wind speeds. The RTHS tests are compared with results from a baseline test involving another fully aeroelastic model (1:150) tested in a conventional manner at the WOW EF. The validation results show good agreement between the RTHS and the conventional aeroelastic model test, demonstrating that the proposed RTHS method is a promising technique for assessing wind-induced aerodynamic vibrations.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Bayesian Calibration of Models for Diblock Copolymers Self-Assembly with Power Spectrum of Microscopy Image Data

Author(s): *Lianghao Cao, *The University of Texas at Austin*; Keyi Wu, *The University of Texas at Austin*; Peng Chen, *The University of Texas at Austin*; J. Tinsley Oden, *The University of Texas at Austin*; Omar Ghattas, *The University of Texas at Austin*;

With the growing impact of model-based predictions in the nanolithography application of block copolymer self-assembly, it is increasingly important to ensure the reliability of the models. In this talk, we consider the Bayesian calibration of models for unguided self-assembly of diblock copolymer thin films, with data produced via top-down microscopy characterization. A likelihood function for the azimuthally-averaged power spectrum of image data is derived. To deal with the generally intractable evaluations of an integrated likelihood induced by aleatory uncertainties in characterization data, we explore several strategies for efficiently performing the calibration task without exact evaluations of the integrated likelihood function. The strategies include the use of pseudo-marginal algorithms, constructing surrogates of the integrated likelihood function, and reducing data dimension for effective inference.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Automating the Classification of Seismically Vulnerable Concrete Buildings

Author(s): *Lissette Iturburu, *Purdue University*; Jean Kwannandar, *Purdue University*; Shirley Dyke, *Purdue University*; Julio Ramirez, *Purdue University*; Xin Zhang, *Purdue University*;

Before the boom of deep learning, a computer's capability for reading structural drawings was limited to hard coded rules that made algorithms identify elements such as walls, columns, dimension lines. This approach, however, was limited to actually working on a very narrow set of framing plan configuration and styles. Newly acquired automated capabilities for reading drawing sets and framing plans through deep learning can be applied to a much broader set of drawings. This development has re-invigorated older but sound concepts for the rapid classification of vulnerable concrete buildings. Scoring metrics such as the Hassan Index had been superseded for more complex and less generalizable indexes that require a great deal of information and expert decision-making, not especially suited for performing a rapid, large city-wide analysis. The strengths of the Hassan Index lie in its simplicity, and thus can readily be applied for a large building inventory, that needs to be assessed for seismic vulnerability in a city. This paper will discuss the development of a technique to analyze structural and architectural drawings and automatically extract quantitative information to classify vulnerability. From this technique, future developments include the training of local building classifiers for risk and vulnerability analysis for local governments that face the question of how to assess their building inventory.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: A Common Framework to Represent, Analyze and Share Wind Pressure Data

Author(s): *Luigi Carassale, *University of Genova*;

Wind-induced loads on structures are often evaluated experimentally through wind-tunnel tests. In this context, the use of multi-channel pressure scanners is a very popular choice as they provide accurate information on the temporal variation and the spatial distribution of the pressure field. The major limitation is the poor spatial resolution which is the consequence of the manufacturing process of the model and the limited number of measurement channels available. The pressure field on the whole envelope of the structure is obtained by an interpolation/extrapolation process, which is not standardized and is mostly formulated on the basis of the empirical knowhow of the laboratory. The ambiguity that is necessarily produced by this lack of standardization reflects into the difficulty in comparing and sharing wind-pressure data deriving from different laboratories. From the designer perspective, the measured pressures need to be spatially integrated to compute the load acting on the structural members. Such integration involves, implicitly, the same interpolation/extrapolation process already mentioned, and therefore the same ambiguity.

This problem may be addressed by establishing a common model to represent the wind pressure field measured through a limited number of pressure taps. This model needs to be general enough to be applied to most of the structure that are usually tested by means of pressure scanners, and should provide results that are consistent with the common laboratory practices.

This paper proposes a framework based on the finite-element (FE) discretization of the structural envelope with the measurement points located in a subset of the FE nodes. The value of the pressure in unmeasured locations is obtained by establishing interpolation rules that are determined univocally once the FE mesh is defined. Using this principle, the model contains both the information of the envelope geometry, as well as the rules to interpolate the pressure field. The adoption of this framework enables simple procedure to share data among laboratories and between laboratories and design offices promoting cooperation and ensuring a reliable exchange of information as well as a consistent treatment of data.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Mechanical Characterization of Seismic Isolators Prototypes with Recycled Rubber

Author(s): Melissa Herazo, *Universidad del Valle, Cali, Colombia*; Andrés Alvarez, *Universidad del Valle, Cali, Colombia*; Albert Ortiz, *Universidad del Valle, Cali, Colombia*; *Luis Felipe Guerrero, *Universidad del Valle, Cali, Colombia*;

According to the United Nations Organization, urban zones carry between 70 and 80 percent of economic production, and almost 55% of the population. Because of this, it is important to develop technological options that allow to preserve the integrity and properties of the population. In the research process to increase reliability of structures and to preserve the integrity and possessions of users, since the early XX century, different seismic base isolation systems (BI) have been developed. The function of BIs is to reduce structure's drifts by including a hyperelastic element with the capacity of absorbing the majority of seismic displacement. This drift reduction produces a stress decrease in elements of the superstructure, resulting in the possibility of reducing the section of elements that compose the seismic resistance system, which can be attractive for construction companies. A variation of BIs is the elastomeric, that can subdivide depending on the materials that compound them: lead core isolators (LRB), high damping isolators with steel plates reinforcement (HDR), fiber reinforced (FREI). In the beginning of development, BI were just considered for use in big structures, but now a days the benefits of using them in lower and lighter structures is highly discussed. According to this opportunity, the main option for low-rise edifications are FREIs, these BIs are cheaper because of the steel replacement. Also, the FREIs can be unbounded (U-FREI), a characteristic which implies that there does not exist a system that connects the isolator and the structure or foundation. This gives the possibility of suppressing top and bottom plates used in other elastomeric isolator types, that also implies reduction in direct and indirect costs. This paper presents an analysis of the mechanical behavior of scaled unbounded fiber reinforced isolators with recycled rubber core using monotonic and cyclical compression, kept load, ultimate compression, and shear test. From these results it is possible to conclude that the development of U-FREIs with recycled rubber core (NUF-U-FREI) satisfies requirements for being used in low-rise residential building projects, and have the compressibility necessary to maintain its elastic properties after loads are applied for long term periods.

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Reduced Order Modeling Applied to Earth Systems: the HydroBlocks Tiling Scheme to Enable Hyper-Resolution Hydrological Simulations

Author(s): *Luiz Bacelar, *Duke University*; Nathaniel Chaney, *Duke University*;

In the past decade, advances in land surface models (LSMs) have improved the modeling of surface energy and water balance representation for weather, climate and hydrological models. However, a regular spatial discretization of LSMs leads to an excessive amount of computational cost for higher resolution simulations. For instance, the need for hundreds to thousands of simulations for model calibration and ensemble runs, hampers its operational applications for continental flood warning systems. Hydroblocks embraces the next generation of LSMs using unsupervised machine learning to reshape and reduce the spatial dimension of numerical calculations, decreasing significantly time-consuming tasks. The hierarchical scheme of clustering regions with same hydrological behavior (Hydrological Response Units - HRUs) increases the computational efficiency while preserving hyper-resolution I/O and land surface heterogeneity. In this present work, we evaluated the energy and water partitioning of two distributed hydrological models sharing the same Noah-MP LSM core: WRF-Hydro (regularly gridded) and Hydroblocks (HRUs). The experiment is performed over the Greenbrier river basin (4290 km²) in West Virginia, where the complex terrain enables a thorough assessment of the diurnal and monthly cycles of latent and sensible heat fluxes, skin temperature and soil moisture of hourly simulations from 2013 to 2020. The spatial-temporal convergence analysis was performed at 1km, 100 m and 30 m spatial resolution. Both models were initialized with the same input conditions, including soil properties states and Noah-MP vegetation parameters. The results show that Hydroblocks' tile scheme helps to converge to the fully distributed WRF-Hydro state at a maximum of 1/3702 of cores-hour. At 30 meters of spatial resolution (20 000 HRUs of I/O), Hydroblocks runs at 15% of the time of WRF-Hydro at 1km (25 600 points of I/O). The major differences were observed for energy partition during the summertime, which could be associated to discretization of vegetation parameters and upscaling of outputs. In summary, the tiling scheme of Hydroblocks, provides a promising approach to accelerate off-line tasks as calibration or on-line operational demand for multiple data assimilation tasks and ensemble runs.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Can a Pure Rocking Model Describe the Rolling of Curved Objects like Disks, Tops, and Gömböcs?

Author(s): *M. David Burton, *University of Oxford*; Manolis N. Chatzis, *University of Oxford*;

The dynamics of curved objects such as spinning tops, rolling disks, and the intriguing gömböc have been of interest to researchers in engineering mechanics. The dynamics of curved objects are normally described by rolling models, if modeled at all, with a continuously changing point of contact with the support. A much different dynamic contact model is pure rocking, where a polyhedral approximation of a curved body is permitted to rotate about a fixed point of contact until it impacts at another vertex and begins rocking about that vertex while sliding and uplift from the support are prohibited. Though the assumptions of pure rocking are different from those for rolling, a pure rocking model describes the motion of curved rolling objects with surprising ease and accuracy.

The model allows for the input of a rigid body of any polyhedral geometry in the form of a stereolithography (STL) file, any desired set of initial positions and velocities, and any desired accelerations to apply (such as an earthquake or other excitation). The model then outputs the dynamic response of the body assuming pure rocking.

This presentation will show the efficacy of an alternative model to study curved objects that would normally be considered to roll. Specifically, objects with curved geometry such as a spinning tippe top, Euler's disk, a gömböc, and a cylinder will be examined while proving the potential for wider use of the model. This is the first known study to examine the motion of multiple curved objects using a pure rocking model. The model can additionally be employed to solve very diverse problems including the gömböc's single point of stable equilibrium, the sound produced by Euler's disk, the factors important to the tipping of the tippe top, and the response of sculptures during earthquakes. The solutions provided by the pure rocking model for a selection of these problems will be presented. Conclusions will be drawn on the importance of considering parameters such as geometry, the coefficient of friction, rigid impacts as an energy dissipation mechanism, and visualization of dynamic responses too rapid for experimental observation. This pure rocking model will be shown to be a valid alternative to study rolling objects that produces qualitatively similar results to experiments. Potential impacts of these findings extend to the acceptability of polyhedral approximations in manufacturing and more efficient computer animation for a variety of dynamic situations.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Effect of Thermal Cycles and Fatigue Loading on Concrete Incorporating Plastic Particles

Author(s): *Madiha Ammari, *The Ohio State University*,

This study aims to reduce the amount of plastic disposed in landfills, and to provide an environmental solution to the ever-increasing shortage of natural aggregates in the United States. Secondhand products made of the thermoplastic Polypropylene (PP) were collected and pulverized to be utilized in concrete. The plastic particles were investigated as partial replacement of fine and coarse aggregate. This experimental study focused on examining the effects of thermal cycles and fatigue loading on the mechanical properties of the thermoplastic-concrete composite. This examination is essential due to the lack of bond and difference in the mechanical and thermal properties of plastic and concrete. To investigate the size effect of the plastic particles utilized in concrete, some concrete cylinders were casted by replacing the fine aggregate and others were casted by replacing the same percentage with coarse aggregate. The percentage of replacement used was 10% of the total aggregate in the concrete mixture with same size replacement. To investigate the effect of percent of replacement, mortar cubes were casted by replacing 0%, 5%, 10%, and 15% of the fine aggregate with plastic particles of the same size. Two sets of specimens were prepared for comparison reasons. The first set of specimens were stored under standard laboratory conditions and tested at the ages of 7, 14, 28, 84 days. Some of the specimens in the second set were exposed to fatigue loading, others to temperature changes between 23oC to 60oC, or -20oC to 23oC. The reduction experienced in compressive strength and modulus of elasticity was recorded between the two sets at different ages. Early results showed a significant and highest strength reduction when specimens incorporating plastic particles exposed to temperature cycles of 23oC to 60oC compared to specimens exposed to temperature changes of -20oC to 23oC or control specimens with 0% replacement. The higher reduction in strength was due to the thermal stresses and consequently the micro-cracks in the cementitious matrix surrounding the surface of expanded plastic particles at high temperatures. The early results also showed a significant reduction in the load cycles before failure when plastic particles replaced fine aggregate compared to coarser particles replacement or the control specimens. This result was due to lack of bond between plastic and the surrounding concrete which caused micro cracks to grow and propagate in the cementitious matrix. The crack propagation was facilitated by the higher distribution of plastic particles when replacing fine aggregate.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Implementation of Machine Learning Models to Predict Storm Surge in Coastal Cities

Author(s): *Mahmoud Ayyad, *Department of Civil, Environmental and Ocean Engineering Stevens Institute of Technology, Hoboken, NJ*; Muhammad Hajj, *Department of Civil, Environmental and Ocean Engineering Stevens Institute of Technology, Hoboken, NJ*; Reza Marsooli, *Department of Civil, Environmental and Ocean Engineering Stevens Institute of Technology, Hoboken, NJ*;

Long-term mitigation and adaptation strategies of coastal cities to storm surge require quantifiable predictions of flood hazards under different scenarios while taking into consideration coastal development. These predictions are often presented in terms of a range of N-year return periods of a peak storm surge height defined as the height with 1/N percent chance of exceedance in any given year. Because the peak storm surge increases with the return period, the higher return periods (low probability) correspond to higher storm surge (high-consequence event) while low return periods (high probability) correspond to lower storm surge (low-consequence event). Consequently, reliable prediction of low probability but high-consequence event (e.g., 1000-year return period) may require tens of thousands of simulations. Given additional uncertainties and the different scenarios for climate change, the number of required simulations may increase by ten folds.

Although high-fidelity hydrodynamic models can predict storm surge heights due to tropical cyclones, the high computational cost hinders the ability to perform the required number of simulations. Toward alleviating that cost, we investigate the use of Machine Learning models, based on a reduced number of simulations, to effectively predict return period curves. We test the models at four coastal locations in the New York metropolitan area. We identify the challenges of developing and analyzing the data sets. The results show that return period curves generated from Machine Learning models are in good agreement with curves generated from high-fidelity hydrodynamic simulations, with the advantage that Machine Learning models require a fraction of the computational time needed to run the simulations.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Assessment of An Ensemble-Based Forecasting System for Storm Surge Prediction: A Case Study Using Tropical Cyclone Isaias

Author(s): *Mahmoud Ayyad, *Stevens Institute of Technology*; Philip Orton, *Stevens Institute of Technology*; Hoda El Safty, *Stevens Institute of Technology*; Muhammad Hajj, *Stevens Institute of Technology*;

Coastal flooding is among the world's most dangerous and damaging natural hazards. Loss of life and damage to personal property result in life disruptions. Damage to infrastructure causes interruptions to supplies of clean water, electricity, and transport that could cripple the economy. Reducing these losses through preparation and mitigation strategies depends on accurate prediction of storm surge and associated uncertainties. In general, uncertainties associated with deterministic forecasts that are based on a specific forecast model and a single set of forcing conditions can be covered by ensemble-based probabilistic forecasting based on a cluster of "member" forecasts generated from perturbed meteorological forcing conditions and/or different forecasting models. Ensemble-based probabilistic forecasting of storm surge is increasingly being used to provide vital metrics such as the near-worst case scenario for emergency management decisions.

The Stevens Flood Advisory System (SFAS; www.stevens.edu/sfas), operated at the Stevens Institute of Technology, is an ensemble prediction system used to forecast total water levels over a broad coastal region and street-scale flood levels for several New York Harbor (NYH) critical infrastructure sites. An ensemble of 96 weather forecast models is used as meteorological forcing to represent the uncertainty in weather forecasting. As a part of our continuous assessment of this system's performance, we evaluate SFAS' performance during Tropical Cyclone Isaias (2020), which tracked northward along the Pennsylvania/New Jersey border and caused the largest storm surge in NYH since Hurricane Sandy. Isaias specific track and speed generated an unusual flood event consisting of a surge that was followed by a blowout and a significant resurgence (re-occurrence of positive surge after wind support ends) that caused minor flooding. The evaluation shows that the super-ensemble spread provided a better or equal estimate of uncertainties compared to sub-ensembles which is based only on one meteorological forcing system. Because of ensemble averaging, the central forecast under-predicted peak water levels and the resurgence peak though these were predicted by some of the ensemble members.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: On the Observability of Discrete Systems with Unmeasured Inputs

Author(s): *Manolis Chatzis, *University of Oxford*; Kristof Maes, *KU Leuven*; Geert Lombaert, *KU Leuven*;

The use of the outputs of a system, typically measured by sensors placed on the system, to estimate the parameters and states of the system, i.e., system identification, is a direction with a great range of applications in various fields of engineering and science. It is often assumed that all the inputs that excite a system are also measured. In practise this is often difficult to achieve. In certain systems the measurement of some of the loads may be impractical, e.g., it would be rather difficult to measure the wind pressure applied at various surfaces on a bridge. As such there is a recognized need for estimating not only some of the parameters and states of the system but also the applied inputs.

To accommodate the needs there has been over the last decade an increasing development of system identification methods, such as Non-Linear Kalman Filters, which can identify the inputs applied to a system, often simultaneously with its states and parameters. In regards of estimating the states, parameters, and unmeasured inputs of a system such filters provide a means of answering the question 'how to?', the question of observability, i.e., 'Is it possible?' was answered more recently. Previous work of the authors defined a method to determine the observability of the states, parameters, and inputs of continuous systems with direct feedback.

Observability algorithms for continuous systems assume that the measurements are obtained at infinite sampling rates. While this allows answering several important questions, it doesn't allow considering aspects such as the effect of zero order-hold on the measurements. Furthermore, it is often desirable to consider different possible representations of the unmeasured signals, e.g., using different interpolation schemes. Such representations of the signal are difficult to be taken into account in observability algorithms for continuous systems.

To bridge this gap, this presentation will introduce a novel observability algorithm for the observability of discrete systems with unmeasured inputs. An efficient algorithm is developed to compute the observability matrix. A novel concept will be introduced which is termed the observability lag and it will be linked to a practical requirement of great importance for identification filters and smoothers. Examples will demonstrate how different representations of the input and the system, and different sensor setups can affect the observability lag for some of the states, parameters and inputs, without changing the observability of the system.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: An Observability Inspired Joint State, Parameter and Input Estimation Extended Kalman Filter

Author(s): *Manolis Chatzis, *University of Oxford*; Kristof Maes, *KU Leuven*; Geert Lombaert, *KU Leuven*;

The property of observability is a prerequisite for the identification of a state, parameter or unmeasured input of a system. The extension of the concept of observability to systems with unmeasured inputs allows researchers to investigate whether a user can hope to properly estimate, without additional assumptions, some of the states, parameters or unmeasured inputs of the system. However, as has also been done in the past for the case of non-smooth systems, observability algorithms also offer possible directions for improving identification algorithms. The authors have recently developed an algorithm for the observability of discrete systems with unmeasured inputs. The representation of a system as discrete allows taking into account different representations of the input, i.e., one can investigate to represent the input as a set of constants that have occurred from a zero-order-hold scheme at the same or different rate than the measurements. Likewise, alternative parametric representations of the input can be investigated. A new identification characteristic which is offered by the discrete observability algorithm is the concept of the lag of observability. This is related to the number of measurements that must be obtained before that parameter/state/parameter related to the input can be estimated.

This concept of observability lag is utilized to create a joint-state-parameter Extended Kalman Filter which can converge to accurate estimates of the states of the system in a nearly online manner through an introduction of a delay parameter, without additional assumptions on the input. The algorithm can further demonstrate why previous algorithms such as the Augmented Kalman Filter required collocation of the excitation and some of the outputs and why it was more beneficial to use certain types of sensors. It will be demonstrated that the new algorithm lifts all of those requirements and is only bounded by the limits predicted by theoretical observability.

Examples will be given where the algorithm is applied to linear and non-linear systems, whose states, parameters and unmeasured inputs are to be identified. It will be shown that various parameters that influence the observability lag such as the number, location and type of sensors, as well as the parametrization of the input, and the integration scheme used for the discrete system, can fully be absorbed by the use of a minimal delay parameter.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: An LSTM Model to Predict the Performance of Elements

Author(s): *Mao Cheng, *University of California, Berkeley*; Tracy Becker, *University of California, Berkeley*;

In numerical simulations, there is always a trade-off between complexity of the numerical model and computational expense. For applications such as real-time hybrid simulation, it is beneficial to rely on the fastest possible models, which are often simple phenomenological models. Generally, these phenomenological models are selected based on a combination of understanding of the physics based behavior as well as experimental data. However, when element behavior is less well understood, due to variations in design or loading, it may be difficult to select a suitable phenomenological model, and the result may be subjective bias or oversimplification. Here, a data-driven method is developed to predict element performance and capture features such as hysteretic damping, hardening, and bi-direction behavior using long short-term memory (LSTM) neural networks. The LSTM model is trained solely on existing experimental data to avoid possible modeling bias from numerical simulations. Lead rubber bearings are used as an example of the method. The model is trained from a database of 10 diverse experiments publically available in DesignSafe with rubber bearings resulting in 1554 records. Bearing features used in training include the inner and outer radius, the total rubber thickness, total height, and shear modulus of rubber. Current axial load, shear displacement, and the shear force from the last time step are also inputs, while the output of the model is the current shear force. With the original Bouc Wen model as a baseline, the LSTM model improved the accuracy while maintaining similar runtime. The LSTM model is then integrated into OpenSees. Researchers can also use the LSTM model as a tool to explore the element behavior for less well understood designs and loadings. With simulated data from the LSTM model, researchers can better understand the performance of elements as well as the influence of its design parameters. The LSTM model can be used for other materials and structural components if sufficient experimental data to train the model can be collected.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Particle Mechanics Approach to Modeling Impact Response and Wave Propagation in Bonded Particulate Systems

Author(s): *Marcial Gonzalez, *Purdue University*;

Particle-scale, meshless models allow simulation of large particle assemblies for less computing cost than traditional finite element methods that discretize each particle in the system. We extend the particle mechanics approach to particle-binder systems, including those with a high solids loading. We develop particle-binder-particle force and moment contact laws that are 1) consistent with elastic theory and 2) resolve behavior at the transition from having intervening binder between the particles to particle-particle contact, and 3) dependent on the material properties of the binder and particle, as well as their geometry. To solve the resulting equations of motion, we also develop an explicit, second-order, variational time integrator for full-body dynamics that preserves the momenta of the continuous dynamics, such as linear and angular momenta, and exhibits near-conservation of total energy over exponentially long times. This presentation presents these modeling approaches to study impact response and wave propagation in large bonded particulate systems over long times. Specifically, we explore the microstructural response of plastic-bonded explosives (PBX) composed of HMX crystals embedded in a Sylgard binder to impacts at various velocities ranging from 10 m/s to 400 m/s. The system includes nearly 100,000 particles and roughly 1.6 million contacts, which enables a statistical characterization of microstructural features during wave propagation with high statistical significance.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Effect of Symmetry Breaking on the Elastic Wave Response of Gyroid Structures

Author(s): *Maria Jose Carrillo-Muñoz, *Wichita State University*; Saranchana Keattitorn, *Wichita State University*; Bhisham Sharma, *Wichita State University*;

Periodic lattice structures offer many attractive mechanical and functional attributes for various engineering applications. Their periodic structure allows engineers to conveniently design them to achieve tailorable strength, stiffness, dynamical, acoustical, and thermal properties. Further, the emergence of additive manufacturing methods has enabled the fabrication of previously infeasible complex geometries, spurring further interest in understanding the relationship between their physical response and their underlying periodic structure. In this presentation, we discuss on the dynamic behavior of lattice geometries with triply periodic minimal surfaces (TPMS). Recent work has shown that TPMS structures offer highly desirable stiffness, acoustic, and thermal dissipation properties. Here, we focus on the wave response of gyroid structures—the most commonly used TPMS structure. We model them using the finite element method and get their dispersion curves by applying the Floquet-Bloch boundary conditions and extracting their eigenfrequencies. We analyze the dispersion curves to understand the emergence of wave attenuation bandgaps and their dependence on the lattice topology. While no complete bandgaps occur, the dispersion curves reveal some directional and polarized bandgaps. Additionally, we observe numerous degeneracies in the dispersion curves, which are linked to the underlying structural symmetry. With an aim of generating additional bandgaps, we lift these degeneracies by systematically breaking the geometrical and material symmetry of the unit cell. Our results show that breaking the symmetry of the gyroid structure results in the generation of new directional and polarized bandgaps. Further, we show the emergence of directional anomalous wave polarization behavior in certain asymmetric gyroid-derived lattices, where S-waves are observed to propagate faster than P-waves. Our work shows that breaking the symmetry of TPMS structures offers an effective way to control their dynamic response.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Identification of Force, Parameters, and Response for Wind-Excited Structures

Author(s): *Marios Impraïmakis, *Columbia University*; Andrew Smyth, *Columbia University*;

The turbulence of the wind is not measured accurately by conventional methods, rendering well-established methods unable to solve the identification problem. Apart from the buildings and transportation structural systems, the success of renewable energy infrastructure also benefits from such an identification solution, where its performance heavily depends on its structural health. Here, a methodology is developed to address this challenge of joint force-parameter-response estimation using a Kalman filter-based real time approach. This output-only methodology allows for a truly realistic understanding of wind-excited structures using limited information. Applications include choice of instrumentation and measurement, diagnostic techniques, and full system monitoring for ongoing estimation and performance evaluation.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: An Approach for Optimal Sequential Sensor Placement Under Steady-State Dynamics

Author(s): *Mark Chen, *Duke University*; Kavinayan Sivakumar, *Duke University*; Gregory Banyay, *The Pennsylvania State University*; Jessica Preston, *Westinghouse Electric Company*; Brian Golchert, *Westinghouse Electric Company*; Timothy Walsh, *Sandia National Laboratories*; Michael Zavlanos, *Duke University*; Wilkins Aquino, *Duke University*;

Identification and monitoring of damage are necessary operations in the maintenance of structures. A robust active sensing framework that integrates model-based inference and optimal sensor placement is proposed. Coupling data-based inference and data acquisition scenarios presents a holistic approach to the monitoring problem. Structural health can be continuously and accurately assessed by solving an alternating sequence of damage estimation and optimal sensor placement problems.

A partial differential equation-constrained formulation for damage estimation is first developed using a conventional model-updating approach with a binary penalization damage parameter. Then, this formulation is linearized around an appropriate nominal damage state to produce an Optimal Experimental Design (OED) problem for desirable sensor locations. The sequential sensing framework is postulated using a variance-minimization approach as follows: given a current candidate damage state associated with the most up-to-date sensor information, find the next sensor location that minimizes the variance in the inferred damage state and update the damage estimator.

The sequential sensing framework is also enhanced by introducing a Modified Error in Constitutive Equations (MECE) functional in the damage estimator. Adding MECE will make the framework more robust by quasi-convexifying the damage estimation problem and hence limiting the damage estimator from being trapped in local minima. This ensures that the sequence of damage estimation problems will converge to the true damage state given arbitrary initial guesses and sufficient sensor information.

Finally, the sequential sensing framework with MECE is demonstrated using numerical and experimental models analogous to digital twins of reactor vessel internals in nuclear power plants. Practical algorithmic heuristics including sensor placement constraints and convergence criteria are explored.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: PDEM Modeling of Borehole Stability in Transversely Anisotropic Rock

Author(s): *Marte Gutierrez, *Colorado School of Mines*; Guowen Xu, *Southwest Jiaotong University*;

The Particle Discrete Element Method (PDEM) is employed to investigate the mechanical behavior of transversely isotropic rocks with non-continuous planar fabrics. In the PDEM model, the rock matrix and fabric are represented as flat joint contacts and smooth joint contacts, respectively. The following are studied using the numerical model: (1) the effects of the microstructure of the rock matrix and the fabric micro-parameters on the shear strength and the fracture patterns of rocks under Brazilian tests, and (2) the model calibration process for determining the micro-parameters and the failure process of borehole stability in layered rock. The results show that: (1) Based on the Brazilian test results of 20 kinds of transversely isotropic rocks with non-continuous planar fabrics, six patterns regarding the relationship between the normalized failure strength (NFS) and fabric-loading angles are obtained; (2) The patterns of NFS curves are slightly affected by the coordination numbers of particle in rock matrix, while greatly affected by the amount of pre-existing micro-cracks in rock matrix, and the stiffness, strength and distributed region of the fabrics; (3) The calibrated results of six typical rocks with different patterns agreed well with the experimental results in regard to failure strength and fracture patterns; (4) The fracture of layered surrounding rock in borehole is concentrated in two zones with the line connecting the center of the two zones is normal to the plane of non-continuous fabrics for isotropic geo-stress field, while the connecting line is deflected to the direction of minor principal stress to a certain extent for non-isotropic geo-stress field.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Computational and Experimental Insights into Life-Cycle Structural Reliability Assessment of Concrete Bridges Under Corrosion

Author(s): *Mattia Anghileri, *Politecnico di Milano*; Luca Capacci, *Politecnico di Milano*; Fabio Biondini, *Politecnico di Milano*;

A recent SEI/ASCE survey highlights that advanced life-cycle models for deteriorating structures are well established for some of the most detrimental damage processes (e.g. corrosion). However, reliability assessment procedures and deterioration models under uncertainties are generally sensitive to change of the probabilistic parameters of the input random variables, and their validation is a difficult task because of the limited availability of data. In this paper, a computational approach to life-cycle reliability assessment of deteriorating structures exposed to aggressive environment is presented and applied to an existing prestressed concrete box-girder railway bridge under corrosion. The material mechanical characteristics and the properties of the exposure scenario are calibrated through an experimental campaign based on non-destructive diagnostic tests and laboratory tests on concrete cores and samples of reinforcing steel bars. Statistical inference and Bayesian updating are used to improve the life-cycle probabilistic prediction model based on the experimental outcomes.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Understanding the Physics Behind Peak Pressure Events

Author(s): *Mattia Fabrizio Ciarlatani, *Stanford University*; Zhu Huang, *Xi'an Jiaotong University*; David Philips, *Cascade Technologies, Inc.*; Catherine Górlé, *Stanford University*;

It is well known that near edges and corners of high-rise buildings with an incoming atmospheric boundary layer strong negative pressure peaks can be observed. Multiple experiments have investigated the formation of these peaks, and methods to quantify their value are well established. However, the physics behind their formation is still unknown.

The aim of this work was to leverage information from validated Large Eddy Simulations (LES) to study the physics driving the formation of the negative pressure peaks observed near the corners and edges of high-rise buildings. For this study, we focused our attention on a 1 x 2 x 0.3 m³ model with an incoming neutral atmospheric boundary layer. The model is representative of a 100m tall full-scale building with a rectangular floor plan.

To pursue our objective, we first performed high resolution pressure measurements on the surface of the high-rise building in two different wind tunnels, namely Politecnico di Milano and Wall of Wind, for multiple wind directions. The measurements were then used to accurately set up the inflow boundary condition for the LES and to validate the numerical results for three different wind directions, namely 10°, 20°, and 30°. Finally, we used the validated LES data to make visualizations through iso-surfaces of Q criterion of the flow near the leeward upper downwind corner during one of these peak events. The visualization was performed for the 20° wind direction, which is the wind angle that generates the most negative values for the pressure peak.

The result from this work is twofold. First, we show that sufficiently resolved and accurately set up LES simulations can correctly match experimental data. In fact, our numerical results for mean, rms, and peak pressure value agree with experimental data both qualitatively and quantitatively over extended portions of the surface of the building for multiple wind directions. Second, we qualitatively identify and describe the physics leading to the formation of these peaks. In particular, the results show how the separations that forms on the roof of the high-rise building are the main responsible for the formation of these peaks. The results also hint at the fact that small-scale turbulent intermittency may play a role in the generation of these negative pressure peaks.

This work is supported by the National Science Foundation under Grant Number 1635137. LES simulations were performed on XSEDE Stampede2 cluster.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Fire Spread in Buildings Considering Seismic Damage to Active and Passive Fire Protection Systems

Author(s): *Maxwell Coar, *Princeton University / HNTB Corporation*; Maria Garlock, *Princeton University*;

Fire ignitions in buildings are more likely to occur following earthquakes due to increases in fuel availability and ignition sources. Simultaneously, active fire protection systems (AFPS) and passive fire protection systems (PFPS), are less likely to perform as designed due to seismic damage. This presentation will discuss a methodology to probabilistically quantify the extent of fire spread in a structure following an earthquake and a fire ignition, with considerations for damage to AFPS and PFPS, using OpenSees finite element modeling software and a purpose-built object-oriented programming library in python.

An archetype 9-story steel moment resisting frame structure is exposed to suites of accelerograms to determine peak floor accelerations (PFA) and interstory drift ratios (IDR). A Monte Carlo study assesses damage to the PFPS (compartment dividers) and the AFPS (sprinkler system). Hydraulic analysis is performed on the damaged sprinkler system to determine pressure and flow availability. The speed and extent of fire spread is modified by the performance of the AFPS and PFPS. Results will be presented in the form of fragility curves with damage states corresponding to the extent of fire spread in the archetype structure. Discussion topics will include: the application of this methodology to additional archetype structures, the effect of deep basins on damage to FPSs and subsequent fire spread, and incorporation of these results into community-level studies of fire following earthquake (FFE).

The primary contributions to the field are 1) the modification of an existing intra-building fire spread algorithm to explicitly account for AFPS and PFPS, 2) the probabilistic analysis of seismic damage to FPSs reduce their efficacy in the context of the previous contribution, and 3) (expected) the application of a seismic intensity measure that accounts for record length and spectral shape to the performance of non-structural systems.

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: A Comparison Between Three Vision-Based Displacement Measurement Methods in Lab-Scale Structural Experiments

Author(s): *Mehrdad Ghyabi, *George Mason University*; David Lattanzi, *George Mason University*;

Capturing structural displacement time-histories under service conditions or controlled load tests provides critical information for structural condition assessments. Measuring displacements directly is often impractical due to inherent technical and experimental difficulties, particularly for field inspection of in-service structures. Therefore, quantifying displacements indirectly from localized acceleration measurements has been the dominant measurement approach for decades, despite numerical and logistical implementation challenges. More recently, the development of high-resolution imaging sensors, along with the emergence of high-performance digital image processing techniques, has led to the emergence of computer vision-based displacement tracking methods. These methods, generally referred to as “optical flow field measurements”, have been demonstrated to work effectively under a variety of laboratory and full-scale field conditions. The measurements are generally less accurate than those obtained from installed sensor arrays, but they have the advantage of providing dense displacement field measurements and do not require direct sensor installation. These approaches can be categorized into three major categories: dense flow, target or invariant feature tracking, and phase-based flow. This paper provides a comparative analysis of these three measurement paradigms for structural monitoring applications. A series of illustrative laboratory experiments are used to highlight key benefits and differences between different approaches.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Life Safety Risk for Coastal Communities Affected by Nearfield Earthquake and Tsunami

Author(s): *Mehrshad Amini, *Oregon State University*; Daniel Cox, *Oregon State University*; Andre Barbosa, *Oregon State University*; Dylan Sanderson, *Oregon State University*;

The Cascadia Subduction Zone (CSZ) is a major source for near-field earthquake and tsunami, which can significantly threaten the coastal community in the Pacific Northwest region. Such cascading multi-hazards not only impose significant direct and indirect economic losses, but also can adversely impact life safety. This study proposes a casualty model to evaluate the life safety risk of near-field earthquake and tsunami at the community level. The model explicitly incorporates two important variables, including: (1) the effect of earthquake-induced damage to the building on the tsunami preparation time, (2) the effect of earthquake-induced debris on the evacuation speed. The survival and casualty rates are calculated for each parcel considering different community preparedness levels. The evacuation travel time is determined based on the shortest path to the shelter. The city of Seaside, Oregon, is selected as a testbed community for this study. The results are compared in terms of the number of casualties to quantify the effect of different mitigation strategies such as using vertical evacuation shelters or seismic retrofitting methods on the resilience metrics. The open-source Interdependent Networked Community Resilience Modeling Environment (IN-CORE) is utilized for the analyses in this study.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Ant Nest Geometry, Stability and Excavation - Inspiration for Tunneling

Author(s): *Meron Belachew, *Georgia Institute of Technology*; Karie Yamamoto, *Georgia Institute of Technology*; Elliot Nichols, *Georgia Institute of Technology*; Danrong Zhang, *Georgia Institute of Technology*; J. David Frost, *Georgia Institute of Technology*; Chloé Arson, *Georgia Institute of Technology*;

Underground construction and tunnel excavation are known to redistribute stresses and cause ground displacement. Most practical projects revolve around a few shape geometries (circular, elliptic, horseshoe shaped). Analytical solutions for stress distribution typically break down at shallow depth. Spatial variability is still a challenge, even in the era of numerical modeling and parallel computing. Seeking to find new approaches for excavation strategies and geometries for underground construction, we propose to look to nature for inspiration. We first conduct a systematic numerical analysis of Harvester ant structures to understand the contribution of the different nest features to the overall tunnel stability. We use simplified models of shafts and chambers that mimic the natural nests to discuss the stability mechanisms as a function of geometric parameters, such as helical shaft pitch and chamber vertical spacing in the case of the Florida Harvester ants. The results thus far have indicated that the interaction between different components of these complex underground structures may be one explanation as to why these insects are successful in building and maintaining such complex underground structures. To complement these models of simplified geometry, we build a model of the actual nest geometry retrieved from the field. This is done in order to identify the basic mechanisms that are contributing to the stability of actual nest geometries so that these mechanisms can be understood and translated to practical problems in engineering.

Using laboratory-based methods, we infer the excavation sequences used by ants from experimental observations and simulate several scenarios using the Finite Element Method (FEM) with the aim of comparing typical ant and human tunneling strategies. Furthermore, we aim to understand the correlation of geometric features of the excavation, such as orientation and size, to the properties of the medium of excavation using FEM modelling that is based on experimental observations. The final section of this study discusses the scalability of ant underground construction practices to tunneling.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Towards a More Sustainable Road Transportation System: Application of Statistical Physics to Smartphone Data

Author(s): *Meshkat Botshekan, *Massachusetts Institute of Technology*; Mazdak Tootkaboni, *University of Massachusetts Dartmouth*; Arghavan Louhghalam, *University of Massachusetts Dartmouth*; Franz-Josef Ulm, *Massachusetts Institute of Technology*;

The expeditious technological advances have provided opportunities to develop smarter and safer road transportation system, one of which is crowdsourcing roadway network data. In addition to various sensors in new-generation vehicles, smartphones with their built-in measurement capabilities have emerged as versatile sensors to probe characteristics of roadway network. Due to their widespread use, smartphones are powerful platform to crowdsource roadway network information, which is particularly advantageous when upscaling the individual impacts to a network level is of crucial importance from both environmental and economic perspectives. As such, with an emphasis on the use of smartphone measurements, we propose statistical-physics frameworks for crowdsourced estimation of road quality, traffic properties and driver behavior.

First, based on the mechanistic model of roughness-induced pavement-vehicle interaction, we propose a probabilistic inverse framework that infers road roughness characteristics and "representative" dynamic properties of vehicle from its response to road undulations. The inverse procedure is a regularized optimization problem that only requires acceleration signal, recorded by passengers' smartphones, as the input. Outputs of this inverse problem are: i) expected value of IRI as well as other ride quality metrics, and ii) vehicle's representative dynamic properties. The handshake between the obtained representative dynamic properties and vehicle class is made through a deep neural network with a classification accuracy of more than 85%.

Second, relying on the ergodic theorem of statistical physics, we hypothesize that internal structure of traffic holds critical information relevant for the spatio-temporal mapping of traffic density, mean velocity, and driver behavior from individual driver velocity recordings. Focusing on the Nagel-Schecknberg traffic model, we demonstrate that memory show universal patterns, resulting in the development of stochasticity-density plots that permit statistical determination of traffic properties from the first- and second-order velocity statistics of the vehicle. This methodology is a powerful alternative to costly classical methods of traffic property estimates.

Finally, we use Carbin Educational app's data set to validate and demonstrate the accuracy and predictive prowess of the presented frameworks. The large-scale algorithmic implementation of such frameworks allowed us to infer and map road quality, as well as spatio-temporal distribution of traffic density and driver behavior at state/country scales. Results of this study provides the needed aggregate data for optimal resource management to reach a safer, more sustainable road transportation system.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Nodally-integrated RKPM for deposition-based three-dimensional printing

Author(s): *Michael Hillman, *Penn State*; Kuan Chung Lin, *National Cheng Kung University*; Feihong Liu, *Penn State*; Hanbin Cheng, *Penn State*; Jiarui Wang, *Penn State*; Aleksandra Radlinska, *Penn State*;

A stable and efficient nodally-integrated reproducing kernel particle method (RKPM) [1] is introduced in this work for effective modeling three-dimensional printing. Deposition types of printing involve topological changes which can be handled well by meshfree methods, but also a fully coupled thermo-mechanical response, depending on the material at hand. Thermo-viscous and visco-plastic flow must often also be considered to handle the rheological material response. First, a thermo-mechanical formulation is developed, where it is shown that nodal integration of the coupled equations results in severe spurious oscillations in the solution, worse than pure mechanical problems. A naturally stabilized and variationally consistent nodal integration is then proposed for the coupled equations to stabilize the solution and provide n th order convergence in the two-field problem [2,3]. Generalized thermo-mechanical theories of the hyperbolic type are also leveraged for a uniform explicit critical time step, with results essentially the same as the classical theory. Benchmark problems are solved to demonstrate the effectiveness of the proposed method in obtaining stable and accurate RKPM for simulations of three-dimensional printing, including fused deposition modeling, and printing of fresh concrete.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Effects of Different Shape Parameters on the Wind Pressure Peak Factors for Hyperbolic Paraboloid Roofs

Author(s): *Michele Barbato, *University of California, Davis*; Fabio Rizzo, *Cracow University of Technology*;

Wind pressure's peak factors are characterized by a complex shape dependence, which makes their prediction very difficult when using analytical models for different geometries. Thus, experimental studies are necessary to validate available or new analytical models for each specific shape and geometry. In particular, very little information is available in the literature for the hyperbolic paraboloid geometry, which is often used for cable net and membrane roofs covering large spans. This paper investigates in detail the shape dependence of wind pressure's peak factors for this specific geometry. It presents a statistical analysis of experimental data taken from wind tunnel tests on eight different geometries, corresponding to squared and rectangular plan shapes, high and low buildings, and two different curvatures of the roof parabolas. Roof zones for which a non-Gaussian behavior is predominant are identified. Experimentally-obtained peak factor statistics are used to determine the accuracy of different analytical models available in the literature, namely the Davenport, modified Hermite, and Translated Peak Process models. This comparison is performed in terms of means and standard deviation errors estimated over the entire roofs. It is concluded that the modified Hermite and the Translated Peak Process model provide the overall best estimates of the peak factor means and standard deviations, respectively. Some preliminary results are also presented on the limiting behavior of the peak factors for highly non-Gaussian wind pressure records.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Compressive Behavior and Constitutive Modeling of Nano-Enhanced UHPC

Author(s): *Milana Cimesa, *University of Nevada, Reno*; Mohamed Moustafa, *University of Nevada, Reno*;

Ultra-High Performance Concrete (UHPC) is a new generation of concrete with superior mechanical and durability properties that has the potential to revolutionize concrete structures and the construction industry. Despite its advantages, there is still a lack of understanding of the behavior of full UHPC components and systems, which is slowing the process of establishing design codes and standards for UHPC. To promote the use of UHPC for larger applications, such as seismic columns in bridges or special moment resisting frames in buildings, more data on the full compressive stress-strain behavior is needed for future modeling. This presentation focuses on an emerging type of UHPC that is reinforced with carbon nanofibers, or nano-enhanced UHPC. To understand the uniaxial compressive behavior of nano-enhanced UHPC, full stress-strain relationships are obtained for numerous 3×6 in cylinders with different steel fiber ratios (0% up to 4% by volume) that are tested at different ages (3 to 28 days). The presentation provides stress-strain curves that can be used for understanding early age behavior of UHPC which can benefit the precast/prestressing as well as accelerated bridge construction industries and guidance on constitutive modeling.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Inexpensive and Scalable Detection of Corrosion Using Semi-Supervised Deep Learning and Minimal Labeled Data

Author(s): *Mohamad Alipour, *University of Illinois at Urbana-Champaign*; Devin Harris, *University of Virginia*;

Inspection of critical infrastructure for signs of distress and deterioration is essential in ensuring the integrity of assets and the continuity of their service. With the growing trends in Operation and Maintenance costs in both public assets and private industries, automated inspection systems are in high demand. While abundant research attention to detecting cracks has resulted in various solutions and publicly available datasets, the problem of corrosion, with an estimated multi-billion-dollar annual economic impact has received little attention. In the absence of publicly available curated image datasets for model training, this study proposes a scalable method to create high-accuracy corrosion detection models using a small amount of web-scraped imagery in addition to a large set of unlabeled data. First, an inexpensive initial convolutional neural network is encoded with knowledge from the web-scraped data, whose predictions are then densified to predict corrosion at the pixel level on a large set of images from a state-wide inventory of bridges. The resulting loss of accuracy around the soft feature edges is also compensated for using a graph-based learning technique called conditional random fields. The demonstrated success of the resulting pixel-level corrosion detection models provides a promising solution for industries such as pipelines, power transmission, marine and offshore, and wind energy structures.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Seismic response of sheet-pile walls considering variabilities in the ground motion and backfill soil density

Author(s): *Mohamed Elghoraiby, *George Washington University*; Majid Manzari, *George Washington University*;

The inherent variability in the soil properties and the uncertainties in the loading conditions render a deterministic analysis method impractical. This is especially true as the performance-based concepts find a more prominent in design of geo-structures. As such it is of vital importance to develop and validate analytical and numerical modeling tools that accommodate the random nature of material properties and loading conditions in geotechnical engineering problems. This work presents the findings of a series of stochastic analyses performed to evaluate the effects of spatial variability of the backfill soil and the role of observed variations in the intensity and frequency contents of ground motions on the seismic response of sheet pile walls supporting liquefiable soils. A random finite element analysis is used to model the centrifuge experiments performed as part of the Liquefaction Experiments and Analysis Project (LEAP). The LEAP-2020 experiments tested scaled models of sheet pile walls embedded in sandy soils with relative densities that ranged from 50% to 75%. The spatial variability of the soil in each centrifuge model was determined from in-flight Cone Penetration Tests (CPT). The vertical spatial correlation length was directly determined from the CPT measurements, while the mean and coefficient of variation of the soil relative density were obtained from a Bolton type relationship that correlates the cone tip resistance with the relative density. The variability observed in the achieved base motions for the LEAP-2020 centrifuge experiments was modeled by generating synthetic time histories that matched the variability observed in the response spectra of the achieved base motions. The results obtained from this analysis sheds light on the effects of the variabilities in the base motion and soil density on the dynamics excess pore pressures and the triggering of soil liquefaction. It also provides insights on the sensitivity of the wall lateral displacement and rotation to these variabilities. The observed variability in the simulation response is compared with the variability observed in the centrifuge experiments. These comparisons allowed for a more in-depth assessment of the capabilities of the current analytical/numerical modeling tools available for seismic analysis of sheet-pile walls and their interactions with the surrounding soils.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Synthesis of Asphalt Binder Nanostructures Via Generative Adversarial Networks

Author(s): *Mohammad Aljarrah, *Texas A&M; University*; Ayman Karaki, *Texas A&M; University at Qatar*; Eyad Masad, *Texas A&M; University at Qatar*;

This study presents a methodology to utilize the capabilities of Generative Adversarial Networks (GANs) in synthesizing nanostructures of asphalt binders. However, large input datasets are usually required to efficiently train GANs, which hinders the feasibility of using them to generate nanostructures for modeling purposes. Consequently, this work proposes a methodology to overcome the limitation of having only a small dataset to train GANs. In this methodology, virtual images of asphalt binders' nanostructures are generated by stochastic Random Fields (RF) to augment images experimentally obtained using Atomic Force Microscope (AFM). Thus, the experimentally imaged and RF generated nanostructures are utilized to train GANs for synthesizing nanostructures. GANs hyperparameters are optimized to expedite the training process and avoid mode collapse usually encountered when training small datasets. Consequently, distributions of nanomechanical properties between GANs-synthesized and original nanostructures are compared. GANs-generated nanostructures are then simulated using finite element (FE) models to study their internal stress distribution and assess similarity in their mechanical responses. The results demonstrated that the probabilistic nature of GANs allows generating probable arrangements of nanostructures, thus accounting for the intrinsic heterogeneity of asphalt binders at the nanoscale, which is reflected in their bulk behavior and field performance. The ability of GANs to reproduce nanostructures with immense accuracy indicates that the complex nature of asphalt binders' nanostructures can be identified and duplicated in efficient and sustainable means with fewer required resources when compared to expensive laboratory tests to achieve similar outcomes.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Modeling the Evolution of Cementitious Materials Chemo-Mechanics from Microscale and Beyond: A Lattice Discrete Particle Approach

Author(s): *Mohammed Alnaggar, *Oak Ridge National Laboratory*; Ying Zhang, *Ezoic*;

Cementitious materials are multi-hierarchical composites at various length scales. In many of these scales, the material can be represented as a particulate composite. At the microscale, particulates are the fines and unreacted cement particles and the matrix is the reaction products network. At the mortar scale, particles are the fine aggregate and the matrix is the paste, and so on. Additionally, lower-scale studies have shown that even the reaction products can be considered or represented using particle mechanics. This multi-hierarchy though comes at a high price in terms of predicting the material behavior knowing its chemical composition since different features appear at various length scales. For example, the pore sizes vary from nanopores up to macroscopic capillary pores of up to several millimeters. Thus, Nano or micro-indentation techniques won't be enough to predict the concrete scale and are only suitable for the size of interest they can probe.

Here comes the strength of the proposed multi-scale chemo-mechanical modeling approach which starts at the microscale by representing the evolution of the reaction products strength and distribution. Using unit cells of the microscale system that account for various zones in the paste (bulk, Interfacial transitional zone, etc...), a similar mortar scale can be formulated that accounts also for the pore structure at such scale. Similarly, the mortar system can be further used to inform multiple unit cells within the concrete mesostructure.

In this presentation, the microscale chemo-mechanical model called Microscale Lattice Discrete Particle Model (uLDPM) will be first presented showing its ability to predict elastic and damage behavior of micro-cubes and micro-beams under compression, fracture, wedge splitting, and micro-indentation. Next, different examples of scaling up will be presented showing the efficiency as well as the challenges in predicting the upper scale behavior from lower scale information.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Stability of Stainless Steel Frames with Different Beam-to-Column Connection Types

Author(s): *Mohammed M. Eladly, *Department of Civil and Systems Engineering, Johns Hopkins University*; Benjamin W. Schafer, *Department of Civil and Systems Engineering, Johns Hopkins University*;

Despite the considerable impact of end conditions on the stability of beams, only a small proportion of investigations into the lateral-torsional buckling (LTB) behavior of stainless steel beams have considered cases with actual end conditions. The current paper presents a numerical study on the effect of beam-to-column connection type on the stability of frame beams produced from stainless steel. Several connection types were examined, including extended end-plate, flush end-plate, and shear end-plate connections. The study was carried out using a verified finite element model that carefully takes into account the complex interactions between connection components. The results demonstrated that the critical moment for lateral-torsional buckling of the beam is obviously affected by the type of beam-to-column joints. While beams with stiffened extended end-plate (SEEP) connections had the greatest critical moment among the investigated cases, beams with shear end-plate connections showed the lowest capacity (50% of that of SEEP joints). Finally, based on FE data, a modification to the analytically-predicted critical moments, using a factor accounting for end connection stiffness, is proposed.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Active Learning for Global Sensitivity Analysis

Author(s): *Mohit Singh Chauhan, *Johns Hopkins University*; Mariel Ojeda-Tuz, *University of Florida*; Ryan Catarelli, *University of Florida*; Kurtis Gurley, *University of Florida*; Michael Shields, *Johns Hopkins University*;

This study develops a learning function to perform Global Sensitivity Analysis (GSA) for computationally expensive models. The computation of sensitivity index through the Pick and Freeze method (Monte-Carlo approach) is infeasible for complex physical models and suffers greatly from the curse of dimensionality. One way to resolve this issue is to use surrogate models for the computation of sensitivity indices, such as gaussian processes (Kriging) or polynomial chaos expansions (PCE). In the literature, numerous surrogate-based learning functions are available, which try to identify an optimal surrogate training set, through adaptive selection of sample points. These learning functions (such as U-function, EIF, EIGF) are popular to achieve different tasks such as Reliability analysis, Optimization, and Global fit. Here, a novel learning function is proposed, with the aim of efficient computation of sensitivity indices. The learning function minimizes the uncertainty in the Sobol Indices and generates an efficient design of experiment to identify important inputs/features with high precision. The performance of the proposed learning function is illustrated through various numerical examples, where true values of the main effect sobol indices are known. Further, the results of sensitivity analysis will be presented from a large-scale experimental setup. This learning function is used to guide a physical experiment in Boundary Layer Wind Tunnel at the University of Florida. The experiment is modeled as a 10-dimensional problem and important features are identified based on the first order sobol indices.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Magneto-Solid Damper: A New Generation of Friction Dampers with Smooth Hysteretic Behavior for Vibration Control of Civil Structures

Author(s): *Mohsen Amjadian, *The University of Texas Rio Grande Valley*; Anil Agrawal, *The City College of the City University of New York*;

Energy dissipation is critical to limiting damage in civil structures subjected to natural hazards such as powerful earthquakes. Friction is one of the most reliable energy dissipation mechanisms that has been widely utilized in damping devices to control seismic response of civil structures. Friction dampers are well-known for having a non-smooth hysteretic behavior caused by stick-slip motion at low velocities, a phenomenon that is inherent in friction and increases the acceleration response of the structure under control unfavorably, despite the fact that the displacement response is reduced due to energy dissipation. The focus of this research is to develop passive and semi-active electromagnetic-based friction dampers with minimized effects of stick-slip motion.

The proposed passive friction damper termed as passive electromagnetic eddy current friction damper (PEMECFD) utilizes a solid friction mechanism in parallel with an eddy current damping mechanism. The friction force is generated by the attractive magnetic interactions between two arrays of permanent magnets (PMs) with a thick ferromagnetic plate, and the eddy current damping force is generated due to the motion of the PMs arrays in the vicinity of two copper plates. The influence of eddy current damping on smooth hysteretic behavior of PEMECFD is investigated by modeling, designing, characterization testing, and model identification and validation of a proof-of-concept prototype in laboratory.

The proposed semi-active electromagnetic friction damper (SEMFD) consists of a ferromagnetic plate and two arrays of thick rectangular ferromagnetic-core coils (FCs) connected in series. The FCs are attached to the two sides of ferromagnetic plate through two non-magnetic friction pads. The damper force is developed due to the friction between the friction pads and the ferromagnetic plate when the FCs moves relative to this plate. The normal force between the friction pads and the ferromagnetic plate is caused by the attractive magnetic interactions between the FCs arrays and the ferromagnetic plate. The magnitude of this force is controlled by a semi-active controller that is capable of varying the current flowing through the FCs in such a way that it is able to avoid stick-slip motion, thereby smoothing the nonlinear hysteretic behavior of SEMFD. The capability of proposed SEMFD and its semi-active controller to control the seismic responses of a multi-story base-isolated building is demonstrated. The numerical results show that the proposed SEMFD is capable of limiting the displacement of base floor in base-isolated building without noticeably increasing the inter-story drifts and absolute accelerations of the floors.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Finite Element Analysis of Chloride Ingress in Prestressed Bridge Girders

Author(s): *Mojtaba Aliasghar-Mamaghani, *Virginia Polytechnic Institute and State University*; Ioannis Koutromanos, *Virginia Polytechnic Institute and State University*; Carin Roberts-Wollmann, *Virginia Polytechnic Institute and State University*; Matthew Hebdon, *The University of Texas at Austin*;

Chloride-induced corrosion is one of the predominant reasons for the long-term deterioration of prestressed concrete bridges. The availability of simulation tools predicting the evolution of chloride content is crucial for the maintenance and – if necessary - timely intervention to prevent extensive corrosion damage. This presentation will describe a nonlinear finite element analysis framework to determine the content of chloride ions in real-life prestressed bridge girders. The proposed approach accounts for multiple, coupled processes, i.e., heat transfer, moisture transport, and chloride advective and diffusive transport. The constitutive models for moisture and chloride transport rely on previous pertinent work, with several necessary enhancements. The modeling scheme is calibrated with data from previous experimental tests on concrete cylindrical and prismatic specimens. Subsequently, a series of validation analyses on prestressed girders is conducted, using data from chloride titration tests conducted on girders removed from two bridges in Virginia after 34 and 49 years of service. The results indicate that the proposed framework can accurately capture the chloride content. The modeling approach also allows the evaluation of the accuracy of simplified, design-oriented tools for estimating the evolution of chloride content with time.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Dealing with Multiscale Complexity and Uncertainty for the Case of the Thin-Shell Classrooms of Cuba's Historic School of Ballet

Author(s): *Moriah Hughes, *Princeton University*; Shengzhe (Jackson) Wang, *Princeton University*; Maria Garlock, *Princeton University*; Branko Glisic, *Princeton University*;

One of the foremost challenges of the diagnosis of historic structures is selecting and completing an analysis of suitable complexity both for the aims of the project and the limitations of the input data (the quantitative and qualitative data derived from the real structure). This project explores how this issue was approached for the specific case of the iconic thin-shell classrooms of the School of Ballet, of the Instituto Superior de Arte of Havana, Cuba, by architect Vittorio Garatti (1964). As complex and unique structures, both in structural form and cross-sectional composition, the classrooms required progressive analysis refinements and simplifications, which were validated against structural behavior metrics, primarily crack patterns. Consequently, this presentation discusses the in-situ explorations and their limitations, the resulting qualitative and quantitative data obtained, the approach (including simplifications and assumptions) to the structural analysis with multiscale complexity and uncertainty, and the means of validating and interpreting the analysis results. It also briefly discusses the importance of the work toward preservation efforts (including the Getty Foundation Keeping It Modern grant for preservation planning) and necessary future work for remaining capacity determination or detailed intervention design.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Prediction of Communities' Flood Resilience in a Changing Climate: A Multi-Stage Framework Using Machine Learning Techniques

Author(s): *Moustafa Naiem Abdel-Mooty, *Vanier Scholar and Ph.D. Candidate, Department of Civil Engineering at McMaster University*; Wael El-Dakhakhni, *Director, INTERFACE Institute for Multi-hazard Systemic Risk Studies at McMaster University*; Paulin Coulibaly, *Director, NSERC FloodNet, Department of Civil Engineering, McMaster University*;

With the increasing impact of climate change, the expansive urbanization within flood prone areas is causing a significant increase in flood-related disasters worldwide. In the past decades, the United States of America and Canada have witnessed a continuous increase in the frequency and magnitude of climate change-induced natural disasters. These events include droughts, floods, wildfires, and most recently, hurricanes. However, most flood risk categorization and prediction efforts have been overlooking the resulting losses and recovery trajectory (i.e., community's Resilience) and instead focusing on the hydrological features of flood hazard. In this work, a multi-stage framework was proposed to accurately categorize and predict changes in communities' flood resilience, and their response to climate change induced hazards. This framework is a step towards developing a complete disaster management plan, with a focus on floods, to further ensure resilience of urban centers. In this framework, the first stage is developing resilience indices using Robustness and Rapidity, integrating them with climate data for the development of a comprehensive prediction algorithm. Such framework enables decision makers to predict, prepare, and enable resilience enhancement strategies. The framework was then applied on historical mainland flood disaster records collected by the US National Weather Services to develop said indices, then coupling them with historical synchronized climate data. This study produced high performance measures in both training and testing datasets, proving its applicability in future climate studies, and lays the foundation for a huge impact in prediction studies on the changes and trajectories in the resilience of the built environment, while taking into account the effect of Climate Change.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Enabling Local Buckling Calculations in Design

Author(s): *Muhie Dean Ahdab, *Johns Hopkins University*; Astrid Fischer, *Johns Hopkins University*; Chu Ding, *Johns Hopkins University*; Bob Glauz, *RSG Software*; Benjamin Schfaer, *Johns Hopkins University*;

The presentation would include an explanation on the development of empirical closed-form analytical expressions for local buckling of cold-formed steel zee sections and hat sections under four conditions: pure compression, major axis bending, minor axis bending with lips in tension, and minor axis bending with lips in compression. The presentation would then discuss how the developed closed-form equations allow for accurate design of zee shapes and hat shapes even beyond the present day commercially available cold-formed steel zee and hat sections. As a result, the developed empirical closed-form analytical expressions may be applied in cold-formed steel design specifications such as AISI S100. A comparison would be done between the current design methods and the authors' proposed closed-form equations to show the advantages that the authors' proposed approach has in calculating the critical local buckling stress and the critical local buckling moment of zee sections and hat sections. Closed-form analytical expressions for other cold-formed shapes such as lipped channels may also be considered.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: A Biomechanical Model for Ultrasound Elastography Imaging of Breast Cancer

Author(s): *Mutaz Dwairy, *Texas A&M; University*; JN Reddy, *Texas A&M; University*; Arun Srinivasa, *Texas A&M; University*;

The interstitial fluid pressure (IFP) plays a key role in cancer diagnosis and prognosis. Most of the analytical models presented in the literature are basically one-dimensional spherical models, but surely this is not the case for tumors. In this work, a clinically relevant model for breast cancer diagnosis has been developed, which can be used in strain elastography. A two-dimensional biomechanical model considering the biphasic effect of extracellular matrix (ECM) and fluid phase has been established, which can predict the temporal profile and the spatial distribution of the IFP over the suspected lesion. A variety of different shapes and positions of tumors have been considered in the simulations. Results clearly show that the IFP distribution is sensitive to the shape and location of the tumor, however, the model can be used to simulate and predict the IFP for any an arbitrary tumor shape, size, and position. In addition, the feasibility of using the proposed model for cancer screening has been validated by presenting different case studies. Heterogenous vasculature and nonuniform blood perfusion are also investigated by incorporating a necrotic core in the center and a well-vascularized region at the periphery.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: The Shifted Boundary Method for Computational Mechanics

Author(s): Guglielmo Scovazzi, *Duke University*; *Nabil Atallah, *Lawrence Livermore National Laboratory*; Kangan Li, *Duke University*; Antonio Rodriguez-Ferran, *Universitat Politècnica de Catalunya*;

Embedded/immersed/unfitted boundary methods obviate the need for continual re-meshing in many applications involving rapid prototyping and design. Unfortunately, many finite element embedded boundary methods are also difficult to implement due to the need to perform complex cell cutting operations at boundaries, and the consequences that these operations may have on the overall conditioning of the ensuing algebraic problems. We present a new, stable, and simple embedded boundary method, named “shifted boundary method” (SBM) [1,2,3], which eliminates the need to perform cell cutting. Boundary conditions are imposed on a surrogate discrete boundary, lying on the interior of the true boundary interface. We then construct appropriate field extension operators by way of Taylor expansions, with the purpose of preserving accuracy when imposing the boundary conditions. We demonstrate the SBM on large-scale solid and fracture mechanics problems.

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Finite Strain FE2 Analysis with Data-Driven Homogenization Using Deep Neural Networks

Author(s): *Nan Feng, *University of Notre Dame*; Guodong Zhang, *University of Notre Dame*; Kapil Khandelwal, *University of Notre Dame*;

Performing multiscale FE2 analysis is computationally expensive since an independent microscopic finite element analysis is required at each macroscopic integration point. To accelerate multiscale FE2 analysis, deep neural network (DNN) based surrogates are proposed for nonlinear homogenization that can serve as effective macroscopic material models. Frame indifference of macroscopic material behavior is ensured by exploiting material strain and stress tensors as the input/output pairs of trained surrogates. An efficient data sampling strategy from the macroscopic deformation space is proposed for generating training and validation datasets. Two training strategies – regular training where only input/output pairs are included in the training dataset via L2 loss function, and Sobolev training where the derivative data is also used with the Sobolev loss function – are compared in several numerical cases where different unit cells and deformation states are considered. Numerical results demonstrate that Sobolev training leads to a higher testing accuracy as compared to regular training, and DNNs can serve as efficient and accurate surrogates for nonlinear homogenization in computationally expensive multiscale FE2 analysis.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Damage Assessment of Reinforced Concrete Tunnel Linings

Author(s): Nan Hua, *Mott Macdonald*; Anthony Tessari, *University at Buffalo*; *Negar Elhami-Khorasani, *University at Buffalo*;

Fire is a major societal hazard with the potential to disrupt major infrastructure systems and drain valuable resources from the community. Extreme fire events, such as the 1999 Mont Blanc Tunnel fire can lead to fatalities and significant damage. Concrete structures typically behave well at high temperatures and do not collapse when subjected to moderate fires. The superior performance of concrete structures under fire, compared to other materials, relates to the low thermal conductivity of the material and the large mass of the structural components. Yet, these structures experience damage and require repair after the fire to resume function.

The available guidelines on damage assessment of concrete structures after a fire are limited, and the evaluation is performed mostly on an ad hoc basis. Post-fire damage and repair classifications in the current guidelines rely on visual inspection, non-destructive testing (NDT), and sampling of material for laboratory testing. The information from visual inspections and NDT techniques can be supplemented with results of advanced modeling and analysis of the structure subjected to fire to guide the damage assessment procedure. Defining quantitative performance measures (e.g., temperatures reached within the cross section) and the associated damage thresholds will enable a systematic assessment of damage and a science-driven decision-making process for repair actions.

This presentation will focus on fire damage assessment of reinforced concrete tunnel linings. First, a series of analyses are conducted to evaluate the performance of tunnel sections under a wide range of ground conditions and identify critical geologic conditions. The results show that moderate-depth tunnel sections in soft soil and the deep tunnel sections in high lateral pressure rock could experience significant irrecoverable damage due to the large deformations and high internal forces, respectively. Second, fire damage classifications in existing guidelines are presented. New fire damage classifications with the associated thresholds are proposed considering the results of advanced modeling. The proposed damage classifications incorporate input from industry experts. The results of the presented research can be used to guide post-fire damage assessment as well as the performance-based design of tunnel fire protection.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: A Multi-Fidelity Polynomial Chaos Greedy Kaczmarz Approach for t Uncertainty Quantification on Limited Budget

Author(s): *Negin Alemazkooor, *University of Virginia*; Mazdak Tootkaboni, *University of massachusetts dartmouth*; Arghavan Louhghalam, *University of massachusetts dartmouth*;

Polynomial chaos expansion (PCE) has been widely used to facilitate uncertainty quantification and stochastic computations for complex systems. Multi-fidelity approaches expedite the construction of the PCE surrogate by blending the efficiency of low-fidelity models and accuracy of high-fidelity models. In this work, we propose a novel non-intrusive multi-fidelity sampling approach that exploits the low computational cost of the low-fidelity model to select a set of high-yield sampling locations for the high-fidelity model. Particularly, the proposed approach draws upon the unique features of the Kaczmarz updating scheme to design a greedy search that explores a large pool of low-fidelity samples and iteratively removes the least contributive ones. Facilitated via a subset updating strategy, the search lands on a small subset of the initial pool which is then used to construct the PCE surrogate for the high-fidelity model. The proposed approach offers a remarkable computational performance, practically delivering accurate results with a high-fidelity sample size about the cardinality of the basis, and as such is amenable to efficient uncertainty quantification on fixed and limited budget. We provide several numerical examples that demonstrate the promise of the proposed approach in substantially reducing the number of high-fidelity samples required for accurate construction of the PCE surrogate.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Machine Learning Based Reduced Order Modeling of Hydrodynamics Forces for Flow Over Oscillating Airfoil

Author(s): *Nida Ahsan, *Stevens Institute of Technology, USA*; Muhammad R. Hajj, *Stevens Institute of Technology, USA*; Imran Akhtar, *National University of Sciences and Technology, Pakistan*; Hamayun Farooq, *Bahauddin Zakariya University, Pakistan*; Ahmad Saeed, *National University of Sciences and Technology, Pakistan*; Mahmoud Ayyad, *Stevens Institute of Technology, USA*;

Abstract:

Propulsive systems in bio-inspired autonomous underwater vehicles (AUV) are often designed using flapping motion. Recent advancement in machine learning tools is also finding applications in fluid mechanics. We investigate the capability of Machine Learning based Reduced Order Model (ML-ROM) for unsteady incompressible flow around a plunging NACA0012 airfoil over a range of the Strouhal numbers. A parallel CFD solver [1] is used to simulate a two-dimensional unsteady flow field around an oscillating airfoil, where the boundaries of the structure are moved through Accelerated Reference Frame (ARF). The proper-orthogonal decomposition (POD) of the flow field snapshot data is employed to obtain pressure modes and temporal coefficients [2]. Since pressure plays an important role in developing hydrodynamic forces, surface pressure modes are also decomposed into lift and drag components to get pressure distribution over airfoil. ML-ROM is developed through the training of these temporal pressure coefficients at different oscillating amplitudes by fixing reduced frequency. The trained function, ML-ROM, can reconstruct temporal evolution of the flow hydrodynamics forces at Strouhal numbers and oscillating amplitudes that were not used in the training process, by-passing the full Navier-Stokes equations.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Mineralogical Compositions via Raman Imaging: From Granites to Clinkers

Author(s): Krishna C. Polavaram, *University of Illinois at Urbana-Champaign*; *Nishant Garg, *University of Illinois at Urbana-Champaign*;

Raman spectroscopy has been used in the characterization of various engineered and natural materials for nearly 50 years. However, hyperspectral mapping or Raman imaging is a relatively new technique that produces phase maps or spectral images of sample surfaces by collecting a Raman spectrum on every pixel. Over the last decade, the capabilities of Raman imaging have significantly improved, primarily due to hardware and software advancements in the Raman confocal microscopes and spectrometers. In this talk, we will outline recent applications of Raman imaging on both natural and engineered materials, and discuss opportunities as well as challenges. Specifically, Raman imaging allows determination of highly accurate and precise mineralogical compositions for a variety of materials, ranging from naturally occurring rocks such as granites to highly engineered powders such as cementitious clinkers. With its ability to provide high-fidelity quantification and high-resolution (micron to sub-micron scale) spatial distribution of phases in complex systems, Raman imaging holds immense promise to serve as a fundamental tool for advancing structure-function relationships in a diverse set of materials.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: A Viscoplastic Damage Model Based on Kinetics of Dislocation, Twinning, and Micro-Cracking for Quasi-Brittle Polycrystalline Beryllium Under Dynamic Loading Conditions

Author(s): *Nitin Daphalapurkar, *Los Alamos National Laboratory*; Daniele Versino, *Los Alamos National Laboratory*; Darby Luscher, *Los Alamos National Laboratory*;

In polycrystalline HCP metals, twinning has an increasing contribution to plastic deformation at high rates of loading. We advanced a viscoplastic damage model, incorporating evolution of micro-crack and dislocation densities, to include deformation due to twinning. Using the Mechanical Threshold Stress (MTS) model of isotropic plasticity as a baseline, the dislocation-based model for deformation twinning adapted in this work implements a physically-based kinetics of twin boundary motion and interaction with dislocation network. A probabilistic expression for twin density evolution was calibrated for polycrystalline hot-pressed beryllium to demonstrate the applicability of the model to simulate the measured uniaxial stress-strain data from split Hopkinson bar experiments. Further, we demonstrate the versatile applicability of the model to textured specimens. We present results for rolled beryllium specimens in through-thickness and in-plane directions, with reasonable comparisons of simulated twin densities with those observed from dynamic experiments.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Incorporating Architected Materials in Multiscale Structural Optimization with Deep Learning

Author(s): *Nolan Black, *Drexel University*; Ahmad R. Najafi, *Drexel University*;

We present and evaluate a machine learning approach for concurrent multiscale structural optimization of architected materials. To incorporate spatially varying architected materials in structural design, we employ a Deep Neural Network (DNN) for microarchitecture/metamaterial design in the context of a macroscale topology optimization. The DNN is not only evaluated as a model for microstructure behavior, but also as a differentiable engine for design optimization. Our presentation demonstrates the DNN's utility in metastructure design optimization and provides insight into the formulation, training, and implementation of DNNs in multiscale structural design.

Concurrent multiscale structural optimization is concerned with the design and distribution of microscale architecture to improve macroscale structural performance. Numerical homogenization is often used to link the micro- and macroscales through an estimation of a microstructure's effective macroscale properties. This estimation, however, requires sufficient separation of length-scale (i.e., many microstructures in a structure), leading to excessive computational costs. This has traditionally limited the design of spatially varying multiscale structures and restricted the microscale design space. We turn to the DNN to alleviate these issues by modeling numerical homogenization for highly parameterized unit cells. Through its iterative training process, the DNN is trained to model numerical homogenization and produce accurate derivative information with respect to the input geometry. We computationally validate the accurate execution and differentiation of the DNN using the Interface-enriched Generalized Finite Element Method (IGFEM) in multiscale optimization. The validation provides critical insight into the DNN training process for materials design. Subsequently, we present a variety of multiscale structural design examples in 2D and 3D and a unique exploration of the derivative information provided by the DNN. We also extend the parameterization of the microstructure designs, increasing the geometric complexity of the design space and expanding the practical applications of complex, spatially varying architected material design in multiscale structures.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Topology Optimization with Spatially Varying Length Scale

Author(s): *Oded Amir, *Technion - Israel Institute of Technology*;

Topology optimization (TO) is a widely used computational design method for achieving an optimal structure for a given design statement. The problem includes an objective that needs to be minimized, such as weight or cost, considering a few constraints, such as allowable stress and deformation. The method updates the design iteratively using the design sensitivities of the objective and constraints. For some optimization problems, the optimized structure may include thin members that might not be manufacturable. The most common tool for constraining the length scale of structural features is by using a filter, much like in image processing, which enforces a minimum length scale on the structure. In density based TO, the filter essentially averages material densities in the vicinity of each design point and its size is considered an input parameter.

The main purpose of the proposed research is to extend the basic formulation of TO such that the minimum length scale is a design variable, alongside the pointwise density. This extension can provide many advantages compared to traditional formulations, for example: avoiding stress concentrations by local increase in length scale; and reducing manufacturing costs by forming a structure with constant length scale, that can be milled with a minimal number of tools.

Controlling the length scale of the optimized structure will be achieved by applying a PDE filter. This filter utilizes the FEM solution of a Helmholtz-type PDE to generate the filtered densities from the underlying mathematical densities that are the design variables in density based TO. The PDE filter approach is computationally more economical than the more common discrete filter. At first, the length scale parameter of the PDE filter is introduced as a single design variable, allowing the optimizer to find the best minimum length scale that is constant in space. Later, we treat the minimum length scale as a continuous field that is represented by distributing design variables throughout the design space. This enables us to tackle several problems that consist of opposing functionals, such as: maximum stiffness versus minimal stress concentrations; and maximum stiffness versus minimum size variability.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Local Stress Constraints in Topology Optimization of Structures Subjected to Arbitrary Dynamic Loads: a Stress Aggregation-Free Approach

Author(s): *Oliver Giraldo-Londoño, *University of Missouri*; Miguel A. Aguiló, *Sandia National Laboratories*; Glaucio H. Paulino, *Princeton University*;

Many structures or structural components are subjected to loads that change in magnitude, direction, or position as a function of time—e.g., structures subjected to impact loading. As such, their design often requires time-domain analyses to prevent material failure from occurring locally at any point in time. In this presentation, we introduce a topology optimization formulation to design lightweight structures subjected to general dynamic loading, in the time domain, while considering local stress constraints at every time step. Although consistent with the local definition of stress, a formulation of this type requires the optimizer to handle a tremendous amount of stress constraints, which may be challenging to achieve using traditional stress-based topology optimization formulations. To address this issue, we adopt an augmented Lagrangian (AL) approach, so that we solve the original optimization problem with local constraints stress as a sequence of minimization problems with only box constraints. This way of solving the stress-constrained problem allows us to handle thousands or even millions of stress constraints without using constraint aggregation techniques based on smooth approximations of the maximum function. We present several numerical examples to illustrate the effectiveness of the approach to design structures subjected to time-dependent loading.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Multiparametric Cutting Force Prediction Model for Various Wood Species

Author(s): *Ondrej Dvoracek, *Kompetenzzentrum Holz GmbH*; Daniel Lechowicz, *Kompetenzzentrum Holz GmbH*; Martin Hauser, *University of Natural Resources and Life Sciences, Vienna*; Stephan Frybort, *Kompetenzzentrum Holz GmbH*;

Wood machining is a key process in the process chain as far as the wood industry is concerned. It is present in every step of wood processing - from tree felling, through timber and furniture production, to wooden waste chipping for reuse or burning. Nowadays, forest composition in temperate climate zones is changing. Broad-leaved species are replacing needle-bearing species. Therefore, to support industrial development and hardwood disintegration-related research projects, a project ROTCUT (ATCZ276), financed by Interreg V-A AT/CZ and co-financed by the Lower Austria Provincial Government, was launched. A unique test rig for linear cutting force measurements with speeds of up to 90 m/s was used within the project. The wood types, oak (*Quercus robur*), beech (*Fagus sylvatica*), spruce (*Picea abies*), tree of heaven (*Ailanthus altissima*), paulownia (*Paulownia tomentosa*), and locust (*Robinia pseudoacacia*) were used for the study at various moisture contents (0% – <32%). Further variables included in the examination were uncut chip thickness (0 – 0.5 mm) and cutting fibre angle (parallel to across the grain). High-speed cameras recorded chosen tests at a frame rate of 200 000 frames per second. The measured data confirmed that the key factor influencing cutting force was cutting velocity. The non-linear dependence was observed for every wood species tested in this investigation. According to the samples' average density, the wood species influence followed the trend, even though cutting mechanisms of soft- and hardwood species are not the same. The tests revealed that the evaluated uncut chip thickness influenced cutting force with linear progression at higher cutting speeds and non-linear trend at lower cutting speeds. Furthermore, the friction component of cutting force was distinct when thin chips were cut. By means of the collected data, a cutting force prediction model was elaborated. Finally, a web application using the model was developed and deployed. Therefore, it can serve researchers and developers as a source of information about forces taking place during cutting employing examined material and process parameters.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Harnessing the Nonlinear Behavior of a Laterally Loaded Arch for Vertical Vibration Isolation

Author(s): Stone Brackett, *University of Oklahoma*; Santiago Navarro Garcia, *University of Oklahoma*; *P. Scott Harvey, *University of Oklahoma*;

Structures and critical building contents are often susceptible to damage from vertical dynamic motion such as that generated by earthquakes. Various systems exist to mitigate damage caused by seismic excitations; however, the study of isolators for vertical excitations lags behind that of horizontal excitations. Moreover, there is an inherent challenge of having a system with low dynamic stiffness (i.e., low natural frequency), but sufficient static stiffness to support the self-weight of the isolated mass without considerable deformation. This paper explores the design of a vertical isolation system utilizing the nonlinear behavior of a laterally loaded arch, in order to generate negative stiffness. This negative stiffness is then counteracted by a positive, linear stiffness from a parallel spring to create quasi-zero stiffness. The quasi-zero stiffness allows for a mass attached to the center of the arch to be effectively isolated from the effects of vertical dynamic motion at the base of the system, while also exhibiting greatly reduced static deformations. An experimental model was produced for the system, with a focus on using lightweight materials and allowing for a low, compact profile. Additive manufacturing (3D printing) was used to fabricate most of the components to allow for engineered perturbations and complex geometries to be realized. Static testing was performed on the model to characterize properties of the 3D-printed arches and the springs and to optimize the system. Initial rise, arch geometry, and boundary conditions provided the parametric variation. Following that, dynamic testing was performed using a vertical shake table to evaluate the isolation performance of the optimized system. Both harmonic disturbances and simulated vertical floor motions were considered. The isolation performance was then compared to expected results under harmonic and seismic loading in order to verify existing theory and the design principle. A comparison of the experimentally determined results and the theorized results is evaluated and will be used for the development of future design iterations.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Initiation of Motion Conditions in a Turbulent Boundary Layer Flow in Aeolian and Fluvial Environments

Author(s): Hridaya Bastola, *Lehigh University*, Cheng Chen, *Lehigh University*, *Panayiotis Diplas, *Lehigh University*,

Scouring of sediments in the vicinity of structures can result in their destabilization and eventual failure. This phenomenon is driven by the same physical processes in both aeolian and fluvial environments. A proper understanding of the conditions prevailing during the onset of scouring of sediments subject to turbulent flows requires us to study the nature of fluctuating forces resulting from these flows and the effect of local particle geometry on threshold of motion conditions. Recent studies show that both force and duration are important in determining the successful dislodgement of individual particles (e.g. Diplas et al., 2008) . Here, we discuss the results of wind tunnel experiments on exposed particles across 16 different local geometries by evaluating the force magnitude and its duration during individual turbulent flow events in the form of dimensionless impulse and energy. Results indicate that larger impulse and energy from such flow events are needed with decreasing relative exposure for particle dislodgements to be successful. For identical base grains, we observe that when the size of exposed particles decreases, the relative difficulty in dislodging the particle increases as they get more shielded from the flow. Much remains to be understood about the flow properties for near-wall interactions on partially exposed particles. To further understand these flow properties, additional results from a CFD numerical simulation using OpenFOAM with an LES model are presented for the case of a spherical particle under four different relative exposures. To simplify the problem, the simulated particle is partially hidden in a flat channel bed instead of being hidden among other surrounding particles. The averaged and instantaneous flow characteristics, including the contributions of drag and lift forces, are calculated during flow events that lead to particle dislodgement under threshold of motion conditions.

Diplas, P., Dancey, C.L., Celik, A.O., Valyrakis, M., Greer, K., Akar, T., "The role of impulse on the initiation of particle movement under turbulent flow conditions". *Science*, 322:717-720, October 31, 2008.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Frustrated Metamaterials as Pop-Up Domes

Author(s): *Paolo Celli, *Stony Brook University*; Olivine Silier, *California Institute of Technology*; Lucas Annink, *Stony Brook University*; Chiara Daraio, *California Institute of Technology*;

Structures designed to change shape in response to external stimuli are becoming increasingly widespread, with applications ranging from everyday objects to large space structures. A current research direction entails expanding the range of achievable shape changes, e.g., by obtaining extreme area changes or by morphing flat objects into complex 3D surfaces. In this talk, I will first briefly illustrate a fully mechanical strategy to turn flat sheets into 3D surfaces. Our rubbery sheets feature non-periodic patterns of cuts, and can be defined as planar kirigami. When pulling them at their boundaries, regions that are designed to undergo small deformations impede the in-plane deformation of regions that tend to deform following mechanism-like motions. This triggers kinematic incompatibilities that result in an out-of-plane buckling of desired regions of the sheet. I will then concentrate on the subsequent steps we took to try to bridge the gap from a strategy that is only bound to work at the tabletop scale using rubbery materials, to larger-scale structural applications. The work culminates with the realization of a meter-scale pop-up structure, and with the structural analysis and modeling of tabletop-scale realizations of that same structure.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Damage Classification of Wood Samples Using Acoustic Emission Technique and Pattern Recognition Network

Author(s): *Parinaz Belalpour Dastjerdi, *University of Maine*; Eric Landis, *University of Maine*;

Damage mechanisms classification in anisotropic and heterogeneous materials such as wood under complicated stress states is challenging. If we are to develop an effective model for performance prediction, understanding these damage mechanisms is crucial. In this work, the acoustic emission (AE) method was employed to monitor the progression of damage in spruce-pine-fir (SPF) wood under compact tension and rolling shear. Rolling shear is important due to its role as a failure mode in cross-laminated timber (CLT). In this study, in order to identify different damage mechanisms, we implemented both supervised and unsupervised neural networks for finding clusters and classifying the AE events. A mel-frequency cepstral (MFC) representation of the AE signals was implemented as input for the unsupervised neural network. It should be noted that the machine learning method is an ideal approach for analyzing a large dataset such as the mel-frequency cepstral coefficients of AE signals. An unsupervised clustering technique, self-organizing map, was applied to find the number of dominant clusters. The unsupervised method enables us to prepare the data set for pattern recognition. First, three different configurations (samples with 0°, 45° and 90° grain angles) with a 5mm pre-crack were tested on a smaller scale under compact tension test. The combined data set of 0°, 45° and 90° shows specific dominant clusters. Secondly, these well-clustered signals were used to train the supervised neural network. A two-layered feed-forward neural network with sigmoid hidden and softmax output neurons was used as a supervised pattern recognition technique. This trained network is applied for classification and prediction of more frequent damages which occurs in the new data set recorded from rolling shear. One of our hypotheses is that cell wall separation, which occurs at 90°, has lower AE energy in comparison with cell wall rupture, which occurs at 0°. For that reason, the cumulative energy of each class seems to be a good criterion to investigate. Further experimentation will help us better correlate the described clusters with specific micromechanical processes. The goal of this research is to gain a better understanding of how damage develops so that the findings can be used in microstructure-based computational models.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Using Physics-Based Models and Machine Learning to Estimate Pressure on a Ship Hull

Author(s): *Patrick Brewick, *University of Notre Dame*;

Hull monitoring systems have been extensively utilized by naval and marine engineers for decades for fatigue assessment purposes as well as to provide valuable information about hull performance in the face of events such as wave slamming loads. Traditional hull monitoring systems have generally focused on strain, which, while helpful in quantifying and tracking fatigue, potentially overlooks issues related to over-pressures created during wave slamming events. Fortunately, recent developments in sensing technology have greatly expanded the potential capabilities of these systems, creating new possibilities for monitoring. For instance, fiber optics constitute a particularly relevant tool given that they are insensitive to electro-magnetic interference, resistant to corrosion, and capable of providing measurements over a broad range of temperatures. Further, fiber optic sensing systems also provide a distributed sensing solution within a single fiber, in which fiber gratings placed at regular intervals along the length of the fiber can create a high density of sampling points. When subjected to deformation, the change in the longitudinal axis of the fiber is registered as shifts in the gratings, and these shifts can be related to longitudinal strain, temperature, or pressure, among several other measurands. Thus, the introduction of fiber optic-based strain sensing has opened new possibilities for distributed sensing within hull monitoring systems.

This talk focuses on the development of modeling methodologies for translating strain measurements collected by hull monitoring systems into predictions of pressure that can better quantify the effects of wave slamming loads. A series of experiments were conducted at the U.S. Naval Academy in which a multi-modal hull monitoring system was affixed to a scale model of a U.S. Coast Guard patrol vessel that was subjected to a series of wave loading scenarios. The hull monitoring system utilized fiber optic sensors, piezometers, and strain gauges to measure both strain and pressure. Using strain measurements, two models, one physics-based and the other created using Gaussian processes, are developed to estimate the resulting hull pressures. Each model is calibrated using an independent data set for training, but they are tested against the same regime of regular and irregular wave loads. This talk will discuss the results of the models performance, including details on their predictive capacities as well as their abilities to quantify their associated uncertainties.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: A Fracture Multiscale Model for Peridynamic Enrichment Within the Partition of Unity Method: Part I

Author(s): *Patrick Diehl, *CCT / Louisiana State University*;

Partition of unity methods (PUM) are of domain decomposition type and provide the opportunity for multiscale and multiphysics numerical modeling. Different physical models can exist within a PUM scheme for handling problems with zones of linear elasticity and zones where fractures occur. Here, the peridynamic (PD) model is used in regions of fracture and smooth PUM is used in the surrounding linear elastic media. The method is a so-called global-local enrichment strategy, see \cite{duarte2007global, birner2017global}. The elastic fields of the undamaged media provide appropriate boundary data for the localized PD simulations. The first steps for a combined PD/PUM simulator are presented. In part I of this series, we show that the local PD approximation can be utilized to enrich the global PUM approximation to capture the true material response with high accuracy efficiently. Test problems are provided demonstrating the validity and potential of this numerical approach.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Additive Manufacturing of Carbonated Cementitious Materials

Author(s): *Paula Bran Anleu, *Oak Ridge National Laboratory*; Yann Le Pape, *Oak Ridge National Laboratory*; Qiyi Chen, *Oak Ridge National Laboratory*; Parans Paranthaman, *Oak Ridge National Laboratory*; Rigoberto Advincula, *Oak Ridge National Laboratory*; Brian Post, *Oak Ridge National Laboratory*; Celeste Atkins, *Oak Ridge National Laboratory*; Adam Brooks, *Oak Ridge National Laboratory*; Elena Tajuelo Rodriguez, *Oak Ridge National Laboratory*;

The cement industry is among the highest CO₂ world emitter despite curbing efforts by the industry. Moreover, the cement industry is among the most energy-intensive of all manufacturing industries, with a share of national energy use roughly 10 times its share of the nation's gross output of goods and services.

Carbonated cementitious materials (CCMs), based on the cycle of limestone, offer a lower-energy demand (fabrication at 800 °C using traditional method instead of ~1,450 °C for Portland cement) and close to carbon-neutral alternative if the strength development can be accelerated in adequate physical environments (CO₂ concentration, temperature, humidity, and pressure) as suggested by recent literature data. Such conditions can be achieved using carbonation chambers (target: precast construction) or in the context of additive manufacturing (e.g., CO₂ injection during printing). CCMs are expected to offer superior durability leading to lower maintenance cost than conventional concrete solutions against potential degradation caused by the presence of silicate-bearing hydrates or minerals (e.g. ASR), for example.

The main goal of this study was to develop a printable Carbonated Cementitious Material (CCMs) design and demonstrate its rapid stiffening for manufacturing 3D printed elements for building construction, i.e., the 'concrete' with enhanced durability performance and CO₂ capture efficiency. The materials development comprises the use of calcium hydroxide, and its distinct chemistry with CO₂. Different formulations and additives including polymer materials enable thermo-mechanical properties that allow these CCMs to have the printability and processability comparable to cement materials used for construction, and other load bearing applications. We have successfully developed printable and castable CCM formulations and demonstrated that the slurry can mineralize CO₂ to calcium carbonate up to 57%.

CCMs-based Additive Manufacturing allows a better control of the physical and mechanical properties at the various phase of the material's life. For example: (i) Rheology of the fresh slurry is controlled by the water to solid ratio to ensure proper extrusion at the printer's nozzle; (ii) The stiffening right after extrusion can be achieved with the use of thermally controlled condensation reactions of thermoplastic resins (e.g., polyvinyl alcohol, polyethylene imine, etc). Controlled stiffening can be achieved by tailoring the curing kinetics; and (iii) Long-term strength development can be achieved by gradual carbonation from varied sources: CO₂ injection at the printer's nozzle, curing in a carbonation chamber for precast or printed elements and natural carbonation. Enhanced durability is also expected thanks to natural carbonation.

Title: Large-Scale Turbulence Modulation in the Wind Tunnel Using a Multi-Fan Flow Control Instrument

Author(s): *Pedro L. Fernández-Cabán, *Clarkson University*; Ryan A. Catarelli, *University of Florida*;

Discrepancies in wind load estimates obtained in boundary layer wind tunnels (BLWTs) and numerical CFD-based models have been largely attributed to differences in specified inflow conditions [1]. This is partly a consequence of uncertainties in the simulated atmospheric boundary layer (ABL) flows during aerodynamic wind tunnel tests. Consequently, results from CFD studies are often put into question given the strong dependence of inflow conditions (e.g., incident turbulence) on peak wind loads acting on sharp-edged bluff bodies (e.g., low-rise buildings). Further, it is well-established that both the magnitude and spatial distribution of peak loads near separated flow regions are strongly influenced by small- and large-scale turbulent eddies entrained in the oncoming wind flow. Nevertheless, physical simulation of the complete turbulent wind spectra (including both large- and small-scale turbulence) for large-scale tests of low-rise building models has not yet been achieved in traditional BLWTs.

The objective of this research is to leverage a novel flow-control instrument, the Flow Field Modulator (FFM), to control large-scale turbulent features of scaled ABL flows in the BLWT and study their influence on the intensity and distribution of wind-induced loads on building envelopes—particularly in flow separation zones that experience strong uplift forces. The FFM is a fully integrated multi-fan array located at the University of Florida (UF) NSF Natural Hazard Engineering Research Infrastructure (NHERI) Experimental Facility. The system is installed in the upwind portion of UF's BLWT and consists of a computer-controlled 2D array of 319 modular hexagonal aluminum ducts containing 228.6 mm diameter 6 blade ducted fans with high-performance brushless DC motors driven by electronic speed controllers. Flow measurement experiments were recently conducted to benchmark the capabilities of the FFM for modulating large-scale turbulent structures in the BLWT. Preliminary results demonstrate the potential of the FFM to inject and precisely modulate large-scale wind flow structures. The present work aims at advancing BLWT flow capabilities to produce repeatable and verifiable BLWT data needed to calibrate the inflow conditions of CFD-based models. Lastly, results from this research may assist in increasing confidence among the wind engineering community regarding the ability of CFD for characterizing extreme wind-induced loads.

[1] Lim, H. C., Thomas, T. G., & Castro, I. P. (2009). Flow around a cube in a turbulent boundary layer: LES and experiment. *Journal of Wind Engineering and Industrial Aerodynamics*, 97(2), 96-109.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Admissible Unconstrained Neural Network Surrogates for Hyperelastic Constitutive Models

Author(s): *Peiyi Chen, *Duke University*; Johann Guilleminot, *Duke University*;

In this study, we present a methodology to construct admissible, yet unconstrained neural network models for hyperelastic materials, with the goal of ensuring both well-posedness and physical consistency in data-driven computational modeling. The procedure involves standard representation results in continuum mechanics, as well as convexity constraints that are enforced through ad hoc mathematical representations. The relevance of the formulation is then assessed by considering digitally synthesized datasets on biological and engineered composite materials.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Data-Driven Multiscale Model for Fiber Composite Properties

Author(s): *Philippe Hawi, *University of Southern California*; Roger Ghanem, *University of Southern California*; Venkat Aitharaju, *General Motors*;

In this work, we present an approach for characterizing and updating the probability densities of the mechanical properties of fibers and resin in a composite material system, as well as predicting the mechanical properties of the final composite part, using measurements from a Three-Point Bend test. Starting with prior distributions for the microscale properties (beta distributions supported on appropriate physical ranges), a set of those properties is randomly sampled and upscaled to macroscale properties using the Rule of Mixtures. This upscaling procedure introduces 2 random factors, alpha and beta, that serve as fudge factors for the tensile and compressive macroscale failure strains. The obtained macroscale properties are used in the material card definition of an expensive computational model (LS-DYNA) representing a 4-layer lamina where each layer is modeled with shell elements using a composite material card. The model is run to build a computational database of 1700 examples with randomized mechanical properties and layer thickness. Out of this computational model, 8 composite properties are extracted (elasticity moduli at different tangents, maximum force and displacement, and absorbed energy). Using the probabilistic learning on manifolds, developed by Soize and Ghanem, the computational database is augmented to 17 million examples and used to estimate the joint density function of 129 random variables (57 microscale properties, 64 macroscale properties, 8 composite part properties). This approach, PLoM, generates samples constrained to an intrinsic structure detected by a diffusion on graphs process (Diffusion maps) using projected stochastic differential equations. Using the augmented database, two tasks are performed. First, experimental observations from Three-Point Bend experiments are used in a statistical conditioning scheme to build a conditional (updated) density function for each of the 57 microscale mechanical properties. The obtained conditional distributions are considerably more concentrated than the unconditional ones. Secondly, nominal microscale mechanical properties are used as statistical conditions to predict the conditional statistics (distributions and expectations) of several composite mechanical properties such as elastic moduli, maximum load and displacement, and absorbed energy.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: A 3D Modeling of the Impact of Internal Erosion on the Stability of Engineering Structures

Author(s): *Pierre-Yves Hicher, *École Centrale de Nantes*; Jie Yang, *École Centrale de Nantes*; Zhen-Yu Yin, *The Hong Kong Polytechnic University*; Farid Laouafa, *INERIS*;

In order to study the impact of internal erosion at the scale of an engineering structure, we have developed a hydro-mechanical continuous modelling approach considering suffusion. This approach involves two models which have subsequently been implemented into a finite element code: a mechanical model for granular soils considering the fines content-dependency and a hydraulic model for suffusion to control the changes in the fines content. The saturated soil has been considered as a mixture of four interacting constituents: soil skeleton, erodible fines, fluidized fine particles, and fluid. The detachment and transport of the fine particles have been modeled with a mass exchange model between the solid and the fluid phases. An elastoplastic constitutive model for sand-silt mixtures has been developed to monitor the effect of the evolution of both the porosity and the fines content induced by internal erosion under the behavior of the soil skeleton. This numerical tool was then applied to a specific dike-on-foundation case subjected to internal erosion induced by a leakage located at the bottom of the foundation. Different failure modes were observed and analyzed for different boundary conditions, including the significant influence of the leakage cavity size and the elevation of the water level at the upstream and downstream sides of the dike. It was found that the decrease of the fines content close to the toe of the dike could stimulate a global sliding failure of the slope. The elevation of the water surface within the foundation at the downstream side increased the loss of the fines close to the toe. On the other hand, the presence of a leakage cavity was capable of leading to the initiation of a sinkhole formed as a consequence of the rigid movement of the soil above the eroded area in the vicinity of the cavity. The location of the sinkhole was found to be related to the location of the phreatic surface. Moreover, the enlargement of the cavity accelerated the formation of the sinkhole. For a larger leakage cavity, the internal erosion within the dike and foundation developed faster, leading to the earlier appearance of a sinkhole at the top of the dike. In terms of failure mode, the presence of a leakage cavity introduced a more "local" failure-collapse mode (ie, a sinkhole) rather than a global sliding failure. Furthermore, the elevation of the water surface within the foundation at the downstream side increased the risk of a global sliding of the slope.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: RFID-Based Crack Prediction for Concrete Structures Under Environmental Uncertainty Using Machine Learning

Author(s): *Pierredens Fils, *University of Connecticut*; Shinae Jang, *University of Connecticut*,

Cracks forming in aging structures can indicate internal damage due to excess loading, material deterioration, and other factors that would lead to expensive reconstruction projects. Thus, structural health monitoring (SHM) and non-destructive evaluation (NDE) techniques aim to increase the service life of said structures. Many SHM and NDE techniques have been in use for decades, however, there remain limitations under environmental uncertainty. Recently, low-cost Radio Frequency Identification Devices (RFID) have drawn attention for crack monitoring and have been implemented in the field under temperature variations but did not account for humidity effects. This paper presents a crack prediction algorithm based on two machine learning algorithms using a novel RFID-based sensing system under humidity variations for field concrete structures. Using a pseudo electromagnetic chamber developed for both temperature and humidity control, artificially cracked concrete specimens are prepared and tested using the RFID-based sensing system for a range of temperature and humidity levels. The raw measurements are pre-processed to calculate the statistical measures, then used for training the Artificial Neural Networks, and finally employed for crack prediction. A Multivariate Linear Regression model is used as a baseline comparison and the results show promise for field implementation on concrete structures where humidity has a high effect.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: A Combined Variational Multiscale Stabilization and Enrichment Method for Problems with Material Heterogeneity

Author(s): *Pinlei Chen, *Penn State University*; Hye-eun Kong, *Penn State University*;

In this presentation, we will present a formulation of a combined variational multiscale stabilization and enrichment method (VMSE) for the analysis of problems with material heterogeneity. The variational multiscale enrichment (VME) method is a global-local approach that has accurate fine scale representation at local small subdomains, where important physical phenomena like material heterogeneity and fracture could take place [1]. From the computational perspective, this method is well suited for problems where mesh refinement is prohibitive to conduct through the entire structure. The local enrichment can not only approximate the residual from the coarse mesh, but also account for the material heterogeneity. The variational multiscale stabilization (VMS) method is employed to enforce the proper boundary conditions at the fine scale, with naturally derived stability tensors. The Integration of VMS interface stabilization and VME multiscale modeling opens a door for embedding different damage models. Numerical simulations are performed to assess the robustness and accuracy of the proposed VMSE framework. We compare our results with the standard FEM method, and the results demonstrated that the VMSE method provides proper boundary restrictions at the fine scale while the material heterogeneity is reflected.

Keywords: Variational multiscale stabilization, Variational multiscale enrichment, Material heterogeneity

Reference:

[1] S. Zhang, C. Oskay, Variational multiscale enrichment method with mixed boundary conditions for elasto-viscoplastic problems, *Comput Mech.* 55 (2015) 771–787.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Active Learning with Multi-Fidelity Modeling for Probability of Failure Estimation

Author(s): *Promit Chakroborty, *Johns Hopkins University*; Michael Shields, *Johns Hopkins University*; Somayajulu Dhulipala, *Idaho National Laboratory*;

Engineering for hazards often requires the estimation of the probability of failure of complex, low-failure-probability systems. As a result of the complexity and small failure probability, classical reliability analysis techniques fall well short of the efficiency required in such cases due to the high computational cost of evaluating the system response at each iteration and the large number of iterations needed. However, using Machine Learned surrogates in place of the response function can reduce computation times. Multi-fidelity modeling is another technique that can reduce computation times by using less expensive models to predict the system response. We propose an algorithm that couples both of these techniques to reduce the computational costs of reliability analysis of complex systems while maintaining acceptable levels of accuracy. Our proposed framework functions by estimating the high-fidelity (HF) model response using information from multiple pairs of low-fidelity (LF) models and corresponding machine-learned correction terms (MLCs). These correction terms are trained using small sets of HF and LF evaluations. Probability weights with Bayesian and Information-Theoretic interpretations are calculated using the Akaike Information Criterion (AIC) and assigned to each LF-MLC pair. Then a surrogate model for the system response (i.e., the HF model) is constructed using these weights to achieve the most accurate predictions or reduce the number of total model calls. No assumptions are made on LF model types or correlations with the HF model. As a final step, the acceptability of the surrogate is checked at each sample point using active learning functions. This response prediction framework is used in conjunction with Subset Simulation (a variance-reduced MCMC method) to conduct reliability analysis. Lastly, our proposed framework is tested on several analytical case studies to demonstrate its efficiency.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Machine Learning-Enabled Contact Detection and Resolution of Irregular-Shaped Particles in Discrete Element Method

Author(s): Zhengshou Lai, *Sun Yat-sen University*; *Qiushi Chen, *Clemson University*; Linchong Huang, *Sun Yat-sen University*;

In this work, we present a machine learning (ML)-enabled contact detection and resolution of irregular-shaped particles in discrete element method. ML-enabled DEM, as with most conventional DEMs, encompasses four main steps in one typical calculation cycle, namely, (1) the detection and resolution of contacts, (2) the evaluation of contact behavior, (3) the calculation of particle motion, and (4) the updating of particle geometric descriptions. Unlike conventional DEMs, the proposed method constructs and employs neural networks to detect particle contacts and resolve contact geometric features. Neural networks take particle geometric descriptors as inputs and output the contact status and contact geometric features. Using two-dimensional elliptical particles as an example, the performance of the ML-enabled DEM is investigated through five numerical experiments and compared with analytical solutions or conventional DEM methods. A sixth numerical experiment involving irregular-shaped particles is also presented to showcase the potential and applicability of the proposed method for other particle shapes. ML-enabled DEM can accurately capture the trajectory and energy evolution of individual particles, the fabric characteristics of dense packing, and the mechanical behavior of packing under large loads, while demonstrating computational efficiency over conventional methods.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Poro-Damage Phase Field Damage Models for Hydraulic Fracture Propagation in Glaciers and Ice Shelves

Author(s): *Ravindra Duddu, *Vanderbilt University*; Xiangming Sun, *Vanderbilt University*; Theo Clayton, *Imperial College London*; Emilio Martinez-Paneda, *Imperial College London*;

Crevasses are predominantly mode I fractures penetrating tens of meters deep into grounded glaciers and floating ice shelves that are hundreds of meters thick. Hydraulic fracture (or hydrofracture) can promote the propagation of water-filled surface crevasses in grounded glaciers and, in some cases, lead to full-depth penetration that enhances basal sliding by altering subglacial hydrology. Hydrofracture of water-filled surface/basal crevasses in ice shelves can promote the propagation of kilometers-long rifts and result in the production of large tabular icebergs. However, to better understand the physical factors (e.g. glacier geometry, stress state, basal and terminus boundary conditions) enabling the full-depth propagation of water-filled crevasses, it is necessary to employ advanced material damage models for representing the quasi-brittle fracture process in glacier ice. With this in mind, we formulated two poro-damage phase field models for hydrofracturing of crevasses, wherein the crevasse is represented by a nonlocal damage zone and the effect of hydrostatic pressure in the crevasse is incorporated based on poromechanics theory. To describe the asymmetric tensile–compressive fracture behavior of glacier ice under self-gravity loading, we tested two crack driving force functions: (1) a strain energy based function with a fracture energy threshold; (2) a stress based function with a tunable damage parameter. We first assessed the performance of the two models against analytical linear elastic fracture mechanics solutions. We next simulated both surface and basal crevasse propagation in idealized land- and marine- terminating grounded glaciers, and ice shelves to illustrate the viability of these models. To conclude, we will discuss prevailing challenges to phase field models for describing iceberg calving processes in real glaciers and ice shelves over glaciologically relevant time scales.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Effect of Boundary Condition and Statistical Volume Element Size on Inhomogeneity and Anisotropy of Apparent Properties

Author(s): *Reza Abedi, *University of Tennessee*; Justin Garrard, *University of Tennessee*; Ming Yang, *The Ohio State University*; Pengfei Zhang, *The Ohio State University*; Katherine Acton, *University of Saint Thomas*; Soheil Soghrati, *The Ohio State University*;

The response of brittle and quasi-brittle materials is greatly influenced by their microstructural architecture. Models that assume spatially uniform fracture strength miss the effect of microscale inhomogeneities on eventual crack patterns and the scatter in certain macroscopic measures, such as ultimate load and absorbed energy. Apparent material properties homogenized by Statistical Volume Elements (SVEs) are generally inhomogeneous and random because SVEs are (much) smaller than Representative Volume Elements (RVEs), which are often used to homogenize elastic properties of solid materials. Accordingly, SVEs provide a viable path to generate physics-based inhomogeneous and random material properties that are suitable for brittle fracture analysis.

We use square SVEs to homogenize elastic and fracture properties of a carbon-nanofiber reinforced polymer. The effect of SVE size and boundary condition (BC) on homogenized properties is investigated. Three different criteria are proposed for the convergence of properties and reaching the RVE limit: 1) A variation-based criterion examines the trend at which the variation of a property decreases versus SVE size; 2) A mean-based criterion examines the rate at which the SVE-mean of property converges to its terminal value; 3) A BC-based criterion examines whether the homogenized properties can be independent of the choice of BC. These criteria show that the geometric property of fiber volume fraction / mass density converges to its homogeneous limit first followed by the elasticity tensor. Fracture strengths have the most complex response as they remain highly inhomogeneous, random, anisotropic, and size-dependent for the SVE sizes considered. This is further discussed in the context of stochastic multiscale material modeling, and well-known size effect models for fracture strength. Furthermore, the square shape of the SVE is shown to induce nonphysical bias angles wherein elastic and fracture properties often take their maximum or minimum values at integer multiples of 45 degrees. The traction BC is shown to be superior to displacement BC by having a weaker form of this anisotropy and higher strength values. Moreover, for the anisotropic domain anisotropy indices converge from below and above for traction and displacement BCs, respectively, thus resembling Reuss and Voigt hierarchy of bounds for elastic properties. Finally, we discuss the extensions of this work to 3D fiber composites with isotropic and various anisotropic layouts of fibers. Particularly, new measures of anisotropy and transverse isotropy of elastic and fracture properties are presented.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Topology Optimization of Additively Manufactured Fluidic Components Considering Overhang Constraints

Author(s): *Reza Behrou, *RunToSolve LLC*; Kathryn Kirsch, *Raytheon Technologies Research Center*; Ram Ranjan, *Raytheon Technologies Research Center*; James K. Guest, *Johns Hopkins University*;

Topology optimization of flow problems holds promise for transforming a number of applications, including materials and devices with optimized energy, momentum, heat transfer, and species transport. Prevalent among these are thermal-fluid systems in energy applications, such as power generation systems utilizing heat exchangers and turbomachinery components that often are designed with parametric modeling techniques. Topology optimization as a form-finding methodology provides a systematic approach to generating novel component and system designs, enabling improvements in efficiencies and/or reductions in cost and volume. Herein we explore the coupling of topology optimization with additive manufacturing (AM) for the design of fluidic components, and specifically focus on the issue of eliminating overhanging features from optimized designs. Such features require the use of support structures during manufacturing, which must then be removed in post-processing, significantly increasing material usage, build time, and post-processing time and cost. The need for support structures can be eliminated by designing all features to be self-supporting, meaning they rise in the build direction at an angle greater than the overhang constraint angle (defined as 45 degrees for many AM processes). Overhang constraints are achieved automatically through the overhang projection methodology, which was recently applied to the internal surfaces of fluid components [1]. This approach is now extended to capture all surfaces, eliminating the need for support structures internal and external to the fluidic device. The incompressible Navier-Stokes equations are used to model the laminar fluid flow, and gradient-based optimization is used to solve the resulting optimization problems. The proposed approach is demonstrated on several classical 2D and 3D fluid topology optimization benchmark problems, and solutions are shown to be self-supporting and buildable without using support structures. [1] Behrou R., Kirsch K, Ranjan R., and Guest J.K. (2022) Topology optimization of additively manufactured fluidic components free of internal support structures. *Computer Methods in Applied Mechanics and Engineering*, 389:114270.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Multi Hazard Assessment of Aging River-Crossing Reinforced Concrete Bridges

Author(s): *Reza Filizadeh, *University of Vermont*; Eric Hernandez, *University of Vermont*; David Rosowsky, *Kansas State University*;

Bridges typically experience various deterioration processes with different time scales; some are long-term (gradual), and others have sudden effects (shock). To determine the performance and reliability of bridges, the combined and coupled effects of multiple hazards should be considered in a life-cycle context. This paper presents a probabilistic computational framework to assess the expected system-level damage and performance of river-crossing reinforced concrete bridges during their service life under the effect of multiple, interacting hazards. The hazards include chloride-induced corrosion, flood-induced scour, and multiple earthquakes. The evolution of corrosion process and scour depths are modeled as continuous processes, which gradually affect the structural properties and capacity. The rate of corrosion is a function of seismic-induced damage, so the corrosion rate will be updated after an earthquake event, and the corrosion process may be accelerated. To quantify the damage state of the structure due to multiple earthquake shocks, a cumulative damage index based on the Park-Ang damage model is determined and updated annually. Monte Carlo Simulation was performed to determine the reliability of bridges during their service life. The proposed framework establishes time and state-dependent demand and capacity models for the structures and considers the interaction of different deterioration mechanisms. The cumulative damage is determined based on comparing the seismic response of the structure to its real-time displacement and energy capacity. The proposed methodology is demonstrated on river-crossing 3-span simply supported concrete girder bridges located in Central and Southeastern United States (CSUS). Results from different hazard modeling scenarios reveal a significant contribution of structural performance from gradual deteriorations in the exceedance probability from damage levels depending on the bridge properties. However, foundation scour could result in increasing the natural period of the bridge, and consequently, reduce the seismic response of the bridge. Despite the complexity of hazard interactions, the effect of multiple hazards is generally more significant on the system performance compared to a single seismic hazard.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Rapid Evaluation of Vibration Mitigation Devices for Transportation Infrastructure Using Real-Time Hybrid Simulation

Author(s): Pablo Agüero-Barrantes, *University of Connecticut*; *Richard Christenson, *University of Connecticut*;

The use of vibration absorbers is proposed to reduce excessive wind-induced vibrations in sign, luminaire and traffic signal support structures, sometimes referred as ancillary structures in the transportation infrastructure. These ancillary structures have a very small level of inherent damping, often around 0.2% (0.002) and moderate increases in damping can provide significant increases in the safety and protection of these structures. Research has been conducted to examine the performance of vibration absorbers in ancillary structures. Often these vibration absorbers have nonlinear and complex behavior as they dissipate energy. While the prior research provides valuable results, there are some challenges related with physical testing to take into consideration. Field-testing of in-service structures has an implicit risk if there is operating traffic during sensor installation and testing. Laboratory testing requires large-scale facilities in order to accommodate structural dimensions. As such, open field laboratories are a feasible option for structure testing, but like in the other cases, the installation of the structure requires the use of equipment like cranes, which makes multiple testing few attractive, without mentioning the cost of structures transportation themselves. In all of these applications, the number of structures to be tested is limited by the physical structures available. On the other hand, full numerical modeling of the structure-damper system can be challenging given the non-linear nature of the damping devices.

In this research, the use of Real-time Hybrid Simulation (RTHS) is proposed as an alternative for testing sign, luminaire and traffic signal structures. Using this technique the structure is replaced by a numerical model; meanwhile the damper is tested physically in the laboratory and is dynamically coupled to the numerical structure. This research will extend RTHS to the evaluation of vibration absorbers to a dynamic range of transportation structures and demonstrate the positive attributes of RTHS that make it attractive for rapid evaluation of innovative solutions in wind-induced vibration mitigation of transportation infrastructure.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Mechanics of Ant Tunnels

Author(s): *Robert Buarque de Macedo, *California Institute of Technology*; Edward Ando, *Université Grenoble Alpes*; Shilpa Joy, *California Institute of Technology*; Gioacchino Viggiani, *Université Grenoble Alpes*; Raj Kumar Pal, *Kansas State University*; Joseph Parker, *California Institute of Technology*; Jose Andrade, *California Institute of Technology*;

Predicting the stability of granular materials under particle removal has wide-reaching applications, including automating tunnel excavations. Searching for general laws that govern granular stability is challenging given the complexity of granular material dynamics. However, knowledge may be gained from the natural world, where organisms have evolved adaptive tunneling strategies. Among these, subterranean-nesting ants execute an innate tunneling behavioral program that can lead to remarkably stable tunnel excavation. We use X-rays to image the process of ant tunnel construction through a particulate substrate. We use these data to create a grain-scale accurate simulation for estimating particle mechanics in the sample during real-time excavation. We present evidence that ants benefit from force redistributions during incremental digging, suggesting techniques for robotic mining. Further, we investigate general laws dictating stability in cohesive granular materials.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Effect of Time-Dependent Bond Slip on Delayed Failure of Reinforced Concrete Frames

Author(s): *Roberto Ballarini, *University of Houston*; Jialiang Le, *University of Minnesota*; Livia Mello, *Structural Integrity Associates*;

Recent discussions in technical committees revealed that reinforced concrete (RC) structures may be susceptible to delayed collapse, thus prompting the consideration of time-dependent material behavior as part of progressive collapse analysis and design.

This work investigates the influence of time-dependent bond slip on the delayed failure behavior of reinforced concrete frames. The time-dependent model of bond slip is formulated based on the mechanism of subcritical damage accumulation along the steel-concrete interface. By numerical simulations of the time history of bond slip under sustained loading, a kinetic model of bond slip is proposed. The model is incorporated into a recently developed reduced-order numerical model for simulations of the progressive collapse of RC frames, which accounts for viscoelastic deformation and time-dependent damage accumulation of the concrete. It is shown that the model can capture the essential deformation mechanisms of the frame under both monotonic loading and sustained fatigue. The simulation shows that the time dependence of bond slip could have a profound influence on the delayed failure of RC frames especially under moderate sustained loading. This finding highlights the importance of understanding the time-dependent bond slip for future study of the delayed progressive collapse of RC structures.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Are Configurational Forces Real Forces

Author(s): *Roberto Ballarini, *University of Houston*; Gianni Royer-Carfagni, *University of Parma*;

In the Treatise on Natural Philosophy of 1879, Thomson and Tait suggest that any attempt to supersede Newton's description of the laws of motion cannot but end in utter failure. A force is something that tends to alter a "body's" natural state of rest, or uniform motion along a straight line, with respect to an inertial observer. The structure of space as given to us in intuition is geometry; it is the possibility of visualizing forces with lines, and their geometrical composition, that facilitates the practical solution of most problems of mechanics. There are cases, however, for which the geometric visualization of such forces is not straightforward. A classical example is that of configurational forces, pioneered by Eshelby to describe the potential movement of defects within the solid state. From the variation of the free energy consequent to the movement of the defect, say an inclusion, an associated force can be inferred due to the natural tendency of the system to achieve lower potential states. However, as admitted by Eshelby himself, such a force is in some sense "fictitious": its existence is demonstrated starting from a consistent continuum theory of mechanics, but the same theory predicts that the resultant of the traction acting along the boundary of the inclusion is null. We show in paradigmatic examples amenable of generalization that a configurational force can be viewed as the resultant of the contact forces acting on the perturbed shape of an object of substance equivalent to the defect, and evaluated in the limit of the shape being restored to the primitive configuration. The expressions for the configurational forces on cracks and dislocations are in agreement with those determined using classical variational arguments. It is hoped that this somewhat novel approach, which has been applied by Bigoni and coworkers to illustrate configurational forces in structural components, may open a new perspective in the use of configurational forces by permitting their physical and intuitive visualization.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Evaluation of Kirigami Façade Concepts Towards Optimal Design for Irradiance and Air Flow

Author(s): *Rodrigo Arauz, *University of Pittsburgh*; Aminallah Poursaghar, *University of Pittsburgh*; John Brigham, *University of Pittsburgh*;

There has been a growing interest in development of design concepts for building façades/façade systems that can adapt to their environmental conditions naturally or through a control mechanism to improve some measure of performance [1]. For the example of photovoltaics integrated within a façade, one key objective could be to have the orientation of the façade or components of the façade change to track the sun and increase the effectiveness of the photovoltaics. Another possibility is opening parts of the façade so that air can flow into the building. Moreover, there has been some focus on the use of intrinsic mechanisms (rather than hinges or multiple mechanical components) to achieve adaptivity for these structures, such as through smart materials and/or origami or kirigami structural concepts. For example, kirigami (i.e., methods based on cutting/removing material) mechanisms have been investigated that can utilize an out-of-plane buckling response to allow portions of the surface to rotate as desired due to in-plane tension or compression [2]. The present study is examining the possibility of using a façade system with a kirigami design to achieve a desired environmentally interactive function, particularly by creating cuts of different size and type throughout the façade, to create a spatially varying adaptive façade. As such, the adaptive façade can then be optimally designed to achieve the “best” possible function based on location and environmental conditions and additional physical constraints. The current effort is focused on development of a numerical representation (i.e., finite element model) of a kirigami façade system, and the use of this numerical representation to evaluate and optimize the performance of an adaptive façade. The objectives considered include maximization of solar energy generation and/or air flow maximization, while simultaneously minimizing the energy required for actuation. A demonstration of the performance of different designs regarding uniform and non-uniform cut patterns for kirigami façades will be presented. These variations will be evaluated and compared with respect to both efficiency of adaptation (i.e., amount of change relative to external energy required), energy generation efficiency (i.e., amount of exposed area and angle of exposure), and potential to facilitate air flow (i.e., amount of open area in the façade).

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[2] Ahmad Rafsanjani and Katia Bertoldi. Buckling-induced kirigami. *Physical Review Letters*, 118(8):084301, 2017.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Innovative Multi-Directional Falling Weight Deflectometer (FWD) Tests and Evaluation Based on a Distribution of the Effective Modulus of Subgrade Reaction

Author(s): *Rodrigo Díaz Flores, *TU Wien*; Mehdi Aminbaghai, *TU Wien*; Lukas Eberhardsteiner, *TU Wien*; Ronald Blab, *TU Wien*; Martin Buchta, *Nievelt GmbH*; Bernhard L.A. Pichler, *TU Wien*;

Falling Weight Deflectometer (FWD) tests are commonly performed as means to gain insight into the state of degradation of pavement plates and of the subgrade that support them. During such tests, a standardized weight is let to fall upon the surface of a pavement plate, while geophones measure the deflections at different points along the driving direction. A commonly used method of evaluation of such tests is to model the structure as a plate on top of a Winkler foundation with a uniform modulus of subgrade reaction. The structure is assumed to behave axisymmetrically. The value of the modulus of subgrade reaction is then optimized such that the deflections measured by the geophones are reproduced accurately. The present contribution is devoted to the improvements of such a testing and evaluation method, as initially proposed by Díaz Flores et al. [<https://doi.org/hcnx>]. The improvements proposed are twofold: The first improvement refers to an expansion of traditional FWD tests, typically performed in one direction, so that they are performed in eight different directions. This allows for a detailed assessment regarding the asymmetries in the behavior of the pavement structure. The degree of asymmetry was quantified by means of a developed asymmetry indicator. It was shown that values of the asymmetry indicator $> 7\%$ refer to asymmetric behavior, while values $< 7\%$ refer to a virtually double-symmetric behavior. Important asymmetries were found in a 22-year-old plate that was scheduled to be repaired soon, while a freshly installed plate was found to behave in a virtually double-symmetric manner. The second improvement refers to an extension of the structural model used to analyze the tests in order to consider an auxiliary surface load as a second optimization variable in addition to the uniform modulus of subgrade reaction. This allows for a very accurate reproduction of the deflections measured by the geophones in every direction. Furthermore, the auxiliary surface load is superimposed with the stress at the bottom of the plate resulting from the Winkler foundation. In this way, a realistic distribution of the subgrade stresses is found, which, after dividing by the deflection field, yields a nonlinear distribution of the effective modulus of subgrade reaction. Finally, the analysis is repeated, but this time also accounting for inertial forces. This new analysis was found to deliver values of the effective modulus of subgrade reaction which were less than 3.5% larger than the ones from the static analysis.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Evidence Theory: What, Why and How in Engineering for Natural Hazards

Author(s): *Ross B. Corotis, *University of Colorado Boulder*; William Seites-Rundlett, *University of Colorado Boulder*; Cristina Torres-Machi, *University of Colorado Boulder*;

There is a demonstrated need for new and improved quantification of uncertainty, particularly for the analysis of structures subjected to stressors caused by natural hazards. For the traditional two classifications of uncertainty, aleatory is handled well by existing probability theory, whereas epistemic remains difficult to incorporate into probability theory-based models. Despite these limitations, probability theory has dominated the characterization of uncertainty.

The field of Artificial Intelligence (AI) is driving development of novel methods of uncertainty assessment free of the limiting constraints of probability theory. One such framework for assessing uncertainty is evidence theory. Evidence theory was originally conceived in the 1970s, and has recently seen expanded applications to problems typically addressed by traditional engineering methods. Evidence theory, however, has yet to be applied in general to applications relevant to infrastructure asset management. This seminar will explore some of the aspects of Evidence Theory, and provide guidelines for its application in engineering settings.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Advancements in the Physical Simulation of Non-Synoptic Extreme Wind Events in a Large Boundary Layer Wind Tunnel

Author(s): *Ryan Catarelli, *University of Florida*; Forrest Masters, *University of Florida*; Brian Phillips, *University of Florida*; Jennifer Bridge, *University of Florida*; Kurtis Gurley, *University of Florida*; Tai-An Chen, *University of Florida*;

This work presents advancements in the development of a large high-performance multi-fan array used in conjunction with traditional passive control devices (e.g., a roughness element grid) in a large boundary layer wind tunnel (BLWT) with the goal of simulating complex turbulent flows produced by non-synoptic extreme wind phenomena. Target events include (but are not limited to) gust fronts, downbursts, derechos, and some aspects of tornadic winds. These phenomena are of particular interest because they can dictate the most extreme wind loads experienced by civil infrastructure in non-hurricane prone regions. A key aspect of these types of events is that they are inherently spatiotemporally non-stationary, i.e., they occur over short spatial and temporal scales. Reproducing these events at model-scale requires physical simulation equipment capable of rapidly modulating wind speed, wind direction, and turbulence characteristics to achieve kinematic similitude with the full-scale wind phenomena. Implementing such a system would permit the investigation of wind loads on scale-model structures produced by non-stationary and/or non-neutral flows for comparison with traditional stationary, neutrally stratified boundary layer wind loading assumptions. This capability would also permit the physical study of nonstationary fluid-structure interaction, flow-induced motions and other bluff-body aerodynamic effects, and provide reproducible data that informs development and validation of CFD simulations.

Given these requirements, a large 2D multi-fan system composed of 319 individually controlled high-performance shrouded propeller assemblies driven by 800 Watt brushless DC motors with electronic speed controllers was designed and fabricated at the University of Florida (UF) Experimental Facility in the NSF Natural Hazards Engineering Research Infrastructure (NHERI) program. This configuration yields high-resolution flow control and provides users with many degrees-of-freedom to produce rapid instantaneous velocity changes as well as generate profile shapes that deviate from traditional neutral boundary layer profiles naturally grown over grid roughness. The ultimate goal for this flow control system is to reproduce the relevant characteristics of time-varying non-synoptic flow fields either as-measured in-situ or modeled / dreamed up by any one among a nation of potential users of this shared-use facility. At EMI we will present the development, validation, and capabilities of this new system, and present a host of potential applications that will enable new discoveries in both fundamental experimental fluids simulation and applied outcomes to achieve more hazard-resilient communities.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Micromechanics of Cementitious Composites with X-Ray Tomography and Diffraction

Author(s): *Ryan Hurley, *Johns Hopkins University*; Darren Pagan, *The Pennsylvania State University*; Eric Herbold, *Lawrence Livermore National Laboratory*; Chongpu Zhai, *Xi'an Jiaotong University*;

Micromechanics theories such as Mori-Tanaka's approximation and Herve-Zaoui's layered-inclusion approximation have been used extensively to predict homogenized stiffness, inclusion stresses, and matrix strains in various composites. However, while these theories accurately predict homogenized properties of many composites, the accuracy of their predictions of stresses and strains within individual phases of cementitious composites has not been assessed with experimental measurements. Here, we therefore use in-situ X-ray tomography, 3D X-ray diffraction, and digital volume correlation to evaluate homogenized stiffness, inclusion stresses, and matrix strains in two cementitious composites. We compare measurements with predictions of Mori-Tanaka's mean-field approximation and Herve-Zaoui's layered-inclusion approximation. We provide some of the first direct support that these micromechanics theories can indeed accurately predict both homogenized sample stiffness and individual phase responses. For samples in which measurements deviate from theory, we further show how to use measurements and theory together to infer properties (or damage) of specific phases. Finally, we discuss new scanning 3D X-ray diffraction measurements performed with the goal of measuring stress fields within inclusions to shed light on the interfacial interaction of inclusions with the surrounding matrix.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Vibration Mitigation Using an Inerter-Based Isolation System

Author(s): *S. Sima Abolghasemi, *University of Tennessee*; Nicholas Wierschem, *University of Tennessee*; J. Brent Knight, *NASA Marshall Space Flight Center*,

Extreme dynamic environments can result in the failure of structures and equipment connected to loading sources. To mitigate the effects of these environments, isolation systems can be used. These isolation systems typically feature low-stiffness connections. In recent years, inerters have been studied as a part of different structural control devices. The inerter is attractive for many structural control methods because it can produce large mass effects despite having a small physical mass through the transformation of translational motion to the rotational motion of a flywheel. While inerters have been considered in structural control, studies on their inclusion in isolation systems are more limited. Furthermore, experimental studies of isolation systems featuring inerters, particularly considering extreme broadband events, is even more limited. This project seeks to study the ability of the addition of an inerter to improve the dynamic performance of isolation systems compared to systems without inerters when considering a random vibration environment. Numerical models of multiple configurations of isolation systems featuring inerters were investigated and one configuration was fabricated and experimentally tested on a shake table. As a simplification to better isolate the effects of the inerter in this work, these numerical and experimental dynamic models were designed to respond only vertically. The results of this study demonstrate that the inerter, with even a small physical mass, can have a large impact on the dynamic properties of an isolated system. These effects include reduced displacements and a shift in the natural frequency of the isolated system that can be achieved without reducing the stiffness of the isolator. Furthermore, the nonlinearities intrinsic to the inerter, mainly backlash, were shown to improve the experimental high-frequency performance of the inerter relative to what is shown in linear numerical models. The strong performance of the inerter in simplified isolation systems observed during this work motivates future studies of inerters in isolation systems designed to mitigate vibration effects in multiple directions and studies on isolation systems with inerters in different application domains.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: A Homogenization-Based Constitutive Model for Unsaturated Clay Rocks with Saturation-Dependent Anisotropy

Author(s): *Sabrina C.Y. Ip, *Stanford University*; Ronaldo Borja, *Stanford University*;

Many clay rocks have distinct bedding planes that give rise to inherent anisotropy in their mechanical properties. Under partially saturated conditions, the mechanical properties can evolve with the degree of saturation, often with higher stiffness and strength after drying. In some clay rocks, the effect of saturation on the bedding normal and bedding parallel directions also differ, resulting in saturation-dependent anisotropy. The cause of saturation-dependent anisotropy in clay rocks has been attributed mainly to the clay particles. The clay aggregates stiffen during drying, but simultaneously, they shrink and form desiccation fractures which soften the material. The competition between these two mechanisms can contribute to changes in stiffness which may act more significantly in certain directions. Few studies have accounted for clay rock microstructure when modeling the behavior of these clay rocks. In this study, we present a constitutive model based on the microstructure of clay rocks, including the presence of clay platelets, micro- and macro-pores and inclusions. The elasticity tensor at the macro-scale is obtained by three homogenization steps. The model was calibrated using experimental data to demonstrate its capability in capturing stiffness anisotropy at various levels of saturation. Through numerical simulations, we demonstrate the role of microstructure on mechanical anisotropy and the mechanical behavior of clay rocks. Overall, the results offer new insight into the effects of microstructure on the behavior of partially saturated clay rocks.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Use of Machine Learning-Based Neural Network Models to Account for Soil-Foundation-Structure Interaction Effects in Real Time Hybrid Simulations

Author(s): *Safwan Al-Subaihawi, *Lehigh University*; Thomas Marullo, *Lehigh University*; James Ricles, *Lehigh University*; Muhannad Suleiman, *Lehigh University*; Spencer Quiel, *Lehigh University*;

Real-time hybrid simulation (RTHS) includes analytical and experimental substructures of a system, where the former are components of the system that are numerically modeled using computational models. Components of the system that cannot be accurately modeled numerically are modeled physically in the laboratory as test specimens. Including soil-foundation components in a RTHS presents numerous barriers. These include incorporating these components into the analytical substructure, requiring a fine discretized mesh of nonlinear continuum finite elements to capture the nonlinearities and strain field in the soil-foundation system. This approach results in too many degrees of freedom in the analytical substructure, and when combined with the nonlinear elements make it CPU intensive. Consequently, the simulation cannot be done in real time. To overcome this barrier, in the presented study a neural network model is used to model the soil-foundation of the system. The neural network model enables the number of degrees of freedom to be significantly reduced while accounting for the nonlinear dynamic characteristics of the soil-foundation components, making it possible to perform true RTHS with soil-foundation-structure interaction. In the approach machine learning is used to train the network to a prescribed accuracy.

A neural network to model soil-foundation components are combined with a 2000 degree of freedom nonlinear finite element model of a 40-story building to create an analytical substructure. The building included outriggers with nonlinear viscous dampers located at the 20th, 30th, and 40th stories in the outrigger system. Some of the dampers are modeled physically in the experimental substructure while eleven remaining ones are included in the analytical substructure using an explicit nonlinear Maxwell model combined with on-line real-time updating to enhance the damper model accuracy. A series of RTHS of the building subjected to severe windstorms were performed. In the RTHS several parameters associated with the training of the neural network are systemically varied to assess the effect on the RTHS results.

The presentation will describe the approach and discuss the RTHS results. The results are compared to a numerical simulation baseline solution in which the complete system that includes the soil-foundation and structural components are numerically modeled. They show that neural networks enable the simulation to be accurately performed in real time. In addition, the RTHS results show that soil-foundation-interaction can have a significant effect on the building's response, indicating that such interaction should be included in RTHS of systems with soil-foundation components.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Assessment of Offshore Wind Turbine Piled Foundation Behavior Using Hybrid Simulation

Author(s): *Safwan Al-Subaihawi, *Lehigh University*; Qasim Abu-Kassab, *Lehigh University*; Sudharsan Kalidoss, *Lehigh University*; James Ricles, *Lehigh University*; Muhannad Suleiman, *Lehigh University*; Richard Sause, *Lehigh University*; Arindam Banerjee, *Lehigh University*; Justin Jaworski, *Lehigh University*; Kevin Wyckoff, *Lehigh University*; Liam Magargal, *Lehigh University*; Tommy Marullo, *Lehigh University*;

Hybrid Simulation (HS) divides the structural system into an analytical substructure with a well-known analytical model and experimental substructure modeled physically in the laboratory. This study extends HS to offshore wind turbines (OWTs) to investigate the behavior of their piled foundation under severe operational conditions. The OWT numerical simulation tool OpenFAST enables high fidelity fluid dynamics modeling with a small computational cost. In this study, the OpenFAST modeling capabilities are integrated into a HS framework where an OWT embedded foundation and surrounding soil are modeled physically in a soil box in the laboratory. The analytical model of the wind turbine above the seabed and the piled foundation beneath are coupled via their interface common degrees of freedom. The displacement compatibility between the two substructures is enforced using mechanical actuators attached to the top of the pile in the soil box. A simulation coordinator was developed where for each time step it determines the hydrodynamic and aeroelastic loads acting on the OWT, uses the forces to integrate the equations of motion, issues the ensuing displacement commands to the two substructures, and receives their feedback restoring forces.

The integrated HS framework will enable assessment of the complex short and long-term behavior of piled OWT foundations. The soil profile below the turbine based on site-specific investigations can be replicated in the soil box; thus the HS framework in this study offers a versatile method to evaluate the performance of OWTs at different geographical locations under realistic loading conditions in the field.

The presentation will discuss the formulation of the HS framework. This includes the unconditionally stable integration algorithms to integrate the equations of motion, solution techniques used to enforce displacement compatibility at the interface between the OWT tower finite element model and the turbine blades' aeroelastic model, and numerical stability associated with the interaction between the integration algorithm and the hydrodynamic load computation.

The presentation will include results from a real-time HS of a 5 Mega-Watt OWT subjected to operational conditions. The OWT was modeled analytically while its piled foundation and the surrounding soil were modeled physically in a soil box. The HS results are shown to capture the behavior of an OWT subjected to hydrodynamic and aeroelastic loading while accounting for soil-foundation-structure interaction effects.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Adaptive Wavelet-Enhanced Cohesive Zone Phase-Field FE Model for Crack Evolution in Piezoelectric Composites

Author(s): *Saikat Dan, *Johns Hopkins University*; Preetam Tarafder, *Johns Hopkins University*; Somnath Ghosh, *Johns Hopkins University*;

A coupled electromechanical finite deformation phase-field model for crack initiation and propagation in nonuniform piezo composite microstructures is developed. Fracture in these microstructures is driven by complex mechanical and electrical mechanisms that lead to strong nonlinearities in the material response. Microstructural descriptors such as fiber volume fractions and the two-point correlation function of their spatial distribution are used to fully characterize the microstructures [1]. A novel Gibbs free energy density function that accommodates the anisotropy of the piezoelectric material and tension-compression asymmetry of damage is proposed. The phase-field model is enhanced with cohesive traction-separation laws at the material interfaces derived from a cohesive potential function [2]. To improve computational efficiency of the coupled electromechanical-phase field FE solver, an adaptive wavelet-enhanced hierarchical framework based on a phase-field error indicator is used [3]. Numerical examples involving different failure mechanisms in the piezo composite microstructures are simulated for examining the performance of the proposed model. The effect of damage on the evolution of the electric field in the microstructures is also studied.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Modeling of Damage and Failure in Heterogeneous Brittle Solids Under High-Rate Compressive Loading

Author(s): *Sakshi Braroo, *Johns Hopkins University*; K.T. Ramesh, *Johns Hopkins University*;

Brittle solids, such as geological media, exoskeletons and endoskeletons of organisms, and materials of protective structures, are ubiquitous in nature and engineering. Most brittle solids have heterogeneous microstructures—being comprised of a polycrystalline or amorphous matrix interspersed with microscale defects such as cracks, precipitates, grain boundaries, and pores. These defects are often initiators of micro-cracking which results in damage-induced softening and non-linearity in stress-strain response. The behavior under dynamic loading is particularly sensitive to the initial defect population because of enhanced microcrack nucleation as compared to crack growth. The stress intensity factors (SIFs) at microcrack tips are also very sensitive to the microstructure, i.e., the size, orientation, and three-dimensional spatial distribution of nearby inhomogeneities. A modelling approach that captures the influence of a crack's local environment should result in improved estimates of crack growth and ensuing damage. Since the peak stress achieved in high-rate compression of brittle solids is the result of the competition between softening due to damage and the rate-effect, estimates of the dynamic compressive strength can also be improved.

To model microcracking under compressive loading, we employ the sliding-crack framework where defects are treated as cracks that can slide and generate wing-cracks. Further, we consider the effect of the heterogeneities in the local environment of a defect by computing its interactions with the neighbors. A damage model which accounts for the statistics of size, spacing and orientation of the cracks is employed and is used to predict an anisotropic increment in compliance at each time step. We estimate the effect of increasing compliance on crack growth by computing the local stress of the defect embedded in an elliptical inclusion of pristine material under a plane-strain setting. This stress is then modified by the effect of neighbors, and crack growth is computed at the next time step. In numerical experiments with unconfined uniaxial loading, we find that the local environment can significantly influence dynamic crack growth. This has implications on damage rate and compressive strength. We also study the competition of microstructural heterogeneity and rate effects on strength. By varying the microstructural attributes we can also make predictions about the heterogeneity of damage in a statistical sense.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Studying the Impact of Aging on Dynamic Response of Concrete

Author(s): *Sannidhya Ghosh, *University of Colorado Boulder*; Petros Sideris, *Texas A&M; University*; Mija Hubler, *University of Colorado Boulder*;

In dynamic performance analysis of existing and design of new reinforced concrete structures, the impact of aging considerations is neglected. This paper studies the effect of long-term creep of concrete under various aging durations on the loading rate or strain rate sensitivity and dynamic response of concrete structures. The rate sensitivity of compression strength and modulus of elasticity of concrete is studied on samples accelerated aged to 2.18 and 9.92 years. Samples are accelerated aged under the combined effect of heat and service load. Both sample sets were exposed to the same elevated temperature under a constant compression load of 27.5% of their 28-day strength for their respective required number of days. Once aged, they were loaded in compression until failure, under different strain rates representative of what a structure would experience in a seismic event. The paper finds that the compressive strength and modulus of elasticity of a younger concrete is more sensitive to strain rate as compared to older concrete and the younger concrete is much stronger and more elastic under higher strain rates than older concrete. The results also show that the Dynamic Impact Factor proposed by the CEB model (Comite Euro-International du Beton - Federation Internationale de la Precontrainte) is an overestimation of concrete strength amplification at high strain rates at older ages. This study provides insight on the effect of aging on the loading rate effect of concrete to better understand the dynamic response of aged concrete structures.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: The Effect of Urban Texture on Flood Hazards

Author(s): *Sarah Balaian, *University of California, Irvine*; Mohammad Javad Abdolhosseini Qomi, *University of California, Irvine*; Brett Sanders, *University of California, Irvine*;

Flood damages around the world have been increasing at a daunting rate, causing extreme socio-economic harm to entire communities. With the increase in urbanization and population growth, a framework for understanding the effects that the changing urban landscape has on natural conditions, such as flooding, has become crucial. While many different approaches to modeling urban floods exist, few consider the effects of spatial orientation and form of urban areas. With this work, we introduce a novel theory which correlates city morphology and urban flood behavior. To do so, we have generated a method of quantifying the density and spatial order of cities to understand its influence on flood hazards. The Mermin order parameter, commonly used in statistical and molecular science, is applied to characterize a city's spatial order, and urban density is characterized by a packing fraction. To study the effects of these parameters, thousands of artificial realizations of cities are automatically generated with differing values of urban density and spatial order. These artificial realizations are used instead of real city models because they allow for better control of morphology parameters and reduce the number of independent variables that could affect observed trends. Floods are simulated within these artificial cities using a fine-resolution hydrodynamic shallow-water model to observe the resulting flood behavior. Using basic hydrodynamic theory and dimensional analysis, a novel generalized theory is developed to understand the relation between these artificial cities and the flood heights they experience. Due to the generalized nature of this theory, it can be applied to real world situations in order to better understand a city's spatial order and predict the impact and behavior of potential floods. Future flood hazard mitigation and urban planning programs can implement these findings to account for effects of urban layout on flood levels. This study provides new opportunities for developing cities to implement more spatially conscious planning and design that will mitigate potential hazards and improve resilience.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: A Coarse-Grained Model for The Mechanical Behavior of Na-Montmorillonite Clay

Author(s): *Sarah Ghazanfari, *North Dakota State University*; H. M. Nasrullah Faisal, *North Dakota State University*; Kalpana S. Katti, *North Dakota State University*; Dinesh R. Katti, *North Dakota State University*; Wenjie Xia, *North Dakota State University*;

Sodium montmorillonite (Na-MMT) is one of the most commonly found swelling clay minerals that have diverse technological and engineering applications. The nanomechanical properties of this mineral have been extensively explored computationally utilizing molecular dynamics (MD) simulations to depict the molecular-level changes at different environmental conditions. As the environmentally found Na-MMT clays are generally sized within hundreds of nanometers, all-atomistic MD simulations of clays within this size range are challenging due to computational inefficiency. Atomistically informed modeling, a coarse-grained (CG) modeling technique can be employed to overcome the spatiotemporal limitation. The current study introduces a CG modeling strategy to develop a computationally efficient model of Na-MMT clay with a typical size over ~ 100 nm by shrinking the atomistic platelet thickness and reducing the number of center-layer atoms. Utilizing the "strain-energy conservation" approach, the developed CG model can well preserve in-plane tension, shear, and bending behaviors of atomistic counterparts. Remarkably, the CG tactoid model of Na-MMT, a hierarchical multilayer structure, can recreate the interlayer shear and adhesion, as well as d-spacing among the clay layers as of atomistic one to a good approximation, while gaining significantly improved computational speed (i.e., several thousand times faster than the atomistic one). Our study establishes the efficacy of the CG modeling framework, paving the way for bottom-up multiscale prediction of mechanical behaviors of clay minerals.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: In-Situ Micro-Mechanical Testing of 3-D Architected Porous Structure

Author(s): *Seo Young Ahn, *The University of Utah*; Brett Reeder, *Lawrence Berkeley National Laboratory*; Bozo Vazic, *The University of Utah*; Robert Wheeler, *USE Inc.*; Pania Newell, *The University of Utah*;

Porous materials are found in a wide range of settings in both nature and man-made structures such as concrete, bones, and plants. Pores in such structures are frequently heterogeneous, containing various shapes ranging from perfectly spherical to irregular sphere-like shapes and multiple sizes from millimeter to nanometer scale. When these porous structures are mechanically loaded, the pores direct the stress fields around their free surfaces, altering their mechanical properties. To better understand the fundamentals and the roles of the pores, the present study focuses on investigating the micromechanical responses of isolated pores in different shapes and sizes. We first design these structures and then print them by using a Nanoscribe 3-D printer. In this study, we investigated the role of porosity, pore shapes and sizes, and pore distribution by conducting series of micro-pillar compression tests in Scanning Electron Microscopy (SEM). The results indicate that porosity as the first-order parameter has the most significant impact on the mechanical response of these micro-architected materials. We also observed that higher-order parameters - pore geometry, distribution, and size effect - influence Young's modulus and residual plastic strain of the porous structure. The horizontally aligned spheroid pore showed a decreasing trend of Young's modulus and increased residual plastic strain compared to the spherical pore, where both structures consisted of the same dimension and porosity. These results highlight how porous materials can be tailored to achieve desired mechanical properties based on the engineering applications of interest.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: GA-Based Offshore Helideck Design with Unity Check

Author(s): *Seung-Hyun Ha, *Korea Maritime and Ocean University*;

A helideck is an essential structure in offshore platforms for the transportation between the land and offshore sites, and it should be carefully designed and installed for the operation of the offshore structure. Unlike the automobile industry, offshore structures are not mass-produced structures and they are usually assembled from the ready-made products of structural steel. In order to consider the manufacturability, the design variable sets were efficiently limited to the standard products in the American Institute of Steel Construction (AISC) code and the cross-section of each structural member was optimized using a genetic algorithm. In addition, due to the conservative nature of the offshore industry, structural unity values were precisely checked as a constraint during the optimization. To verify the optimal design, both linear and nonlinear buckling analyses were tested for the dynamic safety of the helideck.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Numerical Modeling of Phase Transformation Induced Material Fracture and Crack Propagation

Author(s): FNU Sindhusuta, *University of Illinois Chicago*; *Sheng-Wei Chi, *University of Illinois Chicago*; Craig Foster, *University of Illinois Chicago*;

The physical mechanisms triggering intermediate-depth earthquakes remain a puzzle for the scientific community. However, many studies discussed phase transformation being the primary mechanism behind the generation of these hazardous earthquakes. The objective of this study is to develop a numerical model for the simulation of phase transformation-induced failure in geo-materials. The materials of interest include different groups of minerals found in the earth crust such as granulite, eclogite, and olivine. To model the phase transformation behavior, a thermo-mechanical model approach has been taken. A thermodynamically consistent multiscale model, based on Mahnken et al, 2015, has been developed to capture the evolution of phase transformation taking place in such materials under different pressure and temperature conditions. In the model, each material point of the macroscale consists of polycrystals at the mesoscale level which further consists of various phases on the microscopic level. Grain orientation at mesoscale and crystal structure of phases at microscale has also been included in the model. The model also considers visco-plasticity and heat conduction and uses a volume averaging scheme to link different length scales. In the numerical scheme, solution of coupled non-linear equations for the evolution of visco-plasticity and phase transformation has been obtained by a staggered algorithm. Implementation of the abovementioned thermomechanical model has been done using a user subroutine in a commercial finite element software ABAQUS. For the phase transformation model, a convergence study has also been done for different numerical methods. Validation of the model has been done using data for phase transformation from austenite to bainite and for olivine to spinel. For the simulation of microstructural failure in the material, the extended finite element method has been used with the above-mentioned model. The effect of orientation has also been studied on the phase transformation and crack propagation for the olivine to spinel transformation. The model will be further validated with the data obtained from the laboratory experiments done on the materials of interest to investigate the phase transformation-induced instability leading to the formation of macrocracks. For further study, the model will eventually be upscaled to simulate the fault generation at the macroscale (kilometer-scale) and investigate the role of phase transformation in the formation of large-scale cracks or faults.

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: An Investigation on the Effects of Translating Tornadoes on Wind Loading Using a Potential Flow Model

Author(s): *Shuan Huo, *University of Birmingham*; Jin Wang, *Western University*; Fred Haan, *Calvin University*; Gregory Kopp, *University of Birmingham / Western University*; Mark Sterling, *University of Birmingham*;

This study explores the effects of tornado translation on pressure and overall force experienced by an airfoil subjected to tornado loading. A thin symmetrical airfoil was employed to examine the affects that tornado movements may have on a body. The panel method was used to compute the flow around the airfoil and an idealized tornado is represented using a moving vortex via potential flow with the relevant pressure and forces obtained using unsteady potential flow theory. The configuration of the simulation is a 2D plan view of the ground plane, where the airfoil is positioned at a distance from the translating path of the vortex. The vortex translates in the direction parallel to the airfoil where the induced lift force on the airfoil in this context can be considered to be analogous to the side force of a 2D body. Analysis showed that the effect of tornado translation on the pressure coefficient at a particular point on the surface is significant and dependent on the location of the tornado; the maximum total pressure at the point was found to increase by up to 20% when the normalised translating velocity was 10% and increases up to 60% when the normalised translating velocity is 30% of the tangential velocity. The increase in airfoil thickness and relative location of the vortex was also shown to have a significant effect on the overall force. However, the overall force was found to be insensitive to the translation speed of the tornado due to the changes in pressure on either side of the airfoil effectively cancelling each other out. Further investigations also showed that the relative inflow and outflow angle is the primary factor affecting the lift changes on the airfoil and demonstrated that the maximum forces on a body subjected to a moving tornado can be predicted using uniform flow providing that the appropriate range of inflow angles are known. Additionally, the database of National Oceanic and Atmospheric Administration (NOAA) was analysed and showed that the normalised translation speed of the recorded tornadoes across the EF scales, appears to vary from 0.25 to 0.37, with an average of 0.32 (~18.8m/s).

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Finite Strain Ductile Phase Field Fracture Modeling of Steel Structures

Author(s): *Sina Abrari Vajari, *Stanford University*; Matthias Neuner, *Stanford University*; Christian Linder, *Stanford University*;

Computational fracture modeling of steel structures has recently gained much attention, and among many methods the phase field formulation due to its innate ability to predict cracks without a need for ad hoc criteria has proven to be a worthy substitute for costly experimental tests.

However, unlike the well-established brittle phase field formulation, there is not an agreed upon mechanism in relating plasticity and fracture especially in the case of large plastic deformations usually occurring in steel structures.

Furthermore, in contrast to experimental data indicating a relation between ductile fracture evolution and a combination of plastic strain and the level of stress triaxiality, most ductile phase field simulations are limited to two-dimensional cases where these effects are not accounted for. Therefore, this work aims at developing a phase field model for rate-independent ductile fracture of elasto-plastic steels in quasi-static settings.

Accordingly, ductile behavior of steel structures experiencing large amount of plastic deformation before fracture is investigated and all the governing equations are derived following a consistent variational formulation. To accurately capture involved behaviors such as hardening or necking before fracture, a finite strain plasticity model based on the multiplicative decomposition of the deformation gradient is combined with the phase field crack equations.

Moreover, since the evolution of fracture in steels is mostly due to the mechanism of microvoid growth and coalescence, different approaches to use microvoid growth criteria as crack propagation techniques on the context of the phase field fracture model are investigated. Different mechanisms such as plastic strain energy driving the crack and softening of the material with evolution of fracture are as well introduced and compared.

Finally, the simulations results are validated by comparing them to multiple experimental results.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Multifidelity Active Learning for the Failure Analysis of a Nuclear Fuel

Author(s): *Som Dhulipala, *Idaho National Laboratory*; Wen Jiang, *Idaho National Laboratory*; Benjamin Spencer, *Idaho National Laboratory*; Jason Hales, *Idaho National Laboratory*; Michael Shields, *Johns Hopkins University*;

The TRISO nuclear fuel is a robust fuel which has been proposed to be used in several advanced reactor concepts such as microreactors. Given the importance of preventing fission products release from the nuclear fuel, accurate high-fidelity simulations of TRISO models are required for understanding its failure behavior. However, not only is the computational model of TRISO expensive, but also, its fuel parameters can be uncertain, requiring a statistical characterization of failure. To accelerate the statistical failure analysis of TRISO, we use a multifidelity modeling strategy with active learning. Specifically, we replace the expensive TRISO model with a low-fidelity model and train a Gaussian Process to learn when a call to the expensive model is required during the statistical failure analysis. We explore different options for the low-fidelity model which include data-driven and physics-based models. Overall, across several TRISO models, the multifidelity active learning algorithm accurately predicts their failure probabilities irrespective of the choice of the low-fidelity model. However, we noticed that there are differences in the number of times the high-fidelity model is called depending upon the quality of the low-fidelity model. Moreover, while the physics-based multifidelity strategy call the high-fidelity model fewer number of times, the data-driven multifidelity strategy requires the least computational time due to instantaneous low-fidelity predictions.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Machine Learning-Enabled Data-Driven Methods in Hierarchical Constitutive and Damage Modeling of Metals and Composites

Author(s): *Somnath Ghosh, *Johns Hopkins University*; Shravan Kotha, *Johns Hopkins University*; George Weber, *Johns Hopkins University*; Xiaofan Zhang, *Johns Hopkins University*;

This talk will discuss the implementation of Machine Learning algorithms in a “parametric upscaling framework” for hierarchical multiscale modeling of deformation and damage in a wide variety of materials. Parametrically upscaled constitutive models (PUCM) are thermodynamically consistent, macroscopic constitutive models that bridge spatial scales through the explicit representation of microstructural descriptors in equations that constitute these models. Coefficients in PUCM equations are explicit functions of Representative Aggregated Microstructural Parameters or (RAMPs), representing statistical distributions of morphological and crystallographic descriptors of the microstructure. Machine learning algorithms, including symbolic regression and ANN, are used to create these functional forms within the window of constitutive coefficients in the equations. Major advantages of the framework are:

- i. Explicit representation of microstructural descriptors, specifically RAMPs, in macroscopic constitutive relations is an attribute with important implications in structure-material design.
- ii. Very high efficiency with good accuracy of multiscale solutions, is a requirement for most data-driven design algorithms.

The talk will be conducted in three segments, viz. (i) Parametrically upscaled constitutive models or PUCMs for deformation and fatigue in metals and alloys, (ii) Parametrically upscaled continuum damage mechanics or PUCDM models for deformation and damage in composites and (iii) data-driven methods for fatigue modeling. We will conclude with a general assessment of the high efficiency and accuracy of these methods.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: On the Effects of Fabric on the Instability Surface of Granular Materials

Author(s): *Srinivas Vivek Bokkisa, *Georgia Institute of Technology*; Jorge Macedo, *Georgia Institute of Technology*; Alexandros Petalas, *Durham University*; Chloé Arson, *Georgia Institute of Technology*;

Experimental studies have demonstrated that the onset of instability (e.g., liquefaction) in granular materials is dependent on the initial state (void ratio and confinement), fabric, and rotation of principal stresses. Constitutive models developed under the critical state theory (CST) have traditionally been used to investigate the onset of instabilities under various loading paths. However, these models fall short in incorporating fabric effects or anisotropy conditions that can be relevant under realistic field conditions. In this study, a constitutive model formulated under the Anisotropic Critical State Theory (ACST), SANISAND-F, is used to study the onset of instability in granular materials subjected to undrained loading, incorporating the effects of fabric, rotation of principal stresses, and intermediate stress. Specifically, an analytical criterion to predict the onset of instability is derived. The criterion predicts the plastic modulus and the stress ratio at the point of instability. The derived analytical criterion is a function of constitutive parameters, state, intermediate stress, and a fabric anisotropy variable, which couples the effects of fabric and loading direction. The instability stress ratio corresponding to different Lode angles can be represented as a surface that delineates the stable stress states from the collapsible stress states in the three-dimensional stress space. Interestingly, the instability surface constructed using the derived criteria is not hexagonally symmetrical with respect to the origin in the stress space, which is in contrast to typical results based on CST constitutive models. This is because, within the ACST framework, the relative effects of soil fabric and the loading direction are taken into account. Thus, the constitutive surfaces (i.e., bounding, critical, and dilatancy surfaces) are no longer homologous, resulting in a hexagonally asymmetrical instability surface. Therefore, the resistance to flow liquefaction (represented as the distance between the origin and the instability surface) changes as a function of the Lode angle, stress direction, and fabric. Another interesting observation is that the increase of softening response of granular material with the increase in angle between the principal stress axes and the global axes in the shear plane, commonly reported in hollow cylinder tests, can be reversed for high lode angles, depending on the interaction between the fabric and stress tensors. This finding needs to be further explored experimentally.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Subset Simulation-Based Stratified Samplings for Rare Event Simulation in Wind Engineering

Author(s): *Srinivasan Arunachalam, *University of Michigan*; Seymour Spence, *University of Michigan*;

Modern performance-based wind design (PBWD) frameworks require the simulation of extreme responses to evaluate safety against a suite of limit states of interest. The sampling of large intensity wind events for this purpose cannot be efficiently performed using Monte Carlo simulation (MCS) as the failure probabilities can be extremely low. Recent work on the use of stratified-sampling-based MCS for reliability estimation in PBWD reveals the effectiveness of partitioning the sample space through dividing the wind speed range into mutually exclusive and collectively exhaustive intervals. In this approach, MCS is carried out within each stratum to obtain conditional failure probability estimates which can then be collated to simultaneously estimate multiple failure probabilities. It should be observed that this scheme can only be implemented when the wind speed is an input random variable whose cumulative distribution function (CDF) is analytically known. However, in certain applications, such as full hurricane event simulation, the wind speed itself is an output of the hazard model, rendering the aforementioned scheme inapplicable. To this end, this study focuses on the adoption of modified subset simulation to generate samples with increasing wind speeds for integration with stratified sampling. Specifically, the proposed simulation scheme generates realizations within each stratum as Markov chain samples emerging from multiple chains and is seamlessly integrated into the framework of stratified-sampling-based failure probability estimation. The statistical properties of the resulting conditional and overall failure probability estimators are carefully studied with due regard to the intra-stratum as well inter-stratum sample correlations. In spite of this dependence, it is shown that the overall estimator is unbiased, and consistent. The efficiency of the method and its robustness to the number of uncertain parameters is illustrated on a 45-story reinforced concrete archetype building to estimate failure probabilities associated with multiple extreme nonlinear responses.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Efficient estimation of wind-induced nonlinear responses with prescribed mean recurrence intervals through limited suites of wind records

Author(s): *Srinivasan Arunachalam, *University of Michigan*; Seymour Spence, *University of Michigan*;

A crucial requirement of efficient frameworks to realize performance-based wind design is to overcome the computational barrier in performing nonlinear analyses to estimate peak inelastic structural responses. In practice, the problem is exacerbated due to the extremely long duration of wind loads that require consideration, typically in the order of several hours. More specifically, for the purpose of design, potentially nonlinear responses with prescribed mean recurrence intervals (MRIs) are of interest, which are ideally obtained through statistical analysis of thousands of dynamic nonlinear analyses driven by wind load records over a wide range of wind intensities. To alleviate this problem, in this study, an intuitive methodology is proposed and validated. The approach is based on first generating the annual exceedance probability curve (AEPC) of key peak elastic responses, e.g., base moments and shears (including resultants), through direct modal integration. From the elastic AEPC, a discrete set of wind records is identified for each MRI of interest and a complete nonlinear analysis is performed and the required nonlinear responses are evaluated. The expected value of these responses is investigated as an estimate of the T-year nonlinear response. The efficiency and validity of the approach are carefully investigated through application to a full scale 45-story reinforced concrete archetype building located in New York City, NY. A comprehensive comparison between estimates of responses, such as inelastic strains, ductility demands, and peak/residual drifts, with prescribed MRIs obtained using the proposed approach and those obtained from direct stochastic simulation is carried out. To investigate the resulting approximation in depth, a full description of hurricane hazard is considered that is based on the simulation of the entire evolution of storm tracks characterized by time-varying mean wind speed and direction at the building site. In order to efficiently simulate tracks characterized by large wind intensities, particularly to estimate large MRI responses, a simulation scheme combining subset simulation and stratified sampling is employed. The complex aerodynamic response of the building is captured through the adoption of a recently introduced methodology that fuses building-specific wind tunnel data with simulated hurricane tracks to produce multivariate non-stationary/-straight/-Gaussian stochastic wind loads.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Energy-Based Fracture Mechanics of 2D Lattice Materials

Author(s): Shengzhi Luan, *Johns Hopkins University*; Enze Chen, *Johns Hopkins University*; *Stavros Gaitanaros, *Johns Hopkins University*;

This work focuses on the fracture mechanics of lightweight 2D lattice materials made of a brittle parent solid. Different from the monolithic solids, where the stress and displacement fields are described by the stress intensity factors in the traditional fracture mechanics, the complex microstructure of the lattice materials can strongly alter the stress behavior ahead of an existing crack as well as its propagation path under external loads, leading to difficulties in defining the corresponding fields. Here we propose a global energy-based method that combines experiments, modeling, and theory in order to define and predict the fracture properties of lattice materials. Our framework starts from investigating the crack nucleation and propagation path, and thus establishes the crack profiles under certain macroscopic loads. The energy release rate for the lattice materials is then formulated as a function of loading condition, crack length and base material properties. The fracture energy is measured experimentally using tensile tests to failure of cracked specimens with various crack lengths. We then employ Griffith's energy balance criterion to predict macroscopic failure stress and estimate the fracture toughness of lattice materials. Two typical in-plane isotropic lattices, triangular lattice and honeycomb, are employed to better illustrate the methodology. Under uniaxial tensile loading condition, the stretching dominated triangular lattice performs a horizontal crack propagation path similar to the monolithic solids, while the bending dominated honeycomb exhibits an inclined crack propagation path. The crack profile in triangular lattice is fully contributed by crack opening, while the crack profile in honeycomb is a combination of crack opening and crack sliding. The failure of the critical ligament ahead of the crack in triangular lattice is mainly caused by tension, while the failure of the critical ligament ahead of the crack in honeycomb is overwhelmingly generated by bending. This energy-based methodology gives a favorable prediction of the macroscopic critical stress and remains accurate even for small cracks. The fracture toughness obtained by this framework shows a reasonable relationship with the relative density of the lattice as well.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: A Stability Condition for Perfectly-Matched-Layers in 2D Elastic Wave Propagation Simulations

Author(s): *Stijn Francois, *LU Leuven*; Heedong Goh, *City University of New York*; Loukas Kallivokas, *The University of Texas at Austin*;

In the numerical modeling of elastic wave propagation in unbounded domains, Perfectly-Matched-Layers (PMLs) are used as wave-absorptive buffers along truncation boundaries in order to reduce the unbounded physical domain to a finite computational region. Various implementations of PMLs, including the standard PML and the Complex-Frequency-Shifted (CFS-PML), suffer from instabilities associated with long-time simulations. In time-domain simulations, the instabilities take the form of exponential growth that appears to originate suddenly from within the PML buffer, and, invariably, result in the pollution of the wave response within the physical domain. We discuss a recently developed stability condition, based on a conjecture that has been verified numerically. As it is shown, the instabilities are due to (backward-)propagating modes characterized by incoming energy, and their presence is tightly connected to the parameterization of the PML's frequency-dependent mapping function. We demonstrate the existence of the undesirable modes using the associated eigenvalue problems, both in the frequency and wavenumber domain. We further show that the instabilities associated with the standard PML can never be avoided, yet their onset can be delayed, while for the CFS-PML satisfaction of the stability condition completely eliminates the instabilities.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Bi-Fidelity Neural Network Operators for Uncertain Systems

Author(s): *Subhayan De, *University of Colorado Boulder*; Malik Hassanaly, *National Renewable Energy Laboratory*; Matthew Reynolds, *National Renewable Energy Laboratory*; Ryan King, *National Renewable Energy Laboratory*; Alireza Doostan, *University of Colorado Boulder*;

Neural network operators, such as the Deep Operator Network (DeepONet), can approximate solution operators associated with governing equations of physical systems independent of the finite element mesh used to generate the training dataset. To accurately train the DeepONets, however, a large dataset of high-fidelity simulations for multiple realizations of the uncertainty is often required. To alleviate this issue, in this study, we combine a large training dataset from low-fidelity models that are faster to simulate (but are less accurate) with a small dataset from accurate (but expensive) high-fidelity models. Numerical examples of heat transfer in a thin plate with uncertain material property and internal heat source, and power generated in a utility-scale wind farm with uncertain wind speed and direction are used to show the efficacy of the proposed bi-fidelity DeepONets that can produce up to one order of magnitude smaller validation errors compared to DeepONets trained only using high-fidelity datasets generated with similar computational efforts.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Experimental Evaluation of Damage Growth and its Relationship with Stress State for Ductile Fracture in Stainless Steel

Author(s): *Surajit Dey, *North Dakota State University*; Ravi Yellavajjala, *North Dakota State University*;

Ductile fracture is the fracture initiating mechanism in several engineering metals including stainless steel, copper, titanium, aluminum, etc. At high-stress triaxialities (ratio between hydrostatic stress and von Mises stress) ductile fracture is driven by the coalescence of dilated microvoids over a critical volume of the material that originated from pre-existing heterogeneities or material defects. Several existing models capture the strain corresponding to the ductile fracture initiation by incorporating damage parameters that track the growth of microvoids as a function of the state of stress and plastic strain. However, it is still not clear if the developed models are capturing the underlying phenomenon or mapping the fracture initiation strain to functions of stress and strain states and model parameters. This study aims to bridge the gap between the ductile fracture phenomenon and the prediction models by combining microscopy studies on fractographs and statistical analyses.

The objective of this study is to investigate the relationship between experimentally inferred void volume and state of stress and strain characterized by stress triaxiality and effective plastic strain. To this end, uniaxial tensile tests were conducted on 17-4PH stainless steel axisymmetrically notched specimens to achieve stress triaxialities ranging between 0.36 and 1.53. The fracture surfaces of the failed specimens were studied using a 4K Digital microscope. The fracture surface between the center and periphery of the test specimen cross-sections was divided into three distinct regions and high-resolution fractographs were extracted for each of the locations. Two $75\mu\text{m} \times 75\mu\text{m}$ rectangular areas were randomly drawn on the micrograph of each of the distinct regions and 25 micro void areas were sampled from each of the rectangular areas. The present study is based on the assumption that the microvoids at coalescence are approximately spherical and each fracture surface contains nearly one-half of the spherical void on its fracture surface. To extract the stress-strain fields, non-linear finite element analysis was performed on the notched specimens and the variation of stress triaxiality and equivalent plastic strain across the cross-section of the fracture surface was extracted. Furthermore, the evolution of stress triaxiality throughout the fracture process was captured by computing equivalent plastic strain-averaged stress triaxiality for the test specimens. The experimental relationship between micro void volume, stress triaxiality, and equivalent plastic strain will be discussed in the talk.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Topology Optimization of Steel Fiber-Reinforced Concrete Ribbed Floors with a Predefined Load-Bearing Capacity

Author(s): *Tobias Barbier, *KU Leuven*; Geert Lombaert, *KU Leuven*; Mattias Schevenels, *KU Leuven*;

In engineering practice, a structure is typically designed to support a certain load without collapsing, at the lowest possible material cost. In this study, we propose a methodology for the topology optimization of three-dimensional ribbed floor elements made of steel fiber-reinforced concrete.

The optimization problem is formulated as a minimal weight problem with a constraint on the structure's load-bearing capacity, which should be higher than or equal to the design load. We use an optimization strategy suggested by Barbier et al. [1], which uses a simplified damage model to compute a structure's damage distribution in only one step. The accuracy of the simplified damage model is controlled by occasional nonlinear simulations at regular intervals during the optimization.

In this study, ribbed floors consist of two distinct horizontal layers. The top layer of the floor is a horizontal slab with constant thickness. Underneath this slab is a layer of freeform ribs with a constant height, which are obtained by extruding a two-dimensional grid of design variables along the vertical direction. The finite element simulation of the structure is performed on a three-dimensional grid of cubic elements, using the Multigrid preconditioned Conjugate Gradient method [2] to increase computational efficiency. Tests show that the methodology leads to feasible optimized designs.

References:

[1] Barbier T, Shakour E, Sigmund O, Lombaert G, Schevenels M (2021). Topology optimization of damage-resistant structures with a predefined load-bearing capacity. *Int J Numer Methods Eng.*, 1-32. doi: 10.1002/nme.6891

[2] Amir O, Aage N, & Lazarov B S (2014). On multigrid-CG for efficient topology optimization. *Structural and Multidisciplinary Optimization*, 49(5), 815-829.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: SPH-DEM Modeling of Flow Liquefaction

Author(s): *Usama El Shamy, *Southern Methodist University*, Saman Sizkow, *Southern Methodist University*,

Liquefaction-induced flow failure represents an important mechanism that could lead to massive ground deformations. The National Research Council in 1985, defined four specific mechanisms of flow liquefaction. One of those mechanisms is particularly related to shear localization that occurs near the top of a liquefiable sand layer overlain by a surface low permeability crust in a sloping ground. In this scenario, void redistribution may occur in what was originally uniformly distributed void space, leading to the formation of loose sand zone at the top and denser zone near the bottom of the sand layer. The hypothesis is that as the top sand dilates, it attracts pore-water from the denser bottom layer. If a water interlayer forms at the interface between the impermeable crust and the underlying sand, the crust layer would move downslope at a large magnitude.

In this presentation, a fully Lagrangian particle-based method for coupled fluid-particle interaction is utilized to evaluate flow liquefaction of saturated granular soils overlain by an impermeable crust. The solid particles are modeled as spherical particles using the discrete element method (DEM). The smoothed particle hydrodynamics (SPH) is employed to model the interstitial fluid using an averaged form of Navier-Stokes equations that accounts for the presence of the solid phase. The coupling between SPH and DEM is achieved through local averaging techniques and well-established semi-empirical formulas for fluid-particle interaction. The responses of loose and dense level granular deposits overlain by an impermeable crust to a seismic excitation are first analyzed. The loose deposit exhibited significant pore pressure development and liquefaction while the dense deposit barely showed any considerable buildup of pore pressure and did not liquefy. The formation of a water film was visible at the interface between the top crust and the underlying liquefied soil. When the same deposits were tilted to form an infinite slope, the loose deposit exhibited flow liquefaction at the location immediately underneath the impermeable crust and large shear strains accumulated within a thin layer immediately below the crust. Flow liquefaction was marked by dilative behavior at the surface of the liquefied sand and large lateral spreading that continued post-shaking. Void redistribution was observed along the loose deposit in the form of dilation for a thin layer near sand surface and contraction for the deeper depth. The dense sloping deposit did not liquefy and flow liquefaction was not observed.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Characterization of Energy Dissipation During Cyclic Loading of a Sand Damper

Author(s): *Usama El Shamy, *Southern Methodist University*; Ehab Sabi, *Southern Methodist University*; Kostas Kalfas, *Southern Methodist University*; Nicos Makris, *Southern Methodist University*;

The increasing need for structures to meet acceptable performance levels during earthquake and wind excitations has led to the development of various seismic and wind engineering design and retrofit strategies. One such strategy is the addition of fluid and particle dampers in an effort to limit excessive displacements. In this presentation, we introduce results of discrete element method (DEM) simulations of the performance of a pressurized sand damper during cyclic loading. Energy dissipation in the modeled pressurized sand damper originates essentially from the shearing action of the pressurized sand that exploits the stress level-dependency of sand shear-strength and its effect on increasing the dissipated energy during cyclic motion. A series of DEM simulations were performed to study the effects of the stroke amplitude, the frequency of the cyclic loading, the packing density of the granular material, the magnitude of pressure imposed on the sand, and the configuration of the damper on the amount of cumulative dissipated energy. It was found that energy dissipation is mainly due to interparticle frictional sliding. Additionally, the amount of cumulative dissipated energy increased with the increase of pressure level and stroke amplitude. The proposed model sand damper appears to be a promising device for dampers used in structural systems to mitigate vibrations induced by seismic and wind loading.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Survival Probability Determination of Nonlinear Oscillators with Fractional Derivative Terms Under Evolutionary Stochastic Excitation

Author(s): *Vasileios Fragkoulis, *Leibniz Universität Hannover*, Ioannis Kougioumtzoglou, *Columbia University*,

An approximate analytical technique is developed for determining the survival probability and the first-passage time probability density function (PDF) of nonlinear/hysteretic oscillators endowed with fractional derivative elements and subjected to evolutionary stochastic excitation. Specifically, relying on a stochastic averaging/linearization treatment of the problem, approximate closed form expressions are derived for the oscillator non-stationary marginal, transition, and joint response amplitude PDFs and, ultimately, for the time-dependent oscillator survival probability. The developed technique exhibits considerable versatility, as it can handle readily cases of oscillators exhibiting complex hysteretic behaviors as well as cases of evolutionary stochastic excitations with time-varying frequency contents. Further, it exhibits notable simplicity since, in essence, it requires only the numerical solution of a deterministic first-order nonlinear ordinary differential equation. Thus, the associated computational cost is kept at a minimum level. Overall, the developed technique can be construed as an extension of the results in [1] to account for systems with fractional derivative terms.

[1] Spanos P. D., Kougioumtzoglou I. A., 2014. Survival probability determination of nonlinear oscillators subject to evolutionary stochastic excitation, *ASME Journal of Applied Mechanics*, vol. 81, 051016: 1-9.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Physics-Based Graphics Models as Visual Inspection Testbeds

Author(s): *Vedhus Hoskere, *University of Houston*; Yasutaka Narazaki, *ZJUI-UIUC, Zhejiang University*; Billie F. Spencer Jr., *University of Illinois at Urbana Champaign*;

Rapid and automated inspection capabilities in the aftermath of an earthquake can help mitigate the economic and social impacts on affected communities. In the development of such inspection capabilities, automated and robust data processing to extract actionable information is a critical challenge to be addressed. RGB images of damaged structures contain the kind of information used by humans to make decisions in such scenarios. In the quest for methods capable of automatically extracting important information present in RGB images of damaged structures for decision making, deep learning methods have proven highly successful. However, in moving technologies closer to human-level inspection capabilities, two challenges persist: namely, (i) methods that can extract very high fidelity information from images and then conduct high-level reasoning, (ii) annotated datasets that can be used to develop and test such methods. Development of datasets to overcome these challenges are difficult due to the limited availability of images of damaged structures and the difficulty in annotating images. The advances in computer generated imagery (CGI) over the past few decades have made it possible to generate highly photorealistic synthetic images. In this paper, we propose methods to generate synthetic images of damaged buildings informed by their physics. Methods are presented to automatically and systematically consist what we term physics-based graphics models (PBGMs) that form the basis for the rendering of synthetic images. The rendered images are automatically annotated using damage locations implicit in the graphics model. Using the rendered images, supervised deep learning methods are developed and evaluated for more human-like inspections of buildings after a disaster.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Benchmark Tests on Cylindrical Shells Under Combined Bending and Torsion

Author(s): *Victoria Ding, *Johns Hopkins University*; Xiang Yun, *Johns Hopkins University*; Ben Schafer, *Johns Hopkins University*; Shahab Torabian, *Johns Hopkins University*;

Cylindrical shells with large diameter-to-thickness ratios (i.e. normally $r/t > 100$) are widely used in wind turbine towers, while the very thin-walled nature of the cylinders makes stability an essential concern. The cross-sectional loading arrangements of wind turbine towers involve complex interaction of compression, bending, shear and torsion arising from varying load cases of combined environmental and operational conditions, among which bending and torsion are commonly the dominant types of loading. Though there have been extensive research studies on the stability and design of cylinders subjected to isolated loading conditions (i.e. uniform compression or bending), the investigations into the structural response of cylinders under combined bending and torsion have been rather limited. To address the knowledge gap, a comprehensive experimental study was carried out on cylinders under combined bending and torsion, in which a total of 48 cylinders with varying diameter-to-thickness ratios and bending-to-torsion ratios was tested. In the experimental program, a 3D laser-scanning technique was employed to measure the geometric imperfections of each test specimen and the imperfection sensitivity of cylinders under combined bending and torsion was systematically investigated. The test setup, instrumentation, loading procedures and structural response of cylinders, including ultimate resistances, load-deformation characteristics and failure modes are fully reported. The test results are aimed to provide a firm basis for the validation of numerical models and advanced design approaches, such as the Reference Resistance Design, for cylindrical shells under combined bending and torsion.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Multiscale Nonlocal Elasticity: A Distributed Fractional Order Formulation

Author(s): *Wei Ding, *Purdue University, West Lafayette*; Sansit Patnaik, *Purdue University, West Lafayette*; Fabio Semperlotti, *Purdue University, West Lafayette*;

Recent experimental and theoretical investigations have reinforced the understanding that many material classes including, but not limited to, elastic metamaterials, layered composites and biomaterials, and hierarchical structures, all exhibit some degree of multiscale nonlocal behavior. Due to the co-existence of multiple physical mechanisms (such as material heterogeneity, structural hierarchy, and size-dependent effects), nonlocal effects tend to occur and interact across dissimilar scales. The complexity of these types of problems requires novel modeling approaches that can capture the multiscale nonlocal behavior in an accurate and computationally efficient manner.

To address the technical gap between existing modeling approaches and the ability to comprehensively capture multiscale nonlocal effects, this study presents a generalized multiscale nonlocal elasticity theory that leverages distributed order fractional calculus to accurately capture coexisting multiscale and nonlocal effects within a macroscopic continuum. The nonlocal multiscale behavior is captured via distributed order fractional constitutive relations derived from a nonlocal thermodynamic formulation. The governing equations of the inhomogeneous continuum are obtained via the Hamilton principle. As a generalization of the constant order fractional continuum theory, the distributed order theory can model complex media characterized by the simultaneous occurrence of inhomogeneous nonlocality and multiscale effects.

In order to understand the correspondence between microscopic effects and the properties of the continuum, an equivalent mass-spring lattice model is also developed by direct discretization of the distributed order elastic continuum. Detailed theoretical arguments are provided to show the equivalence between the discrete and the continuum distributed order models in terms of internal nonlocal forces, potential energy distribution, and boundary conditions. These theoretical arguments facilitate the physical interpretation of the role played by the distributed order framework within nonlocal elasticity theories. They also highlight the outstanding potential and opportunities offered by this methodology to account for multiscale nonlocal effects. The potential of the methodology is also illustrated via a numerical study that highlights the excellent agreement between the displacement profiles and the total potential energy predicted by the two models under various order distributions. Remarkably, multiscale effects such as displacement distortion, material softening, and energy concentration are well captured at continuum level by the distributed order theory.

In conclusion, the physically consistent distributed order nonlocal elasticity provides a critical step to establish accurate and efficient fractional-order continuum mechanics approaches to modeling multiscale nonlocal continua in real-world complex structures.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Prediction of Waterborne Large Woody Debris Accumulations and Scour for Bridges in Flooding Events

Author(s): *William Hughes, *University of Connecticut*; Wei Zhang, *University of Connecticut*,

Waterborne large woody debris (LWD) has introduced critical damages to many bridges crossing active waterways. In addition to the collision forces, drift buildup constricts flow, producing increased hydrodynamic pressures and exacerbating scour, bank erosion, and channel instability. In the United States, foundation scour from drift accumulation has been found responsible for nearly one-third of bridge failures. Therefore, it is essential to have an efficient methodology to predict debris generation, transport, entrapment, and dimensions, which are consequently necessary to improve public safety, bridge designs, and informed decision-making. However, LWD generation, movement, and geometry are highly site-specific, varying with the regional tree species and hydrological, topological, geotechnical, and climatological properties. To this end, in the present study, a holistic, area-specific probabilistic framework incorporating the risk assessment of local vegetation, weather, and river conditions to predict debris accumulation and scour is developed. From the upstream vegetation tree species and heights, typical debris dimensions and weights are estimated using allometric relationships. Risk assessment of the riparian trees from bank instability and windthrow is conducted to obtain the probability of debris generation. The design log length and subsequent scour under storm scenarios are then computed. The framework is demonstrated in a case study of a bridge in Vermont under the hydrological conditions imposed by Hurricane Irene in 2011.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Multiaxial Real-Time Hybrid Simulation with Model Assisted Compensation

Author(s): *X. Shawn Gao, *MTS Systems*; Michael Dembinski, *MTS Systems*; Shawn You, *MTS Systems*; Brad Thoen, *MTS Systems*;

Multiaxial real-time hybrid simulation (RTHS) is considered a quite challenging subject. The dynamic cross-coupling among multiple actuators requires an advanced control strategy to achieve high quality testing results. In this multiaxial RTHS study, model assisted compensation (MAC) strategy is developed, which uses an inverse model of the testing system to generate a compensation signal for each actuator. MAC can be used for either displacement or force control mode and has been validated on various multiaxial test systems. In RTHS applications, MAC uses a reduced order model of the test specimen along with an inverse actuator model. The reduced order model is generated from finite element model using Craig-Bampton method so that it can be solved in real-time. It contains DOFs of boundary points with dynamic modes of the structure assuming boundary points are fixed. The actuator model is a physics-based model that accurately simulates a variety of dynamic and nonlinear effects of real actuators. In this study, the RTHS validation tests are conducted using a plate structure with four actuators that control motion/force in three degrees-of-freedom. The actuators are spatially close to each other. The specimen is relatively stiff compared with the actuators' maximum payload capacity, which makes the test system a highly cross-coupled system. Both hard real-time and soft real-time hybrid simulation are performed successfully, where MAC shows superior performance in enabling accurate multiaxial motion control. MAC is an inherently stable feedforward type of compensation strategy, which has phase lag/lead tuning gains that can be adjusted on the fly. A virtual test system mimicking the physical test system is also created and is proven to be very useful for diagnostic purposes. The virtual test system uses the same reduced order model discussed above. It also includes forward actuator and servo-controller models. This high-fidelity virtual test system not only could predict the test results, but also, in some instances help identifying the root-cause of system instabilities, as well as evaluate the effectiveness of potential fixes.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Machine-Learned Physics-Informed Constitutive Modeling for Path-Dependent Materials

Author(s): *Xiaolong He, *University of California, San Diego*; Jiun-Shyan Chen, *University of California, San Diego*; Jonghyuk Baek, *University of California, San Diego*; John McCartney, *University of California, San Diego*;

As characterization and modeling of path-dependent behaviors of complex materials by phenomenological models remains challenging due to difficulties in formulating mathematical expressions for mechanisms governing path-dependent deformation, data-driven machine learning models, such as deep neural networks and recurrent neural networks, have become viable alternatives. However, pure black-box data-driven models mapping inputs to outputs without considering the underlying physics behind data suffer from unstable and inaccurate generalization performance, especially when training data is limited. This study proposes a machine-learned physics-informed constitutive modeling approach for path-dependent materials by integrating physical constraints, such as thermodynamics, into data-driven constitutive modeling. Internal state variables essential to the evolution of path-dependent deformation can be learned automatically by models rather than from a priori knowledge. To counteract error propagation issues associated with recurrent model architectures, variability is introduced to model training, enhancing model robustness, accuracy, and generalization performance. The effectiveness of the proposed approach is evaluated by modeling temperature- and path-dependent materials under cyclic loading.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Inelastic Response of Wind-Excited Tall Buildings: Reduced-Order Modeling and Biaxial Load Effect

Author(s): Jinghui Huang, *Texas Tech University*; *Xinzhong Chen, *Texas Tech University*;

Current tall building design to wind does not explicitly permit inelastic behavior even under ultimate wind loadings. This linear design approach may limit the use of more innovative tall building systems with improved performance and economy. The ASCE has recently published pre-standard for performance-based wind design of buildings, which explicitly permits nonlinear dynamic analysis allowing limited inelasticity in the Main Wind Force Resisting System elements. This study examines the inelastic response of tall buildings under simultaneous actions of both alongwind and crosswind loadings using nonlinear finite element model with distributed plasticity and a reduced-order model developed by modal pushover analysis procedure. The accuracy of the reduced-order building model is comprehensively investigated. With the reduced-order model, the inelastic building response is represented by fundamental modes in principal directions. The hysteretic relationships of generalized restoring forces and displacements are determined by static modal pushover analysis using nonlinear finite element building model. These relations are then represented by a biaxial hysteresis model, which leads to state-space equations of the building motion with a reduced-order building model that can be solved by response history analysis or by statistical linearization approach. A comprehensive analysis of response statistics of a 60-story building including time-varying mean, standard deviation, kurtosis and peak factors at different wind speeds is carried out using the reduced-order building model and computationally more demanding finite element model. The results demonstrate the accuracy of the reduced-order building model. The statistical linearization approach based on Gaussian response assumption can also offer good estimations when ductility demand is insignificant but overestimates the response with large ductility demand attributed to non-Gaussian probability distribution of inelastic response. The interaction of inelastic alongwind and crosswind responses is addressed through a comprehensive parametric study, which reveals the most influencing parameters for biaxial response interaction. The challenges faced in the estimation of time-varying mean component of inelastic response is also highlighted.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Evaluating Stimulation Efficiency of Chemically Treated Microproppant Pack in Microfractures Using LBM-DEM Coupling Approach

Author(s): *Yanhui Han, *Aramco Americas*; Feng Liang, *Aramco Americas*;

Hydraulic fracturing is an essential production enhancement technology in stimulating unconventional reservoirs, such as shales and tight carbonates. Besides the primary fractures created by hydraulic fracturing treatment, extensive pre-existing natural microfractures will be reactivated and new microfractures will be created in the far-field regions. Because of small sized apertures of these microfractures, the conventional sized proppants injected with fracturing fluids could not enter them. As a result, these microfractures will close after the release of hydraulic pressure. If these secondary microfractures can be held open during production, in the similar way of the primary hydraulic fractures supported by proppants, the well productivity is expected to be further enhanced. Based on this idea, industry has introduced microproppants into the pad or pre-pad fluid so that they can be placed into the opened microfractures during hydraulic fracturing treatment.

In this work, we aim at investigating the stimulation efficiency by placing chemically treated microproppants, specifically, solid delayed acid generating materials (SDAGM) coated microproppants into the secondary microfractures. Besides preventing the closure of the opened microfractures during the production phase by the microproppants themselves, the selected coating materials on these chemically treated microproppants will degrade under downhole temperature and release the organic acids which will chemically react with the carbonate formation to create extra void space inside the microfractures. The resulted hydraulic conductivities of the microproppant-supported microfractures under two different stimulation scenarios, one with coated microproppant alone and the other one mixing uncoated and SDAGM-coated microproppants, have been evaluated in an LBM-DEM simulator. The simulations showed that fracture conductivity of the microfractures can be significantly improved by placing SDAGM-coated microproppants. The mixed uncoated and SDAGM-coated microproppants can further improve the fracture conductivity than using the SDAGM-coated microproppants alone.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: A Reduction-Based Method for Modelling Lattice Materials

Author(s): *Yash Agrawal, *Johns Hopkins University*; G. K. Ananthasuresh, *Indian Institute of Science Bengaluru*; James K. Guest, *Johns Hopkins University*;

Lattice-based architected materials are gaining significant attention due to their open porosity and potential to offer multifunctional properties. Despite resembling truss-like networks, it has been shown that the geometry of the connections (joints) can play an important role in determining mechanical response. This potentially makes computationally efficient truss and beam modelling insufficient. In contrast, solids-based finite element modelling may offer improved predictions of response but at much larger computational costs. To address these challenges, we present an approach to modelling lattice materials that attempts to capture detailed joint response while leveraging the computational efficiency of beam elements. Classical reduction based methods are used and combined with geometry generation and meshing tools. The approach is evaluated for various unit cell topologies that can be manufactured by (for example) additive manufacturing and 3D weaving and results are compared to those found when using a high fidelity simulation with solid finite elements.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Variability Characterization in Footstep-Induced Structural Vibrations for Online Person Identification

Author(s): *Yiwen Dong, *Stanford University*; Hae Young Noh, *Stanford University*;

Structural vibrations induced by humans contain various information about occupants, including their identities, activities, and health states. Among them, identity is essential for smart buildings as it is the premise to personalized services including access authentication, personnel management, and emergency assistance for patients and the elderly. Person identification typically relies on pre-collected data from the occupants. However, in many real-life scenarios, it is impractical to collect everyone's data, especially when visitors are frequently present. This calls for an online person identification system that gradually learns people's identities as the system observes more data over time.

Many existing online person identification systems use cameras, but they are not suitable for complex indoor spaces due to the direct line-of-sight requirement. They also have raised privacy concerns due to appearance exposure. Other sensing modalities, such as wearables and pressure mats, could be used to reduce these concerns, but they have limited scalability due to device-carrying and dense deployment requirements. Thus, previous studies introduced a person identification system based on footstep-induced structural vibration sensing, which needs only sparsely deployed sensors, is non-intrusive, and is perceived as more privacy-friendly. However, one significant challenge of this approach is the high variability of vibration data due to structural heterogeneity and human gait variations, which makes the existing online person identification algorithms perform poorly.

In this paper, we characterize the variability in footstep-induced structural vibration data to develop a feature transformation approach that enables online person identification. We transform the footstep data into a new feature space where the within-person variability is reduced while the between-person separability is enhanced. To achieve this, we quantify the variability based on the covariance between footsteps, decompose the sources of variability, and design the transformation function based on the dominant variability source. We then formulate an optimization problem that aims to find the transformation parameters which map features to the new space with minimal variability and maximum separability. With these transformed features, we develop an online learning approach based on Dirichlet Process that detects and learns the newcomers' footstep features and then updates the overall footstep feature model on the fly. We evaluate our approach through field experiments with 20 people across 2 structures. For both structures, our method reduces the feature variability by 70% compared to the original data. Our method also achieves a 90% average accuracy in identifying 10 people on each structure starting from 1 person's data only.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Pore Pressure and Spalling Behavior of Loaded Concrete Under Elevated Temperatures

Author(s): Chao Jiang, *Tongji University*; *Yu-Qing Ge, *Tongji University*; Hao-Chuan Zhang, *Tongji University*; Xiang-Lin Gu, *Tongji University*;

Pore pressure measuring device was developed for concrete under elevated temperatures. Effects of the temperature increase and direction of a metal tube, filled with air or silicone oil, on pore pressure measurements in cement-based materials subjected to elevated temperatures were investigated. To this end, heating tests on mortar slabs with metal tubes and thermocouples embedded at different depths by different angles were designed and conducted. Test results showed that the pressure due to temperature increase of a metal tube and its enclosed medium could make a contribution to the total measured pressure. The additional pressure contribution did not exceed 10% of the corresponding total measured pressure in the cases where the total measured pressures were higher than 0.4 MPa. The maximum real pressures reported by metal tubes embedded at the same depth by different angles to the direction of vapor movement did not synchronize and were generally different. The maximum real pressures measured by tubes parallel to the vapor movement direction were higher than those perpendicular to the vapor movement direction. Based on the developed pore pressure measuring device, unilateral heating tests were conducted on concrete specimens under sustained loads to investigate the effects of loads on pore pressure and fire spalling behavior of concrete. Test results showed that: 1) when there is no load, cracks on the exposed surface were allowed to open and propagate so that pore pressures were released rapidly and spalling risks were reduced; 2) higher load levels might constrain the opening and propagation of cracks and incur higher possibilities of spalling and severer spalling depths of concrete.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Toward Crowdsourcing-Based Condition Assessment of Roads Using Deep Learning and Data Fusion

Author(s): *Yu-ting Huang, *Purdue University*; Fangjia Shen, *Purdue University*; Taratal Ghosh Mondal, *Purdue University*; Mohammad Reza Jahanshahi, *Purdue University*;

According to the ASCE report card in 2021, the grade of America's Road system is D. The current poor condition of roads is due to various pavement distresses, such as potholes, that can be hazardous to citizens and lead to huge economical losses due to accidents. The existing practices for pavement condition assessment are expensive, time-consuming, and subjective where a section of the road is evaluated once every two years. To evaluate the condition of a section of the road more frequently and quantitatively, an inexpensive data acquisition system based on a consumer-grade RGB-D sensor is developed in this work for pothole detection. In addition, a lightweight edge computing device is used to control the RGB-D sensor and store the collected RGB-D data. This data acquisition system can be installed on several vehicles to collect large amount of data while driving through out a city. An RGB-D pavement surface dataset is generated. A deep learning-based approach leveraging heterogeneous 2D RGB images and 3D depth maps is developed for potholes segmentation. To this end, an encoder-decoder deep convolutional neural networks (DCNNs) consisting of two encoder networks and one decoder network is proposed to analyze the data for pothole detection. Two encoder networks can capture features from the RGB and depth data separately that the depth encoder network can fully preserve the spatial information of the pothole. The decoder network upsamples the feature map to the same resolution as the input data. Comprehensive experiments using different depth encoding techniques and RGB-D data fusion methods are conducted to investigate the efficacy of the proposed pothole segmentation approach. The results show that the pixel-level RGB-D data fusion approach outperforms the other types of fusion methods in terms of accuracy and robustness. The intersection over union (IoU) score of the pothole using the proposed approach is 0.82 which shows a 7.7% improvement compared to a network trained on solely RGB data. With the semantic segmentation results and depth information, the volume of detected potholes is calculated to quantify the material loss of potholes which can be a potential metric for severity level classification assisting in maintenance decision-making. The result from these comprehensive experiments using an RGB-D pavement surface dataset gathered through the proposed data acquisition system can be a steppingstone for opportunistic data collection and processing through crowdsourcing and internet-of-things in future smart cities for effective road assessment.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: From Full-Scale Monitoring to Digital Twins and Beyond: Scholarship Development Inspired by Dr. Kareem's Vision

Author(s): Yanlin Guo, *Colorado State University*; *Yue Dong, *Colorado State University*;

Dr. Kareem seems to have a precise instinct for discovering important problems and exciting new research topics, which kept inspiring me to develop my research and keep pushing the boundaries. He has pioneered the development of full-scale monitoring systems for iconic high-rise buildings since the 2000s, for example, the Chicago full-scale monitoring project and the SmartSync system in the world's tallest building Burj Khalifa. His forward-looking vision on the real-time monitoring, analysis of non-stationary extreme events and the concept of the internet of things has inspired my PhD research and led to the development and implementation of a real-time nonstationary system identification scheme on Burj Khalifa, which provides advanced data analytics for non-stationary transient windstorms and earthquake events and streaming the results to end-users via internet one decade ago. Following his steps, I have been focusing my research on the development of advanced data analytic tools for extracting in-depth information from full-scale data. I have developed Unmanned Aircraft Systems (UAS)-enabled portable sensing systems and a series of corresponding data analytics techniques based on machine learning, photogrammetry, and computer vision. Recently, his recent advocacy of the potential of digital twins has inspired me to take one step further beyond the internet of things and develop a digital twin framework for transportation infrastructure, which leverages our UAS-enabled sensing systems and automated data processing tools. Dr. Kareem's insights on the role of transient nonstationary extreme winds on structural response and time-frequency analysis later led to our collaborative work on the "Generalized wind loading chain: time-frequency modeling framework for nonstationary wind effect on structures", which was recognized as the 2019 Best Journal Paper in the Structural Hazards category. Dr. Kareem has conducted in-depth research into the urban aerodynamic effects on buildings during major storms using field monitoring, experimental and computational tools and pinpointed the vulnerability of urban building envelopes in extreme winds. His work has aroused my interest in further researching urban aerodynamic and resilience under wind hazards. This presentation will share some examples of how Dr. Kareem's vision has helped shape the scholarship development in structural/wind/natural hazard engineering.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Surrogate Modeling for Engineering Problems with High-Dimensional Input and Output

Author(s): *Yulin Guo, *Vanderbilt University*; Sankaran Mahadevan, *Vanderbilt University*; Shunsaku Matsumoto, *Mitsubishi Heavy Industries*; Shunsuke Taba, *Mitsubishi Heavy Industries*; Daigo Watanabe, *Mitsubishi Heavy Industries*;

In engineering analysis, surrogate models are often employed to replace physics-based models in order to achieve computational efficiency when the physics-based models need to run multiple times. The quality and quantity of data collected from the expensive physics-based model is crucial to the accuracy of the surrogate models. We present a novel surrogate modeling approach for engineering problems with high dimensions in both the input and output spaces. Methods for dimension reduction for both the input and output are investigated: variance-based sensitivity analysis and active subspace discovery for the input space; singular value decomposition (SVD), random projection, randomized SVD, and diffusion map for the output space. The most effective combination of options for input and output dimension reduction is identified in a systematic way, considering accuracy, computational effort, and the suitability for the engineering problem. Gaussian process surrogate models are subsequently constructed in the low-dimensional space. The predictions of the quantities of interest in the original high-dimensional space are obtained using the surrogate models. The errors associated with the predictions consist of surrogate errors and reconstruction errors, and a systematic approach is developed to quantify and compare the relative contributions of these two types of errors. An analysis on an aircraft fuselage panel is used to demonstrate the systematic way of identifying the most effective combination of dimension reduction techniques for surrogate modeling for high-dimensional problems.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Experimental Validation of the Structural Resilience of a Semi-Actively Controlled Base Isolation System Using Real-Time Hybrid Simulation

Author(s): *Yunbyeong Chae, *Seoul National University*; Ramin Rabiee, *Ohio Northern University*;

High damping is very effective to reduce the isolator displacement, especially under long-period ground motions. For this reason, many different types of supplemental damping systems have been developed for base isolation systems such as lead core, U-shape steel dampers, viscous dampers, and friction dampers. However, it should be noted that high damping can increase the acceleration demand of base isolation systems under strong short-period ground motions, potentially leading to the damage of nonstructural components. This can be explained by using the transmissibility theory, where the transmitted force to the superstructure is increased under short-period excitations as the damping increases. Therefore, low damping is beneficial under strong short-period ground motions to enhance the structural resilience, suggesting the use of adaptive damping based on the frequency contents of ground motions. In order to take advantage of these damping characteristics, the transmissibility-based semi-active (TSA) controller was developed, which can make the system damping high under long-period ground motions and low under short-period ground motions by using semi-actively controlled damping devices. The performance of the TSA controller applied to a base isolated building was investigated by conducting real-time hybrid simulation (RTHS). A 3-story base isolated building with rubber bearings and magneto-rheological (MR) dampers were selected for the experimental validation of this study. The base isolation system consisting of one rubber bearing, one MR damper, and three linear bearings was physically tested and the superstructure was analytically modeled. An ensemble of ground motions representing the short- and long-period ground motions were used for RTHS to get a statistical result. It was shown that the TSA controller achieves a high level of performance under long-period ground motions, while maintaining the exceptional performance of a conventional base isolation system with low damping under short-period ground motions, all of which are difficult to achieve with passive damping only.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Large-Eddy Simulation of Cross-Ventilation: Sensitivity Analysis and Comparison of Different Measures of Ventilation

Author(s): *Yunjae Hwang, *Stanford University*; Catherine Gorle, *Stanford University*;

The global Covid-19 pandemic has put a spotlight on the significance of ventilation as it can play an important role towards preventing the spread of airborne diseases in indoor environments. Computational fluid dynamics (CFD) has gained popularity in studying natural ventilation due to its clear advantages over experimental techniques: it provides complete access to the flow solution at any location in the computational domain, and it does not require geometrical scaling. Reynolds-Averaged Navier-Stokes (RANS) modeling is a commonly adopted approach because of its relatively low computational cost, but it can introduce significant uncertainty due to the use of reduced-order turbulence models. To overcome this limitation, a handful of ventilation studies adopt large-eddy simulations (LES), which can more accurately represent the time-dependent turbulent wind. However, limited validation and sensitivity studies using LES have been reported in literature.

Therefore, the objectives of this research are to validate LES of natural ventilation and to identify the most important simulation parameters in determining the effectiveness of natural ventilation. To achieve these objectives, we perform LES for an isolated building with wind-driven cross ventilation, reproducing a reference wind-tunnel measurement available in literature. We first investigate the sensitivity of the flow solution to the resolution of the computational grid as well as to the inflow conditions, and validate the LES predictions against the experiment results. Then, we conduct simulations under various ventilation configurations in terms of opening size and position, and wind direction. The simulation results are analyzed to quantify the effect of these parameters on different ventilation measures, including instantaneous and time-averaged ventilation rate, age of air, and ventilation efficiency. The simulation results indicated that uncertainty in the inflow conditions is non-negligible for detailed ventilation patterns, but does not affect averaged quantities including ventilation rate. In addition, for this isolated building case, the effect of wind direction is more pronounced than the size and location of openings.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Recent Advances in Correspondence-Based Peridynamics: Thin Shells

Author(s): *Yuri Bazilevs, *Brown University*; Masoud Behzadinasab, *Brown University*;

In this two-part talk, we present the recent advances in the correspondence-based peridynamics framework. The overarching goal of this work is to develop an accurate, robust, stable, and efficient methodology for peridynamics enabled with the incorporation of classical constitutive material laws. We adopt accurate methods that make use of higher-order corrections to improve the computation of integrals in the correspondence formulation. We utilize our recently developed bond-associative stabilization technique to ensure numerical stability. We also present the additional developments that enhance the computational efficiency of the framework. Part I of this presentation will focus on the foundations of the correspondence-based modeling, bond-associative stabilization, and will show results for a range of linear and nonlinear solids. Part II of this presentation will extend the correspondence-based bond-associative stabilization methodology to the modeling of general-geometry nonlinear thin shells in the peridynamics framework.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Fusing Infrared and Visible Images of Different Resolutions via Convolutional Neural Network

Author(s): *Zahra Ameli, *University of Maine*; Eric Landis, *University of Maine*;

Accurately locating and quantifying the concrete delamination is essential for decision-making of repair/replacement of bridge decks. However, some inspection areas are hard to reach, and the inspection of these inaccessible areas can be dangerous to inspectors. Furthermore, the use of special equipment, such as scaffold and aerial work platforms, often causes traffic delays and are time consuming. In response to these issues, there are ongoing efforts that use Infrared Thermography (IRT) and RGB sensors mounted on unmanned aerial vehicle (UAV) for bridge defect detection. There are great radiometric and geometric differences between visible and infrared images, as they collect spectral reflectance from different wavelengths with different imaging mechanisms. The performance of the vision-based technique is highly affected by the operational conditions, such as the incident angle, illuminance, and undesired contaminants in the air or backgrounds. Moreover, invisible subsurface cracks cannot be detected with the vision-based technique. By contrast, infrared sensors exhibit unique advantages in overcoming adverse light conditions. In particular, the IR techniques are attractive for the detection of invisible subsurface and surface delamination. Nevertheless, due to limitations of hardware and environments, infrared images are often accompanied by blurred details, serious noise, and considerably low resolution. These limitations encourage the fusion of infrared and visible images to produce a single image, which can simultaneously highlight thermal radiation for target detection and reserve texture information for characterization of appearance.

Despite the notable progress of image fusion, fusing infrared and visible images of different resolutions remains a challenging task. Infrared images constantly suffer from considerably lower resolution compared to visible images. Although downsampling the RGB image or upsampling IR image are two solutions but both of these methods result in inaccurate and blurred fused image. In this study a concrete delamination detection technique is proposed that combines vision and IR images overcoming multi-resolution problem. A densely connected CNN is employed to extract common features from RGB (red, green and blue) and an infrared image that were captured from a bridge using UAV. The results show that macro- and microcracks on concrete surfaces can be detected with a reduced number of false alarms. The uniqueness of this study is attributed to the improvement of the delamination detection reliability based on the fusion of vision and IR images.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Human-Machine Collaborative Inspection Through Mixed Reality

Author(s): *Zaid Al-Sabbag, *University of Waterloo*; Chul Min Yeum, *University of Waterloo*; Sriram Narasimhan, *University of California, Los Angeles*;

In this study, we propose a novel end-to-end pipeline called Human Machine Collaborative Inspection (HMCI) to enable collaboration between Mixed Reality (MR) equipped inspectors and rapid data collection robotic platforms for the purpose of enhanced structural inspections. MR headsets utilize holographic displays and precise head tracking to enable users to visualize accurate 3D holograms that are anchored to the real scene. Thus, MR can allow inspectors to visualize the locations and sizes of structural defects to assist with performing inspections. First, a data collection robot uses its equipped visual sensors to scan the scene to collect images and generate a 3D map of the site. Then, spatial alignment between the robot and the MR device is performed using image-based localization through Azure Spatial Anchors (ASA). The 3D map and images are then sent to a remote server for analysis to detect defects using advanced computer vision algorithms, such as convolutional neural networks, and then spatially matching their 2D pixel coordinates to the associated 3D map of the site. This information is then sent to the MR device so that a 3D holographic object can be automatically overlaid and anchored to the defect's location, alongside relevant information such as type of defect, estimated size, inspection date, and other notes from previous inspections. An experiment was conducted in a lab environment to demonstrate the effectiveness of the proposed system using HoloLens 2 as the MR device and Turtlebot2 as the robot. The Turtlebot2 automatically detected fiducial markers along a pre-planned inspection path using an equipped Azure Kinect RDB-D camera, and the HL2 user was able to view the locations of the detected markers, which were displayed as holograms on the real scene.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: An Attack on Non-Triangular Flexible Polyhedral Surfaces

Author(s): *Zeyuan He, *University of Cambridge*; Simon Guest, *University of Cambridge*;

Are polyhedral surfaces rigid? L. Euler conjectured in 1766 that the answer is true. In 1813, A. L. Cauchy claimed that all the strictly convex polyhedral surfaces are rigid. In 1897, R. Bricard found three types of flexible self-intersected polyhedral surfaces. The conjecture that all the polyhedral surfaces were rigid has been with us for a long time --- but this was disproved by a counterexample in 1977. R. Connelly told us that there is a non-convex triangular flexible polyhedral surface. Thus far, several types of flexible polyhedral surfaces are reported. N. H. Kuiper and P. Deligne modified Connelly's result to an example with 11 vertices, 27 edges and 18 faces. In 1978, K. Steffen found the simplest triangulated flexible polyhedral surface with 9 vertices, 21 edges and 14 faces. In 2011, T. Tachi found a variation with 10 vertices, 24 edges and 16 faces. In 2016, L. Ila, T. Tachi and S. D. Guest gave another extended variation with 16 vertices, 42 edges and 28 faces. All these reported examples are triangular. Are there non-triangular flexible polyhedral surfaces? We take the previous triangular examples as inspiration, and find a method that can generate non-triangular flexible polyhedral surfaces. We think this idea will be useful in generalizing a flexible polyhedral surface and its related structures, which will open up new families of deployable systems with tremendous possible applications.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Stochastic Analysis of Buckling Load of Beams on Elastic Foundation

Author(s): *Zheren Baizhikova, *University of Houston*; Jia-Liang Le, *University of Minnesota*; Roberto Ballarini, *University of Houston*;

Geometrical imperfection is ubiquitous in many load supporting structures including beams, columns and shells. The uncertainty in the fabrication process inevitably causes considerable randomness in the geometrical imperfection, which in turn affects the statistics of the load-carrying capacity of the structural member. In this study, we investigate the stochastic buckling load of beams with random initial geometrical imperfection resting on a nonlinear elastic foundation. The geometrical imperfection is modeled by a zero-mean Gaussian random field, generated using the Karhunen-Loeve expansion, which is characterized by the probability distribution of the local imperfection size as well as the autocorrelation function. The governing equilibrium equation is solved by a finite difference scheme, and the buckling load is calculated from the load-displacement curve. Through Monte Carlo simulations, we obtain the mean and variance of the buckling loads.

The present simulation allows us to study the effects of different length scales, which include the beam length, the autocorrelation length of the geometrical imperfection, and the characteristic wavelength of buckling shape, on the statistics of the buckling load. These results shed light on scale effects on the stochastic buckling load, an important aspect of reliability-based structural design.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Neural-Network Based Wind Pressure Prediction for Low-Rise Buildings with Genetic Algorithm and Bayesian Optimization

Author(s): *Zhixia Ding, *University of Connecticut*; Wei Zhang, *University of Connecticut*; Dongping Zhu, *University of Connecticut*;

Low-rise wood buildings, which occupy over 95% of all residential structures in the U.S., suffer from wind hazards, such as hurricanes, winter storms, and tornadoes. Realistic wind pressures are critical to obtaining the actual responses of buildings for structural design and damage prediction. Wind tunnel experiments provide realistic wind pressure distributions on buildings for structural analysis. However, it is time-consuming and costly to experiment with every building under different wind scenarios. An effective alternative way is to use the neural network (NN) to predict the wind pressures for buildings with different geometries and under various wind directions based on the available databases. However, this method could have a high computational cost due to the challenges of determining an optimal NN structure with suitable hyperparameters. In the present study, the influences of the hyperparameters (namely the input variable and transfer function), the number of data pairs, and the NN structures on the performances of NNs are evaluated when predicting wind pressure coefficients based on building dimensions and roof slopes. To overcome the tedious trial-and-error procedure for optimal NN selection, two new approaches, genetic algorithm-based neural network (GANN) and Bayesian optimization-based neural network (BONN), are proposed. The BONN is demonstrated to be the most efficient, saving 88-94% computational time compared with NN, while the GANN costs about twice the time of BONN. The much higher efficiencies of the proposed two approaches in wind pressure predictions help broaden the application of NN.

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Title: Multiphysics Modeling of Frontal Polymerization based Layer-by-Layer 3D Printing of Thermoset Polymer Components

Author(s): *Zhuoting Chen, *University of Wyoming*; Morteza Ziaee, *Colorado State University*; Mostafa Yourdkhani, *Colorado State University*; Xiang Zhang, *University of Wyoming*;

Frontal polymerization (FP) is a novel curing strategy that relies on a self-propagating exothermic reaction front to polymerize the thermoset monomer resin rapidly. Due to its energy-efficiency and fast delivery of fully cured thermosets, a series of applications related to polymer and polymer composites manufacturing has been developed based on FP, in particular 3D printing [1]. While the current research demonstrates successful printing of 1D, 2D and 3D structures, a key challenge is determining the printing process parameters through trial and error, which hinders its large-scale application.

To better understand different physical processes associated with FP-based 3D printing, and how different process parameters affect the front behavior and printed parts, we develop a multiphysics modeling framework for FP-based 3D printing process within the Multiphysics Object-Oriented Simulation Environment (MOOSE). In this framework, we account for the ink deposition through element activation that constantly adds elements to the simulation domain along a predefined printing path. A coupled thermo-chemical partial differential equation system is solved over the ink domain to simulate the heat transfer and the chemical reaction during the printing process. The model is first validated by comparing the front temperature history during the printing process with experimental measurements. The validated model is able to determine the proper nozzle velocity range, within which the front can follow the nozzle such that the ink is not deforming before curing. The model also reveals the change of front temperature between different layers, and over different layer lengths, providing helpful guidance to the printing experiments for processing parameters selection.

Keywords: Frontal polymerization; 3D printing; thermoset polymer; multiphysics modeling

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Time-Dependent Formulation for Storm Surge Predictions

Author(s): *Aditya Pandey, *University of Illinois at Urbana-Champaign*; Alessandro Contento, *Sapienza University of Rome*; Paolo Gardoni, *University of Illinois at Urbana-Champaign*;

Storm surge is known to cause significant damage. One of the most well-known cases of this is Hurricane Katrina. In the last few years, there has been at least one hurricane with significant storm surge damage per year. Accurate and timely predictions of storm surge are needed to support short-term activities (e.g., evacuation) and long-term activities (e.g., business recovery planning). Probabilistic models of storm surge are required to account for the large number of relevant uncertainties. A few models are available in the literature to predict the maximum surge height at each location in a region of interest. However, probabilistic predictions of storm surge based only on the maximum response neglect important information related to the time evolution of the water height. The proposed probabilistic formulation provides the time evolution of a storm surge as a function of hurricane characteristics, geomorphologic characteristics of the studied area, and local climatological variables. The proposed probabilistic formulation provides correlated predictions of the storm surge height at multiple locations. The model can use data from both high-fidelity simulations and historical records. Considering the time evolution of the storm surge allows us to develop more accurate predictions and take advantage of the increased amount of information that is available as a hurricane approaches landfall. The proposed formulation can help emergency management decisions by providing the latest and most informed predictions of the storm surge. It can be also used to analyze the impact of storm surge on different networks such as road network or power network.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Multi-Objective Topology Optimization of Structural Battery Electrolyte

Author(s): Pejman Reza, *Drexel University*; *Ahmad Najafi, *Drexel University*;

Structural battery composite (SBC) is a new class of multifunctional lightweight materials with profound potential in harvesting electrical energy in the form of chemical energy, while simultaneously providing structural integrity to the system. SBC shows promising potential in addressing the issue of “low specific energy” in lithium-ion batteries. In these materials, carbon fiber works both as a high-performance structural reinforcement and a lithium-ion battery electrode. The composite polymeric matrix (typically referred to as structural battery electrolyte (SBE)) is also in charge of two tasks: transferring the structural load and working as a lithium-ion battery electrolyte.

One of the major challenges in the development of structural batteries is that the mechanical and electrical demands (i.e., high stiffness and high ionic conductivity) are strongly in conflict. In this study, we want to tailor the microstructure of SBE for purpose of maximizing the performance of the battery by making a balance between the ionic conductivity of the battery and its stiffness. Moreover, it is essential to make sure that the electrochemical cycling would not result in a high temperature in the battery. The need to fulfill these disparate functions generates intrinsically conflicting physical property demands. One possible strategy is to form a bi-continuous architecture of two distinct phases for the electrolyte, each addressing different physical demands.

We present a multi-objective multi-physics topology optimization framework to identify the optimized microstructure of SBE that satisfies the aforementioned physical demands. In general, polymer electrolytes are composed of two phases: rigid component for providing structural integrity, and compliant component for ionic conductivity. The rigid phase has high stiffness and thermal conductivity, and low ionic conductivity while the compliant phase has low stiffness and thermal conductivity, and high ionic conductivity. The goal is to determine the ideal microstructures for these two phases to simultaneously address the aforementioned conflicting physical demands

One of the difficulties in solving multi-physics optimization problems is their typical high computational costs associated with solving several physics in each iteration of the optimization process. To alleviate this issue, we implement a low-fidelity resistance network approach for the electrochemical module. Moreover, we utilize the Portable and Extendable Toolkit for Scientific Computing (PETSc), and the parallelization is performed with the aid of Message-Passing Interface (MPI) that allows for distributing the computational memory and workload over several processors.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Remaining Capacity of Corroded Steel Beam Ends in New England

Author(s): *Aidan Provost, *The University of Massachusetts Amherst*; Dr. Georgios Tzortzinis, *Technische Universität Dresden and The University of Massachusetts Amherst*; Dr. Simos Gerasimidis, *The University of Massachusetts Amherst*; Dr. Sergio Breña, *The University of Massachusetts Amherst*;

The United States, has several parts of its infrastructure in desperate need of repair and maintenance which resulted in a D+ rating of United States infrastructure via the American Society of Civil Engineers. Recent work from the UMass group studied corroded beam ends and their remaining structural capacity from the Commonwealth of Massachusetts. Our presentation will discuss our current project, which expands upon this work and is a study of corroded beam ends and bridge deterioration across all the New England states.

Corrosion is a main source of deterioration in steel bridges and is a present problem in the bridges of New England. We have seen that water, ice melt chemicals, and malfunctioning expansion joints greatly contribute to steel beam end corrosion among bridges in New England. The main study began by categorizing the corrosion that is present in steel beam ends. Upon the compilation and analysis of state inspection reports, parameters, and patterns are generated to classify corrosion. Following beam selection and receiving specimens, a section loss assessment is conducted via ultrasonic thickness gauge measurements and LiDAR point cloud measurements. This allows for a thickness contour to be generated and an initial capacity for the corroded beam end to be calculated via hand calculations and a basic finite element model.

The real corroded beam ends are load tested in our Brack structural lab facility at UMass Amherst to find the true capacity and failure mode of the beam. Following this, a final finite element model is generated in Abaqus using the material and beam measurement properties analyzed in the previous steps. This allows for an accurate simulation of the beam end loading and failure. In previous studies, the experimental results and simulations allowed for the researchers to generate new recommendations and equations that estimate the capacity of a corroded beam end using beams from the state of Massachusetts. The current project will consider beam specimens from all of the New England states, significantly expanding the data set used for the development of equations to describe the remaining capacity of deteriorated bridges.

Title: Integrated Node Condition Classifier in Storm Surge Surrogate Modeling

Author(s): *Aikaterini P. Kyprioti, *University of Notre Dame*; Alexandros A. Taflanidis, *University of Notre Dame*; Norberto C. Nadal-Caraballo, *U.S. Army Corps of Engineers*; Madison O. Campbell, *U.S. Army Corps of Engineers*;

This presentation discusses the development of a kriging surrogate model for the prediction of peak storm surge. Surrogate models, also referenced as metamodels, are already used in coastal hazard assessment applications as attractive, data-driven, predictive models that can provide surge estimates very fast and accurately. They are calibrated based on an existing database of synthetic storm simulations, and are able to provide approximations of the expected storm surge, replacing this way the (computationally expensive) numerical model that was used to establish this initial database. For nearshore nodes/locations that have remained dry in some of the synthetic storm simulations, a required first step, before the calibration, is the database imputation which facilitates the necessity of filling the missing data corresponding in dry instances, with some approximate surge estimates that would allow the surrogate model implementation. This imputation is typically performed using some geospatial interpolation technique, with the k-nearest-neighbor (kNN) interpolation being the preferred one. Such surge estimates obtained from this imputation, also termed pseudo-surge, may lead to an erroneous classification for some storms, with nodes classified as inundated (pseudo-surge greater than the node elevation), even though they were actually dry. In order to resolve this, the integration of a secondary, node classification surrogate model, was recently proposed to address such challenges[1]. So for problematic nodes that have been misclassified at least once during the database kNN imputation process, the use of a secondary classification surrogate model was suggested when the primary, storm surge surrogate model would predict the node as inundated. This contribution further examines this integration of the node classification in storm surge surrogate modeling, and the benefits from such an implementation are carefully examined across nodes with different characteristics, revealing important trends for the necessity of the integration of the classifier in the surge predictions. Finally, the combination of the two different surrogate models (node classification and surge prediction) using the probabilistic characterizations of the node classification, instead a deterministic one, is also considered for the entire database. The synthetic storm database used to illustrate these surrogate model advances corresponds to 645 synthetic tropical cyclones (TCs) developed for a flood study in the Louisiana region.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Physics-Based Constitutive Equation for Thermo-Chemically Aged Elastomers Based on Crosslink Density Evolution

Author(s): *Aimane Najmeddine, *Virginia Polytechnic Institute and State University*; Maryam Shakiba, *Virginia Polytechnic Institute and State University*;

We present a physics-based constitutive approach to predict the mechanical response of thermo-chemically aged elastomers. High-temperature oxidation induces two main thermally-driven chemical processes: chain breakage and crosslinking. In the developed approach, we modify the elastomers' hyperplastic free energy to incorporate network changes in their microstructures during thermo-chemical aging. Namely, we revise the network stiffness and the chain extensibility in the well-known Arruda-Boyce hyperplastic free energy. The modification is based on chemical characterization tests measuring the crosslink density evolution. The developed constitutive framework can predict the mechanical response of thermo-chemically aged elastomers independently of any mechanical tests on aged samples. We validate our proposed framework with respect to a comprehensive set of experimental data available in the literature which were designed to capture thermo-chemical aging effects in elastomers. Comparison versus experiments shows that the developed framework can accurately predict the tensile tests conducted on aged samples based entirely on the crosslink density evolution input. Results of this work contribute to the ongoing efforts of characterizing the complex behavior of severely aged elastomers and constitute a step forward in the current research designated to of building self-contained, robust, and predictive physics and chemistry-based computational methods.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Investigation of Self-Tuning Regulator Controllers for Real-Time Hybrid Simulation of Civil Engineering Structures

Author(s): *Alejandro Palacio-Betancur, *Penn State University*; Mariantonieta Gutierrez Soto, *Penn State University*;

Real-time hybrid simulation (RTHS) is an attractive, cost-effective testing method for structures subjected to dynamic loading. RTHS decomposes a structure into partitioned physical and numerical sub-structures that are coupled through actuation systems. Due to the inherent dynamics of the RTHS system, several factors affect the accuracy and stability of the simulation such as time delays, measurement noise, complex boundary conditions, and model uncertainties. However, state-of-the-art hardware and advanced control algorithms can mitigate these effects. For instance, adaptive control schemes are a common approach to solve time delay issues and model uncertainties. Such controllers usually require tuning adaptive gains before the RTHS simulation, but this is a challenging task. For this reason, this study evaluates the accuracy of a series of Self-Tuning Regulator controllers that can calibrate control parameters when plant parameters are unknown. This approach uses the polynomial controller of feedback and feedforward components and online parameter estimation using the Recursive Least Square (RLS) method. The investigation uses the benchmark problem of a three-story building with one Degree of Freedom in a virtual RTHS that considers realistic numerical and experimental models subjected to earthquake loading. It evaluates the proposed controllers' performance and robustness for different partitioned cases and compares them with previously designed controllers for the benchmark problem. The results show the potential of self-tuning regular controllers as a competitive algorithm to tackle the challenges in conducting RTHS of civil engineering structures subjected to natural hazards.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Seismic Analysis of Buildings Retrofitted with Adjacent Viscoelastically Damped Structures

Author(s): Mariateresa Lombardo, *Loughborough University*; Giuseppe Carlo Marano, *Politecnico di Torino*; *Alessandro Palmeri, *Loughborough University / Politecnico di Torino*;

Primary-secondary structural interaction can drastically modify the dynamic behaviour of existing buildings. For instance, the installation of tuned mass dampers (TMDs) is a well-known strategy of passive dynamic control, widely adopted for new and existing structures (e.g., [1]). In recent years, exoskeletons [2], dissipative towers [3] and double-skin facades [4] have been proposed as seismic retrofitting interventions.

The dynamic analysis of primary-secondary systems gives rise to several computational issues, including the non-proportional damping of the coupled system. In fact, existing buildings and modifying attachments can have largely different values of mass, stiffness and damping. Furthermore, the secondary system, including any connecting devices, may include various forms of energy dissipation, e.g., friction, frequency-dependent viscoelastic damping, plasticization and phase-change in metals and alloys.

This paper investigates the combined use of adjacent reaction structures and linear viscoelastic damping to improve the seismic performance of low- to medium-rise buildings. Contrary to other retrofitting solutions, the secondary system is only connected to the primary building on a single floor in the lower part of its elevation. A simplified mass-spring-dashpot system is used together with the Buckingham π theorem to identify a viable design space for the retrofitting solution. Deterministic and stochastic dynamic analyses are carried out to quantify the potential of the proposed intervention and provide design recommendations.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Nanoconfinement Matters in Humidified CO₂ Interaction with Calcium and Magnesium Silicates

Author(s): Mohammad Javad Abdolhosseini Qomi, *University of California, Irvine*; Siavash Zare, *University of California, Irvine*; *Ali Morshedifard, *University of California, Irvine*;

With enigmatic observations of enhanced reactivity of wet CO₂-rich fluids with metal silicates, the mechanistic understanding of molecular processes governing carbonation proves critical in designing secure geological carbon sequestration and economical carbonated concrete technologies. Here, we use first principle and classical molecular simulations to probe the impact of nanoconfinement on physicochemical processes at the rock-water-CO₂ interface. We choose nanoporous calcium-silicate-hydrate (C-S-H) and forsterite as model metal silicate surfaces that are of significance in the cement chemistry and geochemistry communities, respectively. We show that while a nanometer-thick interfacial water film persists at undersaturated conditions consistent with in situ infrared spectroscopy, the phase behavior of water-CO₂ mixture changes from its bulk counterpart depending on the surface chemistry and nanoconfinement. Through free energy calculations, we show that CO₂ could be found in a metastable state near the C-S-H surface, which can potentially react with surface water and hydroxyl groups to form carbonic acid and bicarbonate. These findings support the explicit consideration of nanoconfinement effects in reactive and non-reactive pore-scale processes.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Full Coupling of CO₂-CH₄ Diffusion and Sorption with Solid Deformation in Gas Shale Enhances Natural Gas Recovery and Geological CO₂ Storage Capacity

Author(s): Wei Zhang, *The Pennsylvania State University*; *Amin Mehrabian, *The Pennsylvania State University*;

A thermodynamically rigorous constitutive model is used to describe the full coupling between diffusion, sorption, and solid deformation in organic shale where the pore fluid is the binary mixture of carbon dioxide and methane. The constitutive model is utilized in a numerical solution that simulates cyclic injection of carbon dioxide in shale before producing carbon dioxide and methane from the same. The developed model and solution account for the mutual effects of the resulting rock deformation and sorption affinities of the pore fluid components between one another. The solution further incorporates the various diffusive transport mechanisms that occur in ultralow permeability shale. These processes include molecular diffusion, Knudsen diffusion, and surface diffusion. The accuracy and stability of the presented numerical solution is validated against a special-case solution by commercial numerical solver. Results indicate that removing any of the described coupled processes from the solution would underestimate both the CO₂ storage capacity and enhanced natural gas recovery factor of the organic rich shale. Gas sorption, surface diffusion, sorption-induced deformation, as well as strain-induced changes in gas sorption affinities, are all conducive to both outcomes.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: An Approach for Soft Tissue Material Parameter Estimation from Clinical Imaging Data Using a Three-Dimensional Level Set Method

Author(s): *Aminallah Pourasghar, *University of Pittsburgh*; Timothy Wong, *University of Pittsburgh*; Marc Simon, *University of California, San Francisco*; John Brigham, *University of Pittsburgh*;

A computational approach will be presented for the estimation of the in vivo magnitude and spatial distribution of mechanical material properties of soft tissues from clinical data. To accomplish this, an optimization-based inverse material property estimation procedure using a shape-based objective function applicable to evaluating the difference between the measured and predicted tissue behavior and estimate mechanical properties of tissues from standard untagged clinical imaging and hemodynamic data is introduced. This approach is an extension of prior work by the authors that used a standard discretized version of the Hausdorff distance as an objective function in an iterative approach to material parameter estimation [1]. A key component of the new inverse approach is the use of a continuous three-dimensional shape function of the region of interest that is constructed using a signed distance function. As such, a novel level-set framework is introduced for the objective function that is easily differentiable, and thus, able to be implemented into an optimization framework to identify the material parameters that minimize the difference with respect to a target shape with relative computational efficiency. A set of simulated inverse problems was used to evaluate the inverse solution estimation procedure based on estimating the passive elasticity of human ventricular walls from standard cardiac imaging data and corresponding hemodynamic measurements. In evaluating the results, emphasis will be placed on not just the accuracy of the material parameter estimates, but also on the computational expense (e.g., number of forward finite element analyses) required to approximate the target response. Various levels of heterogeneity will be considered in terms of the effect on solution accuracy and/or need for regularization. Additionally, sensitivity to noise and/or model error will be explored.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Predicting Visual Deterioration in Bridge Decks from NDE Data Through Generative Models

Author(s): *Amirali Najafi, *Rutgers University*; John Braley, *Rutgers University*; Ali Maher, *Rutgers University*;

NDE procedures are excellent at identifying subsurface deterioration (e.g., cracks, delamination, and corrosion). Through periodic NDE surveys, the deterioration causes, and progress are identified and quantified. The deck deterioration is next converted into 2D maps for visualization, and generation of deterioration curves. Many state-level transportation agencies however still rely on traditional visual techniques for assessment of bridge decks and generation of subjective condition indices. The limitation of visual assessment is that: (1) subsurface conditions and other hidden anomalies are not visible, and (2) visual data cannot be used for developing predictive models. In this work, a generative machine learning algorithm is trained using NDE data to predict future visual deterioration. This approach may be attractive to transportation agencies that may not trust NDE-based condition indices and instead prefer traditional visual inspection methods.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Seismic Topology Optimization of Tall Buildings Using Modal Decomposition

Author(s): *Amory Martin, *Exponent*; Gregory Deierlein, *Exponent*;

Topology optimization leads to economical and visually striking designs, which has led to numerous applications in structural engineering, in both research and practice, especially under static loading. However, accounting for dynamic seismic loading remains a challenge due to the computational complexity of the analysis, the design-dependency of the loading, and the stochastic nature of earthquakes. The challenge is to accurately characterize the uncertain seismic behavior of the structure, and at the same time, efficiently solve the optimization problem. In this study, a dynamic topology optimization formulation is proposed based on modal decomposition, termed the sum of modal compliances (SMC). Inspired by earthquake engineering analysis techniques, the formulation is based on the response spectrum analysis, which accurately and efficiently captures the seismic response of the structure. The design-dependent problem of seismic topology optimization is broken down into a series of design-independent subproblems, which are constructed using equivalent modal load forces, and iteratively updated using modal analysis. By taken a weighted average of eigenmodes, the seismic excitation of the structure is minimized. The methodology is applied to tall building structures, for which most of the mass is predetermined, and uses the ground motion response spectrum as the frequency content input. Applications on a high-rise building demonstrate the capabilities of the SMC methodology for conceptual seismic design of building structures. The optimized geometries depend on the frequency content of the ground motion input, especially the contributions of higher modes. Finally, the methodology is applied to a three-dimensional high-rise building with a dual core-bracing system using high-performance computing (HPC). The optimized bracing pattern demonstrates the influence of higher modes on the overall seismic behavior of the structure as well as the interaction of the core and bracing members.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Boundary Layers and Natural Frequencies Predicted Using Granular Micromechanics Based 1D Micromorphic Model

Author(s): *Anil Misra, *University of Kansas*;

For many problems in science and engineering, it is necessary to describe the emerging macro-scale behavior of a very large number of grains by accounting for the micro-scale phenomena. In these cases, continuum models are a preferred approach. Classical continuum theory is unable to take into account the effects of complex kinematics and distribution of elastic energy in internal deformation modes within the continuum material point. Therefore, there is a need for microstructure informed continuum models accounting properly for the deformation mechanisms identifiable at the micro-scale. The granular micromechanics approach (GMA), provides such a paradigm [1-2]. Here we will present the constitutive relationships, governing equations of motion and variationally consistent boundary conditions for a 1D case derived using GMA. The static and dynamic behaviors of a 1D rod are investigated for different boundary conditions. Parametric studies are performed to highlight the effect of material constants and characteristic length scales. The model predicts measurable phenomena such that experimental approaches/protocols can be designed to detect the highlighted effects. For example, under static loading, size-dependency of the system is observed in the width of the emergent boundary layers for certain imposed boundary conditions. Further, for dynamic loading, microstructural effects manifest as deviations in the natural frequencies of the system from their classical counterparts [3].

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Residual-Based Variational Multiscale Modeling with the Finite Volume Method

Author(s): *Anthony Perez, *University of South Florida*; Andres Tejada-Martinez, *University of South Florida*;

The finite volume method, based on the control volume formulation of fluid dynamics, has been previously combined with the Streamline-upwind Petrov Galerkin (SUPG) method, originally developed for the finite element method. The purpose of SUPG is to stabilize the numerical method for advection-dominated flows. The control volume formulation augmented with SUPG has been coined the streamline upwind control volume (SUCV) method by its developers in [1] and [2]. Here we review the SUCV and cast it within the context of residual-based variational multiscale (RBVMS) modeling for large-eddy simulation (LES) following [4]. The subgrid-scale (SGS) model that results is expressed in terms of a SGS anisotropic viscosity and stress. Comparisons will be made between the SUPG SGS viscosity, stress and kinetic energy dissipation and counterpart quantities resulting from the traditional Smagorinsky LES SGS model based on data derived from direct numerical simulation of turbulent channel flow.

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Structural Model Inference and Response Prediction Based on Hierarchical Bayesian Framework and Gaussian Process Regression

Author(s): *Antonina Kosikova, *Hong Kong University of Science and Technology*; Omid Sedehi, *Hong Kong University of Science and Technology*; Costas Papadimitriou, *University of Thessaly*; Lambros Katafygiotis, *Hong Kong University of Science and Technology*;

This paper presents a probabilistic model updating approach, which generalizes hierarchical Bayesian modeling (HBM) techniques by augmenting with Gaussian Process Regression tools. Specifically, it accounts for the residual variability of structural parameters through hierarchical probabilistic model and captures the correlation in the prediction errors utilizing Gaussian processes characterized by kernel covariance functions. The proposed approach is general and versatile in supporting various types of kernel functions, including the three different covariance functions studied herein, namely the well-known squared exponential, the periodic exponential-sinusoidal, and the newly-suggested multi-modal trigonometric kernels [1-2]. To demonstrate the proposed method, the performance of these kernel functions is analyzed using a few numerical examples, wherein the most appropriate covariance structure is selected through Bayesian probability logic. The proposed approach further enhances the state-of-the-art hierarchical Bayesian methods [3], offering significant improvement in the accuracy and robustness of the inferred parameters and predicted responses. Unlike existing methods, this approach predicts dynamical responses reliably by surrogating the prediction error processes and compensating for the missing dynamics and modeling errors.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Innovative Straight Formulation for Plate, Shaped with Re-Entrant Angles, in Bending

Author(s): *Antonina Pirrotta, *University of Palermo*; Carsten Proppe, *Karlsruhe Institute of Technology*;

Very recently [1], it has been introduced an innovative formulation for evaluating the deflection function of a simply supported plate loaded by uniformly distributed edge moments. Framed into Line Element-less Method, this formulation allows the evaluation of solution in terms of deflection, through few lines of algorithm implemented by Mathematica software without resorting to any discretization neither in the domain nor in the boundary. Awesome savings in terms of time and computational costs are achieved.

However, when dealing with sections having re-entrant angles, the aforementioned method cannot be applied in the current form, then this paper aims at extending LEM for these cases.

An innovative formulation will be introduced and implemented through few lines of Mathematica software leading to reliable solutions.

Moreover taking into account the analogy between the bending of simply supported plates loaded by uniformly distributed edge moments and the torsion of a beam, the reliability of the results will be assessed [2].

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Demonstrating the Value of Vibration-Based Structural Health Monitoring Across Different Time Scales

Author(s): *Antonios Kamariotis, *Technical University of Munich*; Eleni Chatzi, *ETH Zurich*; Daniel Straub, *Technical University of Munich*;

Structural Health Monitoring (SHM) can enhance operation and maintenance (O&M;) decision making for structures and infrastructures. Continuous vibration-based SHM is a great candidate for monitoring-based decision support, yet is rarely adopted on real-world structures. An intricacy stems from the fact that civil structures are subjected to a number of damaging processes/events (gradual and shock deterioration) and confounding processes (environmental and operational variability). Different processes act on different time-scales and therefore call for inspection and maintenance actions of different urgency.

Towards demonstrating the value of vibration-based SHM for a wide range of actionable SHM use cases, we recently developed a framework [1], which employs Bayesian decision analysis. The value of SHM (VoSHM) is quantified as the difference in expected total life-cycle costs between two different strategies for optimizing inspection and maintenance plans; one based solely on intermittent visual inspections, and the other based on SHM in combination with inspections. In contrast to other works, we employ a more realistic model of the monitoring system, considering modal data that is continuously identified via operational modal analysis (OMA) schemes. The proposed framework employs Bayesian filtering for sequential Bayesian estimation of the structural deterioration state and the structural reliability. The life-cycle cost minimization problem is solved by means of heuristic decision strategies.

A numerical model of a deteriorating two-span bridge system serves for illustration of the developed framework. This system can be flexibly controlled to model a wide range of SHM use cases across different time scales. Numerical investigations demonstrate the capability of this framework to quantify the potential economic benefit of SHM deployment in an operational evaluation level.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Topology Optimization of Thermofluidic Components

Author(s): *Ardalan Nejat, *Johns Hopkins University*; Jun Wang, *University of Maryland, College Park*; Mark Fuge, *University of Maryland, College Park*; James Guest, *Johns Hopkins University*;

The design space offered by topology optimization is rich and offers tremendous opportunities for improving the performance of devices governed by thermofluidic properties. We will discuss our experiences using the OpenFOAM framework coupled with density-based topology optimization to design forced-convection systems governed by fully coupled Navier-Stokes convection-diffusion equations. Scalability through parallelization will be evaluated, and the performance of different solvers will be discussed in the context of intermediate designs created during the optimization design evolution. Trade-offs between heat transfer performance and pressure drop will be discussed using a series of benchmark 2D and 3D design problems. Manufacturing constraints will be implemented using projection methods, and their impact on component design and performance will be discussed.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Variational Multiscale Immersed Boundary Method for Incompressible Turbulent Flows

Author(s): *Arif Masud, *University of Illinois at Urbana-Champaign*; Soonpil Kang, *University of Illinois at Urbana-Champaign*;

This talk presents an immersed boundary method for weak enforcement of Dirichlet boundary conditions on surfaces that are immersed in the stationary background discretizations. An interface stabilized form is developed by applying the Variational Multiscale Discontinuous Galerkin (VMDG) method at the immersed boundaries [1]. The formulation is augmented with a variationally derived ghost-penalty type term. The weak form of the momentum balance equations is embedded with a residual-based turbulence model for incompressible turbulent flows [3]. A significant contribution in this work is the variationally derived analytical expression of the Lagrange multiplier for weakly enforcing the Dirichlet boundary conditions at the immersed boundary. In addition, the analytical expression for the interfacial stabilization tensor emerges that accounts for the geometric aspects of the cut elements produced when the immersed surface geometry which traverses the underlying mesh. A unique attribute of the fine-scale variational equation is that it also yields a posteriori error estimator that can evaluate the local error in weak enforcement of the essential boundary conditions at the embedded boundaries. The method is shown to work with meshes comprised of hexahedral and tetrahedral elements. Numerical experiments show that the norm of the stabilization tensor varies spatially and temporally as a function of the flow physics at the embedded boundary. Test cases with increasing levels of complexity are presented to validate the method on benchmark problems of flows around cylindrical and spherical geometric shapes, and turbulent features of the flows are analyzed.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: An Inelastic Model with Embedded Bounce-Back Control and a Ghost Mesh Technique for Layered Printing with Cementitious Materials

Author(s): *Arif Masud, *University of Illinois at Urbana-Champaign*; Ignasius Wijaya, *University of Illinois at Urbana-Champaign*;

This talk presents a thermodynamically consistent model for curing processes in 3D printing with cementitious materials. The evolution of mechanical properties as the printed material cures and stiffens results in non-physical reduction in the magnitude of elastic strains when standard constitutive models are employed. This elastic recovery of the printing induced deformation contradicts the experimentally observed behavior of the printed cementitious materials that harden at a nearly-frozen deformed state. A thermodynamically motivated constraint on the evolution of elastic strains is imposed on the Drucker-Prager constitutive model to remedy the non-physical bounce-back effect. An algorithm that appends a strain-projection technique to the elastic part of deformations is developed that complements the inelastic response given by the Drucker-Prager model. It is then embedded in a finite strain finite element framework for the modeling and simulation of cure hardening and inelastic response of the early age cementitious materials [1]. A ghost mesh method is proposed for continuous layer-wise printing of the structures without the need for intermittent mesh generation technique or adaptive remeshing methods. A ghost mesh technique is proposed for sequential printing of layers of material, and a moving point is defined to represent the kinematics of the printing nozzle. At each step, integration points around the nozzle are activated and assigned the actual stiffness and density of the material. This process simulates layered printing of the structure. The model is validated via comparison with experimental data and representative test cases are presented that investigate the mathematical and computational attributes of the proposed model.

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Development of a Physics-Based Model to Simulate an Extra-Terrestrial Habitat with Damageable and Repairable Capabilities

Author(s): Adnan Shahriar, *The University of Texas at San Antonio*; Sterling Reynolds, *The University of Texas at San Antonio*; Arsalan Majlesi, *The University of Texas at San Antonio*; *Arturo Montoya, *The University of Texas at San Antonio*;

The design of long-term deep space habitats is challenging due to the extreme demands of deep space environments. Researchers aim to design resilient extra-terrestrial habitats that operate under deep-space environmental hazards, autonomously detect and repair damages, and remain functional over long periods. A physics-based simulation framework is essential to understand the behavior of space habitats under extreme loading conditions. Incorporating structural damage and degradation in real-time is crucial to assess the system-level performance and capture complex interactions among sub-systems of the habitat, including the structural system, thermal system, and interior environment. This presentation will describe the development of a physics-based, real-time sequentially coupled thermo-mechanical model of a space habitat. The model accounts for hazards, such as solar radiation, thermal loading, internal pressure, and hypervelocity impact. The mesh consists of 21-node brick elements with a center node at the outer face of the element to apply a force function that replicates the loading due to a meteoroid impact. The model simulates the damage due to meteoroid impact at different thermal loading conditions using material softening with the Von-mises and Drucker-Prager yield criteria. Real-time performance was achieved by employing Guyan reduction and domain decomposition techniques. Future work will incorporate damage due to fatigue, material degradation, and plastic deformation caused by solar radiation and thermal expansion over long periods.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Resilience Enhancement of Power Distribution Systems in a Changing Climate: Investment Planning via Multi-Stage Stochastic Optimization

Author(s): Nariman Dehghani, *The Ohio State University*; Abdollah Shafieezadeh, *The Ohio State University*; *Ashkan B. Jeddi, *The Ohio State University*;

Past weather and climate extremes have challenged the resilience of power distribution systems. Despite recent advancements in hurricane resilience enhancement of the grid, incorporating various impacts of climate change in planning frameworks remains an important challenge. Change in climate conditions alters hurricane hazards, and consequently affects hazard vulnerability of distribution systems. The present work addresses this challenge by integrating uncertain climate projections into the investment planning process to reach a resilient distribution system. To achieve this objective, a multi-stage stochastic optimization model is developed that accounts for multitude of uncertainties, including characteristics of hurricane hazards under climate change, physical vulnerability of the system, and recovery process. In this optimization model, the projected effects of changing climate are captured via the representative concentration pathway (RCP) scenarios. The optimization model is devised to find optimal hardening strategies against stochastic hurricane events in order to improve robustness and resistance of the distribution system to extreme events. This model also determines optimal locations for placing distributed generation (DG) units in the system to facilitate strategic formation of microgrids after a disastrous event, allowing uninterrupted supply of electricity in supported areas. The proposed framework is applied to a modified IEEE 33-bus system.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Post-Hurricane Loss Assessment Using Crowdsourcing: A Probabilistic Approach

Author(s): *Asim Bashir Khajwal, *Texas A&M; University*; Arash Noshadravan, *Texas A&M; University*;

One of the immediate requirements following a disaster event is to efficiently collect the data from the affected region and estimate the severity and extent of the damage caused by the disaster event. This information is essential for situational awareness and the informed decision-making required for effective recovery and restoration of the region. The traditional methods of acquiring such data are often expert-dependent and require dispatching trained professionals and inspection teams to perform door-to-door damage assessments. This can be a resource-intensive, inefficient, and time-consuming process. To address this limitation, crowdsourcing in disaster management is emerging as a more efficient and scalable alternative to an expert-centric approach for collecting disaster information. The present study aims to leverage crowdsourcing as a means for enhancing the practice of preliminary post-disaster damages assessment. The damage levels associated with each building, together with the identification of building attributes performed using public intelligence, can then be subsequently mapped to the estimated monetary loss resulting from the disaster event. However, crowdsourcing and participatory sensing are always subjected to uncertainty and unreliability, which can hinder our ability to make decisions with a sufficient level of confidence based on the outcome of crowdsourcing. To address this challenge, the proposed study aims to quantify and reduce the uncertainty associated with the crowd assessment of the damage levels and account for unreliability among the crowd participants. The idea is to develop a statistical inference model that could estimate correct inference about the actual damage levels of the buildings, given the noisy damage labels reported by the crowd participants. However, specific to the problem at hand, (a) ordinality among the damage levels needs to be accounted for, (b) correlation among the crowdsourced labels needs to be incorporated in the inference model. The reliability of crowd workers will also be parameterized in terms of a confusion matrix, quantifying the reliability of each worker over different tasks rather than one single metric. The study is based on modeling the labels as a mixture of multiple independent multinomial distributions. The maximum likelihood estimates of the true labels are then inferred through the Expectation-Maximization algorithm. The proposed framework is tested and demonstrated using real-world post-hurricane damage data outsourced to the anonymous crowd using Amazon Mechanical Turk (M-Turk) crowdsourcing platform.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Probabilistic Data Analytics for Improved Closest Hospital Suggestion in New York City

Author(s): *Audrey Olivier, *University of Southern California*; Matthew Adams, *New York City Fire Department*; Sevin Mohammadi, *Columbia University*; Andrew Smyth, *Columbia University*; Kat Thomson, *New York City Fire Department*; Edward Dolan, *New York City Fire Department*;

This talk will present an initiative, undertaken in collaboration with the NYC Fire Department, to integrate probabilistic data analytics in order to optimize emergency medical services in the greater NYC area. Regarding transports to hospitals, FDNY policy dictates that every patient is to be transported to the nearest – in terms of travel time - appropriate hospital based on medical condition. This goal is achieved through the so-called Hospital Suggestion Pattern, which uses the geographic location of the incident (based on a geographical entity called an atom), to suggest the closest hospital that meets the needs of that patient. Derivation of this pattern must rely on accurate predictions of ambulance travel times. Large amounts of data from two different sources – past atom-to-hospital ambulance transports data as well as AVL and telematics data – are fused to calibrate and correct the ambulance travel time predictions from a road network analysis. When handling such datasets, careful consideration is placed on quantification of both epistemic and aleatoric uncertainties. Aleatoric uncertainties arise from the inherent stochasticity in the system being modeled, i.e., traffic, driver's behavior, uncertainty in the incident location within an atom and so forth. Epistemic uncertainties on the contrary arise from a potential lack of data for certain specific atom-to-hospital routes, considering for instance that the data is highly biased towards hospitals that were recommended by the previous pattern. Furthermore, considering the significant variations in traffic that occur during an average day in NYC, we also present a method to segregate the day into various time blocks for which the Hospital Suggestion Pattern will be different. This analysis relies on the derivation of a particular distance metric between patterns and the use of clustering algorithms to agglomerate hours of the day. As a result of this work, a newly derived Hospital Suggestion Pattern was derived and implemented by the FDNY. We will provide comments on its performance, demonstrating the potential benefits of integrating data analytics tools in real-life applications.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Physically-Informed Deep Learning of High-Dimensional Nonlinear Dynamic Systems Subject to General Stochastic Wind Excitation

Author(s): *Bowei Li, *University of Michigan*; Seymour Spence, *University of Michigan*;

Simulation of structural responses in extreme events, e.g., hurricanes, is of great interest to engineers in both design and analyses. Such simulations often involve significant computational effort due to complex nonlinear behaviors. Moreover, this computational burden can be further exasperated in applications such as uncertainty propagation and numerical optimization where repeated analyses are required. To address this issue, this work is focused on the development of a metamodeling framework through physically-informed deep learning techniques for multi-degree-of-freedom (MDOF) nonlinear dynamic systems subjected to general stochastic wind excitation. The proposed framework entails model order reduction as well as physically-informed deep learning. A global bases for the system is extracted through the proper orthogonal decomposition of snapshots of the high-dimensional response. This enables a projection-based model order reduction to be considered for reducing the dimensionality of the MDOF system. Subsequently, a physically-informed deep learning technique is implemented to capture the dynamics of the reduced system, where physical information on the system is integrated into the loss function. The typically long duration of the wind inputs and outputs can lead to a potentially large computational demand. To address this, wavelet projections were considered to reduce the time histories through transformation to wavelet coefficient series. The deep learning networks were subsequently trained for the mapping between the wavelet coefficient series of the inputs and outputs. As an illustration, a 37-floor building structure is considered for the case study. The metamodel is shown to be capable of accurately reproducing the response time histories of all DOF with an efficiency gain of over six orders of magnitude as compared to the high-fidelity model.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Topology and Shape Optimization Based on the Shifted Boundary Method

Author(s): *Boyan Lazarov, *Lawrence Livermore National Laboratory*; Nabil Atallah, *Lawrence Livermore National Laboratory*; Guglielmo Scovazzi, *Duke University*; Vladimir Tomov, *Lawrence Livermore National Laboratory*;

Topology optimization is an iterative process aiming to find a distribution of two or more materials that minimize a selected performance measure and fulfills a set of constraints. The material distribution is modeled using an indicator function, which is usually relaxed to be continuous. The relaxation allows the employment of gradient-based optimization techniques in the solution process. Ideally, the results from topology optimization will be black and white 2D/3D images with well-defined boundaries. However, for density-based design, the final material distribution field consists of solid, void, and grey transition regions that require post-interpretation. The mesh size necessary for solving the physics of the problem at every optimization step has to be smaller than the width of the grey transition areas. Thus, realistic 3D problems can easily necessitate multibillion degrees of freedom. In addition to the high computational cost, the mesh size limits the design changes resulting in a significant increase in the total optimization cost.

The size of the problem can be reduced by explicitly tracking the solid-void interface. However, due to the requirements for re-meshing and the complexity of the algorithms, the tracking techniques did not receive wide acceptance. Therefore, the goal of this talk will be to demonstrate an efficient alternative - the application of the shifted boundary/interface method for removing the effect of the grey transition on the solution, avoiding re-meshing, reducing the number of optimization iterations, and allowing for efficient parallelization. High-order elements are utilized to express both the solution of the associated physical problem and the density, reducing the size of the problem and the computational cost an order of magnitude. The examples are implemented in MFEM, which is a lightweight, scalable C++ library for finite element methods.

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Measurements of the 3-Component (3C) Dynamic Displacements of Full-Scale Structures Using an Unmanned Aerial System (UAS)

Author(s): *Brandon Perry, *Colorado State University*; Yanlin Guo, *Colorado State University*; Rebecca A. Atadero, *Colorado State University*;

Measuring the 3-Component (3C) dynamic displacements is vital for structural health monitoring and finite element model updating. Currently, these measurements rely on accelerometers or other sensors attached to a structure. Logistical issues impede the implementation of these sensors across many bridges (e.g., wiring, time synchronization if wireless, placement, inability to relocate, and inability to measure displacements directly with accelerometers). Recently, the advancements of Unmanned Aerial Systems (UASs) have allowed for remote sensing of structures with a UAS flying around a structure and collecting data. There are existing studies on UAS-enabled remote displacement measurements; however, the implementation is limited due to 1) only measuring 1C or 2C displacements[1][2], 2) close measuring distance to the region of interest[3], 3) requirements of special lighting conditions, 4) small horizontal measuring distance of the sensors, or 5) requiring unique, identifiable patterns for reference targets. To facilitate 3C dynamic displacement measurements with sensors attached to a UAV in a more generalizable environment, this study proposed a UAS system incorporating: two optical sensors facing the structure and an additional two optical sensors at a 90° angle pointed at a stationary reference (i.e., bridge pier or ground). Each two-camera pair implements stereo vision using natural features inherent in the region of interest. With the natural features identified, the movement of the UAV is tracked, and the true movement of the structure is measured. The UAV will fly 5-meters away from the structure and perform full-field dynamic displacement measurements within a 4x4-meter² area of the structure without requiring special lighting conditions. The proposed system is validated in a controlled lab setting to assess its accuracy and performance. The proposed system allows for a portable 3C full-field dynamic displacement measurement without the need for reference targets.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Quantification of Breakage During the Compaction of Granular Materials Across Strain Rates

Author(s): *Brett Kuwik, *Johns Hopkins University*; Max Garcia, *Johns Hopkins University*; Ryan Hurley, *Johns Hopkins University*;

The compaction of granular materials is ubiquitous throughout disciplines including food production, geomechanics, manufacturing, and penetration of brittle materials. During the compaction of granular materials, three distinct stages are often delineated by inflection points in plots of the logarithm of axial/compaction pressure versus the theoretical density. In each stage, different mechanisms (particle rearrangement, breakage, and intra-particle plasticity) are thought to be dominant. Previous literature has documented these stages of granular compaction during various experiments; however, few studies have quantified the stages using a particle breakage index. Furthermore, few studies have examined the mechanisms active in the third stage of compaction and the effects of strain rate on stage transitions. This presentation focuses on examining granular compaction as a function of strain rate across all three stages of compaction using a particle breakage index and acoustic emissions measurements. Compaction of Ottawa sand was investigated as a function of strain rate by using an MTS load frame, a drop tower impact system, and a Kolsky bar. Breakage was quantified with a relative breakage index defined using the initial, current, and theoretical ultimate particle size distribution (PSD). Porosity evolution was measured using high-speed photography and DIC. Sample stress states were quantified using strain gauges. For all experiments, PSDs were measured in a Morphologi 4ID using 2D images of the particles. For a given strain rate, compaction stages were identified by plotting the logarithm of axial/compaction pressure versus the relative breakage index. Three distinct stages were observed by two inflections points in these plots. These results were compared to a plot of the logarithm of axial/compaction pressure versus percent theoretical density and a slow-down of breakage rates coincided with inflections of the loading path. This result indicates that the rate of particle breakage during compaction is dependent upon the stage of compaction. Increasing strain rates increased the pressure at which stage transitions occurred. In quasi-static experiments, breakage was also measured by recording the number and intensity of acoustic emission events. It was observed that each stage featured different acoustic emission activity, and the stage with the highest acoustic emission activity coincided with peak rate of breakage measured from PSD. We will discuss the applications of this data to mechanism-based modeling of sand penetration.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: A Simple Constitutive Law for Comminuted Ceramics Under Multi-Axial Loading

Author(s): *Bryan Love, *U.S. DEVCOM Army Research Laboratory*;

The flow of comminuted ceramic during multi-axial loading is relevant to longstanding challenges in penetration mechanics for Army applications. Here, we seek to develop a robust, “necessarily complex” constitutive model for use in hydrocodes that takes into account, on average, the evolution of particle sizes and its effect on the pressure-volume and shear behavior of the fractured material. Concepts common to geological/granular materials, such as interparticle locking/jamming, are incorporated into both elastic moduli (and thus wave speeds) and flow strength, in an attempt to elucidate behaviors seen experimentally that are poorly captured in existing models. Relevant ceramics are fully dense during their initial comminution, with free volume only arising during the subsequent shearing of the material, requiring extension of theories towards limiting cases. Careful consideration is given towards the theoretical and numerical simplicity and stability—critical when a constitutive model is evaluated billions of times in a single simulation with a wide range of confining pressures, stress states, and shear strains. The resulting model is demonstrated by illustrating observed physical phenomena from multi-axial experiments that were not present in its predecessors.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Effect of the Structural Wall Modeling in the Seismic Response of Buildings with Force-Limiting Connections Between Diaphragm-to-Wall Joints

Author(s): *Carlos Franco Mayorga, *University of California San Diego*; Kyoungyeon Lee, *University of California San Diego*; Georgios Tsampras, *University of California San Diego*;

This presentation focuses on the effect of the numerical modeling approach used to simulate the nonlinear flexural behavior of reinforced concrete structural walls on the seismic response of building models with force-limiting connections (Tsampras et al. 2016) between the diaphragm-to-wall joints. A twelve-story building with flexure controlled special structural reinforced concrete wall seismic force-resisting system was considered in this study. Two wall modeling approaches were used to simulate the nonlinear flexural seismic response of the wall. The first approach considers a nonlinear spring hinge that assumes lumped inelasticity at the base of the wall. The second approach considers force-based fiber beam-column elements that assume distributed inelasticity along the length of the wall. Experimentally validated material model parameters were used to simulate the stress-strain response of concrete and steel reinforcement fibers of the force-based beam-column elements (Thomsen and Wallace 2004; Birrell et al. 2021). Both approaches assumed linear-elastic shear response. Numerical earthquake simulations of the twelve-story building models were conducted using eighteen design basis earthquake level ground motions. The numerical earthquake simulation results show that the floor total accelerations and the force responses in the building models with force-limiting connections are less sensitive to the wall modeling approach compared to the floor total accelerations and the force responses in the building model with rigid-elastic connections. The distributed inelasticity modeling approach results in larger story drift demands compared to the story drift demands calculated considering the lumped inelasticity modeling approach in the building models with force-limiting connections and in the building model with rigid-elastic connections.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Ignition of Self-Supported Turbidity Currents via Waves and Currents

Author(s): *Celalettin Ozdemir, *LSU Department of Civil & Environmental Engineering*; George Xu, *LSU Department of Oceanography & Coastal Science*; Samuel Bentley, *LSU Department of Geology & Geophysics*;

Turbidity currents are one of the agents that rapidly emplace massive amounts of sediments from the continental shelf to the deep ocean. These energetic flows threaten submarine infrastructure such as submarine telecommunication networks. The initiation mechanisms for turbidity currents vary from earthquake-triggered submarine landslides to tsunamis and tropical cyclone- and current-induced sediment suspension. In this study, the critical conditions for turbidity current generation, triggered by the currents parallel to the shore, are investigated semi-analytically. In this approach, it is postulated that there exists a slow-moving turbidity current that can only be sustained by waves and currents, known as wave- and current-supported turbidity current (WCSTC). The positive feedback between erosion and growth of WCSTCs is incorporated through a non-linear dynamic equation of suspended sediment amount. By analyzing the stability of the dynamic equation developed, critical parametric combinations, i.e., critical shear stress, sediment settling velocity, and slope, that lead to self-supporting turbidity currents are obtained. The critical parameters were in agreement with turbulence-resolving high-fidelity simulations. In this presentation, the development of the dynamic equation of sediment suspension and the implications will be discussed in detail.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: A Concurrent Model Framework for Self-Consistent Homogenization Based Parametrically Upscaled Continuum Damage Mechanics (PUCDM) Model for High Strain-Rate Response of Composites

Author(s): *Chandra Prakash, *Johns Hopkins University*; Somnath Ghosh, *Johns Hopkins University*;

In this work, a Parametrically Upscaled Continuum Damage Mechanics (PUCDM) model is developed for unidirectional carbon fiber/epoxy composites subjected to high strain rate impact. The PUCDM models are thermodynamically consistent, reduced-order macroscale constitutive models with explicit representation of microstructural morphology and microscale damage evolution. Conventional homogenization approaches for predicting the effective dynamic mechanical response of composite materials, neglect the effect of micro-inertia, which has a significant effect under high-strain-rate loadings. The PUCDM model is developed using a self-consistent homogenization framework accounting for microscale inertia due to stress wave superposition and annihilation within the microstructure at high strain rates loading. The proposed framework uses a concurrent model with an RVE embedded in a homogenized domain whose constitutive behavior and damage initiation and evolution are described by the PUCDM model. The concurrent framework considers dynamic effects arising at the boundary of the representative volume element (RVE) due to stress waves interacting with micro heterogeneities. A Lagrange multiplier-based approach enforces the traction reciprocity and displacement continuity between the RVE and the extended homogenized domain. The micro-inertia effect appears as an effective body force in the equations of motion at the macroscale. The phase-field damage model is used for the fiber-matrix interface debonding, fiber breakage, and matrix cracking in the RVE microstructure under high strain rate impact loading. PUCDM parameters are then calibrated using energy equivalence between the RVE and the exterior domain. The resulting PUCDM model is used to analyze the stress wave propagation and damage evolution in composite structures at multiple strain rates in the range of $10^2 - 10^5 \text{ s}^{-1}$. The model is used to capture the effect of fiber distribution on the impact-induced damage and failure phenomena. The PUCDM model with the micro-inertia effect developed in this work offers a relatively simple tool to analyze the dynamic mechanical response of composites under high strain rate loading.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Image-Based Experimental Investigation of Fatigue Crack Initiation and Small Crack Growth of Additively Manufactured Ti-6Al-4V

Author(s): *Changyu Meng, *Arizona State University*; Jie Chen, *Arizona State University*; Luke Hase, *Arizona State University*; Yongming Liu, *Arizona State University*;

Additively Manufactured (AM) Titanium alloy (i.e., Ti-6Al-4V or Ti64) using laser powder bed fusion (LPBF) has excellent potential for industrial applications. However, many previous studies have found that the fatigue properties of AM Ti64 are inferior due to the defects generated from the LPBF process. The process parameters-structure-fatigue properties relationship has not yet been fully understood. Most existing studies for AM Ti64 focused on the safe-life (S-N curve) or long fatigue crack growth analysis. In contrast, the current research focuses on the initiation and growth of small cracks as these stages are dominant for fatigue life of as-built Ti64 components.

The AM defects and their properties are closely related to building parameters, such as laser power and scan velocity, which is often summarized as the process map. Building orientation may also play a vital role in the anisotropy of Ti64 fatigue property. In the current work, another focus is to investigate the influence of contour building parameters on the near-surface defect level and crack growth. As most of the fatigue failures of as-built AM components initiate at the defects within the external contour zone, their effects on small fatigue crack initiation and growth in Ti64 alloy will be explored in a comprehensive approach.

Image-based methodologies are used to perform qualitative and quantitative fatigue analysis. The specimens are scanned using micro-CT before and during the fatigue testing through a periodic procedure, while SEM is applied to observe the final fractured surfaces. The proposed efficient image analysis protocols are used to 1) track the small crack initiation and growth in 4D along the entire gauge section volume, 2) analyze the correlation between crack initiation sites and initial surface and subsurface defects, and 3) quantitatively model the small crack growth behavior. It is worth to mention that a machine learning-based segmentation method is adopted to segment the 3D cracks with blur edges.

The results show that the contour building strategies significantly influence the near-surface defect level and thus the small fatigue crack behavior. The proposed pore influence factor reasonably predicted the detrimental crack initiation sites. An angled building orientation was shown to hinder the fatigue crack growth under uniaxial cyclic loading. This information would provide valuable guidelines for the damage tolerance design of critical fatigue load-bearing AM Ti64 components. In the future, physics-guided machine learning will be adopted to predict the small fatigue crack initiation sites and fatigue life more accurately.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Identification of Seismic Input Motions in a Near-Surface 2D Domain Subject to Unknown SH Incident Waves

Author(s): Bruno Guidio, *Central Michigan University*; *Chanseok Jeong, *Central Michigan University*;

We present a new inversion method for estimating incident shear wave motions propagating into a domain surrounded by the domain reduction method (DRM) layer from sparsely-measured seismic motion data. We consider a 2D domain, of SH wave motions, truncated by wave-absorbing boundary conditions (WABC), and the DRM is utilized to inject incident waves into the domain.

We identify an effective seismic force (equivalent to incident waves) at the DRM layer that can induce the wave responses being identical to their counterparts measured at sensor locations on the top surface. The state-adjoint-control equations-based inversion method minimizes a misfit between measured motions induced by targeted effective forces and their estimated counterparts.

The numerical results show that our reconstructed effective force agrees with their targeted counterpart after systematic postprocessing is applied on the reconstructed force. We will discuss the theoretical background on this postprocessing and justify it. To accurately reconstruct the targeted effective force, a minimal number of sensors per distance is required, and it clearly depends on the dominant frequency or wavelength of incident waves.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Analytical Modeling and Laboratory Characterization of Elastic Moduli Dispersion and Poromechanical Responses of Dual-Porosity Dual-Permeability Porous Materials

Author(s): *Chao Liu, *Aramco Americas: Aramco Research Center-Houston*; Dung Phan, *Aramco Americas: Aramco Research Center-Houston*;

The elastic moduli dispersion of materials is a topic of great interest in many engineering practices. Such dispersion is regularly measured on laboratory-preferred cylindrical samples of various nature, from solid dry to single-porosity and dual-porosity dual-permeability fluid-saturated materials. Analytical modeling of these laboratory tests is desired as it is effective and time-efficient in the interpretation of the experimental results and the characterization of poromechanical properties of the material. To this end, for the first time, we present analytical modeling of the elastic moduli dispersion and the poromechanical behaviors of a dual-porosity dual-permeability fluid-saturated cylinder under a dynamic forced deformation test. Our dual-porosity dual-permeability poroelastodynamics solution can be easily reduced to the elastodynamics and the single-porosity poroelastodynamics ones.

We illustrate our solution with a naturally fractured rock sample and discuss the effects of natural fractures, pore fluid, and sample size on the dispersion of elastic moduli and poromechanical behaviors. It has been known that to maintain a constant displacement amplitude, the force applied depends on frequency, reaching a low at the resonant frequency and a high at the antiresonant frequency. Our simulations additionally show that the force also changes significantly between three models (elastodynamics, single-porosity poroelastodynamics, and dual-porosity dual-permeability poroelastodynamics), thus underlying the need to carefully apply an appropriate model to the studied material. Spatial distributions of poromechanical quantities, such as pore pressure and strain, are shown to be mostly uniform at low frequencies and become increasingly nonuniform at high frequencies. The simulations also reveal that the dynamic Young's modulus and Poisson's ratio are highly dependent on the Biot's and Skempton's coefficients, the sample's dimension, and the loading frequency. The dispersion trends of these dynamic elastic moduli vary as the loading frequency approaches the material's resonant and anti-resonant frequencies. Finally, we apply our analytical solution to match laboratory-measured dynamic Young's moduli and Poisson's ratios of rock samples from the North Sea and a shale sample from Mont Terri. The good matches found between simulations and laboratory data show the effectiveness of our solution. We envision that our solution will advance the understanding of the mechanism behind the dynamics of dual-porosity dual-permeability fluid-saturated porous materials. A direct benefit of the solution is in the analytical simulation and interpretation of laboratory experiments with applications in many engineering areas such as civil engineering, seismic monitoring, hydraulic fracturing, and human bone/organ injuries.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Ductile Fracture of Advanced High Strength Steels at Elevated Temperatures

Author(s): *Chenzhi Ma, *Johns Hopkins University*; Thomas Gernay, *Johns Hopkins University*;

The ability to predict the failure of steel structures under fire is an important requirement to support the development of performance-based structural fire design. While considerable research has focused on the modeling of the fire behavior of steel structures, there is still limited data on the ductile fracture behavior of different steel grades under elevated temperatures. Experimental characterization of ductile fracture at elevated temperature is necessary to feed into constitutive models for simulation of limit states of steel members and connections in the fire situation. In this presentation, we will describe an ongoing experimental effort to characterize the ductile fracture behavior of cold-formed high strength steels at elevated temperature. The study considers one advanced high-strength steel (AHSS) grade with nominal yield stress of 825 MPa and a high-strength low-alloy (HSLA) steel with nominal yield stress of 340 MPa. Five different coupon shapes are engineered to generate various stress states at the failure location. The steels are tested to failure at temperatures ranging from 20 °C to 700 °C and under different stress states. The presentation will discuss the combined experimental-numerical strategy used to relate the equivalent strain at fracture and the stress triaxiality, which then allows constructing the temperature-dependent fracture locus for each steel grade. The results show the effects of stress triaxiality, temperature, and steel grade on the ductile fracture behavior. New predictive models are proposed to predict the fracture loci of the tested cold-formed high-strength steels at elevated temperatures up to 700°C. Finally, we will discuss the incorporation of these ductile fracture models into a comprehensive plasticity-damage constitutive model for steel at elevated temperature. This research aims to advance the modeling capabilities for assessing the fire performance of steel structures, including through detailed modeling of connections and other members subjected to multiaxial stress states in the fire situation.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Wind-Induced Vortex Interaction on T-Shaped Bluff Bodies.

Author(s): *Chia Mohammadjani, *Florida International University*; Manuel Matus, *Florida International University*; Ioannis Zisis, *Florida International University*;

Abstract

Unsteady turbulent flow around bluff bodies incorporates a vast domain of scientific fields in aerodynamics and aeroelasticity with a thick margin of uncertainties in their application in structures. The vortex structure due to flow separation on sharp-edged bluff bodies has been studied extensively in the past. High wind-induced pressures on civil engineering structures are associated with these vortices, e.g., conical vortices are responsible for particularly high suction on building roofs. An area within this topic that appears not to have been studied adequately, is related to the interaction of vortices generated by flow separated on orthogonally connected bluff bodies and flat plates. Several examples of such complex integrated volumes do exist in civil engineering structures, such as balconies attached to mid/high rise buildings, rooftop equipment, podium-like structures, canopies, etc. The interaction between the volume and the plate together, as a form of a T-shaped bluff body, leads to vertical/horizontal turbulences which are responsible for high wind-induced pressures, and more importantly, causes relocation of the high pressure/suction zones.

The current study has completed a limited set of wind tunnel tests and a more detailed experimental investigation is underway. Physical testing will help us inspect and understand the mixing of those vortices in T-shaped bluff bodies for different wind directions. Up to date results appear to explain some unconventional pressure rises over the bluff body's surface and show that the leading-edge vortex (LEV) stretches forward, causing negative pressure zones at the central part of the flat plate and the interaction line with the bluff body. The importance of mixed vortex formations in a T-shaped bluff body will help to better understand its aerodynamic performance and critical parameters related to the codification and design loads.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Modeling of NHERI-UCSD Upgraded 6-DOF Large High-Performance Outdoor Shake Table

Author(s): *Chin-Ta Lai, *UC San Diego*; Joel Conte, *UC San Diego*;

The NHERI-UCSD Large High Performance Outdoor Shake Table (LHPOST) was commissioned on October 1, 2004, and was used extensively since then to conduct a variety of high-quality large- and full-scale structural and geo-structural tests with its significant payload capacity and unlimited specimen height. Funded by the National Science Foundation (NSF), the project to upgrade the LHPOST from its previous 1-DOF to the current 6-DOF configuration started in October 2018 and the LHPOST was closed for operations in October 2019 to enable the construction of the upgrade

The 6-DOF LHPOST, referred to as LHPOST6 to distinguish it from the 1-DOF LHPOST, consists of four horizontal inline actuators and six vertical actuators with pressure balanced bearings to drive the steel platen, as well as three nitrogen-filled hold-down struts to provide the overturning moment resistance. The hydraulic components are controlled by servovalves to generate actuator forces and velocities, while the hold-down struts passively respond to their displacements and introduce elastic restoring forces along their axes. In this study, a model of the LHPOST6 under bare table condition is developed to represent the open-loop dynamics of the shake table system, namely from the servovalve spool positions to the platen motion. This model contains two parts: (1) a servovalve model to simulate the nonlinear behavior from the fourth-stage spool position to the flow into and from the chamber(s) for each actuator and the flow mass conservation equation to obtain the actuator forces, and (2) the kinematics between the platen and the components as well as the rigid body dynamics of the platen to simulate the platen motion based on the resultant forces from the the components connected to the platen, including the dissipative (e.g., friction and viscous) forces.

The LHPOST6 open-loop model is validated using experimental data acquired during the acceptance tests performed on the LHPOST6 in July 2021 – January 2022. The LHPOST6 model parameters are identified/calibrated using the sine wave and triangular wave test data. In the model validation process, the recorded servovalve positions calculated by the MTS 469D shake table controller are treated as the input of the open-loop model, and the simulated platen motion, which is the model output, is compared to the recorded achieved table motion to investigate the model prediction capability. The validated LHPOST6 model can then be used in further studies to investigate the interaction between various test specimens and the shake table system.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Inspection of Cracks in Welded Joint Using Active Thermography and Deep Learning-Based Detection

Author(s): *Chisung Kim, *Korea Advanced Institute of Science and Technology*; Hoon Sohn, *Korea Advanced Institute of Science and Technology*;

Welding is a connection method that makes two materials act as one structure. And, welding has not only higher bonding efficiency, but also easier reparability than other connection methods such as bolting and riveting. Therefore, welding is widely used in many manufacturing fields as well as civil engineering fields. However, the weld is vulnerable to cracks, especially when repeated and accumulated loads are applied to the weld. Once a crack occurs in the weld, it grows rapidly, causing material failure and even structural collapse. Therefore, it is important to accurately inspect weld cracks at an early stage so as not to cause a huge loss to human safety and economy. Recently, crack inspection using computer vision and deep learning-based detection has been actively studied. However, these crack inspection studies are difficult to apply to welded joints for two reasons. First, there are many patterns with colors and shapes similar to cracks on the welded surface. Therefore, no feature difference between patterns and cracks is measured by a normal vision camera. Second, securing real weld crack data enough to train deep learning-based detection is difficult. Not enough training data cause overfitting and poor accuracy problem. In this study, a new weld crack inspection method that overcomes the above two problems is proposed. First, an active thermography system, which generates heat on the welded surface and measures corresponding temperature change, is used for weld crack inspection. Thermal feature difference between patterns and cracks occurs, which is measured by the active thermography system and analyzed through deep learning-based detection. Second, Generative adversarial network (GAN) is used to supplement insufficient weld crack data by generating more diverse weld crack data than conventional data augmentation techniques such as rotation, flipping, and scaling. The proposed method consists of the following: 1) measurement of thermal feature and image processing, 2) detection of crack. The effectiveness of the proposed method is validated through detection performances in field-testing.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: A Comparative Study of Methods for Two-Phase Minimum Length Scale Control in Topology Optimization

Author(s): *Christiaan Mommeyer, *KU Leuven*; Geert Lombaert, *KU Leuven*; Mattias Schevenels, *KU Leuven*;

Topology optimization searches for an optimal distribution of material within a design domain, resulting in a design with two phases: solid (presence of material) and void (absence of material). When all features belonging to a phase can be covered by a disk (2D) or ball (3D) with a certain diameter entirely contained within that phase, the design has a minimum length scale of that diameter in the phase under consideration. A design with a minimum length scale in both phases is often desirable because it can be more easily manufactured and avoids stress concentrations around sharp corners or in small features of the design. For achieving such a two-phase minimum length scale in topology optimization, several techniques have been developed. Robust topology optimization (Sigmund 2009, Wang et al. 2011, Lazarov et al. 2016), in which morphologically dilated and eroded designs are considered in a min-max approach, is most commonly used. Other techniques make use of geometric constraints (Zhou et al. 2015), morphological close and open operations (Hägg and Wadbro 2018), or a two-phase projection approach (Carstensen and Guest 2018). More recently, Liang et al. (2020) suggested a method for achieving a two-phase minimum length scale in their canonical relaxation framework for topology optimization.

In this contribution, the strengths and weaknesses of methods for two-phase minimum length scale control are assessed critically, by comparing them when they are applied to minimal compliance and compliant mechanism designs. Existing techniques are tested, as well as new techniques, introduced in this contribution, which make use of Augmented Lagrange or p-norm aggregation for constraints on the non-discreteness or on the length scale violation of a design. Four quantitative aspects are taken into consideration: the value of the objective function, the measure of non-discreteness of the design, the degree of length scale violation in the two phases, and the calculation time needed for the optimization process. The ease of implementation and parametric fine-tuning necessary for the technique, are also reported on. This study finds that the robust topology optimization approach and the approach of using geometric constraints (the two oldest methods) give overall the best performance.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Optimization of Local Topology and Stacking Sequence in Laminated Composites Considering Strength Criteria

Author(s): *Chuan Luo, *Johns Hopkins University*; Federico Ferrari, *Johns Hopkins University*; James Guest, *Johns Hopkins University*;

Fiber-reinforced composite materials have been widely used in industries like aerospace, aeronautical, automobile, etc. Various design methods have been developed based on topology optimization that capture and fully leverage the promising properties of laminated composites to satisfy stiffness and strength demands relevant to engineering applications. However, most strength-based designs focus on failure criteria based on a two-dimensional state of stress, while damage initiation are most often governed by both in-plane and interlaminar stress components. Therefore, we implement a topology optimization framework for optimizing the fiber orientation of each laminate sheet within a stack (the stacking sequence) and across the structural domain while considering different failure mechanisms including non-interactive criteria maximum stress and maximum strain, interactive criteria LaRC-2D, as well as other criteria for predicting delamination initiation. The problem is formulated as minimizing the maximum failure index of tow-steered composite laminates subjected to manufacturing constraints related to fiber orientations.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Deep Neural Network-Based Regional Seismic Loss Assessment Considering Correlation Between EDP Residuals of Building Structures

Author(s): *Chulyoung Kang, *Seoul National University*; Taeyong Kim, *University of Toronto*; Oh-Sung Kwon, *University of Toronto*; Junho Song, *Seoul National University*;

Strong earthquakes can induce many structural failures, leading to casualties and socioeconomic losses in urban areas. Thus, it is essential to evaluate the regional seismic losses accurately considering uncertainties and correlations of structures' engineering demand parameters (EDP). To this end, Kang et al. (2021) proposed an incremental dynamic analysis-based method to estimate the variances and correlation of residuals in EDP termed "EDP residual." Since this method requires a significant number of structural analyses and modeling efforts, regression models were also proposed in Kang et al. (2021). However, improvement of estimation accuracy remains a challenge due to the approximation in the regression models. This study proposes two deep neural network (DNN) methods for efficient and accurate estimation of the EDP residuals of building structures. The first method is to estimate the EDP residuals of buildings where EDP residuals of each mode of a building is predicted with DNN models. Then, the residual of the buildings is evaluated through a mathematically derived formula which integrates the contributions of residuals of each mode to the residual of the building. In the second method, the EDP residuals of buildings are predicted with DNN models where three structural characteristics of a building structure are used as input variable: the first and second modal periods and damping ratio. To handle the EDP residuals of general building structures, all DNN models are trained with the structural analysis results using 1,499 ground motions from the NGA west database. The proposed methods are verified by comparing existing regression models and their applications to numerical examples of regional loss assessment.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Algorithms to Optimize the Printing Ink for 3D Printing

Author(s): *Claudiane Ouellet-Plamondon, *ETS Montreal*;

The 3D printing of concrete has the potential for improving the resources efficiency and climate change impact of construction. Digital construction enables novel structural and multifunctional design. There is a wide array of binders, granular materials, and admixtures available, which influences the chemical, physical, and mechanical processes during 3D printing. The performance target depends on the printing process, the materials available, the cost, and the application. We develop optimization algorithms based on discussion with expert groups to select the raw materials based on the construction context, which influences the type of binder. The technical targets are then selected for the fabrication selected based on coupled chemical, physical, and mechanical processes. The workability tests are important for the extrusion and the pumpability. The buildability and shape stability can be predicted from the direct shear tests. The final strength is measured from compressive strength. Design of experimental with a fractional design plan allows optimizing the number of experiments. The algorithms are being developed for cementitious binders and alkali-activated materials. The environmental impacts of the starting materials are being incorporated in the algorithms, from life cycle assessment parameters. Other performance criteria will be added, including economic and application-specific.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Long-Term Performance of Aged RC Structures via Life-Time History Analysis

Author(s): *Codi McKee, *Texas A&M; University*; Petros Sideris, *Texas A&M; University*; Mija Hubler, *University of Colorado - Boulder*,

This presentation will investigate the behavior of reinforced concrete (RC) frames over the entire life-time of the structure. Over their service life, RC structures age and often experience corrosion of their steel reinforcement and large creep-induced deformations. Reinforcement corrosion significantly reduces the capacity of RC members and causes cracking of the concrete cover, which accelerates the degradation of RC structures. On the other hand, creep-induced deformations cause stress redistribution over the structure, which often results in localized structural damage and the need for repairs. While these two phenomena are important in determining the state of structures prior to an earthquake occurring at the given time during their service life, they are treated separately. However, it is expected that as corrosion progresses, stress re-distribution over the member cross-sections will exacerbate creep deformations, thus affecting the stress re-distribution over the structure.

To address this challenge, this study proposes and investigates the concept of lifetime history analyses, where a structure is analyzed throughout its service life via a time history analysis that starts with the application of the gravity loads at the beginning of service life and ends after an earthquake occurs at a designated time during the service life. During this analysis, reinforcement corrosion and concrete creep are simultaneously considered, thus accounting for their coupled contribution to the response. Corrosion degradation herein includes rebar cross-section area reduction over time as well as degradation of the yield strength, peak strength, strain at peak strength, and strain and strength at fracture over time. The response of the concrete was modeled with a chain of Kelvin-Voigt elements, calibrated to capture recoverable and non-recoverable creep strains, in series with a concrete damage constitutive model that captures the response during application of seismic loads.

Life-time analyses are performed for a variety of target ages, namely 25, 50, and 75 years. The long-term analyses are concluded with monotonic and pushover analyses as well as dynamic analyses with suites of ground motions scaled to various intensities to demonstrate differences in performance metrics due to aging.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Semi-Active Structural Control Using Electromagnetic Transducers: Experimental Validation via Real-Time Hybrid Simulation

Author(s): *Connor Ligeikis, *University of Michigan*; Jeff Scruggs, *University of Michigan*;

Electromagnetic transducers show great promise in the context of semi-active structural control applications. By converting mechanical into electrical energy, these devices behave analogously to linear dampers with controllable damping coefficients. In addition, very little external power is required for their operation, making them attractive for use during extreme events such as earthquakes. In this work, we present bench-scale RTHS results demonstrating the feasibility of implementing semi-active control strategies using an electromagnetic transducer. The numerical substructure is a SDOF building model with linear stiffness and damping, subjected to a random base acceleration excitation. The physical substructure consists of a permanent magnet synchronous machine coupled with a ball-screw mechanism to convert rotational to linear motion. An electromechanical actuator (i.e., a 20-kW induction motor with planetary roller screw) is used to enforce the displacement compatibility condition, and a dSpace DS1103 unit is used to solve the numerical substructure's equations of motion and compute actuator commands in real-time. We demonstrate two types of control laws: optimal static velocity feedback and performance-guaranteed control (PCG). The PCG approach is unique in that it is mathematically guaranteed to improve upon the performance achievable using any static feedback control law. This is in contrast to many semi-active control strategies, such as clipped-LQG where no analytical guarantees can be made regarding closed-loop system performance. The experimental results are compared to numerical simulation results obtained using an identified phenomenological model of the transducer.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: From d'Alembert to Bloch and Back: A semi-Analytical Solution of 1D Boundary Value Problems Governed by the Wave Equation in Periodic Media

Author(s): *Danial Panahandeh Shahraki, *California Institute of Technology*; Bojan Guzina, *University of Minnesota - Twin Cities*;

We propose a simple semi-analytical model for solving one-dimensional (1D) boundary value problems governed by the wave equation in periodic media at arbitrary frequency. When the boundary value problem is well-posed in that the excitation frequency does not match any of its resonant frequencies, any solution that satisfies the field equation and boundary conditions is the (unique) solution of the problem. This motivates us to seek the solution in the form of Bloch waves that by design solve the wave equation with periodic coefficients. For a given excitation frequency this assumption leads to a quadratic eigenvalue problem in terms of the wavenumber k which, in turn, produces a d'Alembert-type solution in terms of the "right"- and "left"- propagating (or evanescent) Bloch waves. In this vein, the solution of a boundary value problem is obtained by computing the amplitudes of the two Bloch waves from the prescribed boundary conditions. For completeness, we consider situations when the driving frequency is: (i) within a passband, (ii) inside a band gap, (iii) at the edge of a band gap (the so-called exceptional points), and (iv) at band crossing (repeated eigenfrequency). From simulations, we find that the semi-analytical solution – expressed in terms of either propagating, evanescent, or standing Bloch waves – is computationally effective and reproduces the numerical results with high fidelity. Consistent with related studies, we also find that the solution of the boundary value problem undergoes sharp transition in a frequency neighborhood of exceptional points. One of the most intriguing results of this study is our finding that near exceptional points, the global resonance of a periodic medium could be induced by "microscopically" adjusting the support locations so they coincide with a shared node of the germane Bloch eigenfunctions. This opens a door toward the design of adaptive wave control systems whose performance can be tuned by adjusting the boundary conditions – as opposed to altering the properties of a periodic medium.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Converging Shock Driven Surface Instabilities in Soft Hydrogels

Author(s): *Daniel Pickard, *Massachusetts Institute of Technology*; Dmitro Martynowych, *Massachusetts Institute of Technology*; Jet Lem, *Massachusetts Institute of Technology*; Anwar Koshakji, *Massachusetts Institute of Technology*; Shaoting Lin, *Massachusetts Institute of Technology*; Xuanhe Zhao, *Massachusetts Institute of Technology*; Keith Nelson, *Massachusetts Institute of Technology*; Bianca Giovanardi, *Massachusetts Institute of Technology*; Raul Radovitzky, *Massachusetts Institute of Technology*;

Intense surface oscillatory eruptions are observed in a confined cylindrical film of hydrogel subject to laser-induced converging pressure loading. A shock-capturing elastodynamic numerical simulation is used to study the dominant mechanisms causing this mechanical instability. Our numerical results indicate that instabilities develop around the boundary of the hydrogel due to the combined effects of negative radial acceleration and the development of compressive circumferential hoop stress along the boundary. Both of these effects require large amplitude oscillations when compared to the characteristic domain size and are easily achieved in the experimental setting of laser induced inertial cavitation of soft hydrogels.

The complex interaction between the boundary and the ensuing converging, reflecting and diverging nonlinear stress waves which cause the instability is found to be fundamentally different from the mechanisms responsible for the well-known, shock-driven Richtmyer-Meshkov instability. Moreover, the time scale of the emergence of the experimental instability is much larger than that of the reflection of shock waves, which is in stark contrast to previously studied shock-driven instabilities. Our experimental results and accompanying numerical models indicate that this instability has not been reported in the soft matter literature.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: A Methodology to Support the Adaptive Reuse of a Historical Dwelling: the Case Study of a 'Sobrado' House-Type.

Author(s): *Daniele Melo Santos Paulino, *The Pennsylvania State University*; Ella Hill, *The Pennsylvania State University*; Heather Ligler, *The Pennsylvania State University*; Rebecca Napolitano, *The Pennsylvania State University*;

The historical center of São Luís is host to a diverse urban ensemble reminiscent of the 18th and 19th centuries. The architectural typology founded there illustrates the strong influence drawn from the Portuguese style known as Pombalino, developed during the reconstruction process of Lisbon after the 1755 earthquake. Thus, the buildings in this region maintain relevant historical features, recognized by UNESCO in 1997 as World Heritage Site. Conserving heritage buildings can help sustain cultural traits while adapting them to modern needs aggregates economic and environmental concerns [1,2]. The present study proposes a methodology to support the adaptive reuse process of Sobrado buildings, the main architectural typology in the historical center of São Luís. It combines two methods to automate the adaptive reuse process: shape grammars (SG) and genetic algorithm (GA). This process focuses on the analysis and redesign of floor plans. Primarily, the methodology provides an iterative tool to automatically determine the location of elements on a given floor plan, considering spatial, structural, and daylight requirements. First, a transformational grammar for the Sobrado dwelling is defined, considering potential multi-family residential arrangements. Then, an optimization module using GA is adopted to evaluate structural solutions considering the damage state of existing structural elements, which for the Sobrado building are primarily masonry walls. The GA incorporates a structural analysis module, allowing the evaluation of potential solutions according to their structural performance. Combining these two approaches results in an efficient design tool, which can approximate different stakeholders in the design processes, such as professionals, contractors, and future users.

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Finite Element Model Updating of Maritime Infrastructure Based on Gaussian Process Regression of Point Cloud Data

Author(s): *David Lattanzi, *George Mason University*; Ken Nahshon, *NSWC-Carderock Division*; William Graves, *George Mason University*;

Remote sensing technologies such as laser scanning and photogrammetry are now able to generate 3D point clouds capable of resolving structural details at the millimeter scale. The result is that computational geometric analysis of these point clouds can now be leveraged to update physics-based numerical models with a level of accuracy suitable for structural analysis applications. In this work, we explore high resolution point cloud analysis in the context of stiffened grillage panels, analogous to those commonly found in marine ship structures. For stability-critical grillages, the initial distortions of the panel play a key role in determining the eventual collapse mechanism. Here, the ability to characterize these distortions in point clouds and subsequently updated a finite element model will be shown. Full-scale grillage panels were subjected to compression testing and stability-induced collapse at the Naval Sea Surface Warfare Center – Carderock Division. To characterize these distortions numerically, point cloud data was collected prior to testing and mapped to a finite element model via Gaussian process regression. This approach provides explicit uncertainty quantification through the variance estimation at each prediction location, as compared to surrogate metrics such as point density and surface roughness. The Gaussian uncertainty also allows for an envelope analysis based on the the variance interval within a point cloud measurement. The results show general agreement between the updated numerical model and experimental data with respect to the observed failure mechanisms and load-shortening curves. Overall, the developed approach provides a pathway for 3D imaging to be used in a variety of finite element model updating applications.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Hydration of Sustainable Cementitious Composite with Internal Conditioning by Functionalized Montmorillonite

Author(s): *Dayou Luo, *University of Massachusetts Lowell*; Jianqiang Wei, *University of Massachusetts Lowell*;

Internal curing has been proven an effective approach to improve cement hydration and concrete properties, while there still exist significant gaps in understanding the efficiency of natural pozzolans, like clays, in this practical technique. Montmorillonite (MT), a reactive clay mineral, has been commonly used as a supplementary cementitious material for cement substitution towards enhancing mechanical strength, durability and sustainability of cement composites. However, the critical challenges, including the extreme water absorption and poor dispersion of MT particles in the cement matrix that negatively impact concrete performance, remain unresolved in this field. In this study, by leveraging the unique water sorption behavior of MT, a novel internal conditioning technique that integrates the benefits of pozzolanic reactions and internal curing was developed. To optimize the role of MT, functionalizations of this clay mineral with two non-ionic surfactants, t-Octyl phenoxy poly ethoxyethanol (C₁₄H₂₂O(C₂H₄O)₁₀, TX-100) and polyethylene glycol ether (C₁₅H₂₄O(C₂H₄O)₁₀, PEG-10), were performed. Then the role of the internal conditioning in enhancing cement hydration, modifying hydration product evolutions, and improving the mechanical strength of cement composites was investigated by partially replacing cement with the functionalized MT saturated with water. The hydration kinetics and development of hydration products of the functionalized MT-based internal conditioning were monitored by isothermal calorimetry, thermogravimetric analysis, activation energy, X-ray diffraction, attenuated total reflection-Fourier transforms infrared spectroscopy, and Raman spectroscopy. To uncover the influences on cement property evolutions, the developments of mechanical strength, microstructure, and chemical shrinkage during hardening were examined. The results indicate that the cement hydration was enhanced by the functionalized MT-based internal conditioning with lower activation energy. Increased chemical shrinkage, more effective portlandite consumption, and formations of additional calcium-silicate-hydrates incorporated with aluminum and aluminum-rich products in the presence of functionalized MT were observed. Compared to raw MT, more densified microstructure and higher strength were obtained from the internal conditioned cement composites containing the functionalized MT.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Fluid-Structure Interaction with ALE Formulation and Skeleton-Based Structural Models

Author(s): *Dimitrios Kalliontzis, *University of Houston*;

This research study investigates a fluid-structure interaction (FSI) framework that combines an Arbitrary Lagrangian-Eulerian (ALE) formulation with skeleton-based structural models consisting of force-based frame elements. A methodology is developed to enable coupling between fluid and force-based frame elements through an ALE formulation. In the proposed methodology, communication between the fluid and skeleton-based domains is performed through a geometric model of the physical fluid-structure interface. With the use of force-based frame elements, the intent is to perform accurate FSI calculations in cases where axial, flexure, and shear motions dominate the structural responses, such as bridge and building systems. The proposed framework is evaluated against FSI problems involving steady and unsteady incompressible laminar flows and different structural models representing horizontal (beam) and vertical (column) solid members.

Title: Exploring the Impact of Excitation and Structural Response/Performance Modeling Fidelity in the Design of Seismic Protective Devices

Author(s): *Dimitrios Patsialis, *University of Notre Dame*; Alexandros Taflanidis, *University of Notre Dame*; Agathoklis Giaralis, *City, University of London*;

The design of seismic protective devices (SPDs), such as fluid viscous dampers, tuned mass dampers and inerter-based vibration absorbers, requires the adoption of appropriate models for describing the excitation, for estimating structural response and for quantifying performance. This study investigates the impact of modeling fidelity on the design of SPDs focusing on these different aspects of the problem formulation that are carefully chosen so that consistency is established. For the excitation, both stationary and non-stationary descriptions are adopted, and for the non-stationary formulation the use of either stochastic ground motion models or scaling of recorder ground motions is considered. Consistency across these characterizations is achieved by establishing compatibility of the corresponding response spectrum. For the structural response, the use of either linear or non-linear structural models is examined, and for the performance quantification both average response and risk-based estimations are considered. The structural models in the case study are originally developed in OpenSees, and to achieve higher efficiency in the SPD design optimization, the reduced order modeling framework recently developed by the first two authors is leveraged. To accommodate a comprehensive comparison for the SPD designs, a bi-objective performance assessment framework is adopted, similar to previous studies from the authors [2,3], considering both the structural vibration suppression and the device control forces as objectives. The impact of the model fidelity is examined by comparing the performance of the designs established through the lower fidelity modeling assumptions (stationarity assumption, linear structural model, average performance estimation) to the performance of the designs corresponding to the higher fidelity assumptions (non-stationary description, nonlinear structural model, risk-based performance estimation), the latter considered to offer the higher accuracy representation of the actual performance. Implementation for all the aforementioned devices are examined, for two different benchmark structures. Results reveal that the use of lower fidelity models may indeed provide sub-optimal performance in certain settings and may compromise the effectiveness of the protective device.

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Improving the Computational Efficiency of Life-Cycle Building-Performance Estimation Through Reduced Order Modeling and Multi-Fidelity Monte Carlo Techniques

Author(s): *Dimitrios Patsialis, *University of Notre Dame*; Alexandros Taflanidis, *University of Notre Dame*; Dimitrios Vamvatsikos, *National Technical University of Athens*;

Performance-based earthquake engineering (PBEE) provides a versatile framework for the quantification of life-cycle performance of building systems. Different PBEE variants exist, with main point of distinction being the fidelity of the models for describing nonlinear structural response and for assessing component or system level vulnerability. Across these variants, the most comprehensive life-cycle performance description is established using nonlinear response history analysis (NLRHA) to define structural response and assembly-based vulnerability to quantify damages and associated consequences. The quantification of the life-cycle performance is established by considering different seismicity levels, represented through appropriate intensity measures (IMs), and by using a number of appropriately selected ground motions, serving as input to the NLRHAs. Statistics defining the life-cycle performance for the output variables can be ultimately obtained considering the various sources of uncertainty impacting them: annual occurrence rates of IMs, response variability for each seismicity level, damage and consequence variability given the structural response. The computational burden for the estimation of these statistics is defined through the total number of NLRHAs performed, which is proportional to the number of seismicity levels considered and the number of NLRHAs utilized per level, and can be very high when high-fidelity finite element models (FEMs) are used to describe structural response. To alleviate this burden, it is common to establish some type of approximation for the uncertainty propagation, using a moderate only number of seismicity levels and ground motions per level. This greatly reduces the total number of NLRHAs needed, but reduces the accuracy of the life-cycle estimates. An even bigger approximation can be accomplished by replacing altogether the NLRHA with a simplified, nonlinear static analysis. This contribution considers two alternative implementations to accommodate the desired computational efficiency while facilitating substantially higher accuracy for the uncertainty propagation: (a) use of reduced order models that are calibrated to closely match the original FEM; (b) adopting a multi-fidelity Monte Carlo setting that combines the original FEM to guarantee unbiased predictions and the reduced order models to establish higher computational efficiency. The improvements accommodated for the life-cycle performance estimation are examined for three benchmark structures by comparing results to approaches that utilize the aforementioned approximations for two different output variables: repair cost (resiliency quantification) and embodied energy associated with repairs (sustainability quantification). To accommodate comprehensive comparisons, estimation of first and second order statistics (mean and variance), as well as of the entire distribution of the output variables are examined.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Unraveling the Mechanisms of Severing of Cellular Actin Filaments During Cancer Progression

Author(s): *Dinesh Katti, *North Dakota State University*; Sharad Jaswandkar, *North Dakota State University*; Kalpana Katti, *North Dakota State University*;

The dynamic remodeling of an actin cytoskeleton is observed in cellular processes such as motility and cytokinesis, tumor cell transformation, and metastasis. The actin filament (F-actin), a linear, helical, and polar polymer formed by the head-to-tail assemblage of actin monomers, is the actin cytoskeleton's central element. The actin-depolymerizing factor (ADF)/cofilin protein family members are the severing proteins responsible for F-actin disassembly. All eukaryotes express ADF/cofilin that plays a critical role in speeding up the actin cytoskeleton remodeling. Our experimental work using 3D bone mimetic cancer testbeds that reproduce bone metastasis sites for breast cancer and prostate cancer show considerable dynamics of cellular actin filaments associated with changes to the cofilin regulation during cancer progression. Here, we model the molecular interactions between the actin filament and ADF/cofilin to elucidate the depolymerization mechanisms and altered mechanical properties of the actin filament. In this work, we utilize molecular dynamics (MD) simulations to predict the structural features of cofilin-actin boundaries. Furthermore, the steered molecular dynamics (SMD) simulations mimic these boundaries' structural evolution and the severing process dynamics under various deformation modes. In this work, the molecular model of bare F-actin was built based on a cryo-electron microscopic (EM) structure described in the literature. To understand the role of mechanical loading on the F-actin severance by ADF/cofilin, we built the computational models of partially and fully cofilin decorated F-actin. We show that the nanostructural spatial heterogeneity produced by the cofilin-decorated segment leads to the formation of locally fragile regions that facilitate F-actin severance. We found that the partially decorated actin filaments with cofilin have lower compressive strength than those that are fully decorated with cofilin. We also observed that partially cofilin-decorated actin filaments are more flexible than fully cofilin-decorated actin filaments. SMD simulations of F-actin models allowed us to analyze and track the effects of loading rate and loading conditions on the biophysics of F-actin severing by ADF/cofilin. This work unravels the fundamental mechanisms that play a vital role in the cytoskeletal dynamics of cancer cells during cancer progression at the bone metastasis site.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Optimal Maintenance Policy for Large-Scale Infrastructure Systems by Parallelized Multi-Agent Deep Reinforcement Learning

Author(s): *Dongkyu Lee, *Seoul National University*; Junho Song, *Seoul National University*;

As infrastructure systems such as transportation and water distribution networks deteriorate due to aging and corrosion, decision-makers need to assess their system-level risks to devise an appropriate operation and maintenance policy to minimize the losses caused by system failures over their lifecycles. Recently, Markov decision processes has been used to identify optimal decision-making policies within a given time horizon. In complex systems consisting of many components, however, it is potentially intractable to find the best solutions because the numbers of state and action spaces increase exponentially. To overcome this curse of dimensionality, this study suggests a multi-agent deep reinforcement learning framework termed Clustering-based Parallelized Multi-agent Deep Q-Network (CPM-DQN). CPM-DQN introduces parallel computing into the divide-and-conquer strategy, which identifies multiple subsystems by clustering and assigns an agent to each subsystem. At the macroscopic level, the given environment is copied to each computing device. In each copied environment, agents observe the states of structures within the corresponding clusters and establish policies to maximize decomposed rewards. The agents periodically synchronize with the best ones, thereby contributing to improving the master policy. Numerical examples demonstrate that the proposed method outperforms baseline policies including conventional maintenance schemes and the set of optimal policies at the subsystem-level.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Investigations of Dual Probe Nondestructive Evaluation of Concrete

Author(s): Justin Harris, *University of Maine*; *Eric Landis, *University of Maine*;

The ability to determine characteristics of cured concrete is often desired for the inspection of existing concrete structures. With the intent to investigate the relationship between concrete physical properties and non-destructive evaluation techniques (NDE), ultrasonic and electrical resistivity measurements were taken for a group of concrete specimens over a span of 28 days. This group of concrete specimens consisted of 15 specimens, which varied along water/cement ratios and curing conditions in an attempt to assess a range of different environments. The different curing conditions consisted of lime water bath curing, sealed, and air dried. Electrical resistivity measurements were taken using the uniaxial method and ultrasonic measurements were taken via the through transmission technique. The electrical resistivity data was analyzed for values of formation factor. The formation factor is defined as the relationship between the total resistivity and the resistivity of the fluids in the pores of the concrete. The resistivity of the fluid in the pores was determined using values from the Virtual Cement and Concrete Testing Laboratory by NIST. The values of formation factor are of interest since the formation factor has been cited as a value with implications in the microstructural properties of cementitious materials. For ultrasonic measurements, the pulse wave velocity was calculated. The pulse wave velocity is defined as the distance traveled (ie specimen length) divided by the time taken for the pulse to travel this distance. The results from this study discovered an exponential relationship between the pulse wave velocity and formation factor for saturated specimens using a multidimensional unconstrained nonlinear minimization method. With the formation factor's relationship to strength and microstructural properties, this relationship may lead to predicting strength and pore structure using relationships to a simple ultrasonic property.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: On the Coupling of Structural Degrees of Freedom in Transient Soil Structure Interaction for Non-Parallel Soil Layers

Author(s): Amauri Ferraz, *University of Campinas*; Ronaldo Carrion, *University of São Paulo*; Lucas Agatti Pacheco, *University of Campinas*; *Euclides Mesquita, *University of Campinas*;

A three dimensional version of the Direct Boundary Element Method (DBEM) in the frequency domain is used to synthesize compliance functions (matrices) describing the dynamic response of massless block foundations interacting with soils presenting arbitrary, non-horizontal layering. Upon the block foundation, frame structures are introduced. A classical modal analysis procedure of the structure using displacement coordinate relative to the block foundation is performed, allowing for the Frequency Response Functions (FRFs) of the structure relative to the block foundation to be synthesized. The structure FRFs are coupled to the soil FRFs, leading to a set of structural and foundation frequency responses, in which the soil influence is incorporated. From coupled the soil-foundation-structure FRFs, new modal data, i.e. eigenvectors and eigenvalues, are extracted by distinct methods. Once the new modal quantities are available, a set of orthogonal equations of motions can be written and integrated to deliver the transient response of the coupled soil-foundation-structural system. One advantage of this formulation is that it allows to consider an arbitrary number of the structure degrees of freedom. This methodological approach is used to study the coupling of vertical, horizontal and rocking degrees of freedom of the frame foundation. The analysis is performed in the plane built by the frame foundation. The question to be addressed is whether the coupling of vertical and horizontal and rocking in plane degrees of freedom are dependent on the number of structure degrees of freedom considered in the analysis, as a function of the considered soil profile. Classical horizontally layered soils as well as non-horizontally layered soil models are considered.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Autonomous Subsurface Defect Detection in Concrete Bridges Using Impact Echo

Author(s): *Faezeh Jafari, *University of North Dakota*; Sattar Dorafshan, *University of North Dakota*;

Conventionally, the Peak Frequency method has been used to interpret impact echo (IE) data to detect the presence and location of subsurface delamination in reinforced concrete bridge decks. The properties of a defect are determined by recognizing the frequency domain related to maximum amplitude value in the spectrum. However, features of IE signal in the time domain have not been utilized in the past for defect detection. Omitting the time-domain features of the IE signals and focusing only on the frequency-domain properties could lead to false detection of the defects. This study aimed to detect defect and sound regions by leveraging the properties of IE signals time series as well as frequency domain. First, we acquired raw IE data of three bridges on the Long-Term Bridge Performance (LTBP) website. Secondly, IE signals were collected from five bridges (SDNET2021) in Grand Forks, North Dakota deck. To analyze the data, the IE signals of SDNET2021 were classified into two classes (defect and sound) based on the chain dragging. Then, a preprocessing filtering approach was employed to recognize significant peak points and selected features of IE signals in both datasets. Following this, a support vector machine (SVM) trained to detect a defective zone from the sound area based on the feature of IE signals collected from SDNET2021 in the time and frequency domains. Next, the IE signals of three bridges in LTBP were used as test data to assess the performance of SVM network. Finally, the result of SVM classification in terms of defect and sound in both IE datasets were compared with frequency approach.

Keywords: Impact echo signals, Support vector machine, bridge decks, delamination detection, peak frequency approach.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Fast Convolution-Based Peridynamics for Modeling Plasticity and Ductile Fracture

Author(s): *Farzaneh Mousavi, *University of Nebraska-Lincoln*; Siavash Jafarzadeh, *The Pennsylvania State University*; Florin Bobaru, *university of Nebraska-Lincoln*;

Prediction of ductile fracture is vital to numerous industries. Peridynamics (PD) is a nonlocal reformulation of continuum mechanics which uses integrals instead of derivatives in its governing equations. This makes PD models very suitable of simulating the nucleation and propagation of discontinuities such as cracks. PD has been mostly used to predict brittle fracture, but more recently several authors have introduced PD models for simulating ductile fracture and failure [1,2,3]. PD models for ductile fracture usually use correspondence models, which enables the use of classical constitutive models in a PD framework. These approaches also open the path for using classical continuum damage models (e.g. models based on a tearing parameter [2], the classical Johnson-Cook approach [3]) within the PD framework.

There are two ways for deriving an elastoplastic model for large deformations: (1) using the native elastoplastic PD model (where the constitutive relationship between the PD force and extension states are directly defined in the nonlocal setting without passing through the classical/local theory) capable of modeling large deformations, and (2) using the PD correspondence models [1,2]. While native PD models are costly compared to solving a classical/local model, the correspondence approaches are even more expensive because they require back-and-forth “translations” between forces/displacements and stresses/strains representations. Recently, an efficient computational method for peridynamic formulations of diffusion [4], and of elasticity and brittle fracture [5] was introduced. The fast convolution-based method (FCBM) uses FFT-accelerated quadrature and a Fourier-compatible approach to apply boundary conditions. In this study we use the FCBM to formulate a discretization for a class of PD correspondence models. This allows us to use classical plasticity damage models, while resulting in significant efficiency gains compared with previous discretization methods. We use the Johnson-Cook damage model to capture ductile failure in 3D samples with different geometries.

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Neural Networks-Based Elementwise Classification to Detect Multiple Voids in a Solid Using Elastic Waves

Author(s): *Fazle Mahdi Pranto, *Central Michigan University*; Shashwat Maharjan, *Central Michigan University*; Bruno Guidio, *Central Michigan University*; Stephen Lloyd, *Central Michigan University*; Chanseok Jeong, *Central Michigan University*;

We present a new method to detect random number of voids in a 2D plain strain solid subject to elastodynamics via artificial neural networks (ANNs). The potential of neural networks to learn critical input- and output-layer data has made it possible to attempt to solve an inverse problem of this type. An elastic wave source excites the solid, containing random number of voids, and wave responses are measured by sensors placed around the solid. We present various ANN architectures for tackling the considered inverse problem as an element-wise binary classification problem that predicts element types i.e., a regular or a void element. The ANNs receive the displacement field of wave signals from sensors and predict regular elements as '0's and void elements as '1's. To this end, we generate training data, which consist of input-layer features (i.e., measured displacement signals) and output-layer features (i.e., regular or void elements in a 2D domain). When the training data is generated, we utilize the level-set method to avoid an expensive re-meshing process, which is otherwise needed for each different configuration of voids. To showcase the validity and robustness of the neural networks, an independent void element configuration, which is different from the training dataset, is tested.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Solving Boundary Value Problems by Strong and Weak Form Methods Using Reproducing Kernel Peridynamics

Author(s): *Feihong Liu, *The Pennsylvania State University*; Michael Hillman, *The Pennsylvania State University*;

Peridynamics has been attractive as a non-local integral formulation which precludes spatial derivatives, that prove difficult in the class of local differential equations. Nevertheless, recently it has been shown that when formulated under the state-based correspondence principle, the methods can yield non-convergence and lacks the inherent accuracy expected in a numerical method in simple problems such as a patch test. Reproducing kernel peridynamics (RKPD) has been proposed as a generalization of this formulation, where both a simple correction can be introduced to restore convergence, as well as high-order formulations if desired. The original peridynamic-type gradient (differentiation by integration) can also be cast as a general RKPD operator, such that high-order derivatives, as necessary for the strong form collocation method, can be obtained.

In this presentation, we investigate two general approaches for solving boundary value problems based the operator: an RKPD collocation method and an RKPD Petrov-Galerkin method. First, various boundary conditions treatments are tested for the class of weak form-based methods. Since the RKPD operator is a pseudo-derivative, and therefore the classical weighted residual method is not applicable, various forms of test functions are investigated. A strong-form based RKPD method is then proposed, where high-order derivatives are obtained using the general operator for use in the boundary value problem at hand.

To assess the ability of the methods for solving boundary value problems, two-dimensional Poisson and elasticity problems are employed. The results of patch tests and convergence tests for the proposed approaches are presented, where convergent results can be reliably obtained for RKPD collocation methods, while the Galerkin-based methods need careful attention.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Application of Variability Response Functions for Cross Laminated Timber Panels with Nonlinear Constitutive Laws

Author(s): *Fiona O'Donnell, *Swarthmore College*; Sanjay Arwade, *University of Massachusetts Amherst*,

The growth of wood leads to natural variation in material properties. Randomly heterogeneous material properties lead to variation in performance of wood products. In structural applications, characterizing the variability in mechanical properties such as stiffness and strength are critical for the efficient use of material in design. This is particularly important in wood composite products like Cross Laminated Timber (CLT), which allow for an averaging of material properties. Typically, stochastic problems are solved by Monte Carlo simulations which are computationally intensive, particularly for complex systems. The Variability Response Function is a well-established concept for efficient evaluation of the variance of stochastic systems where properties are modeled by random fields. Recently, the Variability Response Function (VRF) method was successfully applied to spatially varying elastic properties in dimensional lumber to quantify their impact on the variation in displacement response of a CLT panel. The existence of variability response functions has been proven for statically determinate beams with arbitrary nonlinear constitutive laws. This work applies the Variability Response Function to bilinear material properties in dimensional lumber and quantifies the influence of heterogeneous material properties on nonlinear CLT performance. The model is validated by Monte Carlo Simulations. Using this method, novel CLT panel layouts can efficiently be studied, increasing opportunities for traditionally low-value species to be used in CLT panels. Three case studies are provided to demonstrate the application and utility of the developed method.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Initial Considerations for the Development of a National Full-Scale Testing Infrastructure for Community Hardening in Extreme Wind, Surge, and Wave Events (NICHE)

Author(s): *Forrest Masters, *University of Florida*; Arindam Chowdhury, *Florida International University*; Amal Elawady, *Florida International University*; Hermann Fritz, *Georgia Institute of Technology*; Catherine Gorle, *Stanford University*; Tracy Kijewski-Correa, *University of Notre Dame*; Frank Lombardo, *University of Illinois at Urbana-Champaign*; Pedro Lomonaco, *Oregon State University*; Kristin Taylor, *Wayne State University*; John van de Lindt, *Colorado State University*; Paul Vasilescu, *Aerolab*; Ioannis Zisis, *Florida International University*;

This presentation will provide a comprehensive overview of a new large multi-university, interdisciplinary effort to design a National Full-Scale Testing Infrastructure for Community Hardening in Extreme Wind, Surge, and Wave Events (NICHE), which was recently funded through the National Science Foundation's Mid-Scale Research Infrastructure (MsRI) program. Led by a consortium of nine universities and a wind tunnel design consultancy firm, the project will leverage field observations, computational modeling, and physical experimentation to design a combined extreme wind, storm surge, and wave simulation facility for the study of full-scale low-rise buildings and large-scale infrastructure systems or community models.

The centerpiece of the project is an integrated design testbed (IDT) that couples computational fluid dynamics (CFD) modeling with experiments in a physical design testbed (PDT), which is anticipated to be a 1:3 scale proof-of-concept prototype of the future facility. The IDT will be the principal tool for [a] addressing fundamental science questions, e.g., determining an appropriate relaxation of Froude and Reynolds number similarity requirements, defining the sequencing and interplay of multiple hazards on infrastructure performance, [b] innovating new experimental capabilities such as the simulation of nonstationary conditions, e.g., gust fronts and downburst outflows, and [c] minimizing experimental uncertainties that ultimately propagate into the codification of research findings. Hybrid (cyber-physical) simulation will also be explored to offer users a suite of simulation options when examining the combined effects of wind and wave loading.

Within the context of designing an experimental facility, this presentation will (1) briefly summarize the history of major facility development for the study of wind/coastal hazards, (2) present a landscape study that identifies existing facilities in the US (i.e., boundary layer wind tunnels and wave flumes/basins) that could potentially be retrofitted or upgraded to accommodate the scientific requirements of NICHE, (3) provide conceptual designs for the PDT, and (4) present findings from early two-phase flow CFD modeling employing computationally efficient unsteady Reynolds-averaged Navier–Stokes equations (RANS) as well as large eddy simulation (LES) models using the volume of fluid method to track the free surface interface.

Title: Discovering Nonlinear Structural System Dynamics Based on Compressive Sampling Concepts and Tools

Author(s): *G. D. Pasparakis, *Leibniz Universität Hannover*; V. C. Fragkoulis, *Leibniz Universität Hannover*; I.A. Kougioumtzoglou, *Columbia University*; M. Beer, *Leibniz Universität Hannover*;

A data-driven technique based on compressive sampling concepts and tools (e.g., [1]) is developed for discovering the governing equations of stochastically excited structural systems exhibiting diverse nonlinear behaviors and/or following a fractional derivative modeling. This is done by relying on measured data and by utilizing a state-variable formulation of the system governing equations. Further, an appropriately selected expansion basis is employed for approximating the system nonlinear dynamics. This leads to either an over- or under-determined system of equations to be solved based on sparsity-promoting numerical techniques for determining the active coefficients in the expansion basis.

Note that the technique can be construed as an extension of the pioneering work in [2, 3] to address some of its limitations. Specifically, an l_p -norm ($0 < p < 1$) minimization formulation is developed herein for promoting solution sparsity and for yielding a compact and interpretable model. Next, a parameterized dictionary learning approach is proposed for circumventing the a priori selection of function basis and for increasing the accuracy of the obtained solution. Also, a Bayesian formulation is developed for quantifying the accuracy degree associated with the model estimate. Various structural systems are considered in the numerical examples for demonstrating the reliability of the technique, even in cases of limited/incomplete measured data.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Guided Post-Earthquake Reconnaissance Considering Resource Constraints for Regional Damage Inference

Author(s): *Ge Ou, *The University of Utah*; Mohamadreza Sheibani, *The University of Utah*;

The extent of loss in a seismic hazard can be moderated with the on-time allocation of funds and initiation of recovery tasks. Among various examinations conducted following the hazard, buildings damages are assessed as part of the reconnaissance survey to learn and document the impact of the earthquake on structures. The results of the survey are used in financial aid estimation, which is crucial for the community's rapid recovery acts after the hazard. Due to the urgent need for this information, the amount of information gained per unit of time should be optimized. This article aims at answering the question of how to maximize the information gained in the presence of resource constraints by directing the efforts of a reconnaissance surveying team. A data-driven method is proposed that actively learns the patterns of damage and recommends the most informative buildings to be inspected while considering the resource limitations. The framework utilizes an efficient active learning method based on mutual information and was developed for Gaussian process regression (GPR) to identify the information-rich cases. To assess the contribution of information gain and resource allocation in the overall outcome of the damage inference, two simulated earthquake testbeds are studied. It is shown that in a co-optimization approach, damage labels of the majority of buildings can be accurately predicted after one week of damage inspections.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Overcoming Volumetric Locking in Higher Order Material Point Methods

Author(s): *Georgios Moutsanidis, *Stony Brook University*;

Displacement-based formulations, such as the traditional finite element method (FEM), suffer from volumetric locking in the near-incompressible limit. To address this issue, reduced/selective integration techniques, as well as more advanced B-bar and F-bar type formulations [1], were developed and popularized in the FEM community. Similar techniques have been developed for various meshfree and particle methods, such as the material point method (MPM). Recently, with the advent of isogeometric analysis (IGA) [2], several MPM researchers have replaced the low order linear shape functions of the background domain with splines due to their higher order smoothness and continuity that eliminates the so-called cell-crossing instability [3]. Nevertheless, the issue of volumetric locking has not yet been thoroughly investigated for higher order MPM. In this work we present a novel formulation for overcoming locking in versions of MPM where higher order shape functions are used for the background discretization. The proposed framework is based on the well-known B-bar and F-bar techniques but tailored to MPM. The presented numerical examples exhibit reduced stress oscillations and are free of volumetric locking.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: PI-VAE: Physics-Informed Variational Auto-Encoder for Stochastic Differential Equations

Author(s): Weiheng Zhong, *University of Illinois at Urbana-Champaign*; *Hadi Meidani, *University of Illinois at Urbana-Champaign*;

We propose a new class of physics-informed neural networks, named physics-informed Variational Auto-encoder (PI-VAE), to solve stochastic differential equations with only a limited number of scattered measurements of the parameters of the equations. We encode the physics laws into the architect of VAE using automatic differentiation and change traditional loss function to Maximum Mean Discrepancy (MMD) to improve our model performance. Neural network parameters used for approximating the quantities of interest are updated iteratively using stochastic gradient descent algorithms. We test our algorithms on approximating stochastic processes and solving different types of problems (i.e. forward, inverse, and mixed problems) of SDEs. The satisfactory accuracy and efficiency of the algorithm are numerically clarified in comparison with the physics-informed generative adversarial network (PI-WGAN).

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Graph Neural Networks for Efficient Seismic Reliability Analysis of Highway Bridge Systems

Author(s): Tong Liu, *University of Illinois at Urbana-Champaign*; *Hadi Meidani, *University of Illinois at Urbana-Champaign*;

The highway bridge system is a critical part of the infrastructure system since the highway system carries a large volume of traffic flow and plays a vital role in connecting critical locations in extreme events. Seismic reliability analysis of bridge networks is an important task where network response measures, such as node-level connectivity conditions is calculated under probabilistic earthquake events. We propose a fast approach based on graph neural networks (GNN) to compute node-to-node connectivity given different target nodes. This GNN is generalizable to various earthquake events and even can be trained on one network, and be tested on another network. To train the model we use bridge information and condition assessments report for a large bridge network in Bay Area and demonstrate the accuracy and computational efficiency of the proposed approach. This can enable fast decision support systems that inform maintenance planning and asset managements to improve critical infrastructures.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Topology Optimization with Filament Interface Considerations for Extrusion-Based Additive Manufacturing Processes

Author(s): *Hajin Kim, *Massachusetts Institute of Technology*; Jackson Jewett, *Massachusetts Institute of Technology*; Josephine Carstensen, *Massachusetts Institute of Technology*;

Extrusion-based additive manufacturing (AM) processes deposits a stream of material onto a 2D slice of a design, layer-by-layer, until the final 3D shape is fabricated. Examples of material extrusion-based AM processes includes bioprinting, fused filament fabrication and concrete 3D printing. In contrast to traditional manufacturing techniques that typically require either formwork and/or material removal, extrusion-based 3D printing reduce the material use by eliminating the need for formwork and facilitating realization of more complex, materially efficient structures. The rise in popularity of extrusion-based AM fabrication methods has created a need for new design methods that can leverage the design possibilities while incorporating the relevant manufacturing constraints. Topology optimization is one such method, and is often suggested as a powerful design-for-AM approach.

However, it is well established that the filament-centric and layer-by-layer techniques used in extrusion-based technologies can result in high anisotropy of the final physical structures. Research on tailoring topology optimization to material extrusion-based AM has largely ignored this fact and instead worked towards limiting its effect by simultaneous design of structure and tool paths. To address the source of the anisotropy, namely the interface between filaments, this work aims to incorporate the anisotropy within the topology optimization framework. This is done while restricting a geometric nozzle size constraint in the filtering operations of a density based topology optimization algorithm.

This work presents an algorithm that can more accurately capture fabrication by an extrusion-based AM process. In addition to the nozzle size constraint, a multi-material formulation is implemented to reflect the difference in behavior of the filament interfaces and the main body of the filament itself. A modified Discrete Object Projection method is used while the Solid Isotropic Material with Penalization (SIMP) method penalizes intermediate densities. The Method of Moving Asymptotes (MMA) is taken as the gradient-based optimizer. The algorithm is demonstrated on 2D benchmark examples.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Determination of the Cohesive Fracture Energy of Biofilms Using Scratch Tests

Author(s): *Haklae Lee, *Northwestern University*; Ange-Therese Akono, *Northwestern University*;

Biofilms are dynamic bacteria colonies that grow on wet surfaces and that consist of bacterial cells surrounded by nutrients and the extracellular polymeric substance. Biofilms are at the origin of up to 80% of human bacterial infections. Recent studies have tied biofilm resilience to their mechanical integrity, specifically, their viscoelastic response and cohesive fracture energy. However, quantifying the cohesive fracture energy of biofilms has so far remained a challenge given that biofilms are thin, adhered to surfaces, and dynamic. In this study, we employ scratch tests to measure the cohesive fracture energy of *Pseudomonas fluorescens* biofilms. We use a microscopic scratch tester and in our tests a diamond Rockwell C probe moves across the surface under a prescribed linearly increasing vertical load. We apply nonlinear viscoelastic fracture mechanics to extract the fracture parameters from scratch tests conducted at various loading rates and scratching speeds. This study is significant to devise novel method to probe the cohesive fracture energy of biofilms.

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Title: Three-Dimensional Printing of High-Sensitivity Micro-Architected Piezoelectric Hydrophone with Designed Beam Pattern

Author(s): *Haotian Lu, *Mechanical and Aerospace Engineering, University of California, Los Angeles, CA 90095, USA.*; Victor Couedel, *Mechanical and Aerospace Engineering, University of California, Los Angeles, CA 90095, USA.*; Huachen Cui, *Departments of Civil and Environmental Engineering, University of California, Los Angeles, CA 90095, USA.*; Rayne Zheng, *Departments of Civil and Environmental Engineering and Mechanical and Aerospace Engineering, University of California, Los Angeles, CA 90095, USA.*;

Piezoelectric hydrophones are crucial in underwater applications, including communication or seafloor mapping. Limited by the brittleness of piezoelectric ceramics, conventional manufacturing methods are limited to hydrophone elements with simple geometries such as disk, cube, or cylinder, restricting the sensitivity, directivity patterns, and working frequency bandwidth. Here, we present a design and additive manufacturing strategy for a new class of 3D architected hydrophone concept consisting of rationally designed micro-architectures, capable of broad working frequencies and arbitrary directivity patterns.

By tuning the 3D topology of the electro-mechanical micro-architectures, we achieve inversely designed piezoelectric charge coefficients, such that the voltage response of the activated piezoelectric metamaterials can be either suppressed, reversed, or enhanced from the soundwave of a given direction. Attributed to its high piezoelectric voltage constant, the sensitivity of the printed hydrophone achieves ~10 dB higher than commercial hydrophones, and achieves broad bandwidth varying from 100 Hz to 10 MHz. We show through a combination of experiments and theoretical calculations, that the packaged smart metamaterials are capable of sound source detection underwater, liquid quality monitoring as well as sound communication isolations and filtering suitable for a variety of underwater communications.

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Title: Hydrodynamic Characteristics of Shape Morphing Curved-Crease Origami Surfaces

Author(s): *Hardik Patil, *Civil and Environmental Engineering, University of Michigan*; Evgueni Filipov, *Civil and Environmental Engineering, Mechanical Engineering, University of Michigan*;

Fabrication and assembly of smooth curved surfaces for application in ship hulls or vehicle bodies is often a costly, time-intensive, and complex process. In contrast, the principles of origami allow rapid and efficient fabrication of surfaces from flat sheets. Sheets, when folded along curved creases, reduce joint complexity, improve overall structural stiffness, allow easy assembly, and only require a small initial footprint. To exploit these properties, we used the bar and hinge model to design and analyze curved-crease origami patterns to form surfaces resembling planing hulls upon folding. The study shows that the hull geometry is sensitive to the crease pattern, and the surfaces can morph moderately based on the extent of folding, making them a suitable candidate for controlling fluid flows. Next, we used a simplified mathematical model to predict the motion of a planing boat to study the hydrodynamic characteristics of curved origami surfaces, including drag force, heave and pitch amplitude, and acceleration. The results show that surface hydrodynamic characteristics depend significantly on the crease pattern, and the performance can be optimized with variations to the initial design. This study highlights the potential for origami to create smooth curved surfaces and paves the way for shape morphing origami structures in aerospace, civil, marine, and mechanical engineering fields.

Keywords: Curved-crease Origami, Ship Hulls, Hydrodynamic Performance, Shape Morphing Surfaces

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Title: Thermomechanical Cyber-Physical Testing: Control Requirements

Author(s): *Herta Montoya, *Purdue University*; Amin Maghareh, *Purdue University*; Shirley Dyke, *Purdue University*; Arturo Montoya, *The University of Texas at San Antonio*;

Hybrid simulation, also known as cyber-physical testing, is an innovative technology that has transformed engineering experimentation and helped researchers expand modeling capabilities. However, breakthroughs are necessary to expand the range of hybrid simulation methods and thus, enable experiments with loading conditions representing multiple hazards. Notably, there is an opportunity to provide analogous testing capabilities to conduct thermomechanical experiments through hybrid simulation. This presentation discusses the development of a novel technique to establish thermomechanical cyber-physical testing as a viable method for engineering experimentation. First, the technique is established and demonstrated using a dynamic 2D finite element model of a two-layered system subjected to thermal loading. The complete two-layer system model serves as the reference structure, and then for hybrid simulation is partitioned into two one-layer systems sharing common interface conditions. The top layer is chosen as the numerical substructure, while the bottom layer represents the experimental substructure. The interface conditions between the numerical and experimental substructures include temperature and heat flux, thus acting as an ideal thermal transfer system. The partitioned model is then verified in terms of its ability to simulate the dynamics of the two-layer system with idealized dynamic thermal loading at the interface. Next, a more realistic situation is considered with the dynamic thermal loading imposed by a thermal transfer system to the experimental substructure. Finally, a thorough analysis is performed to evaluate the heat transfer capabilities at the interface and characterize several sources of error (i.e., non-uniform thermal loading, experimental lags). These studies serve as a reference to develop control requirements to impose thermomechanical loading through a new type of hybrid simulation experiments.

EMI 2022

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Title: Evaluation of Knowledge Transfer Models for Estimating the Lateral Strength of Reinforced Concrete Columns

Author(s): *Hongrak Pak, *Texas A&M; University*; Stephanie Paal, *Texas A&M; University*;

Transfer learning aims to extract knowledge from one or more source tasks and apply the knowledge to a different task for more accurate predictions. This study has presented the feasibility of knowledge transfer techniques in a real-world structural engineering dataset. The main purposes of this study are to investigate different knowledge transfer techniques, apply them to accurately estimate the lateral strength of reinforced concrete columns with only a small amount of training data, and compare the transferability of each transfer learning method. According to the various source and target domains, three different experiments are carried out to demonstrate the usefulness of transferring knowledge across: section type, shear reinforcement area, and concrete compressive strength. In all cases in this study, knowledge transfer techniques show better prediction performance than the models trained without any knowledge transfer techniques. Therefore, we can conclude that transferring pre-trained knowledge from the source domain enables a model to better explain the response variable in the target domain. The performance improvement is particularly emphasized when the available data for the target domain is small. This indicates that a good ML model can be obtained by adopting a knowledge transfer technique, even with a small number of training samples. Thus, transfer learning can be one way to address the data scarcity problem in structural engineering. Furthermore, transferring the pre-trained knowledge is more associated with the underlying physical relationship between the source and the target domains and less associated with the discrepancy between the source and the target domain distributions.

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Title: 3D Printed Tubular Lattice Metamaterials with Enhanced Mechanical Properties

Author(s): *Huan Jiang, *University of Louisville*; Hannah Ziegler, *University of Louisville*; Zhennan Zhang, *University of Louisville*; Sundar Atre, *University of Louisville*; Yanyu Chen, *University of Louisville*;

Tubular lattice structures have sparked tremendous attention among researchers due to their lightweight and excellent mechanical performance. However, the current studies of tubular lattice structures are largely focused on axial compression or tension. This limited their potential applications since different disciplines have disparate requirements. For instance, in soft robotics, the parts with tubular structure configuration entail bending resistance and flexibility; in medical engineering, the stents made by tubular structure are required to exhibit high radial strength and flexibility. In our work, we designed a new type of tubular lattice architecture by rolling up the planar lattice structures with a negative Poisson's ratio. We then investigated the bending performance by conducting three-point bending, and compression behavior by performing radial compression through a combined experimental and numerical approach. Our results show that the proposed tubular structure displays a more compliant behavior. The ductility increases by 85.4% and 72.7% compared to the conventional tubular structure for bending and compression experiment, respectively. Numerical simulations revealed that, for bending, the proposed tubular structure is featured with local indentation due to auxetic effect while the conventional structure is characterized by global bending; for compression, the circumferential ligaments of the proposed tubular structure are compelled to bend along both radial and axial direction due to auxetic effect while the ligaments of conventional structure bend mainly along the radial direction. The auxetic-effect-lead mechanism contributes to the robust mechanical behavior. Furthermore, the parametric study exhibits that tunable behavior can be obtained by manipulating the geometric parameters. The findings here guide designing robust tubular lattice metamaterials for applications ranging from biomedical engineering to robotics engineering.

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Title: Design of Structural Steel Hollow Sections Using Machine Learning Techniques

Author(s): *Hyeyoung Koh, *University of Wisconsin-Madison*; Hannah Blum, *University of Wisconsin-Madison*;

Codified design rules for hot-rolled and cold-formed steel square and rectangular hollow section (SHS and RHS) columns include a series of design formulae to determine the buckling resistance. To account for uncertainties affecting the capacity in addition to sparse data in certain parameter ranges when generating the design formulae, resistance factors are included to promote safe designs. This study proposes a unified data-driven approach to predict the capacity of steel SHS and RHS compression members. As machine learning studies using both analytical and experimental results are still rather limited, this study uses a database consisting of 600 test data and 4,000 finite element (FE) data for steel SHS and RHS columns. The database is obtained from multiple previously published studies and accounts for a range of member slenderness, steel grades ranging from normal to high-strength, and both hot-rolled and cold-formed formation processes. Input features considered in this study consist of material properties including modulus of elasticity and yield strength, geometric properties including cross-sectional parameters and member and element slenderness ratios, and formation process. A multi-layer perception, which is a subset of neural networks, was evaluated to examine the buckling strength estimation. To examine how different data sources affect the predictive performance, three separate models were developed: (i) experimental data only, (ii) FE data only, and (iii) combined data. In addition, the feature importance approach was employed to determine the most impactful factors affecting column resistance. The feature ranking results were utilized to determine which features had minimal impact on the model predictions, and thus could be removed to reduce the computational effort without compromising model predictive performance. Comparisons between the three model outputs are discussed as well as a comparison of the capacities derived by AISC 360 and the predicted capacity from the proposed machine learning models. The results of this study provide suggestions for future implementation of machine learning-based structural design.

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Title: Stability Analysis of Rotary-Straightened Steel Members with Multiple Stiffness Reduction Models Using Machine Learning

Author(s): *Hyeyoung Koh, *University of Wisconsin-Madison*; Barry Rosson, *Florida Atlantic University*; Hannah Blum, *University of Wisconsin-Madison*;

Rotary straightened wide-flange cross-sections have a different residual stress pattern compared to convention hot-rolled steel members. The assumed residual stress pattern has a strong influence on structural behavior, especially in members subjected to inelastic buckling. Previous research has indicated that the current stiffness reduction model provided in Chapter C of AISC 360 for stability design is not appropriate for rotary straightened W-shapes. A stiffness reduction (τ) material model for rotary-straightened hot rolled sections was previously developed and validated for a specific set of cross-section sizes and load conditions. This paper presents a machine learning-based sensitivity study to examine how geometric parameters affect the ultimate capacity of hot-rolled steel members while considering the current and proposed stiffness reduction models.

Beam finite element (FE) models of beam-columns were created in MASTAN2 and analyzed by a second-order inelastic analysis. A range of common cross-section geometries was investigated, from W10 (10 inch, 254 mm nominal depth) to W14 (14 inch, 356 mm nominal depth). The beam-column models were loaded with multiple axial utilization ratios and with uniaxial bending about the major or minor axis. Input features used for training the machine learning model consisted of cross-sectional parameters, slenderness ratio, and axial load utilization ratios, while ultimate loads recorded from the FE analyses are output variables. Separate deep learning models for the current AISC 360 Chapter C provisions and τ stiffness reduction model for rotary-straightened members are developed to predict the load capacity. Next, the SHAP method is used to interpret the trained models such as measuring feature importance and identifying significant features. Finally, the feature rankings resulting from the deep learning models are discussed and compared to a conventional correlation approach. This study provides further understanding of the stiffness reduction model's influence on the stability design of rotary straightened hot-rolled steel members.

EMI 2022
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Title: Stochastic Response Determination of Nonlinear Dynamical Systems: A Wiener Path Integral Technique Accounting for Fractional Derivative Modeling

Author(s): *Ilias Mavromatis, *Columbia University*; Ioannis Kougioumtzoglou, *Columbia University*; Apostolos Psaros, *Brown University*;

A technique based on the Wiener path integral (WPI) is developed for determining the stochastic response of nonlinear systems endowed with fractional derivative terms and/or subjected to excitations modeled via fractional-order filters. Specifically, the expression for the probability that the Wiener process follows a specific path with given boundary conditions is provided in closed form. Next, relying on this expression, and considering a discrete version of the stochastic differential equation governing the system response process in time, a functional change of variables is performed. This yields an analytical closed form expression for the probability that the system response process follows a specific path with given boundary conditions. In this regard, the system response joint transition probability density function (PDF) is given as a WPI over the space of all possible trajectories. Further, relying on a variational formulation and on the most probable path approximation yields a deterministic fractional boundary value problem to be solved numerically for obtaining the system response joint PDF.

Overall, an alternative novel WPI technique formulation is developed herein based on functional change of variables. In comparison to earlier efforts, which resort to the Chapman-Kolmogorov equation as the starting point (e.g., [1]), the Markovian assumption for the system response process is circumvented. Thus, systems with fractional derivative terms can be treated by the WPI technique as well; see also [2] for a relevant discussion. Note that the developed technique can be construed as an extension of the results in [3] to account not only for systems endowed with fractional derivative terms, but also for stochastic excitations modeled via fractional-order filters. Various systems are considered in the numerical examples for demonstrating the reliability of the technique. Comparisons with pertinent Monte Carlo simulation data are included as well.

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Title: Out-of-Plane Compressive Stiffness of Spin-Valence Kirigami Units

Author(s): *Isabel M. de Oliveira, *Princeton University*; Sigrid Adriaenssens, *Princeton University*;

Kirigami spin-valence is a deployable system where patterned cuts are made in sheet material so that the sheet becomes vertically extensible [1]. Cut patterns are designed with units composed of a polygonal hub nested within another polygon (original polygon) where thin elements (legs) connect both geometries. The hubs can be popped out of the plane of the sheet material when they rotate with respect to the original polygon. The deployed hub vertices can be connected to adjacent hub vertices to form a space frame configuration. Examples of applications of origami and kirigami-inspired structures go from building façades and deployable bridges to metamaterials with tunable properties [2]. The fabrication of stiffer structures from flat sheet material is of interest to the construction industry for many reasons, including flat packaging and shipping the material to the construction site and rapid deployment and assembly of the structure. These features provide possible reduction of cost, construction material, and transportation resources. A metallic spin-valence kirigami with quadrilateral units was modeled with shell finite elements to characterize the structural system in [3]. That characterization concluded that this system could be used for façade and sculptural work, but the system should be stiffened for loadbearing applications. Considerable gains in stiffness should be achieved if changes in the geometry and cut pattern were provided for the space frame configuration. To study how additional stiffness can be achieved in this system, we first develop a simplified finite element model with beam elements and rotational hinge stiffness that is calibrated with previous work [3]. Then we use the simplified model to study different polygonal configurations under out-of-plane compressive loading. These configurations vary with respect to leg length to width ratio, and deployment height to polygon radius ratio. After finding configurations that present higher stiffness and global buckling multipliers, we perform a more detailed numerical model with shell elements to compare and verify results.

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Title: Comparison of 3D Printed Topology-Optimized Structures Designed with Different Modelling Resolutions

Author(s): * Jackson Jewett, *Massachusetts Institute of Technology*; Grace Harrington, *Massachusetts Institute of Technology*; Josephine Carstensen, *Massachusetts Institute of Technology*;

Topology optimization is a powerful free-form optimization method that has been shown to generate high-performing structures with a limited volume of material. Its ability to derive highly efficient designs has already been implemented in commercial applications, such as within the aerospace and automotive industries. In efforts to encourage its broad adoption, substantial research has been focused on improving manufacturability of topology optimized designs. In many cases, this has meant a focus on obtaining 0-1 designs in 2D and 3D. However, many of the methods necessary for 0-1 outputs create nonlinearities in the design space, making it difficult to identify global or high performing local minima, increasing computational cost, and creating sensitivity to parameter selection.

In some cases, it may be advantageous for designers to appropriately interpret continuous optimized results, rather than enforcing 0-1 outputs from an optimization. Advances in manufacturing have made it possible to realize graded designs both on the macroscale as a variable sheet problem, and on the micro scale where some additive manufacturing technologies can locally distribute the material properties. Computer simulation and real-world structural testing can help illustrate which optimization methods are best suited for a given design and fabrication circumstance.

This research seeks to perform physical tests on small-scale (200 mm) 3D printed beams designed using topology optimization with different modelling resolutions. One beam design will permit continuous density values within a 2D design domain, and interpret those values as varying thicknesses along the structure. This approach will be compared to extruded 2D beams designed with minimum length scale control using the Heaviside projection method [1], as well as 3D topology-optimized beams. The designs generated in 2D space are obtained using modified versions of DTU's 88-line code [2], and the 3D optimization code is based on the Multigrid-CG approach [3]. All results perform the optimization using the Optimality Criteria method. Several samples of each structure will be 3D printed and tested so their real-world performance can be accurately assessed. Stiffness and ultimate strength will be measured to evaluate the merits of each design methodology.

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Title: Hybrid Mechanistic- and Data-Driven Estimation of Concrete Beam Shear Failure Mechanics

Author(s): *Jacob Pavelka, *Texas A&M; University;*

Traditional, mechanistic modeling methods focus on using physical laws, empirically derived relationships, assumptions, and idealizations to model the complex systems encountered in infrastructure. While these methods produce models with sufficient accuracy and computational efficiency for many systems, there are still systems where an increase in these metrics is desired. Recently, in conjunction with the increase of machine learning's popularity as a modeling method, hybrid mechanistic- and data-driven modeling methods have been developed to remedy the deficiency found in mechanistic and data-driven methods alone, being computational expense and epistemic uncertainty for mechanistic methods and generalizability and interpretability for data-driven methods. This work presents a hybrid model of the shear failure mechanics of concrete beams without shear reinforcement that increases simulation accuracy over mechanistic methods and increases interpretability over data-driven methods. Shear failure mechanics of concrete beams have often been described as a "riddle" because many of the constitutive relationships present in the cracked portion of the beam are difficult to quantify. Additionally, accurate representation of crack kinematics without observing the cracking process is difficult or impossible to obtain, restricting the accuracy of the shear crack's constitutive relationships. The specific hybrid modeling method presented in this work operates by only having a portion of the total model represented by data-driven methods, preferably the portion with the most epistemic uncertainty, and having the rest represented by well-defined mechanics. This method is termed now as data-driven inclusion modeling. Using a data-driven method's ability to provide excellent accuracy in unknown but observed systems reduces the inaccuracy caused by epistemic uncertainty, and leaving the rest of the model largely mechanistic increases its interpretability. Along with presenting an example of these new methods of modeling, this work will show the benefits of this modeling regime in general, encouraging further development in its field.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Concurrent Multiscale Modeling of Damage Evolution in 2D Materials

Author(s): *James Lee, *The George Washington University*; Jiaoyan Li, *The State University of New York at Buffalo*;

Research on two dimensional (2D) materials, such as Graphene and Molybdenum Disulfide (MoS₂), has attracted thousands of researchers worldwide. Due to the extraordinary properties of 2D materials, research interests extend from fundamental science to novel applications. It is obvious that multiscale modeling is an effective way of studying materials over a realistic length scale and time scale. It opens up a new opportunity to connect engineering applications with basic science.

To begin with, a set of more general governing equations for non-equilibrium molecular dynamics (NEMD), covering thermomechanical-electromagnetic coupling effects have been derived. The principle of objectivity, popularly adopted in continuum mechanics, has been utilized to derive the NEMD. Then Young's modulus, Poisson's ratio, heat conductivity, heat capacity, and thermal expansion coefficient are evaluated at atomistic scale. This useful information enables us to perform concurrent multiscale modeling of graphene and MoS₂ consisting molecular dynamics simulation in atomic region to finite element analysis in continuum region.

With these preparations, we will present our newly formulated concurrent multiscale theory. The key challenge in constructing a concurrent multiscale theory hinges at the formulation of the interfacial conditions, which determine the communication between atoms and continuum and between molecular dynamics and continuum mechanics. At the interface, let each node in the finite element mesh corresponds to a group of atoms. The interfacial conditions are assumed as (I) each node is anchored at the mass center of its corresponding group, (II) the heat flux into (out of) each node is equal to the heat flux out of (into) the corresponding group.

Concurrent multiscale modeling enables us to investigate crack initiation, propagation, branching, and closure, without the need to assume the situation with single crack tip and self-similar crack propagation. One may also study fatigue by varying the magnitudes and frequencies of the cyclic loading, without relying on empirical formula.

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Baltimore, MD, May 31 - June 3, 2022

Title: Human-Centered Steel Bridge Inspection Using Computer Vision and Augmented Reality

Author(s): *Jian Li, *The University of Kansas*; Rushil Mojindra, *The University of Kansas*; Ali Mohammadkhorasani, *University of New Mexico*; Fernando Moreu, *University of New Mexico*; William Collins, *The University of Kansas*; Caroline Bennett, *The University of Kansas*;

Human visual inspection is currently the de facto approach for bridge maintenance as bridge inspections strongly rely on inspectors' expertise and experience. However, current inspection practice lacks a reliable mechanism to detect small defects of steel bridges such as fatigue cracks as well as a human-centered, efficient and cost-effective methodology to document and track these defects. This research aims at integrating modern computer vision and augmented reality (AR) technologies to empower bridge inspectors to perform robust fatigue crack detection, characterization, tracking, and documentation in the field. First, a novel fatigue crack detection method is proposed based on tracking local distance change through computer vision to overcome strong parallax effects in 3D video scenes commonly seen in steel bridges. Second, a unique interactive AR software package is developed for the Microsoft HoloLens 2 to convert the crack detection result into holographic images overlaid on top of the real-world bridge to facilitate human-centered inspection. Third, a framework is created through an online database to enable seamless integration of the computer vision and AR components for near real-time fatigue crack inspection. The developed methodology is demonstrated using realistic laboratory setups including a compact, C(T), specimen with a 2D scene for in-plane cracks and a large-scale bridge girder specimen with a 3D scene for distortion-induced fatigue cracks.

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Title: An Overview of Micromorphic Theory and Its Recent Development for Thermomechanical-Electromagnetic Coupling

Author(s): *Jiaoyan Li, *University at Buffalo*; James Lee, *George Washington University*;

Micromorphic theory was first constructed in 1964 by Ahmed Cemal Eringen [1]. Since then, this theory and its special case, micropolar theory, has been continuously developed by Eringen and finally condensed into two books [2, 3]. Micromorphic theory is a continuum field theory, developed in parallel with classical continuum mechanics, which is mathematically rigorous and numerically efficient. It envisions a material body as a continuous collection of deformable particles with finite size and inner structure.

In this talk, we will first briefly introduce the basic laws for mass, microinertia, linear momentum, moment of momentum, energy, and entropy in micromorphic theory. The reduction from Micromorphic theory to micropolar theory and classical continuum theory will be discussed. To couple mechanics with electromagnetics, the Maxwell's equations are employed for the derivations of the body force, body moment, and energy source of electromagnetic origin. Then we consider the generalized strains, temperature, temperature gradient, electric field, and magnetic flux as the independent constitutive variables; the generalized stresses, generalized Helmholtz free energy, entropy density, heat flux, polarization, magnetization, and current as the dependent constitutive variables. General and linear constitutive equations will be systematically and rigorously derived. Through the gauge transformation, we show that the Maxwell's equations are reduced to two wave equations for a scalar potential and a vector potential with forcing terms. Finite element formulation for displacements, micromotions, temperature, scalar potential, and vector potential will be presented. Physical meanings will be discussed.

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Title: A Live Load Model for Bridge Condition Assessment Based on Traffic Simulations and Influence Lines

Author(s): *Jihwan Kim, *Seoul National University*; Junho Song, *Seoul National University*;

The live loads of bridges in operation are affected by their site-specific traffic environments. Therefore, when evaluating the condition of a bridge periodically, live load effects should be estimated based on the unique traffic environment of the bridge rather than a general design live load model. To this end, many studies have been conducted to accurately estimate the live load effects using traffic data and simulations, e.g. Weigh-In-Motion (WIM) data and microsimulation models. However, these studies had limitations in that a large amount of traffic data and high computational costs are required. To overcome these, this study develops a live load model for bridge condition assessment, which enables engineers to calculate live load effects conveniently and efficiently based on the given traffic environment. Representative truck models and lane load models which can vary depending on important factors of live load effects (traffic environments, assessment periods, and shapes of influence lines) are proposed based on traffic data and simulations. In particular, this study calculates the lane loads with a focus on the effect of the shape of the influence line on the estimation of the live load effect to avoid the biases by uniformly distributed loads (UDLs) for highly nonlinear shapes of influence lines. Four parameters are introduced to characterize the shape of an influence line after an investigation on the influence lines of main members of short-span to long-span bridges. A surrogate model is constructed via the adaptive Gaussian process to estimate the coefficients for the lane load model using machine learning methods. In the case of representative truck loads, the models are defined based on the assessment periods, axle loads, axle spacings data, and correlation between axle loads and spacings. Numerical examples are provided to compare the live load effects by the developed live load model to those by an existing traffic simulation method. The results confirm the accuracy and usefulness of the developed model for the purpose of bridge condition assessment.

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Baltimore, MD, May 31 - June 3, 2022

Title: Turning Telecommunication Cables into Distributed Acoustic Sensors for Bridge Health Monitoring

Author(s): *Jingxiao Liu, *Stanford University*; Siyuan Yuan, *Stanford University*; Bin Luo, *Stanford University*; Biondo Biondi, *Stanford University*; Hae Young Noh, *Stanford University*;

We introduce a new bridge health monitoring (BHM) system based on existing telecommunication cables. BHM allows us to diagnose damage in earlier stages, which is essential for preventing more severe damage and collapses that may lead to significant economic and human losses. However, conventional BHM systems require dedicated sensors on bridges, which is costly to install and maintain and hard to scale up. To overcome these challenges, we introduce a new system that uses Distributed Acoustic Sensing (DAS) to collect dynamic responses of the bridge from fiber cables deployed for telecommunications. In other words, we transform widely installed telecommunication fibers into a long-offset virtual strain sensor array with a high temporal and meter-scale spatial resolution. We use DAS responses to extract important bridge damage-sensitive information (e.g., natural frequencies, strain mode shapes, and displacement mode shapes). This approach does not require on-site installation and maintenance of dedicated sensors and equipment on bridges.

In this work, we formulate an elemental strain state-space model that considers strain responses from the telecommunication cable as observations of the actual bridge dynamics. With this model, we estimate bridge natural frequencies and strain mode shapes using a data-driven subspace system identification algorithm. We then reconstruct displacement mode shapes by double integrating the estimated strain mode shapes. One challenge of reconstructing displacement mode shapes from DAS measurement is that the double integration may not be stable because the process of integrating noise propagates. To overcome this challenge, we derive and fit physics-guided parametric shape functions to the estimated strain mode shapes based on bridge dynamics and conduct analytical double integration on the fitted functions. This method overcomes the instability problem caused by numerical double integration methods and improves the estimation accuracy by physically constraining the shape function.

We evaluate our system with real-world field experiments on a concrete continuous span bridge 57 m long in San Jose, California, with fiber cable running in a conduit under the deck. Our system successfully identified the first three modal frequencies with a 0.06 Hz mean absolute error compared with those extracted from the accelerometers installed on the deck. In addition, our system reconstructed the first three displacement mode shapes in a meter-scale resolution and achieved 0.80 modal assurance criterion compared with those from the accelerometers. Overall, our evaluation shows promising results for the applicability and feasibility of turning telecommunication cables into large-scale, cost-effective, and high-spatial-resolution BHM systems.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Overcoming Mutual Exclusivities in the Mechanical Properties of Cellular Solids via Direct-Ink Writing

Author(s): *Jochen Mueller, *Johns Hopkins University*;

Despite recent advances in a variety of technologies, the ability to create stiff and strong lightweight structures that are also tough remains an elusive goal, as these properties are typically mutually exclusive. Nature overcomes these limitations by combining complex mechanisms that span across multiple length scales. However, synthetic replications of these structures are confined to specific geometries, highly anisotropic, or limited in build volume. In this talk, I will present multiple examples from recent research that show how such trade-off can be overcome by combining modern computational design with advances in multimaterial 3D printing. Specifically, the different hierarchy levels of cellular solids are evaluated and individually optimized. Some of the most promising results were found on the strut level, which is often neglected when it comes to toughness. As such, it has been shown that both continuous and discrete material gradients can increase the toughness – both before and after failure – by more than two orders of magnitudes, with no negative effects on the stiffness, strength, and failure strain. The principles are complementary to existing approaches, scale-independent, and extendible to geometries other than struts. As a result, they can have a substantial effect on the safety, cost, and environmental impact in volume and weight restricted applications, such as aircrafts, helmets, or packaging.

Keywords: 3D printing, additive manufacturing, lattices, cellular solids, functionally graded materials

EMI 2022

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Title: UHPC Made with Recycled UHPC and Optimized with AI – an Infinite Reusability?

Author(s): Valdrin Maliki, *TU Wien, Faculty of Civil Engineering*; Dana Daneshvar, *TU Wien, Faculty of Civil Engineering*; Teresa Liberto, *TU Wien, Faculty of Civil Engineering*; Gabriel Reiter, *mixteresting GmbH*; Hermann Schichl, *University of Vienna, Faculty of Mathematics*; *mixteresting GmbH*; *Johannes Kirnbauer, *TU Wien, Faculty of Civil Engineering*; Agathe Robisson, *TU Wien, Faculty of Civil Engineering*; Waltraud Stoellinger, *TU Wien, Faculty of Civil Engineering*;

Ultra-high performance concrete (UHPC) is designed to minimize water-to-binder ratio and maximize strength. This is done through the optimization of packing of all solids in the mixture, as well as the use of superplasticizer. In this study, we use recycled UHPC (freshly milled) to design a more sustainable UHPC, where the recycled UHPC is used to replace the sand ($D_{50}=320\ \mu\text{m}$), the quartz powder ($D_{50}=24\ \mu\text{m}$) and the cement itself ($D_{50}=12\ \mu\text{m}$). Results show that recycled concrete can fully replace the sand without compromising the 1-D, 7-D and 28-D strengths. The quartz powder can also be replaced by recycled UHPC, either fully, with a drop of 28-D compressive strength by 10 w%, or by half, without any drop in compressive strength. Lastly, and more importantly, replacing the cement with recycled UHPC by 10 w% results in a negligible 28-D compressive strength loss. Replacing cement at a rate of 50 w% results in a drop of strength by 30 %, from 121 MPa to 86 MPa. Surprisingly, when replacing 100 % of the cement with recycled concrete, the 28-D compressive strength still reaches 23 MPa. These results can at least partially be explained by the freshly milled reactivity of the recycled UHPC powder, measured by oscillatory rheology.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Impact of Hazard Uncertainty Evolution on Variability of Building Seismic Damage Assessment

Author(s): *Jorge Mario Lozano, *Georgia Institute of Technology*; Iris Tien, *Georgia Institute of Technology*; Elliot Nichols, *Georgia Institute of Technology*; J. David Frost, *Georgia Institute of Technology*;

Following an earthquake, damage assessment methodologies are useful for estimating economic impacts and casualties in a region. These methodologies combine ground motion data with structural properties of a building to estimate physical damage to a structure. In recent years, the range and availability of earthquake information has improved the ability to assess multiple earthquake parameters (e.g., PGA, PSA at 0.3 seconds), including uncertainty information. The USGS ShakeMap, for example, quantifies the uncertainty of these parameters at each location. However, most damage assessment methodologies treat earthquake uncertainty in a static manner, meaning that even when more information, including evolution in the uncertainty of the hazard, is provided during the disaster response period, evaluations of building damage use only one uncertainty value. This paper investigates the impact of including the uncertainty evolution of the USGS ShakeMap in the damage classification of buildings. Damage assessment is illustrated with the widely used FEMA HAZUS methodology and applied to the Indios earthquake in Puerto Rico in 2020. The ShakeMap ground motion data shows that uncertainty in ground motion parameters can change by up to 45% during the aftermath of the earthquake. A Monte Carlo simulation-based approach is then introduced to estimate the convolution of three random variables: ground motion, building fragility, and damage state. This process results in the distribution of damage states given a scenario of ground motion uncertainty. Comparison of the distribution of damage states at every stage of the disaster when hazard uncertainty evolution information is included with results from current methodologies demonstrates the need to include dynamic hazard uncertainties in the assessment of building seismic damage. Implementing this methodology in damage assessment decreases the propagation of error when estimating disaster event impacts and is useful for more accurate post-disaster resource management and emergency response.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Comparing Mechanical Response of Porcine Skin for Penetrating and Non-Penetrating Ballistic Impacts

Author(s): *Joseph LeSueur, *Medical College of Wisconsin / Marquette University / Zablocki Veterans Affairs Medical Center*; Carolyn Hampton, *Medical College of Wisconsin / Zablocki Veterans Affairs Medical Center, DEVCOM Army Research Laboratory*; Jared Koser, *Medical College of Wisconsin / Marquette University / Zablocki Veterans Affairs Medical Center*; Sajal Chirvi, *Medical College of Wisconsin / Zablocki Veterans Affairs Medical Center*; Frank A Pintar, *Medical College of Wisconsin / Marquette University / Zablocki Veterans Affairs Medical Center*;

Mechanical properties of soft tissue have been extensively investigated in high-speed ballistic penetration studies but lacks comparisons of penetrating and non-penetrating biomechanical properties of skin, which may be utilized for predictive modeling and design of preventive body armor. Due to viscoelastic properties of skin, tissue displacement is rate dependent, but mechanical response during ballistic impact also depends on penetration. A Helium-pressurized launcher was used to accelerate 3/8" (9.525 millimeters) diameter spherical projectiles of varying material: stainless-steel (n=26), Si3N4 (n=24), and Delrin acetal plastic (n=24) ball bearings toward ten front and seven rear whole porcine legs from seven pigs (39.53 +/- 7.28 kg) at projectile velocities below and above V50, the velocity with 50 percent probability of penetration. Penetration was defined as projectile entry into the tissue accompanied by plastic deformation to the epidermal and dermal layers of the porcine leg. Tracker video analysis software was used to determine projectile velocity at impact from the perpendicular view and radial wave displacement from the in-line view. An average maximum surface wave speed, occurring directly after impact, was calculated for each projectile material and categorized as a penetrating or non-penetrating impact. As the wave travelled further away from the impact site, surface wave speed decreased due to energy dissipation by the viscoelastic skin. Elastic components of skin allowed recoil to original shape, but penetrating impacts plastically deformed the skin and delivered energy to deeper tissue, resulting in significantly slower surface wave speeds. Assuming a homogeneous isotropic linear elastic material without viscous properties, theoretical shear wave speed was obtained from experimental Rayleigh surface wave speed measurements. Theoretical shear wave speed values were used to derive elastic modulus, shear modulus, bulk modulus, and corresponding mechanical properties of skin for penetrating and non-penetrating ballistic impacts¹, which may be used for skin impact models. Non-penetrating stainless-steel projectiles generated an average surface wave speed of 60.62 m/s, resulting in 57.65 m/s, 11.12 MPa, 3.76 MPa, and 92.65 MPa for shear wave speed, elastic modulus, shear modulus, and bulk modulus of porcine skin, respectively. Larger surface wave speeds of non-penetrating impacts correlated with larger elastic moduli, shear moduli, and bulk moduli compared to penetrating impacts for each projectile material. Compared to in vivo indentation experiments, larger elastic moduli were expected in ballistic impact since substantially greater indentation depths and loading rates were generated.

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Influence Functions for 3D Full-Spaces Subjected to Bi-Quadratically Distributed, Time-Harmonic Loads

Author(s): Edivaldo Romanini, *Federal University of Mato Grosso do Sul*; *Josue Labaki, *University of Campinas*; Iago Cavalcante, *University of Campinas*; Euclides Mesquita, *University of Campinas*;

A common difficulty in modeling discontinuous contact problems is representing accurately sharply-varying contact tractions. The edges of rigid footings interacting with the surface of the soil, and the tip of buried trenches interacting with its surrounding soil are examples of problems in which sharp variation of contact tractions occur. This poses a challenge to discretization schemes such as the boundary element method, typically used to model such problems, in that these traction variations are difficult to represent using the widely available piece-wise constant elements. This paper presents a derivation of novel time-harmonic influence functions for three-dimensional full-spaces. In this formulation, external loads are considered to have arbitrary bi-quadratic variations within the full-space, which are more suitable to represent sharply-varying contact tractions. The derivation of the influence functions consists of decomposing the coupled differential equations describing the medium into two independent fields, together with a transformation into the Fourier space, in which the equations can be solved algebraically. A boundary-value problem corresponding to the bi-quadratically-varying loads is imposed in the transformed space. Final expressions for the time-harmonic displacement and stress fields in the full-space are expressed in terms of double Fourier integrals, to be evaluated numerically. The paper discusses strategies for their accurate evaluation, and brings selected numerical results. These influence functions can be thought of as bi-quadratic elements, which can be used within the boundary element and meshless method frameworks to solve a variety of problems in engineering practice.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Reynolds-Averaged Simulation of Langmuir Turbulence in the Coastal Ocean

Author(s): *Juan Penaloza Gutierrez, *University of South Florida*; Andres Tejada-Martinez, *University of South Florida*;

Langmuir turbulence in the coastal ocean is driven by winds and waves and is characterized by Langmuir cells (LCs) that can span the full depth of unstratified water columns. LCs consist of wind-aligned parallel counter-rotating vortices, which when spanning the full depth of the water column can result in significant sediment resuspension and subsequent lateral transport. A solution strategy based on Reynolds averaging is introduced, relying on the coherency and persistence of full-depth LCs. Here the full-depth cells are treated as a secondary component to the wind and/or pressure gradient-driven primary flow. The resolved LCs and associated statistics will be compared with their counterparts in large-eddy simulation (LES). The comparison shows that the Reynolds-averaged approach can reproduce cell meandering and merging (i.e. the so-called Y junctions), a requisite for capturing the proper crosswind scales of the LCs. The merging occurs less frequently over time as the cells grow after being spun from rest. The Reynolds-averaged approach will be extended to simulations involving a coastal boundary through coupling with a wave model predicting the Stokes drift velocity of the surface waves. Studies based on this approach will be presented investigating the impact of variable water column depth, the coastal shore, wind direction, and wave direction on the structure and intensity of the LCs.

Title: Finite-Element Modeling of Timber-Concrete Composite Floors in Fire

Author(s): *Julie Liu, *Oregon State University*; Erica Fischer, *Oregon State University*;

Timber-concrete composite (TCC) floors are a structural component utilized in mass timber buildings, constructed from a timber slab or beams joined with shear connectors to a concrete slab. Finite element models were developed in the commercially available finite element program Abaqus utilizing sequentially-coupled heat transfer and stress-based analyses to investigate the behavior of TCC floors during a fire scenario. Three different mass timber panels were investigated: nail-laminated timber, cross-laminated timber [1], glulam [2], and mass plywood panels, all composite with normal-weight concrete. The models used 4-node linear quadrilateral heat transfer and plane stress elements. Timber and concrete material behavior were simulated using temperature-dependent thermal properties and mechanical properties from Eurocode 2, Eurocode 5, respectively. Concrete damaged plasticity was implemented within the models to account for cracking in tension and crushing in compression in accordance with CEB-FIP Model Code 2010. Shear connectors were defined as point-to-point zero-length wire connectors at the timber-concrete interface with slip modulus and yield force obtained from pushout tests [1]. Calculated temperatures from heat transfer analysis were in good agreement with experimental data [3]. Stress-based analysis methods were benchmarked against deflections and failure loads from ambient temperature bending tests of TCC floors [2]. Sequentially-coupled heat transfer and stress-based analyses were performed by applying calculated temperatures from heat transfer analysis to stress-based analysis to calculate the behavior of TCC floors under simultaneous loading and fire exposure. Moment capacity and deflections were compared to experimental data [1]. The design assumptions of elastic materials and elastic or fully yielded shear connectors were evaluated against internal stresses and connector forces from the stress-based analysis. These finite element modeling techniques can be applied to improve understanding of the fundamental behavior of TCC floors in fire and develop performance-based structural fire engineering approaches for mass timber structures.

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Development of Active-Learning-Based Surrogate Method for Estimating Reliability of Stochastic Wind-Excited Systems

Author(s): *Jungho Kim, *Seoul National University*; Sang-ri Yi, *University of California, Berkeley*; Junho Song, *Seoul National University*;

In efforts to manage the risk of unexpected failures caused by strong winds, it is of great significance to evaluate their reliability considering variabilities arising from the external wind excitations and structural systems [1]. First-passage probability has been widely adopted as a reliability measure of a system to predict the risk under such circumstances [2]. Although several methods have been proposed to assess the first-passage probability, their applications to practical problems were hampered by substantial computational costs. Therefore, reducing the number of system performance evaluations is an essential task with the growing complexity of modern engineering systems. This study proposes a new active-learning-based surrogate method to address the computational challenges. The conditional distribution of the maximum structural response is utilized to represent the mixture-distribution-based formulation of the first-passage probability. This procedure employs a heteroscedastic Gaussian-process-based surrogate model to predict the distribution parameter functions. In addition, an adaptive training process of surrogates is introduced to identify the best design of experiments by utilizing the exploration-exploitation trade-off. Several numerical examples are investigated to demonstrate the accuracy and efficiency of the proposed method. The results confirm that the method enables convergence toward reliable estimates with significantly fewer structural performance evaluations.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Fluid Induced Migration of Prostate Cancer Cells Towards Bone Metastasis

Author(s): *Kalpana Katti, *North Dakota State University*; Haneesh Jasuja, *North Dakota State University*; Sharad Jaswandkar, *North Dakota State University*; Dinesh Katti, *North Dakota State University*;

An estimated 1.41M cases of prostate cancer were reported worldwide in 2020 leading to 375,304 deaths according to the WHO. The mortality in prostate cancer results from bone metastasis and the resulting skeletal failures. We have designed a novel testbed of prostate cancer through use of a tissue-engineered nanoclay scaffold. The testbed involves seeding nanoclay scaffolds with human mesenchymal stem cells followed by seeding with prostate cancer cells after bone growth is achieved. There is limited knowledge of the mechanisms associated with the role of biomechanical cues enabled by the interstitial fluid flow of the media on prostate cancer tumor growth and cell migration. We have designed and fabricated a novel bioreactor to evaluate the effect of interstitial fluid flow on the prostate cancer migration at bone metastasis. The bioreactor model and the transwell insert were designed using computer-aided design (CAD) software (SolidWorks v.2018, Dassault Systems). The theoretical analysis of the hydrodynamic behavior of the bioreactor was conducted by computational fluid dynamics (CFD), using a SolidWorks flow simulation package. The inlet flow rates of 0.05 ml/min and 0.2 ml/min were applied to the bioreactor model based on experiments. From CFD results, we concluded that the physiological velocity was achieved at 0.05 ml/min flow rate. We observe that high flow rate induces apoptosis in highly metastatic prostate cancer cell line PC3 via TGF- β 1 mediated signaling. We also evaluate the percent cell migration in the proximity of bone microenvironment under dynamic conditions. Our results indicate that interstitial fluid flow does not alter the CXCR4 level, but bone proximity upregulates CXCR4 levels that lead to increased MMP-9 levels. CXCR4 is considered as a crucial regulator of invasiveness and metastasis of prostate cancer. High CXCR4 expression in prostate cancer cells is associated with their bone metastasis ability. In addition, both integrins and MMP-9 levels were upregulated by fluid flow conditions, contributing to increased migration rate under dynamic conditions. Our studies suggest that integrins play distinct role in response to fluid-induced mechanical cues and act as mechanosensory agents that transduce mechanical signals via integrin-MMP 9 signaling axis to promote flow-induced motility of prostate cancer cells. Overall, this study demonstrates the critical role of interstitial fluid flow in prostate cancer invasion and metastasis. Understanding the critical role of interstitial fluid flow in promoting prostate cancer progression will aid in development of new therapies for advanced-stage prostate cancer and provide improved therapy for patients.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Optimizing Soil Simulations Using the Discrete Element Method (DEM)

Author(s): *Karam Jaradat, *Virginia Polytechnic Institute and State University*; Sherif Abdelaziz, *Virginia Polytechnic Institute and State University*;

The aim of this study is twofold, 1) to determine the proper grain-scale parameters of membrane boundaries in discrete element simulations (DEM), and 2) to determine the minimum size of stress measurement within the soil assembly. Triaxial testing of sandy or clayey soils results in shear banding and stress localization prior to and at failure. Different failure modes can develop, including barreling/bulging, slip shear plane, or a combined failure mode. Such failure mechanisms cannot be examined using DEM simulations of soils utilizing rigid boundary conditions. To model flexible boundaries, we utilized membrane boundary conditions that permit rotational but not the translational motion of the membrane constitutes, allowing the soil specimen to deform freely while maintaining the appropriate boundary condition (mean effective stress, for drained conditions or zero volume change for undrained conditions). The membrane stiffness is determined through a series of DEM simulations, where the robustness and accuracy of the flexible boundary condition are verified against rigid ones to achieve a similar macroscopic response. After that, we performed a sensitivity analysis of the size of stress measurement to determine the minimum measuring zone size required to capture the macroscopic response to ensure computational efficiency. Results from this study suggest the rate at which the particles rotate or reorient control the DEM specimen failure mode (bulging, slip shear plane, or combined failure mode).

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Inverse Design of Omnidirectional Shields for Band-Gapping Acoustic Waves in 3D

Author(s): *Ke Ma, *The University of Texas at Austin*; Heedong Goh, *The University of Texas at Austin*; Loukas Kallivokas, *The University of Texas at Austin*;

We are concerned with the design of a periodic shield for the omnidirectional and directional band-gapping of acoustic waves in three spatial dimensions. The goal is to arrive at the shield's material composition, when either a single or multiple band gaps are prescribed.

To this end, we describe the design of the shield's unit cell, cast as a dispersion-constrained optimization problem over the cell's Irreducible Brillouin Zone. Accordingly, we define a Lagrangian comprising the band gap objective – cast as the

vanishing of the group velocity at the gap frequencies – and the unit cell's side-imposed Floquet-Bloch eigenvalue problem. Next, we appeal to the Hellman-Feynman theorem to express the group velocity in terms of the Floquet-Bloch

eigenvalues and eigenvectors, and convert the constrained optimization problem into an unconstrained problem amenable to a standard adjoint method.

Thus, the shield's unit-cell properties are obtained through an iterative process, commonly used in inverse medium problems.

We demonstrate the methodology with numerical experiments: first, we show that the target band gaps are realized for shields of infinite periodicity in 3D.

Secondly, we turn to metasurface assemblies, and using time-domain simulations, we show that the intended band gap effect is indeed realized in a transient setting as well.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Cylindrical Microplane Model for Compressive Kink Band Failures and Size Effect in Fiber Composites

Author(s): *Kedar Kirane, *Stony Brook University*; Jing Xue, *Stony Brook University*;

This work presents a novel 3D cylindrical microplane model for the longitudinal compressive failure of fiber reinforced composites by fiber kink band formation. The salient novel feature of this model is a cylindrical system of microplanes, introduced to capture the transversely isotropic behavior of the unidirectional lamina. The model implicitly resolves the macro-micro equilibrium to calculate the local fiber rotation in the kink band, thus defining the orientation of the cylindrical microplane system. This allows an intuitive formulation of the kink band triggering mechanism involving axial inter-fiber microcracks at the microplane level. The internal friction is formulated at the microplane level, via a thermodynamically consistent combined damage/friction scheme, which is integral to compressive failures. The model formulation is general enough to allow application to both brittle and ductile matrix materials, and to in-plane and out-of-plane kinking. The model is shown to predict well the geometric features of the failure, including damage localization, in-plane and out of plane kink band formation and propagation accompanied by the local fiber rotation. Further, the model can capture the entire load displacement curve including the peak load, the prolonged post-peak load plateau, and most importantly, the quasi-brittle fracture mechanics-based strength size effect.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Micromechanical Effects of Notch Size in Concrete Under Fatigue Loading

Author(s): *Keerthana Kirupakaran, *National Institute of Technology Puducherry*; Chandra Kishen J. M., *Indian Institute of Science*;

Presence of cracks and flaws are inherent characteristic features of cementitious materials, and this has driven the application of fracture mechanics concepts to study crack propagation behavior in concrete. In several experimental and analytical studies, notches are deliberately introduced in concrete specimens to understand its influence on fracture behavior of concrete. While the studies focused on concrete under static loading have shown the influence of notch size on strength, fracture process zone size and fracture energy, its effects under fatigue loading are not well explored in the literature. Fatigue of concrete is a complex multiscale fracture phenomenon, wherein the material undergoes progressive stiffness degradation at a nominal stress well below the critical stress limits. As fatigue behavior is influenced by several parameters including load, material and geometry, the effect of notch size particularly on fatigue fracture characteristics is not explicitly understood. In order to develop life predictive fatigue models for concrete, it is important to understand the micro-mechanical effects of notch size under fatigue loading.

In this research, flexural fatigue experiments are performed on notched concrete beams with three different notch-to-depth ratios, 0.20, 0.35 and 0.50. Two sets of fatigue tests are performed. In the first set, the beams are subjected to 80% of their peak load in a constant amplitude cyclic loading. In the second set, all the beams with different notch sizes are subjected to a maximum amplitude corresponding to 90% of static peak load as obtained in the beam having notch-depth-ratio of 0.5. Acoustic emission and digital image correlation techniques are used to understand the mechanisms of fracture occurring in the fracture process zone under fatigue loading. The experimental results revealed, no definite trend with respect to the notch size in the first set of fatigue experiments, however in the second set the influence of notch size is observed only in specimens with 0.5 notch-to depth-ratio. Further, an increase in critical fatigue crack length beyond which unstable crack propagation occurs, is observed with increase in notch size. These experimental observations are encapsulated into an analytical model which is derived by unifying fracture and damage mechanics concepts.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Structural Phase Transition in a Simplex Tensegrity

Author(s): Armin Motadel, *Tennessee State University*, *Kehinde Omotayo, *Tennessee State University*, Ranganathan Parthasarathy, *Tennessee State University*,

Tensegrity structures can be treated as a particular category of granular materials, where the relatively stiff struts carrying pre-compression can be viewed as grains which are physically isolated from each other "floating" in a sea of pre-tension. A three-strut simplex with six tension members and three compression members is the simplest three dimensional tensegrity structure. A structural phase transition in a three-strut simplex has been experimentally observed for the first time using a physical model built using wood struts and elastic bands. When the structure is compressed to a critical state, further deformation is accommodated by internal rotation of one of the struts, rather than potential energy change in the bands. At the end of the transition, the structure reaches a new configuration which is a twin of the undeformed one. Using potential energy minimization under constraints that mimic the experiment, a similar behavior has been demonstrated using numerical simulation. A potential application of the observed phenomenon is to greatly reduce the energy required to switch between two desired shapes in active morphing structures such as airplane wings or opening bridges. The transition can also be exploited to design impact-absorbing structures based on lattice materials formed by combination of individual simplex modules.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Homogenization-Based Optimization of Lattice Structure Using Granular Micromechanics Approach

Author(s): *Kehinde Omotayo, *Tennessee State University*; Samal Aminashairi, *Tennessee State University*; Ranganathan Parthasarathy, *Tennessee State University*;

With the recent progress in additive manufacturing, lattice structures are being intensively researched for applications such as shock absorption, biomaterial scaffolds, and aerospace structures. They can be considered as structures at the scale of the lattice features, but materials at scales which are orders of magnitude larger. The materials and geometry of lattice structures can be optimized to meet target mechanical properties at the larger scale. In particular, homogenization-based optimization has been extensively studied since it saves computational resources as compared to full-resolution analysis. In this work, we show that the granular micromechanics approach is especially suitable for homogenization-based optimization because of the possibility to obtain closed form relationships between the macro-scale properties and the microstructural features. In particular, for bending-dominated lattices, we have come up with a method to calculate strain concentration tensors based on interpolation between the case of zero-stiffness joints or hinges, and the case of affine strain. In contrast to affine approximation which gives stiffness that differ from the finite element analysis results by an order of magnitude, those from this method closely match the finite element analysis. We show that the method is effective for two-dimensional lattices with slender beam elements, including auxetic lattices. The theoretical framework developed in this work can be extended to three-dimensional lattices as well. Effects of inter-nodal stiffness and orientation distribution of the struts on the macro-scale properties are specifically determined and compared against results from finite element analysis. Finally, the developed approach has been implemented in an optimization scheme to tune the element orientations and stiffnesses for target mechanical properties of the lattice.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Respiration Monitoring Using a Motion Tape Chest Band

Author(s): Yun-An Lin, *University of California, San Diego*; Emerson Noble, *University of California, San Diego*; Taylor Pierce, *University of California, San Diego*; Chin-Hsiung Loh, *University of California, San Diego*; *Kenneth Loh, *University of California, San Diego*;

The measurement of vital signs (such as respiration rate, body temperature, pulse, and blood pressure), especially during extraneous activities, is essential for physical performance and health monitoring. A variety of wearable chest band sensors have been developed, commercialized, and widely used in consumer and healthcare settings. The plethora of technology choices also means that each unique chest band sensor may require different data acquisition hardware and software systems, and data may not be transferable between platforms. Therefore, the objective of this work was to develop a low-cost, disposable, respiration sensor that could be attached onto any elastic chest band. The approach was to spray-coat graphene nanosheet (GNS)-based thin films onto unidirectionally stretchable elastic fabric to form a piezoresistive material. Snap buttons were incorporated at the ends of the fabric so that they could be attached onto any chest band, removed at any time, and replaced for a new data collection event. The resistive nature of the nanocomposite sensor means that they can be easily interfaced (e.g., using a voltage divider) with any existing data acquisition (DAQ) module while adding respiration monitoring capabilities. To facilitate testing of these nanocomposite respiration sensors, a miniature DAQ module with four sensing channels was also prototyped. Then, tests were performed with human subjects wearing a nanocomposite chest band and a reference commercial respiration monitoring chest band. Simultaneous measurements of subject respiration verified the respiration monitoring performance of these low-cost, disposable, nanocomposite fabric sensors. A signal processing scheme was also implemented in order to output respiration rate in real-time.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Experimental Studies on the Design Parameters of Pressurized Sand Dampers

Author(s): *Konstantinos Kalfas, *Southern Methodist University*; Nicos Makris, *Southern Methodist University*;

This paper presents experimental results from various configurations of an innovative low-cost fail-safe sustainable energy dissipation device in which the material surrounding the moving piston and enclosed within the damper housing is pressurized sand.

The proposed sand damper does not suffer from the challenge of viscous heating and failure of its end seals, and it can be implemented in harsh environments with either high or low temperatures. Its symmetric force output is velocity-independent, and it can be continuously monitored and adjusted at will with standard commercially available strain gauges installed along the post-tensioned rods that exert the pressure on the sand. Component testing at various geometric configurations, pressure levels, stroke amplitude, and cycling frequency show that the proposed pressurized sand damper exhibits stable hysteretic cyclic behaviour with increasing pinching at larger strokes.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Rail Defect Detection by Noncontact Vibration Measurements

Author(s): *Korkut Kaynardag, *The University of Texas at Austin*; Chi Yang, *The University of Texas at Austin*; Salvatore Salamone, *The University of Texas at Austin*;

A rail defect detection prototype is under development at the University of Texas at Austin. This prototype aims at detecting transverse cracks located in the railhead. This is because such defects cause rail breaks, leading to serious accidents. Therefore, the railway transportation community is interested in the detection of such defects at high speeds that will not prevent the routine operation of railroads. The prototype under development uses two laser Doppler vibrometers (LDVs) placed vertically in front of operating trains to sense the propagating waves in railhead that are induced by the wheel-rail interactions. This is achieved by using the waves having frequencies between 30 kHz and 100 kHz (the frequency range of interest). In this range, the waves are localized at different sections of rail such as railhead, web, and foot, and therefore the measurements from the railhead record the waves propagating in the railhead. Two measurement points allow for observing the changes in the amplitude of waves due to a transverse crack by eliminating the effect of random vibrations induced by the wheels. This study presents the results of field tests carried out at Technology Transfer Center, Inc in Pueblo, CO. In these tests, the test train which was installed with the prototype traveled at different test speeds up to 30 mph on a test track. A welded rail joint was used in the test track to represent a transverse crack since such joints cause wave reflection as transverse cracks do. At first, the LDV signals were filtered with an in-house developed impulsive noise filter since impulsive noise was observed in the recorded signals. Then, the LDV signals were bandpass filtered in the frequency range of interest. Afterward, a multi-dimensional probabilistic damage index based on the change in the amplitudes of the signals and the correlation of the signals was developed to identify the defect's location. Results demonstrated that the developed system was capable of finding the defect at all test speeds. It must be emphasized that, up to the authors' knowledge, an LDV based rail defect detection system is new and has the potential to offer reliable damage detection at high speeds.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Wind: A Force for Good

Author(s): *Lance Manuel, *The University of Texas at Austin*; Paul Veers, *National Renewable Energy Laboratory*;

The legacy of Ahsan Kareem's contributions related to natural hazards – primarily though not exclusively dealing with wind – has left an indelible, deep and valued imprint on our collective knowledge toward the safe design of tall buildings, long-span bridges, offshore structures, etc. While his contributions in the wind energy arena have been relatively modest, even there his influence began early and has been noted [1]. We discuss some of these physical and stochastic underpinnings that have informed the safe and reliable design of wind turbine units and plants. Our “flight” will take us through challenges overcome by borrowing from Kareem's work and ideas in different places – whether it was in turbulence power spectra and coherence function characterizations, gust factor definitions, efficient spatio-temporal stochastic decompositions of wind fields, or extreme climates [2].

Starting with efficient representations of the atmospheric boundary layer and related mesoscale wind fields and on to turbine-scale inflow field characterization, rotor aerodynamic loads, and control systems, parallels are highlighted between these linkages and the more familiar building/building modeling chain that works analogously with the atmospheric boundary layer, wind fields, aerodynamic admittances, structural dynamics characterizations, and passive/active control. We will discuss the evolution in multi-scale modeling and simulation efforts in the wind energy community over the last 40 years and highlight how and where deterministic and stochastic approaches introduced or made more accessible by the works of Kareem and others have played important roles.

While civil engineers have historically dealt with complexities from wind with a view toward avoiding failures by innovative design, the wind energy industry and research community has seen wind as a force for good, something that can be harnessed and controlled for what it has now become—a most viable clean energy source. Bold and creative wind energy design concepts have benefited from all our learned attempts at keeping wind at bay in structural design because, to quote C. S. Lewis, “You find out the strength of a wind by trying to walk against it, not by lying down.”

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Robust Wireless Structural Control Considering Actuation Signal Loss

Author(s): Thao Truong, *University of Minnesota*; Peter Seiler, *University of Michigan*; *Lauren Linderman, *University of Minnesota*;

Feedback control systems are one approach to achieve tighter performance guidelines as structural engineering moves towards a low-damage design philosophy. Their realization for civil applications requires considering both reliability and the large-scale of these structures. Wireless communication for such distributed control systems offers flexible network architectures and potentially lower cost. However, signal loss, delay, sampling, and limited bandwidth can limit their performance. This research presents a controller synthesis approach to mitigate signal loss, particularly in the actuator link. In the presence of actuator signal loss, the traditional linear quadratic gaussian (LQG) control algorithm can result in instability when signal acknowledgement is not present. The proposed robust control approach, referred to as a linear quadratic gaussian controller with uncertain control actions (LQG/UCA), reduces the sensitivity to random signal dropouts at the actuators by considering a designed uncertainty in the control forces. The H₂-norm of the LQG system with perfect acknowledgement is used for tuning of the uncertainty parameter. The proposed control synthesis is demonstrated on the three-story benchmark structure subjected to earthquake excitation. In the case study, a small amount of signal dropouts destabilizes the traditional LQG controller. On the contrary, the new LQG/UCA controller successfully maintains the stability and performance of the control system without knowledge of the random occurrence of the signal dropouts. Furthermore, simplicity is an attractive feature of LQG/UCA that provides interpretability and scalability. The control synthesis is similar to the traditional LQG synthesis with an additional unknown disturbance. This simple model is easy to interpret for designers who are familiar with LQG control.

EMI 2022
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Title: A Simple Implementation of Localizing Gradient Damage Model in Abaqus

Author(s): *Leong Hien Poh, *National University of Singapore*; Yi Zhang, *National University of Singapore*;

With the localizing gradient enhancement, a damage model for quasi-brittle materials is able to achieve regularized softening responses, with localized damage profiles corresponding to the development of macroscopic cracks, to resolve the numerical spurious effects induced by the conventional gradient enhancement. The typical implementation strategy for a gradient enhanced model is to solve the system of governing equations simultaneously. Focusing on the finite element (FE) package Abaqus, a user element subroutine is required to define the finite elements with additional degrees of freedom for the nonlocal field. Moreover, with user elements, additional effort is required to visualize the numerical results. To an inexperienced engineer / researcher, these requirements can be challenging. In this paper, a simple implementation of the localizing gradient damage model is elaborated. By utilizing the in-built coupled thermo-mechanical elements in Abaqus, the user only needs to define the material constitutive laws, as well as the sensitivity terms with respect to the field variables. Post-processing of results can be done directly in Abaqus. The applicability and ease of implementation are demonstrated via several examples, including those that utilize the Abaqus features of element deletion, contact between surfaces, as well as the incorporation of cohesive elements.

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Baltimore, MD, May 31 - June 3, 2022

Title: Thermal Modeling of Laser Powder Bed Fusion Additive Manufacturing of Refractory Materials

Author(s): *Li Ma, *Johns Hopkins University Applied Physics Lab*; Gianna Valentino, *Johns Hopkins University Applied Physics Lab*; Mitra Taheri, *Johns Hopkins University*; Morgana Trexler, *Johns Hopkins University Applied Physics Lab*;

Refractory metals, e.g., tungsten, are an extraordinary class of materials, known for their exceptional properties including high melting temperatures, thermal conductivity, stiffness and strength. While these materials are desirable for high temperature and extreme environment applications, their limited room temperature ductility makes the fabrication and implementation challenging. Additive manufacturing (AM) has many potential advantages, particularly in the processing of refractory metals. However, the process parameters needed to fabricate defect-free parts, as well as the effects of AM processing on material properties, are not fully known. In this work, we will computationally study the effect of laser processing parameters on the solidification behavior of tungsten alloys. Single track melt pools will be modeled using computational fluid dynamics software, FLOW3D, and validated with AM experiments across a range of processing parameters (e.g., laser power, velocity). The results from this work will enable rapid development of AM processing parameters for refractory metals and alloys.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Carbon Nanofibers (CNFs) Dispersed in Ultra-High Performance Concrete (UHPC): Mechanical Property, Workability and Permeability Investigation

Author(s): *Linfei Li, *University of Colorado Boulder*, Boning Wang, *University of Colorado Boulder*, Mija Hubler, *University of Colorado Boulder*,

Previous research on cementitious materials has sought a new cement-based construction material that can break through the performance delivered by regular concrete. One of such materials, ultra-high performance concrete (UHPC), was developed 30 years ago and can provide extremely high compressive strength of up to 300 MPa while maintaining workability. The introduction of macroscale fibers in UHPC helps to achieve flexural strengths of up to 40 MPa, from a microscale point of view, such fibers are too large to control the propagation of microscale cracks. In this presentation, carbon nanofibers (CNFs) are studied as alternative reinforcement fibers.

Due to the van der Waal's forces and the hydrophobic property of the fibers, CNFs tend to bundle together during the mixing stage with cementitious material. An inhomogeneous distribution of CNFs in concrete can result in no impact or decreased mechanical performance. In addition, the atomically smooth surface of bundled CNFs also causes an unstable interfacial bond strength with the cement matrix. Therefore, a comprehensive study of UHPC-CNF composites is conducted which optimizes the UHPC mix design and selects the most effective dispersion technique based on the corresponding improvement of mechanical, workability, and permeability performance. Specifically, UHPC mix designs were developed based on published literature and industry reports. One of these mix designs was selected as the 'optimal mix design' based on targeted performance metrics, i.e. compressive strength and slump. The optimal mix design was then applied as the base UHPC mixture. Different CNF dispersion techniques and sensitivity analyses were reported considering the optimal dispersion time, dispersion method, and amount of HRWR applied, etc. The flexural properties of UHPC-CNF composites, porosity measurement, and SEM images were used to evaluate the effectiveness of the dispersion of the CNFs. Then, the selected UHPC-CNF composite behavior was assessed mechanically by compression testing, in terms of workability by slump test and calorimetry test, and permeability by wicking and ponding tests.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Optimal Generation of Multivariate Hurricane Intensity Maps Using Multivariate Hazard Quantization

Author(s): *Liyang Ma, *Lehigh University*; Daniel Conus, *Lehigh University*; Wei-Min Huang, *Lehigh University*; Paolo Bocchini, *Lehigh University*;

The Hazard Quantization (HQ) method was developed for the effective sampling of hazard intensity measure (IM) maps with a single intensity measure. However, this method cannot be applied to the optimal sampling of multiple intensity measure maps with very different stochastic properties such as maximum wind speed and storm surge levels, which are the two most critical intensity measures for a hurricane event.

This paper first introduces a novel algorithm that extends the traditional "Functional Quantization by Infinite-Dimensional Centroidal Voronoi Tessellation" (FQ-IDCVT) to the quantization of multivariate fields. Then, a multivariate approach to HQ is proposed based on the new algorithm and is tailored to the optimal sampling of hurricane events.

A case study on the Florida Panhandle region is presented. The sample space is represented by a large set of pairs of IM maps for wind speed and storm surge levels, with each pair representing a specific hurricane event. The simulated pairs of IM maps carry the stochastic characteristics of the associated hurricane events, such as the cross-correlation between wind speed intensity and storm surge levels at different sites of the region. The proposed multivariate HQ method is implemented to generate a reduced set of maps representative of the whole sample space. The ability of the proposed multivariate Hazard Quantization methodology to provide an accurate estimation of the hazard curve for both intensity measures and to correctly capture the spatial autocorrelations and the spatial cross-correlation among the two intensity measures is investigated quantitatively.

A building portfolio loss assessment is performed for the study region, and a quantitative comparison is made between the loss computed using the entire sample space and using the reduced set of samples. The results demonstrate the accuracy of the proposed method for its application to regional loss analysis.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: A Wiener Path Integral Quadratic Approximation for Stochastic Response Determination of Nonlinear Multi-Degree-of-Freedom Systems

Author(s): Ying Zhao, *Quzhou University*; Apostolos Psaros, *Brown University*; Ioannis Petromichelakis, *Columbia University*; *Ioannis Kougioumtzoglou, *Columbia University*;

The accuracy degree of the Wiener path integral (WPI) technique for determining the stochastic response of diverse nonlinear multi-degree-of-freedom (MDOF) dynamical systems is enhanced. This is done by employing a quadratic approximation in the WPI functional series expansion. It is shown that compared to the standard most probable path WPI approximation (e.g., [1]), the quadratic approximation yields enhanced accuracy in evaluating the system joint response probability density function (PDF). This is primarily due to the fact that fluctuations around the most probable path are also accounted for by introducing a localized state-dependent factor in the approximate evaluation of the WPI. Further, a significant advantage of the enhancement relates to structural reliability assessment, and to the fact that the required in the most probable path approach PDF normalization step is circumvented. Thus, low probability events, e.g., failure probabilities, can be determined in a direct manner without the need for obtaining the complete joint response PDF first. The herein developed technique can be construed as an extension of the results in [2] to account for MDOF systems. Various nonlinear MDOF oscillators are considered for demonstrating the efficiency of the technique. Comparisons with pertinent Monte Carlo simulation data are provided as well.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Determination of Ultimate Capacities of In-Situ Prestressed Stayed Columns Through Probing

Author(s): *Luke Lapira, *Imperial College London*; Jiajia Shen, *University of Bristol*; Ahmer Wadee, *Imperial College London*; Rainer Groh, *University of Bristol*; Leroy Gardner, *Imperial College London*;

Prestressed stayed columns are structural systems where the compressive load capacity is enhanced through pre-tensioned external cable stays. However, much research has demonstrated that subcritical post-buckling responses are usually triggered when implemented prestressing levels theoretically maximize critical buckling performance. Presently, a pilot numerical framework is developed to determine the in-situ ultimate strength of such columns by applying a system of probing forces in the pre-buckling range for various columns with different levels of initial prestress. The aim is to develop a non-destructive testing methodology for initially imperfect stayed columns to determine their sensitivity to potential changes in prestressing levels from temporal environmental effects. With the development of such a system, it will be possible to assess the in-service structural health of stayed columns and whether any remedial measures or repairs need to be undertaken.

Title: Localized Approximations by Polynomial Chaos Expansions for Highly Non-Linear Functions

Author(s): *Lukáš Novák, *Brno University of Technology*; Miroslav Vorechovský, *Brno University of Technology*;

It is typically highly computationally demanding to create a polynomial chaos expansion (PCE) approximation of a mathematical model with high local non-linearity. Computational requirements grow exponentially with both the maximum polynomial order p of PCE and the dimension of given stochastic model. Unfortunately, in the case of functions with localized non-linearities, it is typically necessary to use high p despite the fact that a major part of the function could have been approximated with significantly lower p . A possible solution to this problem is a selection of a sparse set of basis functions by best-model selection algorithm, which can dramatically reduce the number of basis functions and thus the number of evaluations of the original mathematical model.

Another solution used in the present paper is to divide the whole design domain into sub-spaces, each approximated by a low-order PCE. This contribution presents a novel algorithm for the iterative identification of the strata containing significant non-linearity and approximation of the whole original function by local PCEs. The proposed algorithm is based on recently proposed variance-based adaptive sequential sampling [1], which is employed to identify sub-spaces containing significant non-linearities. The whole iterative process contains the following main steps: constructions of an initial global PCE; identification of sub-space associated to the highest variance density (non-linearity); division of the design domain; extension of the experimental design; constructions of local PCEs for each stratum; identification of the strata associated to the highest variance density and its division.

The whole iterative process is repeated until the target accuracy of PCE is achieved, or the computational budget is exhausted. The significant advantage in comparison to existing methods is the possibility to identify single strata, which is further divided, and new sampling points (calculations of the original mathematical model) are only in the identified strata, which leads to only reduction of computational cost per iteration. The performance of the proposed approach will be demonstrated on numerical examples.

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Title: Selection of Simulated Earthquake Ground Motions for Nonlinear Analysis of Near-Fault Structures

Author(s): *Maha Kenawy, *Exponent*, David McCallen, *University of Nevada, Reno*;

Assessing the potential risks to civil structures in urban communities close to active earthquake faults imposes several challenges on engineers. Earthquake ground shaking near the fault is highly sensitive to the characteristics of the fault rupture, seismic wave propagation patterns and site conditions. Along with the sparsity of available near-fault earthquake field recordings, this sensitivity leads to significant uncertainty in predicting the intensity of ground motion caused by large earthquakes at short distances from the fault, and its impacts on infrastructure. In this study, we leverage the use of physics-based fault rupture simulations and high-performance computing tools to predict the seismic demands on modern building structures at a regional scale. We focus on characterizing the unique features of near-fault earthquake ground motion that influence the risks to structures—most importantly, the presence of strong velocity pulses—using a database containing approximately 24,000 simulated records. We combine fault rupture and structural simulations to develop a procedure for selecting simulated earthquake records for nonlinear dynamic analysis of near-fault structures, and assess the bias associated with different selection criteria and ground motion intensity measures. The proposed procedure minimizes the bias in the predicted structural demands using a small representative sample of earthquake records without altering the records' characteristics, and may eliminate reliance on empirical techniques to selectively classify near-fault records based on the presence of strong ground velocity pulses. The procedure may also facilitate incorporating unaltered physics-based simulated earthquake ground motions into performance-based seismic design of near-fault structures.

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Baltimore, MD, May 31 - June 3, 2022

Title: Calibration of Material Constitutive Model Using Hierarchical Bayesian Inference

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Material constitutive models play an integral role in defining the material behavior in finite element (FE) models of civil structures or civil infrastructure systems; they are in turn governed by several parameters. The values of these parameters need to be calibrated for the FE model to simulate the actual physical system behavior as closely as possible. Hence, the estimation of such parameter values from experimental data is a topic of crucial interest. In recent studies, the inference of the parameters of a commonly used non-linear uniaxial steel material model, the Menegotto-Pinto model, was performed using a dataset of stress-strain response from cyclic tests conducted on thirty-six coupons from steel reinforcing bars, representing a sample across three different manufacturing mills, two different manufacturing standards, and six different strain histories. In these previous studies, parameter estimation was performed using either deterministic optimization techniques calibrating these material parameters to values that best predict the response as compared to the experimental data, or classical Bayesian inference that considers these material model parameters as random variables, embedding them with various uncertainties. However, the aleatory type of uncertainty that tends to exist inherently in different specimens of the same kind, specifically in the coupons of the previously used dataset, is not captured by these two methods. This study focuses on overcoming this shortcoming through hierarchical Bayesian modeling (HBM) and estimation of the parameters of a steel material model, incorporating aleatory uncertainties in the formulation. The values of the material model parameters and of the hyperparameters of the probability model for aleatory uncertainty are estimated from the same dataset that was used in the previous studies. Utilizing the HBM framework, it was possible to perform sampling in a 308-dimensional variable space by leveraging parallel computation using the Metropolis-within-Gibbs sampling algorithm, and thus jointly update the probability distribution of the material model parameters as well as the aleatory uncertainty model parameters. The results from the non-hierarchical (i.e., 'classical') and hierarchical Bayesian inference methods, respectively, are compared and the "shrinkage" effect is observed in the latter case. Also, derived from the dataset considered, a probability distribution is then proposed for the Menegotto-Pinto material model parameters for ASTM (A615 and A706) Grade 60 reinforcing steel. This probability distribution model is aimed towards applications in structural reliability analysis.

EMI 2022
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Title: Seismic Performance of Pile Foundations in Liquefiable Soils Considering Material and Geometric Nonlinearities

Author(s): *Majid Manzari, *George Washington University*;

Seismic performance of pile foundations in liquefiable soils has been the subject of extensive research efforts in recent years. In the case of long piles embedded in liquefiable soils, it is expected that the seismic response will involve both material and geometric nonlinearities. Despite significant progress in constitutive and numerical modeling of soil liquefaction as well as nonlinear analysis of structural systems, a more complete understanding the effects of geometric nonlinearity of pile foundations in their interactions with the surrounding soil requires further in-depth analyses and evaluations. In this work, an analysis approach is presented to identify/quantify these effects using fully-coupled nonlinear soil-structure interaction simulations that account for both the material and geometric nonlinearities in the piles. To assess the validity of the proposed approach, a number of comparisons with the experimentally observed soil-pile interaction effects in liquefiable soils are conducted. It will be shown that the modeling of geometric nonlinearity and its role on identifying the instability of the piles in the area of weakened support from the surrounding soil can be used to explain the main cause of the collapse of bridge piers in several past earthquakes.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: A Cost-Aware and Sensitivity-Based Active Learning Algorithm for System Reliability

Author(s): Pietro Parisi, *ETH Zurich*; *Maliki Moustapha, *ETH Zurich*; Stefano Marelli, *ETH Zurich*; Bruno Sudret, *ETH Zurich*;

The safety of structures is generally assessed using structural reliability analysis within a probabilistic framework. The parameters describing the system, which are affected by uncertainties, are represented by random variables and a set of so-called limit-state functions determine whether the system fails. The goal of the analysis is then to estimate the probability of failure of the system.

Many techniques have been developed to achieve this goal and can be classified into approximation-, simulation- and surrogate-based methods. While approximation methods often lack of accuracy, simulation-based methods are computationally expensive. Surrogate-based methods, on the other hand, are an efficient alternative, especially when used in the so-called active learning framework.

In active learning reliability, an inexpensive proxy of the limit-state function is built by sparsely evaluating the original limit-state function. This results in an experimental design that can be iteratively enriched so as to improve the accuracy of the approximated limit-state surface. Combined with an appropriate reliability estimation algorithm, this ultimately leads to accurately estimating the failure probability within a moderate computational cost.

This idea has been largely investigated in the recent years and a plethora of active learning methods has been proposed in the literature as shown in recent reviews [1,2]. However, most of these contributions are limited to component reliability problems, i.e. when there is only a single limit-state function. System reliability, where there are multiple limit-state functions combined in a non-trivial way, is indeed more complex to solve. This is due to the presence of multiple (possibly disjoint) failure domains and their uneven contribution to system failure.

In this work, we propose an active learning reliability method for system reliability problems. We devise a framework combining PC-Kriging and subset simulation. We make use of density-based clustering and Sobol' sensitivity analysis to identify the most important points to add to the experimental design and the most relevant limit-states to refine. Furthermore, the proposed method is cost-sensitive, i.e., it factors in the relative cost of evaluating each limit-state function. The algorithm is illustrated and validated on a set of analytical functions and eventually applied to a network of transmission towers.

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Title: A Novel Approach to Computing Generalized Variability Response Functions for Structures with Random Parameters

Author(s): *Manuel Miranda, Associate Professor, Hofstra University;

A major issue in stochastic structural mechanics is the difficulty in validating the probabilistic description of the random system parameters assumed in many studies. Investigations usually require extensive sensitivity analyses with respect to these parameters, and this can lead to prohibitive computational cost and possible loss of insight on their relative effect.

In order to address the issues mentioned above, the concept of the Variability Response Function (VRF) has been proposed in the past as a means of systematically capturing the effect of the spectral characteristics of the random system parameters [1]. The existence of the classical VRF can be rigorously derived only for the case of linear elastic, statically determinate structures; on the other hand, for many other structural mechanics problems, the derivations require the assumption of small parameter variability. Either way, the classical VRF is a purely deterministic function that is independent of the probabilistic characteristics of the system parameters.

To overcome the restrictions of the classical VRF approach, a Generalized VRF formulation was introduced, and was successfully applied to structures with linear and nonlinear constitutive laws [2,3,4,5]. In the present work, we present an alternate approach to computing Generalized VRFs. We believe this novel methodology has greater applicability, is more versatile, and shows less dependence on the probabilistic characteristics of the random parameters than previous efforts along these lines. Numerical examples are also presented to illustrate these ideas; the examples involve the random buckling load of beam-columns with random bending stiffness. It should be noted that random buckling problems have received relatively less attention in past VRF literature [6].

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EMI 2022

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Title: Data-Driven Parsimonious Modeling and Analysis of Dynamic Cerebral Autoregulation via Diffusion Maps

Author(s): *Maria Katsidoniotaki, *Columbia University*; Ketson Roberto Maximiano Dos Santos, *Ecole Polytechnique Federale de Lausanne*; Eliza Miller, *Columbia University*; Ioannis Kougioumtzoglou, *Columbia University*; Randolph Marshall, *Columbia University*;

A data-driven technique based on diffusion maps is developed for parsimonious modeling and analysis of dynamic cerebral autoregulation (DCA), which is the ability of the cerebral vasculature to regulate cerebral blood flow in response to rapid changes in blood pressure. DCA dysfunction is associated with a number of neurological disorders, and thus, devising precise and accurate techniques for DCA analysis, monitoring and control is of growing importance to patient care. This may allow for targeted and personalized management of blood pressure in patients with acute neurological illness.

In this regard, various techniques have been proposed over the past few decades for increasing the precision and accuracy of DCA modeling and diagnostics. These methods typically employ continuous monitoring of blood pressure (BP) and cerebral blood flow (CBF), and consider an input-output relationship between BP and CBF to be identified. However, the majority of these methodologies either rely on strong assumptions (such as linearity of the input-output relationship and stationarity of the data), or employ exceedingly large and complex parameterizations that reduce the interpretability of the model and provide limited insight regarding the autoregulation mechanism (e.g., neural network approaches).

Herein, relying on the concept of diffusion maps (e.g., [1,2]), the rather strong assumption of an input-output relationship between BP and CBF is circumvented. In fact, a more general state-space description of DCA dynamics based on the variables BP, CBF and their time derivatives is considered, which yields a low-dimensional representation of the intrinsic dynamics. This is done by performing an eigendecomposition of the Markov matrix of a random walk on a graph constructed over the dataset domain. Therefore, the obtained eigenvectors and eigenvalues determine a new coordinate set embedding the high-dimensional information into a low-dimensional space. Further, the ratio of the two most significant eigenvalues indicates whether the underlying system is governed by fast or slow dynamics. Furthermore, the potential of this ratio to be used as a diagnostic tool and a biomarker for indicating healthy versus impaired DCA function is assessed by considering healthy individuals and patients with unilateral carotid stenosis.

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Title: Damage Sensitivity Features in Steel-Concrete Composite Beams Under Moving Loads

Author(s): *Mariateresa Lombardo, *Loughborough University, UK*; Giuseppe Marano, *Politecnico di Torino, Italy*; Alessandro Palmeri, *Loughborough University, UK*; *Politecnico di Torino, Italy*;

Structural efficiency and economy of construction make steel-concrete composite members the ideal solution in a wide range of building and bridge designs. Composite action in steel-concrete beams is typically achieved with discrete or continuous connectors such as shear studs and perfobonds. Under static and dynamic loads, a relative movement occurs between the concrete slab and steel girder, which in turn may lead to damage initiation and propagation.

Different models exist for the structural analysis of steel-concrete beams. In the FE (finite element) model proposed by Gata et al. [1], for instance, 14 DoFs (degrees of freedom) are used to represent the in-plane axial and transversal deformations. As a result, quadratic and cubic shape forms discretize the fields of axial and flexural displacements in the concrete slab and steel girder, achieving a satisfactory compromise between modeling accuracy and computational effort.

In the FE model of a beam, the presence of damage can be represented through discrete or continuous models, e.g., linear or nonlinear springs at the damage locations and damage smeared over one or multiple FEs (e.g., Donà et al. [2]). Different damage models result in different structural responses, affecting the fidelity of the analysis.

Similarly, different loading models can be used to represent the effects of a vehicle crossing a bridge. Depending on the vehicle-to-bridge mass ratio, the velocity of the vehicle, and the purpose of the analysis, influence lines, moving forces, moving masses, and moving oscillators offer relative pros and cons.

This paper investigates the effects that different modeling choices for localized damage and moving load can have on a range of damage sensitivity features (DSFs) used the structural health monitoring (SHM) of steel-concrete composite bridges, namely: i) modal frequencies, ii) modal shapes, iii) transverse velocities and accelerations, iv) the envelope of vibration, v) bending strains, and vi) steel-to-concrete relative movements. The analyses provide a comprehensive basis for comparing and selecting computational models and SHM strategies for existing and new steel-concrete composite bridges.

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Equivalent Turbulence Profiles from Randomized Terrain in a Boundary Layer Wind Tunnel

Author(s): *Mariel Ojeda-Tuz, *University of Florida*; Mohit Chauhan, *Johns Hopkins University*; Ryan Catarelli, *University of Florida*; Michael Shields, *Johns Hopkins University*; Kurtis Gurley, *University of Florida*;

This project investigates whether matching of first and second order turbulence profiles in boundary layer wind tunnel flow is sufficient for producing consistent peak wind pressures. The hypothesis is that multiple roughness configurations can produce equivalent second-order wind fields, but differing higher-order properties that may produce non-equivalent peak loads on test subjects.??

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This study harnesses the availability of two tools: the boundary layer wind tunnel offers an automated, high degree of freedom, rapidly reconfigurable roughness element grid ('Terraformer'), and an active machine learning algorithm (ML) was developed.??

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A homogeneous Terraformer configuration was established as a baseline, with each of 1116 roughness elements set at 8 cm height. An automated gantry system was used to move 3 cobra probes to predetermined locations within a measurement plane to quantify the wind field and establish a benchmark second order profile. 25 repeats were conducted to statistically quantify acceptable error bounds among identical experiments.??

The Terraformer element grid height scheme was then defined as a single harmonic in the along wind direction, described using wavenumber and amplitude parameters to be identified by the machine learning algorithm. This parameter space was divided into a grid and experiments were conducted for 25 different Terraformer configurations. The second order profile from each was compared to the benchmark profile, and evaluated for equivalence. Outcomes were used to train the ML and inform the initial conditions to further explore the parameter space.

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The ML then used the automated instrumentation and Terraformer to find the regions of the Terraformer parameter space that produce profiles statistically equivalent to the benchmark profile. Every subsequent Terraformer configuration was determined utilizing the accumulated outcomes of every previous experiment. After a sufficient number of configurations were conducted, the equivalent second-order parameter space emerged. We have begun to explore this space for higher order characteristics that may differ within the second order equivalent region, potentially leading to fundamental discoveries regarding the limitations of boundary layer wind tunnel simulations.?

To date, studies have been carried out for several Terraformer parameterization schemes. The integrated experimental procedure has been successfully conducted for 1198 unique roughness configurations. Without ML, an estimated? ~10x more experiments would be necessary to evaluate the hypothesis. The latest results and implications will be presented during the EMI 2022 minisymposia. The data collected from the experiments is being curated for publication in the NHERI DesignSafe Data Repository within the next 12 months.

Title: Modeling Concept for the Estimation of Bending Strength and Height Effect of Glued Laminated Timber Beams

Author(s): *Markus Lukacevic, *TU Wien*; Christoffer Vida, *TU Wien*; Josef Füssl, *TU Wien*;

Numerical simulations provide a highly efficient way to estimate the bending strength of glued laminated timber (GLT) beams. A reliable estimation of the strength requires the consideration of adequate material behavior and relevant failure mechanisms.

Therefore, our approach [1] uses section-wise constant material properties, i.e., longitudinal stiffness and tensile strength, which were derived along entire timber boards based on the procedure proposed by [2]. [3] proposed the use of discrete cracks without predefined positions within the framework of the extended finite element method (XFEM). Additionally, the formation of progressive crack networks is enabled by implementing cohesive surfaces between adjacent lamellas. For the validation, four-point bending tests of GLT beams were simulated to estimate the bending strength of specific beams from an experimental study with well-known knot morphology, which was presented by [4].

Finally, the height effect on the bending strength was studied by simulating GLT beam sections loaded with a constant bending moment. The beam heights ranged from 135 mm to 3000 mm, and the boards were randomly arranged within the GLT beams. As a result, we obtained fitted probability distributions of the bending strength for different global failure criteria and beam heights.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Physics-Informed Data-Driven Prediction of Normal Strain Field in Concrete Structures

Author(s): *Mauricio Pereira, *Princeton University*; Branko Glisic, *Princeton University*;

Concrete exhibits time-dependent behavior due to rheological effects, such as creep and shrinkage, that are challenging to predict due to their stochastic nature and dependence on loading and environment conditions, such as temperature and humidity, as well as concrete composition. Several empirical models to predict creep and shrinkage in concrete currently exist in the literature. However, empirical models are fitted to databases largely composed of laboratory tests of limited time span and that do not capture the effects of size, rebar interaction, load eccentricity, and differential creep and shrinkage, which limits their scope of application. A numerical model of the structure is typically required for their application in predicting long-term behavior in real structures. Notwithstanding, the optimal parameters to minimize fitting error on the database are unlikely to be the optimal parameters for prediction of time-dependent behavior on a specific structure of interest. Recently, data-driven approaches using structural health monitoring have shown promise towards long-term prediction of time-dependent behavior in concrete structures, but such approaches involve prediction at single sensor level, requiring a different model for each sensor, and do not leverage the structure geometry and loading. In this work, a physics-informed data-driven approach for long-term prediction of the 2D normal strain field in a prestressed concrete structure is introduced. The method employs a simplified analytical model of the structure, together with a data-driven model for prediction of the temperature field, and embedding of neural networks into coefficients governing the time-dependent behavior of the structure. In contrast to previous approaches, the model leverages assumptions about moment distribution and is trained simultaneously on data of multiple sensors, enabling the estimation of the strain evolution at any point of interest along the structure. Furthermore, the model also enables the decomposition of temperature-dependent strain from the total measured strain, and yields as output an apparent static strain that facilitates holistic interpretation of multiple sensor's data.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Structural Optimization Through a Markov Decision Process and Deep Reinforcement Learning Framework

Author(s): *Maximilian Ororbia, *The Pennsylvania State University*; Gordon Warn, *The Pennsylvania State University*;

In this research, we model structural optimization as a Markov decision process (MDP) solved with deep reinforcement learning. In the context of the MDP, the states correspond to specific structural configurations that are represented as finite graphs, the actions correspond to available graph alterations modeled after topological design grammars, and the immediate rewards are expressed to be proportional to the improvement in the altered configuration's performance with respect to the design objective. The sequential decision process starts with an initial structural configuration that is then altered through a sequence of discrete actions taken by the agent. Each action alters the configuration, transitioning the current configuration to a new state, and continues until a terminal state is reached. Prior work showed that the agent can generate the best design solution, for small and moderately sized state-action spaces employing a tabular Q-learning algorithm. However, as is well known, as the dimensionality of the learning/planning task increases, tabular reinforcement learning algorithms can become inefficient. Hence, in this work, deep reinforcement learning is integrated into the structural optimization MDP framework to alleviate the dimensionality challenge, and includes the development of a set of features that are generally applicable in describing structures represented as graphs, as well as devising a reward signal so that the agent generates the best design solution.

The framework is demonstrated through application to the optimization of planar truss structures considering binary cross-sectional areas. The objective of the design task is to generate the truss topology that minimizes the displacement at a specified node for a given external force(s), subject to stability and volume constraints. Several different truss design examples are presented, each considering different load and support configurations, as well as domains, that is state space dimensionalities. For all examples, the agent effectively learns an optimal policy that generates a high performing solution, often the best design solution. Notably, the agent adeptly learns the optimal policy, even when the policy requires actions that initially result in poor performing configurations, yet are necessary to generate the best design solution. Through comparison to another optimization method, the MDP framework is observed to result in higher quality optimized solutions with lower computational effort. Progress on ongoing refinements, for example, considering multiple discrete cross-sectional areas, will also be presented.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: A Microstructure-Based Porous Crystal Plasticity Finite Element Model for Additively Manufactured Ti-6Al-4V Alloys

Author(s): *Maxwell Pinz, *Johns Hopkins University*; Somnath Ghosh, *Johns Hopkins University*;

Demonstrating great promise in new design and manufacturing modalities, additive manufacturing of Ti-6Al-4V allows for the production of near-net shape components with a nearly unlimited design space with a high-performance material system. However this new processing modality, has significant drawbacks compared to traditional manufacturing techniques that rely on subtractive machining methods, as the microstructures created by the additive manufacturing process necessarily have very different thermal histories. The full potential of AM Ti6Al-4V can only be realized with accurate and efficient material models enabling the use additive manufacturing in production of flight certified components.

Modeling a Widmanstätten, alpha phase microstructure, as observed in AM Ti6Al4V, is a multi-faceted problem that necessitates a multi-scale approach. Direct numerical simulation of the microstructure is inherently difficult due to the ultra-fine alpha laths on the order of a single micron. This is compounded by a difficulty in obtaining experimental or statistically equivalent 3D microstructures from which to construct explicit material models. The effective crystal plasticity model presented parametrically accounts for the morphology of the alpha laths, while directly modeling the slip systems of each of the 12 possible variants of alpha lath within the parent beta grain. This approach eliminates the necessity of explicitly reconstructing the alpha microstructure, while allowing for the simulation of substantially larger computational domains.

One of the largest modalities of defect generation within additively manufactured microstructures is not necessarily unfavorable arrangements of microstructure that lead to stress concentrations, but rather porosity that is absent in more traditional manufacturing regimens. To account for and augment our effective crystal plasticity model, a Gurson-style porosity evolution framework is incorporated to account for statistically distributed porosity throughout the bulk of the material, allowing this important failure mechanism to be incorporated.

The need to incorporate statistically equivalent representative volume elements of the effective crystal plasticity model is a core tenant of multi-scale modeling, and subsequently designing an effective and efficient testing and validation regimen. A methodology for the generation of statistically equivalent representative volume elements of polycrystalline parent prior beta grains is presented, allowing for the parametric generation of statistically equivalent microstructures that may arise from different processing conditions. This approach allows for the efficient simulation of other processing build parameters.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Structural Simulations via Finite Element Network Analysis

Author(s): *Mehdi Jokar, *Purdue University*; Fabio Semperlotti, *Purdue University*;

The concept of Finite element network analysis (FENA) is introduced and its application to the simulation of simple fundamental structures is presented. FENA is a physics-informed deep learning based framework for the simulation of physical systems. It is equipped with groups of surrogate neural network models, which can simulate classes of problems (for example fundamental structural elements such as beams and plates) without requiring ad hoc problem-specific training. All the surrogate models are pre-trained and available in a library, hence drawing a conceptual analogy to finite element analysis. These characteristics are possible thanks to the unique transfer knowledge property of bidirectional recurrent neural networks (BRNN) that allows mapping a sequence of elemental properties and applied inputs to the response of a physical system.

In this study, FENA is presented and applied to the static analysis of two fundamental structural elements: slender Euler-Bernoulli beams and thin Kirchhoff plates. The capabilities and performance of the FENA platform are illustrated via multiple sample cases. Specific post-processing tasks, such as stress-strain calculations, are also discussed. All the solutions predicted by FENA are compared with the numerical results produced via finite element analysis, which is treated as the ground truth. All the comparisons are in excellent agreement.

Another remarkable property of FENA is its ability to assemble pre-trained network models in order to simulate large-scale multi-component systems without the need for further training. This is possible thanks to the concept of network concatenation that allows lifting one of the most significant obstacles to the widespread application of deep learning for the simulation of physical systems, that is the need for problem specific training. In this study, we present a generic network concatenation algorithm based on variational principles, which enables the assembly of either similar (such as two plate elements) or dissimilar (such as beam and plate elements) network models. Although the framework is applied and numerically validated for structural analysis, the concept of FENA is highly general and can be readily extended to a broad spectrum of physical simulations.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Using Resonance to Mechanically Amplify Floor Vibrations

Author(s): *Melanie McCloy, *Princeton University*; Zoe Haynes, *UC Berkeley*; Zhaoshuo Jiang, *San Francisco State University*; Juan Caicedo, *University of South Carolina*;

Detection of human activity inside a structure through the use of vibration measurements is an efficient and noninvasive way to track a building's inhabitants. However, vibration levels can be very small and detectable only with very sensitive instrumentation. Using regular sensors could result in less accurate and less sensitive data. For example, one application of this system is detecting walking speed and falls in a nursing home. Older adults will sometimes walk very softly or shuffle if movement is painful for them, and this causes the vibrations to be very small. This paper explores ways to amplify these vibrations in order to maximize accelerometer output. In order to accomplish this, a multi-degree of freedom resonator was designed and tested. The process to design the resonator, experiments to test the resonator, and experimental results will be discussed. Results show that the resonator was able to amplify vibration such that regular acceleration sensors could be used. Challenges and opportunities of the use of resonators in floors to measure small vibrations will be highlighted.

This research was performed as part of the Integrated Academia-Industry REU in Smart Structure Technologies program.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Numerical Analysis of Post-Tensioned Engineered Cementitious Composite Members with Unbonded Tendons

Author(s): *Mi Jin Jung, *University at Buffalo*; Pinar Okumus, *University at Buffalo*;

Concrete members post-tensioned with unbonded strands are used to achieve longer spans, accelerated construction and repairability. However, due to lack of bond between concrete and strands, flexure cracks are concentrated and strands may not yield at flexure failure, limiting structural efficiency. This research aims to develop and validate a simplified and computationally efficient analysis method to predict the flexural behavior of post-tensioned concrete beams with unbonded strands. The analysis results are validated test data from the literature. The analyses are then used to investigate enhancements of flexure strength and displacement capacity using Engineered Cementitious Composite (ECC). ECC is a tensile strain hardening material and is selected because of its potential to distribute plasticity in these members. Numerical models utilize fiber-based beam-column elements and principles of displacement compatibility. The outputs of the analyses are the load-displacement relationship, stress increase in strand at ultimate flexure load, and failure mode. The results of the analyses show that the use of ECC led to an increase in the cracking load, the ultimate load, and stress in unbonded strands at ultimate load but had little effect on stiffness and failure mode. Overall, ECC is deemed a viable material for concrete members with unbonded post-tensioning strands.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Chemomechanical Properties of 3D Printed Cement Pastes Containing Halloysite Nanoclay

Author(s): *Michael Kosson, *Vanderbilt University*; Lesa Brown, *Vanderbilt University*; Florence Sanchez, *Vanderbilt University*;

Extrusion-based 3D printing using 'cement inks' is a promising emerging technology in the construction industry. However, there are several aspects relating to the extrusion process of cement inks that need to be considered before broad application in industry, including rheological requirements, formed filament characteristics, and mechanical performance of the hardened printed material. Thixotropic nanoclays have been identified as a class of material that could be an effective additive for 3D printed cement-based materials. This study quantifies the effects of including halloysite nanoclay in cement inks on the microstructure and mechanical properties of 3D printed cement-based filaments and structures. Macromechanical testing and grid nanoindentation coupled with scanning electron microscopy and energy dispersive x-ray spectroscopy constitutive phase analysis are used in concert to provide a multiscale characterization of the effects of halloysite nanoclay on the properties of 3D printed cement pastes.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Evolution of Bridge Aeroelasticity and Wind-Resistant Design of Long-Span Bridges: The Contributions of Ahsan Kareem.

Author(s): *Miguel Cid Montoya, *Texas A&M; University-Corpus Christi*;

Wind-resistant design of long-span bridges has been based throughout history on the contemporary capabilities to model the wind, wind-induced loads, and bridge responses. First approaches date back to the XIX century when engineers like J. A. Roebling adapted their designs to improve the performance of bridges under strong wind mainly based on their skilled intuition. The remarkable advances in the first half of the XX century in terms of the number of constructions and span lengths were halted by the collapse of the Tacoma Narrows Bridge in 1940. This led to the adoption of more conservative designs for almost three decades, but motivated research efforts on bridge aeroelasticity. The fundamental contributions by Prof. Davenport and Prof. Scanlan in the 60s and 70s established the basis of the current bridge buffeting and flutter theories. In the same decade, the adoption of streamlined box decks, proposed by W. C. Brown, and applied for the first time to the Severn Bridge, revamped the development of bridge aeroelasticity. However, the increasing spans of bridges built in the last decades, currently surpassing 2 km, and the development of ultra-long-span bridge projects and research initiatives, exploring the feasibility of main spans from 2 to 5 km, along with the adoption of multi-box decks, shown the limitations of linear aeroelastic models. Key contributions by Prof. Kareem highlighted the need for considering multiple nonlinear features to properly model the wind, bridge deck aerodynamics, and bridge responses, including non-stationarity, non-Gaussianity, and non-linearity, and developed numerous frameworks to deal with these issues. Furthermore, he advanced the design tools for tailoring the cross-section of buildings and bridge decks. This study reviews the evolution of the wind-resistant design of bridges and the current and prospective impact of Ahsan Kareem's work on the field.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Physics-Constrained Gaussian Process Model Through Kernel Design for Prediction of Hydrodynamic Interactions Between Wave Energy Converters in an Array

Author(s): *Min Li, *University of Michigan*; Gaofeng Jia, *Colorado State University*; Hussam Mahmoud, *Colorado State University*; Yi-Hsiang Yu, *National Yang Ming Chiao Tung University*; Nathan Tom, *National Renewable Energy Laboratory*;

To improve the efficiency of wave farms and achieve maximum power generation, the layout of wave energy converters (WECs) in an array needs to be carefully designed so that the hydrodynamic interactions can be positively exploited. For this, the hydrodynamic characteristics of the WEC array under different layout need to be calculated. However, such calculations using numerical models usually entail significant computational cost, especially for large arrays of WECs. To address the computational challenge, a physics-constrained Gaussian process (GP) model is proposed to replace the original expensive numerical model and predict the hydrodynamic characteristics of the WECs for any array layout. By exploring the relationship between the WEC array (i.e., the input) and different hydrodynamic characteristics (i.e., the output), we summarize a set of physical constraints/features, including invariance, symmetry, and additivity. These available prior knowledge about the input-output relationship are then directly embedded in the constructed GP model through designing physics-constrained kernels. In particular, a double sum invariant kernel is first developed to incorporate the invariance and symmetry features, and then an additive kernel is developed to incorporate the additive feature of the problem. The invariant kernel and the additive kernel are then integrated to construct the physics-constrained GP model. Compared to the standard GP model, the proposed physics-constrained GP models require less training data to achieve desired accuracy in predicting the hydrodynamic characteristics, and is also less vulnerable to the curse of dimensionality (i.e., good scalability for large arrays) due to the use of an additive kernel. The efficiency, accuracy, and scalability of the proposed approach are demonstrated through an application to predicting the hydrodynamic characteristics for WEC arrays of different sizes and layouts.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: A Multi-fidelity Stochastic Simulation Scheme for Estimation of Small Failure Probabilities

Author(s): *Min Li, *University of Michigan*; Srinivasan Arunachalam, *University of Michigan*; Seymour Spence, *University of Michigan*;

Computing small failure probabilities is often of interest in reliability analysis of engineering systems. However, this task can be computationally demanding if conventional stochastic simulation schemes are used, such as Monte Carlo simulation (MCS), since they typically require repeated evaluation of a computationally expensive high-fidelity model. To address this computational challenge, this work proposes a multi-fidelity scheme to enable efficient evaluation of small failure probabilities. The overall idea is to integrate information provided by models of varying fidelity therefore reducing the required number of high-fidelity model runs while maintaining the accuracy of the estimated failure probabilities. More specifically, multiple low-fidelity models with fast approximation of the system model are first developed. A probabilistic relationship between the low-fidelity response and the high-fidelity response is then established based on a small number of high-fidelity runs by applying a Gaussian process regression (GPR) model. To achieve sufficient prediction accuracy with minimal high-fidelity evaluations, a stratified sampling strategy is combined with an adaptive design of experiment therefore enabling intelligent generation of training data. The main goal is to allocate more training data around the target exceedance probability and facilitate higher prediction accuracy only for the region of interest. Finally, in calculating the small failure probabilities (i.e., probabilities that the high-fidelity response exceeds specific thresholds), low-fidelity models are first evaluated for a large number of MCS samples of the uncertain modal and load parameters, and the corresponding low-fidelity response are used to predict the high-fidelity response with rigorous confidence bounds based on the constructed GPR model. Due to the reduced computational cost of the low-fidelity models, the multi-fidelity approach can achieve significant speed-ups, as compared to direct simulation of the high-fidelity model, in estimating small failure probabilities. To demonstrate the efficiency and accuracy of the proposed multi-fidelity approach, failure probabilities associated with multiple limit states of a high-fidelity nonlinear finite element model of a 45-story archetype steel building subject to stochastic wind excitation are computed and compared, in terms of efficiency and accuracy, to those estimated from standard stochastic simulation approaches.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Adaptive Eigendeformation-Based Reduced-Order Homogenization Model for Composite Materials

Author(s): *Min Lin, *University of Wyoming*; David Brandyberry, *University of Illinois at Urbana-Champaign*; Xiang Zhang, *University of Wyoming*;

Computational homogenization provides a straightforward way to concurrently couple microscale simulation to a structural simulation, as in FE², and is readily able to model a wide range of materials and structures. However, the inherent computational cost associated with computational homogenization prohibits its wide application, especially in the case of nonlinear constitutive responses. This has led to an emerging effort to develop reduced-order models (ROM) for multiscale modeling. The Eigendeformation-based reduced-order homogenization model (EHM) is an attractive method for this purpose, and has seen significant advancement with applications to metals, composites, and other heterogeneous materials [1-2]. EHM operates in a computational homogenization setting, with a focus on model order reduction of the microscale problem and is based upon precomputing elastic microstructure information.

EHM partitions the microstructure into a number of sub-domains (also known as parts), and precomputes coefficient tensors including each part's localization tensor and the interaction tensors between parts. By assuming a uniform strain response over each part, a reduced-order nonlinear system can be solved for the part-wise responses to replace the full field microscale problem, achieving high computational efficiency for moderately low levels of error. While previous studies have shown a hierarchical sequence of ROMs ranging from low fidelity-high efficiency to high fidelity -low efficiency can be achieved by different microstructure partitioning, typically only a single ROM is used in the same simulation.

In this research, we present an adaptive EHM where the simulation gradually refines the ROM used to better balance efficiency and accuracy. To achieve this adaptivity, we begin with the finest ROM we are considering and compute the coefficient tensors (i.e., localization and interaction tensors). Coarser partitionings are then constructed by combining two finer parts into a single coarser part. This way, coefficient tensors of the coarse parts can be directly computed from the ones associated with the finest ROM. As the initial response is generally near-linear, a coarse ROM is sufficient to capture this response. Once inelastic deformation starts and localization starts to accumulate, the simulation adaptively switches to a finer ROM to improve computational accuracy. The data transferring between the coarse and refined ROM, as well as the switching criteria are discussed. The performance and accuracy of the proposed framework is evaluated by comparison with EHM with a fixed ROM partition and the reference direct numerical simulations.

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: An Efficient and Accurate Point Estimate Method for Probabilistic Moments Evaluation

Author(s): *Minhyeok Ko, *The Pennsylvania State University*; Konstantinos Papakonstantinou, *The Pennsylvania State University*;

Evaluation of probabilistic moments of quantities of interest (QoI) is a critical component of many uncertainty quantification problems. In most general cases, analytical output moment expressions cannot be derived and sampling methods, in various forms, can only be utilized for moment estimation. The Monte Carlo method is the most straightforward sampling technique for such estimations, requiring however a considerable number of samples for sufficient accuracy, which can often be computationally prohibitive. This issue has led to variance reduction sampling techniques. An alternative way to numerically estimate probabilistic moments is through classical quadrature techniques that overall work well in very low dimensional spaces, since the number of required model calls increases exponentially with the dimensions. Some sparse variants can instead be used to alleviate this issue mildly, particularly with lower quadrature levels. Owing to these challenges, another approach to this problem is sought through development of dedicated probabilistic techniques resembling quadrature methods, such as the Point Estimate Method (PEM) and the Unscented Transformation (UT). PEM and UT based methods rely on deterministic, weighted sampling points, established by matching a few input moments, sometimes doing so by employing optimization techniques for each problem. Several methods have been accordingly suggested, mainly having linear or exponential increase of the number of required samples with increasing dimensions, counterbalancing computational demands and estimation accuracy. In this work, we suggest a new Quadratic Point Estimate Method (QPEM) with $2n^2+1$ sampling points, where n is the number of dimensions, that is general and applicable to all problems, providing analytical expressions for sample locations and weights without requiring any optimization procedure. QPEM can exactly characterize at least all input moments up to, and including, 4th moments for general distributions and 5th moments for symmetric ones. Hence, it can significantly improve the estimation accuracy of the output QoI moments, in relation to PEM and UT methods with linear samples increase, while at the same time having an affordable and competitive computational cost up to a notable number of dimensions. The validity, outstanding performance, and efficiency of QPEM are showcased against numerous other sampling methods in a series of examples with varying dimensionality from 5 to 100. Studied examples also vary in scope, from polynomial functions, to problems involving trusses and frames, to a nonlinear beam described by a spatial stochastic field.

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Buckling of a Confined Steel Shells Subjected to a Solid/Solid External Loading - Experimental Approach and Simulation

Author(s): *Mohamad Jrad, *Universite de Lorraine*; Ali Limam, *INSA de Lyon*; Norman Mathieu, *Universite de Lorraine*; Frederic Bumbieler, *Andra*; Hamid Zahrouni, *Universite de Lorraine*; Mahdia Hattab, *Universite de Lorraine*;

Steel casing pipe are widely used in underground facilities for protection purposes. Usually in these applications (buried pipelines, steel casing in oil and gas production wells, ...), a steel cylinder is confined within a deformable cavity and subjected to external loading. Soil pressure and soil rigidity are the critical factors to determine the mechanical behavior of the steel cylindrical shell and its possible buckling. In addition, the critical buckling pressure can be strongly dependent on the loading conditions. The nature of the loading and the external medium stiffness, as well as the sensitivity to geometric imperfections have significant effect on the system stability. To study this phenomenon an experimental device has been developed in the laboratory to carry out buckling test on confined cylindrical shells. In this device, the external loading can be induced by various types of confinement as sand or geotechnical materials. Several sensors are used to measure different data during the test as the local pressure applied on the casing, deformation and displacement on different points and the critical buckling pressure. Hostun S28 sand was used as confinement material during the tests. An anisotropy in the loading condition induced by the granular nature of the confinement media has been observed. A single-lobe buckling, characteristic of the buckling of confined cylindrical shells is systematically observed. These experimental results are currently used to calibrate numerical simulation in order to obtain a representative model.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Exploratory Study of System Identification and Seismic Response Monitoring of Pipeline Systems Using Drone Videos

Author(s): *Mohamed Moustafa, *University of Nevada, Reno*; Luna Ngeljaratan, *University of Nevada, Reno*;

There has been increasing interest and use of aerial robotics, also known as unmanned aerial vehicles (UAVs) or drones, especially in the past decade, for infrastructure inspection. However, current applications use drones mostly for service condition assessment or offline post-disaster damage survey. The goal of this presentation is to provide an overview of an ongoing exploratory study at the University of Nevada, Reno that extends video-based seismic assessment and SHM to online drone videos. In this study, a drone was used to capture live/online videos from a multiple-shake tables testing of a pipeline system. The pipeline system has been instrumented with sticker targets and principles of digital image correlation along with drone drift correction algorithms have been explored to extract the dynamic response and conduct a modal analysis and system identification of the pipeline system. The presentation will conclude with the list of challenges for online dynamic response and system identification using drone videos as well as recommendations for future research in this area.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Data-Driven Estimation of Hurricane-Induced Wave Loads on Elevated Coastal Buildings Based on CFD Simulations

Author(s): *Mohammad Moeini, *The Pennsylvania State University*; Nathan Brown, *The Pennsylvania State University*; Ali Memari, *The Pennsylvania State University*;

Hurricane-induced storm surge and wave loads on buildings are among the most devastating forces that could cause catastrophic failures in coastal residential buildings. However, the effect of hurricane wave loads on buildings is not clearly addressed by building codes and design guidelines. Specifically, the dependence of wave forces on building geometry, building height, and wave properties is still not sufficiently researched. This is in part because experimental and computational studies are typically costly and time-consuming to perform, prohibiting multiple tests with various building configurations and loading conditions. To narrow the knowledge gap, this research develops a data-driven model of the wave forces on elevated buildings based on Computational Fluid Dynamic (CFD) simulation data. Using a Latin Hypercube Sampling technique, approximately 300 samples consisting of different building geometry and wave properties are generated for CFD simulations. In combination with the data already reported in the literature, an Ensemble Learning technique is employed to provide an estimate of the flood loads given the building and wave properties. This research expands the current knowledge of the hurricane wave loads and surge effects on residential building by extending the range of the variables already investigated as well as employing more robust statistical algorithms for hurricane-induced wave load prediction.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Simplified Procedure for Estimating the Wind Load Coefficients of Telecommunication Towers and Microwave Antenna

Author(s): *Mohanad Khazaali, *Lehigh University*; Liyang Ma, *Lehigh University*; Keivan Rokneddin, *AIG General Insurance*; Matteo Mazzotti, *University of Colorado Boulder*; Paolo Bocchini, *Lehigh University*;

Telecommunication towers are designed to withstand strong winds and preserve the functionality of the attached nonstructural components (i.e., microwave antennas). The microwave antennas can be located at any height along the tower and are attached to the main members (i.e., legs) of the tower. These antennas modify the airflow and accelerate it around the tower in most cases, depending on the wind direction. Thus, the wind loads will be increased due to the interaction between the antenna and the tower. Design codes do not address this interaction explicitly, only by means of safety factors. Previous studies have performed wind tunnel tests in order to compute the wind load coefficients accurately. Unfortunately, experimental studies are time-consuming and their results are difficult to generalize to different tower configurations.

This paper provides a parameterized and straightforward protocol based on computational fluid dynamics (CFD) analysis for expedited estimation of the wind load coefficients (drag and lateral coefficients) for a lattice steel tower with a cylindrical antennas. The Spalart-Allmaras turbulence model is adopted in this study because it is relatively stable, shows good convergence, and has moderate resolution requirements. Moreover, the Spalart-Allmaras model provides a robust solution to air flow estimations close to the air cell boundary (wall). The wind load coefficients as a function of the wind direction for three different tower panels with a cylindrical microwave antenna are modeled as case studies. It is observed that the interaction between the tower and the microwave antenna has a significant impact on the wind load patterns. Large variations in the computed interference factors are found; interference factors larger than unity are observed in many cases (increasing the wind loads). It is also found that the drag forces computed by design standards are larger than those computed by the proposed simulation, calibrated with experimental results. A systematic overestimation of the loads may be appropriate for design purposes but not for resilience and risk analyses (when the accurate estimation rather than a conservative one is needed).

The adopted procedure and the findings of this study can be of great importance for the telecommunication industry, which looks for reliable results with low computational efforts. In addition, it can enhance the risk and fragility analyses of telecommunication towers under strong winds.

EMI 2022
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Title: Physics-Based and Data-Driven Portfolio Fragility Curves for Telecommunication Towers Under Hurricanes

Author(s): *Mohanad Khazaali, *Lehigh University*, Paolo Bocchini, *Lehigh University*,

In 2017, Hurricane Irma caused major damages to infrastructure systems, particularly telecommunication system. The strong winds led to the collapse of many telecommunication towers and interrupted communication services because several antennas were damaged. Similarly, Hurricane Michael in 2018 led to significant damages in the telecommunication sector. These are just examples of how vulnerable our telecommunication infrastructure is to relatively frequent events. This study focuses on predicting the loss of telecommunication functionality over a region caused by a hurricane. To do so, the study combines physics-based collapse fragility curves and data-driven service fragility curves for portfolios of telecommunication towers. Two regions affected by Hurricanes Irma and Michael were studied to calibrate and validate the models.

The area around Miami (i.e., an urban region) was analyzed under Hurricane Irma, while the Florida Panhandle (i.e., a rural region) was examined under Hurricane Michael. Hurricane intensity measures (i.e., wind speeds) of the examined hurricanes and data for all towers were collected using available online sources for wind and cell towers. The recorded wind speeds were converted to 2 min sustained wind at 10 m height, the most common parameters for fragility curves. Next, the intensity measure was interpolated over the region of interest.

In order to estimate the percentage of collapsed towers in each county, fragility curves for different structural classes (i.e., water tank, monopole, guyed and lattice tower) were adopted from the literature and converted to be consistent with the selected intensity measure, while the service fragility curves were calibrated by minimizing discrepancy with the cell tower outage data provided by the Federal Communications Commission (FCC) for the studied events. In all analyses, the spatial correlation among the telecommunication towers was considered in the model.

The findings of the study can be used to quantify the regional telecommunication system performance under strong wind events and help decision makers identify critical components and regions at highest risk of being disconnected. It may also be possible to extrapolate the results and apply them to other regions, to study and enhance the communication system resilience.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Time-Varying Shear-Wave Velocities in a High-Rise During the 2019 M7.1 and M6.4 Ridgecrest Earthquakes from Wavefield Interferometry

Author(s): *Monica Kohler, *California Institute of Technology*; German Prieto, *Universidad Nacional de Colombia*;

Seismic interferometric techniques for structural health monitoring are based on cross correlation or deconvolution of wavefields produced by earthquakes or ambient vibrations at two locations inside buildings between which constructive interference produces coherent waves. These techniques are applied to data from Community Seismic Network MEMS accelerometers permanently installed on nearly every floor of a 52-story steel moment-and-braced frame building in downtown Los Angeles. The sensors relay continuous 24/7/365 acceleration waveform data and shaking intensity parameters using the Amazon Web Services cloud environment. Wavefield data from the instrumented high-rise from before and during the 2019 M7.1 and M6.4 Ridgecrest, California earthquakes are processed for impulse response functions. The concept of impulse response functions is generalized here to show that a building's nonlinear response can be monitored and quantified through time-varying measurements of representative pseudo-linear systems in the time domain. The building was not damaged during this earthquake, but temporary nonlinear behavior observed during the strong motions provides a unique opportunity to test this method's ability to map time-varying properties. The waveforms are used to extract the building characteristics such as seismic velocity and damping, and the time-lapse changes in these properties. Shear-wave velocities in the building's horizontal directions are found from linear regression to the impulse response function's direct and scattered energy arrivals, and are compared with a consistently-observed average shear-wave velocity of 225 m/s from ambient vibration time periods. The broadband velocities are reduced by as much as 10% during building shaking, and their restoration to pre-earthquake levels is found to be a function of the decrease in shaking amplitude levels over a broad frequency band. These observations are all made over time scales of seconds, throughout the entire duration of building shaking. High-resolution spectrogram analysis indicates temporary drops in eigenfrequencies that are consistent with the velocity observations: 7%, 6.5%, and 8.5% reductions in the first (0.2 Hz), second (0.6 Hz), and third (1.2 Hz) translational east-west modal frequencies, respectively. The benefits of this approach to structural health monitoring are that it does not depend on modal identification, structure type or materials, or similar a priori assumptions, and it can map nonlinear response on small spatial scales.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Non-Local Continuum Modeling of Damage in Elastic and Viscoelastic Porous Media

Author(s): *Mostafa Mobasher, *New York University Abu Dhabi*; Yijun Chen, *Columbia University*; Haim Waisman, *Columbia University*;

Fracture initiation and propagation in porous media is often coupled with several physical phenomena including solid skeleton gradual softening, viscous response, and variations in the fluid-flow characteristics. In this work, we present a novel model for the representation of non-local continuum damage in porous elastic and viscoelastic media. The model is based on a thermodynamically consistent definition of constitutive and state laws that account for non-local damage and time-dependent material response. A mixed finite element implementation is presented, including a derivation of a consistent tangent matrix. The model has been used to analyze benchmark geomechanics problems such as consolidation in one- and two-dimensions, and fluid-driven fracture problems. The numerical results include several investigations of the effect of different material property values on damage evolution and spatial attributes. The modeling results show good agreement with previously published numerical and experimental data. In addition, the model is used to analyze the competition between the energy dissipation mechanisms in a poroviscoelastic media, and in particular the complex interplay between viscous, damage and fluid flow dissipation mechanisms will be presented.

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EMI 2022
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Title: Hydration-Induced Densification of C-S-H Gel Studied Based on NMR Data: Investigation of Different Curing Temperatures

Author(s): *Nabor Jiménez Segura, *TU Wien*; Christian Hellmich, *TU Wien*; Bernhard L.A. Pichler, *TU Wien*;

In cement pastes hydrating under 20 degrees centigrade, the mass density of the C-S-H gel increases with decreasing specific precipitation space (Königsberger et al., CCR, 2016, <https://doi.org/f82z6v>). The here presented analysis is based on proton nuclear magnetic resonance relaxometry measurements of cement pastes hydrating isothermally under water, at curing temperatures from 10 to 60 degrees centigrade (Gajewicz, PhD thesis, Univ. Surrey, 2014). The analysis shows that the developments of Königsberger et al., see above, are also applicable to curing temperatures differing from 20 degrees centigrade. This allows for the development of an analytical hydration model which quantifies the hydration-driven evolution of the volume fractions of clinker, solid hydrates, as well as capillary and gel pores, as a function of the hydration degree and the initial water-to-cement mass ratio. The hydration model refers to three stages. In the first stage, solid C-S-H with no gel porosity precipitates on the surfaces of clinker grains. In the second stage, gel-porous C-S-H grows into the capillary pore space and, at the same time, solid C-S-H also precipitates in the gel pores, resulting in densification of the C-S-H gel. In the third stage, when the water-filled capillary porosity has vanished because it was fully filled by the C-S-H gel, precipitation of solid C-S-H in gel pores results in a progressive densification of the C-S-H gel.

EMI 2022
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Title: Non-Intrusive Coupling of Multi-Physics Codes for Eulerian-Lagrangian Solid-Solid Interaction Using Immersed Finite Element Method

Author(s): *Narendra Nanal, *Rensselaer Polytechnic Institute*; Lucy Zhang, *Rensselaer Polytechnic Institute*; Mark Christon, *Sandia National Laboratories*; David Hensinger, *Sandia National Laboratories*;

Multi-physics interactions often involve multiple physical behaviors which are often modeled with multiple simulation codes and different meshes. Traditional means of multi-physics coupling, e.g., fluid-structure interaction, often involve complex and problem dependent mesh updates, such as the ones used in the Arbitrary Lagrangian-Eulerian (ALE), and/or require intrusive ways of quantity exchange in one or multiple simulation codes. To mitigate the implementation and computational cost, we developed a non-intrusive coupling approach using the Immersed Finite Element Method [1] (IFEM). IFEM has shown to be an effective and efficient volume-based method that can easily couple solvers representing different phases, e.g., fluid, solid, without manipulations of an existing code and/or data structure. In this study, OpenIFEM [2] (an open-source implementation of coupling of Eulerian-Lagrangian solvers using IFEM method) is coupled with SABLE (Eulerian solid mechanics shock physics code provided by Sandia National Labs). The codes are built and launched independently. Each code keeps track of MPI ranks associated with each application's communicator. Sending and receiving of the key quantities from and to each solver are conducted at each time step via synchronized MPI communications. The MPI communications are designed to manage the differences in the data structures of the two codes. The coupling is established without manipulating existing codes and their data structures. Several tests involving mechanical shock wave loading with Lagrangian-Eulerian solid-solid interactions are performed to demonstrate the validity and effectiveness of the immersed approach.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Learned Operator Surrogate Models for Parametric PDEs

Author(s): *Nicholas Nelsen, *California Institute of Technology*;

Operator learning has recently emerged as a modern tool to accelerate applications that necessitate repeated queries of high-fidelity scientific simulations, such as design optimization and uncertainty quantification. In this work, we describe recent machine learning-based surrogate modeling techniques that are designed to quickly and scalably emulate the nonlinear operators that define forward and inverse problems arising in the mechanical sciences. As a point of departure from traditional learning approaches, these methods are built to operate between infinite-dimensional input and output function spaces and are thus able to handle input parameter spaces of arbitrarily high dimension after discretization. Once trained, the models can cater to an extremely flexible class of input functions at query time. Our main contribution is a data-informed kernel regression approach that generalizes traditional random feature methods to function spaces. As a sparse, parametric, and statistically-founded approximation to a operator-valued Gaussian process (GP), the method is trainable from relatively small datasets and enjoys superior computational complexity compared to the analogous full GP regression while still maintaining the hallmarks of GPs, namely, natural interpretability and automatic uncertainty estimates. We numerically demonstrate that in practice, the algorithm is able to accurately solve parametric partial differential equation (PDE) problems at a fraction of the cost of high-fidelity solvers, especially on modern GPU hardware, and serve as an efficient surrogate within outer-loop tasks such as PDE-based Bayesian inverse problems.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: From Randomness to Determinism and the Emergence of Bulk Viscoelastic Properties

Author(s): *Nicos Makris, *Southern Methodist University*;

This paper builds upon past theoretical and experimental studies on Brownian motion and microrheology in association with a recently published viscous-viscoelastic correspondence principle for Brownian motion and shows that for all timescales the mean-square displacement of thermally driven Brownian micro-particles suspended in any linear, isotropic viscoelastic material is identical to the creep compliance (retardation function) of a linear mechanical network that is a parallel connection of the linear viscoelastic material (within which the Brownian microspheres are immersed) and an inerter. This finding uncovers that the time derivative of the mean-square displacement is essentially the impulse response function; whereas, the velocity autocorrelation function of the Brownian particles (2nd time derivative of the mean-square displacement) is the impulse strain-rate response function of the viscoelastic material-inerter parallel connection. The emergence of these bulk viscoelastic properties show that the random process of of the thermally driven Brownian motion of a collection of particles can be fully described with the deterministic time-response functions of the viscoelastic material-inerter parallel connection.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Tensile Deformation in Polyurea: An All Atom Molecular Dynamics Study

Author(s): Arunjyoti Sinha Roy, *Johns Hopkins University*; *Nilanjan Mitra, *Johns Hopkins University*; Somnath Ghosh, *Johns Hopkins University*;

Polyurea is a segmented thermoplastic elastomer consisting of a hard segment (typically diphenyl methane diisocyanate monomers with urea linkages) and a soft segment (typically polyether molecule). The material typically demonstrates improved performance under dynamic high strain rate loading situations, as has been shown in literature. The competing interplay of the hard segment (HS) and soft segment (SS) of the molecule towards performance improvement has been postulated in numerous literature but there has not been any comprehensive study which categorically demonstrates the deformation mechanisms within the molecule subjected to a specific type of loading condition using an all-atom model. As part of this work, evolution of bond stretch, bond angle and bond dihedral for the HS and SS regime has been shown along with evolution of other global parameters such as entanglement ratio, free volume and internal energy associated with the system. It can be anticipated that the study will improve upon the fundamental understanding of the material performance and through a detailed comprehension of inter and intra-molecular dynamics in the hard and soft regime can help in tuning (or designing) of new polyurea molecules with further enhancement of performance.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Application of Bayesian Model Updating Technique for Bridge Structures and Structural Components Using Experimental Field Test Data

Author(s): *Niloofar Malekghaini, *University of Nevada, Reno*; Farid Ghahari, *University of California, Los Angeles*; Harsh Nandan, *SC Solutions Inc.*; Ertugrul Taciroglu, *University of California, Los Angeles*; Matthew Bowers, *SC Solutions Inc.*;

The inherent uncertainties in prior mechanics-based finite element models put these models at disadvantage to mirror the real-world structures. A Bayesian model updating technique can help quantify and reduce these uncertainties. In this technique, the prior mechanics-based finite element model is integrated with the measured responses to reduce the discrepancies between the measured and finite element predicted responses. The updated finite element model is a beneficial asset for structural health monitoring and damage diagnosis. This study focuses on the application of Bayesian model updating technique using real-world data. For this purpose, a series of experimental field tests are carried out on bridge structures and structural components and the measured acceleration responses are used to update the prior finite element model of the target structure. The performance of the Bayesian model updating technique is evaluated through observation of the identified modal parameters and the existing damage in the structure. The successfully updated finite element model is utilized to help diagnose potential damages incurred by the target structure.

Title: Analysis of Tapped Granular Systems Using Machine Learning Approaches

Author(s): Vishagan Ratnaswamy, *New Jersey Institute of Technology*; Anthony Rosato, *New Jersey Institute of Technology*; Youngjin Chung, *New Jersey Institute of Technology*; *Noor Mili, *New Jersey Institute of Technology*; Denis Blackmore, *New Jersey Institute of Technology*; Jonathan Dye, *New Jersey Institute of Technology*;

We report on dynamic simulations of microstructure development in disordered assemblies of N monodisperse spheres within a tapped container. The average solids fraction of an assembly was computed at a tap completion when its kinetic energy was essentially zero. An ensemble of 25 realizations was evolved over the span of $M = 20,000$ taps from which 25 solids fraction evolution curves were obtained. Drastically different progressions of individual realizations were observed that featured sporadic, pronounced jumps in solids fraction over the duration of a small number of taps. This behavior is consistent with a collective reorganization process that has been previously reported in the literature as an inherent physical feature of the density relaxation process [1-4]. Visualizations further revealed the formation of crystalline regions separated by dislocations that facilitated bulk sliding motion in the system through laterally periodic boundaries. Simulations conducted at a higher tap acceleration promoted a larger frequency of jumps in density over the M taps, resulting in more of the realizations attaining an apparent a final saturation density.

A recurrent neural network model - developed with training sets consisting of 60% of the solids fraction data extracted from the realizations - was used to forecast the ensemble-averaged density in the limit of a large number of taps. The model appeared to be able to capture the jumps observed in the actual simulation data beyond the training set. By using a dimensionality reduction technique (i.e., principal component analysis), each of the M configurations (coordinates of N spheres) was reduced to a point in the plane. A graph of these points showed a stratification of the solids fractions associated with system evolution from random to crystal-like microstructure. This result suggests that a dimensionality reduction of the configurations using physical concepts may yield similar results.

Our findings thus far suggest that from a data perspective, it is possible to analyze the evolution of granular microstructure by applying deep learning methods. The inclusion of physical quantities into the learning feature space, such as fabric tensors, inter-particle forces and stresses, may provide an enhanced ability to model and understand the evolution process towards the development of predictive surrogate models.

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Adaptive Shape Memory Alloy Cable-Based Isolation Systems

Author(s): Sasa Cao, *Guangzhou University*; *Osman Ozbulut, *University of Virginia*; Fei Shi, *Guangzhou University*; Jiangdong Deng, *Guangzhou University*;

Seismic isolation systems can effectively enhance response of bridge structures under earthquakes. However, unseating of superstructure may occur due to increased displacement demands at the isolation level under strong ground motions. The restrainers made of steel or FRP can be used to prevent unseating, however; these restrainers are designed to remain elastic and do not dissipate energy. Supplemental damping devices can also be incorporated to limit the isolation displacements. Nevertheless, the installation of either restrainers or dampers requires additional space and may increase costs. An alternative strategy is the use of adaptive isolation systems that can alter their response under different levels of seismic hazard. Shape memory alloy (SMA), a metallic alloy that can recover large nonlinear deformations upon removal of applied load, has been widely explored for seismic applications over the past two decades due to its good energy dissipation capacity and unique self-centering ability. Several SMA-based isolation devices have been proposed to control seismic response of bridge structures. However, most of these studies have been numerical investigations and only a few small-scale experimental investigations are conducted.

This study explores the response of two large-scale SMA-based isolation system that combines multiple groups of SMA cables and a lead rubber bearing (LRB) to perform effectively under frequent, design and extreme level seismic events. The developed isolation systems are subjected to a cyclic lateral loading to characterize their hysteretic response. The response of the proposed isolation system is evaluated comparatively with a conventional LRB isolation system under increasing amplitude cyclic loads. The effects of loading rate and vertical pressure on the response of the SMA-based isolators are also evaluated. High-fidelity finite element models of the isolators are developed and analyzed to assess the behavior of the different SMA cable groups at different stages of the loading. The results are discussed in detail to highlight challenges and opportunities for SMA cable-based seismic isolation systems.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Dynamic Homogenization of Periodic Origami Inspired Structures

Author(s): *Othman Oudghiri-Idrissi, *University of Minnesota*; Bojan Guzina, *University of Minnesota*;

We establish a dynamic homogenization framework for linear elastic wave motion in periodic origami-inspired structures. Using a "bar-and-hinge" paradigm of the periodic origami structure, we conduct a finite wavenumber - finite frequency homogenization (FW-FF) in the spectral neighborhood of simple, repeated and clusters of nearby eigenfrequencies at an arbitrary wavenumber within the first Brillouin zone. For completeness, a source term acting on the nodes of the discrete structure is considered, expanded in Bloch waves and included in the analysis, and periodic (internal) homogeneous Dirichlet boundary conditions are systematically considered. We express the leading-order (system of) effective equation(s) in the considered spectral neighborhoods and we approximate asymptotically the corresponding Bloch dispersion relationship. We illustrate the developed framework by comparing numerically the Bloch dispersion relationship to its asymptotic approximation for (i) a 2D-periodic Miura-ori structure and (ii) a 1D-periodic Miura tube. We conclude the numerical portrayal by presenting the effective motion of the 2D-periodic Miura-ori structure near the edge of a band gap and within a band pass.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Effect of Microstructure and Surface Notch Geometry on Fatigue Crack Nucleation in Titanium Alloys

Author(s): *Ozge Ozbayram, *Johns Hopkins University*; Shraavan Kotha, *Johns Hopkins University*; Somnath Ghosh, *Johns Hopkins University*;

This paper uses the Parametrically Upscaled Constitutive Model (PUCM) and Parametrically Upscaled Crack Nucleation Model (PUCNM) to study microstructure-sensitive fatigue crack nucleation in components of Ti alloys containing notches. The PUCMs are thermodynamically consistent, macroscopic constitutive models, whose parameters are explicit functions of Representative Aggregated Microstructural Parameters or (RAMPs) of microstructural morphology and crystallography. A significantly reduced number of solution variables in the PUCM simulations make them several orders of magnitude more efficient with good accuracy. This study will present a modeling framework for predicting fatigue crack nucleation in laboratory specimens and as well as structural components of the alloy Ti-6Al-4V using PUCM and PUCNM. Microstructural statically equivalent RVEs, M-SERVEs, are simulated with the computational homogenization of crystal plasticity finite element (CPFE) to develop the PUCM and PUCNM. Micromechanical analysis data is used to calibrate the coefficients of PUCM and the crack nucleation cycle number and locations are obtained by neural network algorithm in the PUCNM scheme. First, the 3D macroscopic domain is reconstructed by matching correlation functions of the microstructural parameters based on the EBSD scans and correspondingly the RAMPs. To capture the notch effect, RAMPs are assigned to the notched geometry from the background mesh using element centroids. After performing the creep simulations, crack nucleation locations are predicted using PUCNM. The same procedure is followed to simulate the structural component. Predictions of PUCNM for the double notched lab specimen shows that at low stress levels, cracks nucleate on the surface because the notch introduces the stress gradient. However, at high stress levels, cracks nucleate on the subsurface since the microstructural effect is higher than the stress gradient. For the smooth bar specimen, crack nucleation is predominantly on the subsurface at all stress levels and driven by the microstructural variability. Therefore, it is concluded that both notch and microstructural heterogeneity affect the stress concentration and as a result crack nucleation mechanism. These results match the experimental observations. When PUCM and PUCNM are used to simulate an engine disk with a notch, it is observed that nucleation is driven by the stress concentration due to notch and microstructural heterogeneity. Overall, this work shows promising predictions of PUCM and PUCNM models on fatigue crack nucleation mechanisms of different laboratory specimens and structural components, including the microstructural dependency and the notch effect.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Model Updating, Condition Assessment, and Maintenance of Multi-Component Systems Under Correlated Deterioration Processes

Author(s): *Pablo G. Morato, *University of Liege*; Charalampos P. Andriotis, *TU Delft*; Konstantinos G. Papakonstantinou, *The Pennsylvania State University*; Philippe Rigo, *University of Liege*;

Civil infrastructure forms the foundation of socioeconomic growth. It is, therefore, crucial to quantify and control the risks induced by the exposure of engineering systems to deterioration mechanisms. Physics-based deterioration models, such as fatigue or corrosion, are often characterized by significant uncertainties. These can be reduced through data collection from inspections and/or monitoring, which in turn enable more informed and rational maintenance planning and decisions. Either for physical reasons or to alleviate the computational complexities that arise when treating multi-component systems, deterioration processes are often assumed probabilistically independent among various components. However, many environments are characterized by highly correlated deterioration mechanisms, defying the basis of this assumption. In this work, we formulate structural inspection and maintenance decision-making problems as Partially Observable Markov Decision Processes (POMDPs), with state transition and observation models constructed as dynamic Bayesian networks (DBNs). Leveraging on the conditional relationships among the relevant random variables, environments under general deterioration dependence are modeled through Gaussian hierarchical structures and related hyperparameters, thereby decoupling the original joint probabilistic structure of the system to independent component-wise DBNs. We further investigate the effects of maintenance actions and inspections on these modeling hyperparameters. The final factored DBN state space, equipped with actions, observations, and rewards, forms a POMDP that is solved via a deep decentralized multi-agent actor-critic (DDMAC) reinforcement learning scheme, in which policies are approximated by actor neural networks at the component level, and are guided by a value function, approximated by a critic network at the system level. Since DDMAC adjusts the actor-networks weights based on system beliefs and noisy rewards, the resulting policies also intrinsically consider all underlying dependencies. The efficacy of the framework is showcased in structural systems exposed to fatigue deterioration under various correlation settings and is compared with existing state-of-the-art planning methods and decision rules.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: A Molecular Dynamics Study of the Interplay Between Nanopores and Pre-Existing Fracture

Author(s): *Pania Newell, *University of Utah*;

Understanding the structural and mechanical properties of porous silica have gained attention from engineering and scientific communities due to its technical applications in ceramics, biomedical devices, fuel cells, etc. Controlling porosity and pore morphology at the nanoscale has become a research interest in recent years. The mechanical properties of silica have been measured through various techniques such as nano-indentation. Similar to the macroscopic scale, the introduction of pores into silica leads to a dramatic reduction of Young's modulus at the nanoscale as well. Moreover, the presence of isolated pores leads to stress concentration which contributes to the fracture initiation and propagation, resulting in lowering fracture toughness of the porous system in comparison with the bulk. This presentation numerically investigates the effect of nanopore structure in addition to porosity on mechanical and fracture properties of amorphous silica (a-SiO₂). Different pore shapes (e.g., circular, square, and triangular) and sizes were selected based on the experimental observation of pores in SiO₂-based materials. Molecular dynamics simulations coupled with a the-state-of-the-art reactive force field (ReaxFF) have been adopted for this investigation. We also looked at the combination of different pore morphology and pre-existing fractures with different orientations. The results revealed that the variation in the nanopore structure influences Young's modulus and critical energy release rate (GIC) of a-SiO₂. In particular, for the same exact porosity, the circular pore has the highest impact on Young's modulus, while the square pore has the most influence on GIC. We then systematically investigated the combination of different pore shapes and pre-existing cracks. Pre-existing cracks are located at 30°, 45°, 60°, and 90°. The further investigation of pore morphology and pre-existing crack shows that the overall mechanical properties are greatly influenced by the pore shape which can be reflected through the spatial distribution of von Mises stress. The results also show that the overall, GIC increases with the increase of ligament length (also known as pore wall thickness). These results provide key insights for the future design of nanoporous materials with desirable mechanical properties.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Integrating PINNs with FEM to Model Non-Local Continuum Damage

Author(s): *Panos Pantidis, *New York University Abu Dhabi*; Mostafa Mobasher, *New York University Abu Dhabi*;

Complementary to conventional numerical methods, physics-informed neural networks (PINNs) have recently emerged as an ideal candidate to solve partial differential equations (PDEs), opening the pathway to data-driven scientific computing. Nonetheless, PINNs have been thus far used mainly in isolation from other numerical techniques such as the finite element method (FEM), rendering the potential of their synergistic integration still virtually unexplored. In this work, we present a novel finite element framework which utilizes a PINN as a major computational component and focuses on the continuum damage analysis of quasi-brittle materials. Our framework uses a local elasticity solver, where the local strain map is first calculated and subsequently transformed to an equivalent nonlocal strain map. The latter is predicted from a PINN which is trained on the nonlocal-gradient damage PDE, and it is then used to compute the nonlocal damage. This strain-spatial relationship enables the network to learn the nonlocal interactions between the material points and therefore to be integrated in the FEM solver as the local-to-nonlocal strain intermediate step. As a result, the proposed method tackles the vital drawbacks of both the local and nonlocal-gradient method, respectively being the mesh-dependency and computational cost, since it yields a nonlocal damage field using a negligible fraction of time additional to the local solver. Finally, we showcase through a series of numerical examples the computational efficiency and generalization capability of our framework.

Keywords: PINNs, FEM, damage mechanics, nonlocality

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Macroscopic and Microscopic Derivation of Higher Order Elasticity Tensors for Different Material Symmetry Groups

Author(s): *Payam Poorsolhjoui, *Eindhoven University of Technology*, Pouriya Pirmoradi, *Eindhoven University of Technology*; Akke Suiker, *Eindhoven University of Technology*;

In this presentation we present an analysis of the effects of various planes and axes of elastic symmetry on the higher order elasticity tensors from both microscopic and macroscopic viewpoints. The analysis includes the effects of first and second derivatives of displacement as well as the coupling effects between the two aforementioned kinematic measures. Accordingly, the nonzero components of the fifth- and sixth- order elasticity tensors of materials with one plane of elastic symmetry and those with two orthogonal planes of elastic symmetry, as well as orthotropic materials, transversely isotropic materials, and isotropic materials are formulated. The required identities between the nonzero components are also presented.

To investigate the effects of mechanisms of elastic symmetry on the macroscopic behavior from a microscopic viewpoint, the analysis of higher gradient elasticity via Granular Micromechanics Approach is also performed. In this approach, the material is envisioned as a collection of grains interacting with their neighbors and a statistical representation of the directional distribution of microstructural features yields the macroscopic behavior of the material. Using spherical harmonics expansions to incorporate the directional distribution of particle properties in the material, the effect of elastic symmetries on higher order elasticity tensors for anisotropic materials are investigated. Closed form solutions for higher order elasticity tensors of isotropic materials and transversely isotropic materials as functions of the inter-granular stiffness coefficients and grain sizes are presented.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Machine Learning-Enabled Estimation of Crosswind Load Effect on Tall Buildings

Author(s): *Pengfei Lin, *Harbin Institute of Technology, Shenzhen*; Gang Hu, *Harbin Institute of Technology, Shenzhen*; Fei Ding, *University of Notre Dame*; Chao Li, *Harbin Institute of Technology, Shenzhen*; Yiqing Xiao, *Harbin Institute of Technology, Shenzhen*; Kam Tim Tse, *Hong Kong University of Science and Technology*; Kenny Kwok, *The University of Sydney*; Ahsan Kareem, *University of Notre Dame*;

Due to the complexity and importance of crosswind vibrations of tall buildings with rectangular cross-sections, current research on crosswind vibrations of rectangular tall buildings mainly relies on expensive wind tunnel tests and time-consuming numerical simulation techniques. Therefore, this paper intends to use machine learning technique to quickly and accurately predict the crosswind response of rectangular tall buildings.

This paper presents an approach to predict crosswind force spectra and associated response of tall buildings with rectangular cross-sections based on machine learning (ML) technique and random vibration-based response analysis. An efficient ML algorithm, light gradient boosting machine (LGBM), was trained to predict crosswind force spectra of the tall buildings by using the database from the Wind Engineering Research Center at the Tamkang University embedded in the aerodynamic database of NatHaz Modelling Laboratory. Furthermore, an unsupervised ML algorithm, K-means clustering, was employed to advance the understanding of the crosswind force spectrum characteristics of the tall buildings. The effects of three factors, i.e., ground roughness, aspect ratio and side ratio, on the force spectra were discussed based on clustering. To predict the crosswind response of tall buildings, case studies were carried out to validate the predictive accuracy of the LGBM model combined with random vibration-based response analysis. The results demonstrate that the proposed method combined with the multiple database-enabled design module for high-rise buildings developed by the NatHaz Modelling Laboratory at the University of Notre Dame is effective and computationally efficient to provide fast and accurate predictions of the crosswind force spectrum and associated crosswind responses of rectangular tall buildings.

In summary, it can be concluded that ML techniques can be a reliable tool to supplement traditional wind tunnel model tests and numerical simulations. Furthermore, the product of this study offers designers a preliminary design framework for the assessment of crosswind force spectra and response of rectangular tall buildings in the early design stage. This paper has laid a foundation for adopting a ML scheme to predict the wind-induced responses of tall buildings and other potential applications in wind engineering.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Sustainability Potential of Tailored FRP-Reinforced Concrete Structures Through Optimized Design and Robotic Fabrication

Author(s): *Philipp Preinstorfer, *University of Cambridge*; Robin Oval, *University of Cambridge*; Mishael Nuh, *University of Cambridge*;

The concrete industry is facing major challenges due to the climate crisis. 6-7% of global carbon emissions can be traced back to cement production. Moreover, huge amounts of natural resources are used in the building sector. New strategies must be deployed to increase the sustainability of concrete structures. As such, tailored FRP-reinforced concrete structures offer a promising avenue for material and weight savings.

Conventional steel reinforced concrete structures can be massive in shape and execution with a high wastage of cement that in many cases would not be necessary for the load bearing capacity. The simple prismatic shape of many concrete structures is mostly chosen due to the low cost of the material. Moreover, the concrete cover that is needed to avoid corrosion of the reinforcement limits the design of steel-reinforced structures in a wide range. In contrast, FRP-reinforced concrete allows for a reduction in the material mass, since the reinforcement with its inert chemical characteristics does not have to be protected by an excessive concrete cover. Through the optimization of the geometry according to the stress state under different conditions, more efficient structures in terms of material usage can be designed. In the symposium's presentation, an optimized design of a FRP-reinforced ribbed hexagonal shell element is presented. The design is inspired by nature and allows for a crucial reduction of the material mass needed.

Comparative studies show that the optimized design is able to withstand similar loadings than a conventional RC-element. A key barrier for the realisation of such rather complex designs is the fabrication process. In a feasibility study it is shown that the production of such structures can be done by automated robotic concrete spraying. This synergy of innovative materials and production techniques leads to significant reductions in the material mass needed and the embodied CO₂ relative to a representative RC-element and therefore increases the sustainability of such concrete structures.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Multi-Scale Phase Field Approach for Modeling Fracture Behavior in Rubber-Like Materials

Author(s): *Prajwal Kammardi Arunachala, *Stanford University*, Sina Abrari Vajari, *Stanford University*, Matthias Neuner, *Stanford University*, Christian Linder, *Stanford University*,

Rubber-like materials are known for their desirable properties like high stretchability, low modulus and high toughness, and hence find myriad applications in many blooming fields like stretchable electronics and implantable sensors. So, computational models for predicting the crack propagation in such materials are vital for quantifying their behavior. In this study, we propose a phase field fracture model built on top of a multi-scale polymer network model for capturing the fracture behavior in elastomers. A non-Gaussian statistical mechanics-based model is utilized for modeling the behavior of chains at the microscopic scale. Additionally, the internal energy due to molecular distortions, which has been found to be a dominant contributor for the fracture initiation, has been incorporated in the chain model. The amount of macroscale damage in the material is modeled to be microscopically driven by the degradation in the chain properties while satisfying the second law of thermodynamics. This is advantageous for further modeling the effects of multi-scale phenomenon like strain induced crystallization, wherein changes at the microscale have been found to affect the fracture behavior [1]. The deformation at the macroscale is bridged with the microscale chain stretches using the non-affine Maximal Advance Path Constraint [2], which has been found to take into account the anisotropy in the chain deformation along different directions. The performance of the model is validated by comparing the load-displacement response and crack propagation path with existing experimental data.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Using Coarse Sensing Pressure Mat to Identify Human Activity

Author(s): *Pressley Perry, *University of South Carolina*; Anthony Washington, *Florida State University*; Zhaoshuo Jiang, *San Francisco State University*; Juan Caicedo, *University of South Carolina*;

This presentation discusses the use of a cost-effective mat to identify human activity in a floor. The mat identifies pressure points with a coarse resolution, making the technology less costly than current pressure mats. This presentation discusses several classifiers designed to identify the type of activity a person might be doing on the mat ranging from walking, sitting on a chair, standing or a simulated fall (laying on the ground). Experiments performed with a 10 meter long mat indicate that the classifiers tested could detect between very different type of activities (e.g. sitting vs walking). However, activities such as standing or sitting on a chair are more difficult to determine. The presentation includes a description of the mat, the experimental program, training and validation of the classifiers, and discussion of the final results.

This research was performed as part of the Integrated Academia-Industry REU in Smart Structure Technologies program.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Predicting Plasticity in 2D Model Metallic Glasses Using the Local Yield Stress and Diffusion Maps

Author(s): *Rahul Meena, *Johns Hopkins University*; Thomas J. Hardin, *Sandia National Laboratories*; Spencer Fajardo, *Johns Hopkins University*; Michael Chandross, *Sandia National Laboratories*; Michael Falk, *Johns Hopkins University*; Michael D. Shields, *Johns Hopkins University*;

Failure in amorphous solids arises from local rearrangements in the material's atomic configurations and how these respond to stress. To this end, the Local Yield Stress (LYS) method was recently developed to probe local regions and quantify their susceptibilities to plasticity by measuring the incremental stress required to trigger a local rearrangement. While this methodology shows great potential for enhancing predictive plastic theories, because of its computationally demanding nature, it is not a viable method for describing the material structure. We propose a manifold learning-based framework to extract microstructural descriptors from atomistic configurations. More specifically, we deploy Diffusion Maps (a nonlinear manifold learning technique) to systematically extract the structural information features from the high-dimensional data (cartesian coordinates of local clusters of atoms and relate this structure to LYS). Due to the nature of the problem, a "point" corresponds to a geometric conformation of atoms, and thus meaningful similarity measure between configurations must be devised for capturing the actual distance between two points. Therefore, we utilize the newly developed Gaussian Integral Inner Product (GIIP) distance metric to measure the similarity between cluster of atoms. This metric addresses noise sensitivity, continuity, smoothness, radial cutoff, and permutation and rotation invariance, which makes it robust for measuring similarity in randomly distributed atomic structures. We start with the silicate glassy system to identify defects using geometric conformation of atoms to demonstrate its practicability. Finally, our application is a two-dimensional binary glass-forming system, deformed with an incremental Athermal Quasistatic Shear (AQS) method. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525 (SAND2022-1056 A).

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Geometric Scaffolds for Knitting

Author(s): *Randall Kamien, *University of Pennsylvania*;

Origami and kirigami on paper leads to rigid materials owing to the high shear modulus of the paper. How do you model the folding and cutting of materials that stretch? We have been studying the behavior of knitted fabrics by considering scaffolds with fixed topology yet flexible geometry. Here we will cover the structure and function of these scaffolds.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Modeling of creep Behavior in Shale Rocks Induced by Chemo-Mechanical Loading

Author(s): *Ravi Prakash, *Texas A&M; University*; Venkata Radha Sai Bhavana Varanasi, *Texas A&M; University*; Jeffrey Bullard, *Texas A&M; University*; Sara Abedi, *Texas A&M; University*;

Coupled chemical and mechanical processes cause dissolution and precipitation of multiple phases in the rocks that redistribute stress in neighboring phases. This redistribution causes deformational changes of the rock composite. The purpose of this study is to investigate the link between microstructural evolution and creep behavior of shale rocks subjected to chemo-mechanical loading through modeling of the time-dependent deformation induced by the dissolution-precipitation process. The model combines the microstructural evolution of the shale rocks with the stress/strain fields within the material over time. The modeling effort is complemented by an experimental study in which shale rocks are exposed to CO₂-rich brine under elevated temperature and pressure conditions. A thermodynamic-based microstructure evolution model is developed to generate the full evolutionary pathway of the rock microstructure subjected to chemical and mechanical loading. The time-evolving microstructures are then incorporated into a finite element model to simulate the creep induced by dissolution and precipitation processes. Following the calculation of the viscoelastic deformation of the shale composite, the combined models are utilized to predict the time-dependent stress and strain fields in different zones of reaction.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Effect of loping Sand/Bedrock Interface on the Static and Dynamic Response of the Adobe Pyramid of Huaca de la Luna, Perú

Author(s): Anna Remus, *Department of Mechanical Engineering, University of Rochester*; Lale Yilmaz, *Department of Mechanical Engineering, University of Rochester*; Selman Tezcan, *Department of Mechanical Engineering, University of Rochester*; *Renato Perucchio, *Department of Mechanical Engineering, University of Rochester*;

Huaca de la Luna is a monumental religious complex located in the North coast of Peru built in different stages from 100 AD to 650 AD by the Moche civilization using millions of adobe blocks. The complex is located near Trujillo, in one of the world regions with major seismic activity along the Pacific Ring of Fire. The specific focus of the present study is the main stepped pyramid at the center of the complex. Built on the east slopes of the Cerro Blanco Mountain, this large structure consists of the superposition of horizontal platforms added on top of each other during successive construction stages. The pyramid presents severe structural damage near the north-west corner. The static and dynamic response of the pyramid is analyzed using 2D plane strain nonlinear FE models representing the east-west cross-section positioned in the middle of the pyramid together with the underlying bed rock and soil profiles. Archaeological excavations indicate that along its east and west side the pyramid is built directly on layers of soft sand, with large adobe blocks serving as the foundation layer. However, the actual foundation conditions on the inner portion on the pyramid base which follows the east-west downslope of the Cerro Blanco are presently unknown. Assuming the presence of an interposing sand interface of unknown thickness between the base of the pyramid and the sloping bedrock, we adopt a design of experiments approach to numerically evaluate the combined effect of (a) the sand layer thickness with (b) different frictional conditions between bedrock, sand layer, and the adobe base of the pyramid. The analysis is performed in Abaqus/CAE Explicit using the concrete damaged plasticity and the Mohr-Coulomb formulations for modeling adobe bricks and sand layers respectively.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Sea Ice Summer Decline: LS-DEM Simulation Using MODIS Data

Author(s): *Rigoberto Moncada Lopez, *California Institute of Technology*; Mukund Gupta, *California Institute of Technology*; Andrew Thompson, *California Institute of Technology*; Jose Andrade, *California Institute of Technology*;

Changing climatic forcing induces earlier and more extensive disintegration of Arctic Sea Ice, which plays a vital role in regulating oceanic and atmospheric processes. Understanding this decline process is fundamental for better forecasting of sea ice concentration and predictions of ice-free Arctic summers. In this work, we use a Level Set Discrete Element Method Simulation (LS-DEM) to measure the evolution of sea ice concentration, floe size distribution (FSD) diameters, number of floes and thickness, starting with geometries obtained from NASA MODIS images. The model accounts for sea ice thermal coupling with the ocean and the resultant melt and thickness reduction, as well as the effects of this melting over breakage behavior and the feedback of breakage and melting. This LS-DEM simulation is done using field data parameters like ocean temperature, wave amplitude and wave frequency from various field observations and models, to control external forcing, and MODIS images for the region of Baffin Bay, to keep track of floe size distribution changes. Based on our results, we conclude that breakage plays a critical role in accelerating the disintegration of fully formed floes and that concentration and floe size distribution evolution are sensitive to the initial FSD and thickness of ice and initial and transient states of the ocean and atmosphere (particularly for temperature). Further testing with different environments, datasets, and with added breakage mechanics, will better constrain the parameters of the LS-DEM model, which can lead to improved predictions of ice loss in polar regions.

Title: Dynamic Point Clouds-Based Structural System Identification Using a Multi-Channel Lidar

Author(s): Jaehun Lee, *Hanyang University*; *Robin Eunju Kim, *Hanyang University*;

Structural system identification from dynamic responses of the structure provides key information about the structure in the field of structural health monitoring (SHM). Traditionally, researchers have investigated algorithms and applications to measure the dynamic behaviors of structures through physically contacting sensors, such as accelerometers and Linear Variable Differential Transformer (LVDTs). Although numerous studies showed successful examples of contact sensors, their requirements are: (i) need to have a direct attachment on the structure, which usually are environmentally harsh, and (ii) obtain only a point response from a designated location of the sensor. Such features limit the longer use of those sensors (the life span of sensors is shorter than that of the structure) making the periodical maintenance of the sensor inevitable. In addition, to perform the system identification of a larger structure, a large sensor network must be implemented. Therefore, recent studies explore alternative approaches such as non-contact sensors, that are maintenance-efficient and capable of measuring the dynamic responses of multiple points of a structure from smaller sensor networks. Thus, this paper presents a system identification of structures using dynamic point clouds measured from a multichannel Lidar. The hardware and mechanical challenges that limit the direct use of raw data are explored and resolved firstly: (i) Hyperbola scan pattern due to orientations of lasers in multichannel Lidar is corrected, (ii) Tilted axes of the sensor and range uncertainties are adjusted from coordinate transformation, and (iii) Unsynchronized point clouds due to different measured time are aligned using time synchronization strategy. The proposed approach has been validated from two types of laboratory-scale structures: a flexible cantilever beam and a four-story shear building. In both structures, a comparison of Lidar and numerical model showed that the first natural frequency can be identified within 5% error and a modal assurance criterion value yielded over 99%. The results show the potential of using a single Lidar sensor for measuring the dynamic response of multiple points. The capability will further enable full-scale monitoring of large-scale private infrastructure for SHM.

This work is supported by the Korea Agency for Infrastructure Technology Advancement grant funded by the Ministry of Land, Infrastructure and Transport (Grant 22CTAP-C164093-02).

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: A Phase-Field Formulation for Cohesive Fracture Based on the Park-Paulino-Roesler (PPR) Cohesive Fracture Model

Author(s): *Rogelio Muñeton-Lopez, *University of Missouri*; Oliver Giraldo-Londoño, *University of Missouri*;

The Park-Paulino-Roesler (PPR) cohesive fracture model has proven effective to model quasi-brittle fracture for a wide range of applications including multi-scale fracture, fragmentation, composite material failure, and rate-dependent fracture. One of the key attributes of the PPR model is its inherent ability to control the softening shape of the traction-separation relationship both in mode I and mode II loading, which sets it apart from existing cohesive zone models (CZMs), in which the softening shape is defined a priori. Like other CZMs, the PPR model is well-suited for modeling fracture propagation when the crack path is known a priori but its implementation may become complex in situations where the crack topology is not known beforehand. To overcome this limitation, we recast the PPR cohesive fracture model within a phase-field modeling framework, which allows us to model arbitrary crack nucleation, propagation, branching, and coalescence using a straightforward multi-field finite element implementation. We introduce constitutive functions (crack density function and degradation function) consistent with the PPR model, which guarantee ϵ -convergence of the regularized PPR model for a vanishing length scale parameter. We will discuss several numerical examples to show that the regularized model converges to the original PPR model and to demonstrate the model ability to simulate complex crack topologies.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Identifying Building Attributes that Influence Hurricane Damage by Using Dimensionality Reduction Techniques

Author(s): *Saanchi Singh Kaushal, *Penn State University*; Mariantonieta Gutierrez Soto, *Penn State University*; Rebecca Napolitano, *Penn State University*;

With hurricanes spanning over multiple states and causing considerable damage, the need for rapid damage assessments has become more pronounced. Estimating damage is essential following a disaster to determine the extent and level of building damage, identify means of repair and retrofit and form a basis for future disaster preparedness. Conventionally, the assessment involved a response team that surveyed specific regions to collect damage data which was often challenging in widespread disasters with damaged transportation systems. To address this, multiple studies are now informed by computer science and use multimodal approaches to determine the extent and specificities of the damage. These current methodologies primarily focus on the overall deterioration of the structure but often fail to inspect building attributes influencing the damage. The proposed work seeks to identify these attributes using machine learning techniques and develop a damage prediction model. At present, there is limited information about the role of the age, the number of storeys, main wind force resisting system and retrofit of a building on its behaviour during a disaster. A preliminary study on Hurricane Michael resulted in a 75% accuracy for damage prediction, where the number of storeys and the main wind system was identified as primarily influencing the damage. The approach involved i) investigating relationships between building components with the disaster and ii) developing and testing supervised algorithms to evaluate feature importance. The overarching of this research is to lay the foundations for rapid damage prediction in disaster-prone regions, retrofit ideas for specific building attributes and improve building resilience.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Machine Learning Based Bridge Load Posting Prediction and Associated Uncertainties

Author(s): Sai Bandaru, *Department of Civil and Environmental Engineering, Louisiana State University;*
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This study develops a machine learning based framework to predict load posting decisions for bridges. Additionally, uncertainties associated with the machine learning based prediction are quantified herein. Deterioration due to aging can lead to structural deficiencies over time, which may prevent bridges from carrying legal loads safely. To ensure safety, bridges are load posted and the maximum loads allowed on the bridge are reduced. Load rating and posting decisions are based on inspection reports and structural analysis. However, herein, a novel machine learning based approach is presented to predict the load posting decision for bridges. For this purpose, on-system bridges in Louisiana were considered. The National Bridge Inventory was used to obtain bridges' characteristics, which were used as predictors. To predict load posting decisions, different classification techniques were evaluated including support vector machines, random forest, neural networks, and logistic regression. Based on their prediction accuracy, random forest model was selected. For different bridge classes, the resulting models had a prediction accuracy ranging from 70% to over 95%. These models were also used to determine the most important features that affect load posting. The results show that for all bridge classes, in addition to inventory and condition ratings, bridge dimensions are some of the key predictors for load posting decision. Additionally, the uncertainty associated with predictions obtained from the random forest models was quantified using infinitesimal jackknife estimates. These estimates were used to understand the sensitivity of the prediction variance with the number of trees in the random forest.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Robustness of Multilayered Random-Network Architected Material Through Experimental Testing

Author(s): *Sagnik Paul, *University of Illinois at Urbana-Champaign*; Ann C. Sychterz, *University of Illinois at Urbana-Champaign*;

Advancement in additive manufacturing techniques have paved way towards the design and development of materials with desired properties. Polymeric materials can be structurally defined by its coordination number, which is the number of links attached to a single node, and link density, a measure of the length of the links. A computational study based on adaptive quasicontinuum method studied the effect of coordination number and link density on the stretch behavior of polymer networks [1]. Investigation of the behavior with respect to its strength and fracture of such materials built on microstructural networks at the macroscale is crucial for implementation in civil infrastructure. In this paper, a double layered architected material is developed harnessing 3D printing inspired by this concept. Stratasys Objet500 Connex3 printer with Vero family of rigid materials is used with an approximate Young's modulus value of 2-3 GPa. One layer consists of nearly-regular short-link networks formed by interconnecting random points extracted from Latin Hypercube Sampling (LHS). The other layer consists of relatively longer links that randomly connects any two nodes of the other layer as a reinforcing layer, the length of which can vary from two to eight times the length of the short links approximately. An algorithm is developed that produces the geometry for a layer of short nearly-regular links superimposed with a layer of randomly-oriented longer links at a given percent density value with length of short-links, length of longer links and percent density as input parameters. Coordination numbers of four, six and eight are implemented for the short-link layer. The square-shaped specimens, sides ranging from 5cm to 10cm, are hooked from two opposite ends and are loaded on one end to determine its ultimate tensile strength. Preliminary testing includes five specimens of each parameter to study the effect of the coordination number and longer link density on the ultimate tensile strength of the material. Finite element analysis is performed to identify the failure regions of the architected material and are compared with experimental results. Experimental results will guide understanding the fracture characteristics of the architected material at a macroscale and how the topological concept can be extended to design fracture-resilient tension elements.

Keywords: Architected Material, Additive manufacturing, Random-network material, Robustness, Fracture-resilient;

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Machine Learning for Pre-Hurricane Damage Prediction of Structures

Author(s): *Samuel Leach, *Texas A&M*; Stephanie Paal, *Texas A&M*;

This study proposes a novel framework for the prediction of structural damages caused by a hurricane event. In current practice, following a hurricane event, inspectors manually evaluate damaged structures and assign a damage state classification according to FEMA guidelines. Application of Machine Learning methods to post-event damage classification has received significant attention in the past decade. Current state-of-the-art applications in automating the assigning of damage states have focused on post-event UAS-driven image classification. These works have achieved moderate success using damage classes with varying similarity to established FEMA guidelines. This work proposes a framework for predicting FEMA damage states at a single structure level prior to an event. Using a pre-curated dataset of structural characteristics and predicted best track storm data, the novel approach can be used to optimize post-event response efforts. The methodology was validated using a dataset of structural features and the best track storm data gathered following Hurricane Michael. Notably, the novel method achieved classification performances on par with the state-of-the-art post-event inspection accuracies using a dataset entirely constructed of non-damage-related features. These results show that the proposed framework is capable of performing pre-event damage prediction with the same level of performance as the current post-event damage classification methods. The exclusive use of features available prior to event damage allows this framework to be implemented by municipalities and emergency organizations to provide valuable information in planning emergency response deployment plans prior to an event occurring. Further, following an event, emergency responses can be quickly optimized through an updated model using the recorded storm track data in place of predicted path. This will greatly enhance the ability of these organizations to quickly, accurately, and efficiently perform evaluations, request relief funds, and begin community recovery.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Probabilistic Digital Twin for Additive Manufacturing

Author(s): Paromita Nath, *Vanderbilt University*; *Sankaran Mahadevan, *Vanderbilt University*;

This work presents a detailed methodology for constructing and deploying a digital twin (DT) for the laser powder bed fusion (LPBF) process in additive manufacturing (AM). The digital twin also accounts for the various sources of uncertainty and the variability in AM process by incorporating model uncertainty and process variability. For the LPBF digital twin, the physical system is the actual manufacturing process consisting of the AM machine, the printing environment, the part being printed, and the action of printing. Additionally, the AM process is also monitored using sensing equipment such as thermal cameras for surface temperature measurements, profilometer for surface roughness, etc. The virtual representation of the LPBF in the digital twin consists of a physics-based model of the LPBF process to predict the quantity of interest (QoI), i.e., porosity.

The physics-based model is replaced by a cheaper surrogate model to enable faster computation required in uncertainty analysis and decision-making (process optimization and process control) when the DT is deployed. A two-step surrogate model is proposed when the QoI is not directly observable during manufacturing, connecting process parameters first to the measured quantity (melt pool width) and then to the QoI (unmelted volume fraction). The initial prediction model is validated using available data.

The digital twin is deployed for both initial process optimization and online process control. A robust optimization formulation (with process parameters as decision variables) is used to minimize the mean and standard deviation of the difference between the target QoI and the predicted QoI. During the manufacturing, the data collected from the online monitoring system is used for diagnosis and inference of the current part quality, and for Bayesian updating of the uncertain model parameters and the model discrepancy term; this updated model is used for predictive control of the process parameters for subsequent layers. The digital twin is thus tailored for the particular individual part being produced, and is used for online, real-time adjustment of the LPBF process parameters, in order to control the QoI in the manufactured part.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: On the Modeling of Porous Structures via Variable-Order Calculus

Author(s): *Sansit Patnaik, *Purdue University*; Mehdi Jokar, *Purdue University*; Fabio Semperlotti, *Purdue University*;

Several theoretical and experimental investigations have highlighted the prominent role of size effects (and, more in general, nonlocal effects) in porous structures. The spatial distribution of porosity, in terms of the pores' location, size, and distribution, leads to a position-dependent nonlocal response associated with an overall position-dependent softening of the structure; in other terms, the strength of the nonlocal effect is strictly determined by the spatially-varying porous microstructure. Existing modeling approaches share common limitations that are rooted in the intrinsic trade-off between accuracy and computational efficiency. More specifically, current approaches require either a detailed representation of the microstructure, hence favoring accuracy over computational efficiency or a reduced order (homogenized) approach that favors computational speed over accuracy.

This study presents the application of variable-order fractional calculus to model the mechanical response of porous structures. The reformulation of the classical continuum mechanics framework by means of variable-order kinematics enables a well-posed and thermodynamically consistent approach to model media exhibiting position-dependent nonlocal behavior. Further, this study discusses a deep learning-based approach capable of identifying the variable-order distribution (describing the porous medium) based on the knowledge of its mechanical deformation.

The performance of the overall approach is illustrated by simulating both the linear and the geometrically nonlinear responses of porous beams and plates subjected to either mechanical or thermomechanical loads. The variable order approach shows excellent accuracy when compared with the traditional rule of mixtures homogenization technique; a widely used approach in the modeling of porous structures. The method also shows remarkable computational efficiency when compared with a 3D finite element analysis that fully resolves the porous beam geometry. Although the results are presented in the context of porous structures, the methodology is very general and it is expected it could be extended to a variety of applications characterized by multiscale behavior including, but not limited to, composites, architected materials, geological and biomaterials.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Physics-Based Machine Learning for Probabilistic Damage Diagnosis in Concrete

Author(s): *Sarah Miele, *Vanderbilt University*; Pranav Karve, *Vanderbilt University*; Sankaran Mahadevan, *Vanderbilt University*;

Reliable methodologies to detect, localize, and/or track internal crack growth in aging concrete structures are essential to ensure satisfactory performance over their intended lifespan. Machine learning (ML) models have become increasingly popular in structural health monitoring (SHM) as they learn the complex relationships between the damage and sensor data. This work evaluates the performance of ML techniques to support hidden crack localization using a nonlinear dynamics-based diagnosis technique, vibro-acoustic modulation (VAM). The diagnostic ML models require labeled training data (sensor data corresponding to known damage states) under different operating and testing conditions. The lack of sufficient experimental monitoring data for structures with varying degrees of damage is a key problem in training ML models for SHM. This problem can be alleviated by using physics-based models to generate the required training data. The simulation of the governing physics mimicking a diagnostic test for a structure can be computationally expensive, raising another challenge in obtaining the required training data. To alleviate the computational burden of simulating the governing nonlinear dynamics of the VAM technique for large real-world (three-dimensional) structures, we first train deep-learning (feed-forward neural network) models for damage diagnosis using data generated using solely two-dimensional computational domains containing hidden cracks. Two types of artificial neural network (ANN) models are built: (1) a classification model that identifies whether a sensor location has the presence or absence of damage, and (2) a numerical prediction model that enables Bayesian estimation to obtain the posterior probability distribution of damage location and size. We also investigate the fidelity of the physics models, to determine whether the available computational resource budget should be expended on numerous low-fidelity physics simulations, a small number of high-fidelity simulations, or a combination of both. Additional classification models are trained using varying amounts of data from physics simulations of different fidelities, and the performance of these models is evaluated. The single- and multi-fidelity physics-informed, diagnostic ML models are validated using VAM test data collected from a 2ft x 2ft x 0.5ft cement slab containing internal cracks at known locations, induced by alkali-silica reaction.

Title: Phase Field Method-Based Modeling of Fracture in Wood

Author(s): *Sebastian Pech, *TU Wien*; Markus Lukacevic, *TU Wien*; Josef Füssl, *TU Wien*;

Wood, as a naturally grown material, exhibits an inhomogeneous material structure as well as a quite complex material behavior. For these reasons, the mechanical modeling of fracture processes in wood is a challenging task and requires a careful selection of numerical methods. Promising approaches like limit analysis or the extended finite element method (XFEM) in combination with microstructure materials models deliver good but not yet satisfying results. Particularly the latter approach, including XFEM, has severe difficulties with crack paths in regions with complex morphology, mainly around knots. Therefore, in this work, the focus is laid on the recently emerging and very popular phase field method [1]. Especially geometric compatibility issues that limit the use of XFEM can be avoided, as the crack is not discretely modeled but smeared over multiple elements. This allows the formation of complex crack patterns, defined by the underlying differential equations and boundary conditions but not restricted by the mesh geometry.

The present implementation contains a stress-based split [2] which allows proper decomposition of the strain energy density for orthotropic materials. Furthermore, the geometric influence of the wood microstructure on crack propagation is taken into account by a structural tensor scaling the length scale parameter of the phase field [3]. For solving the system of differential equations, a staggered approach is used where the phase field equation and deformation problem are solved separately. The staggered approach is enhanced with an additional Newton-Raphson loop that ensures convergence.

The developed algorithm was tested on various problems. Compared to XFEM more computation time was needed as the phase field method requires a finer discretization. However, crack patterns, including branching and merging, could be modeled very stable and accurately, even in the vicinity of knots where the material structure of wood is particularly complex and interface zones exist.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Computational Design of Additively Manufactured Composite TPU Materials

Author(s): *Seda Oturak, *The Pennsylvania State University*, Callie Zawaski, *The Pennsylvania State University*, Melinda McKeehan, *The Pennsylvania State University*, Wesley Reinhart, *The Pennsylvania State University*;

Thermoplastic polyurethane (TPU) materials are advantageous in application areas demanding especially high elasticity. In addition to this, the combination of unique properties such as high strength, high toughness, malleability, and biocompatibility makes them useful in a variety of applications such as automotive parts, power tools, prosthetics, medical devices, and sporting goods. Moreover, their compatibility with multi-material additive manufacturing capability increases the range of possible properties in the resulting composite compared to the neat material. However, this complexity also significantly complicates the design process. We consider a hyperelastic constitutive model for a two-component composite TPU material which is produced by fused filament fabrication (FFF) method. The model is implemented in the open-source finite element (FE) software FEniCS. Uniaxial compression tests were performed on neat samples of each component and composite samples with different reinforcement morphologies to parameterize the model. With a parameterized constitutive in hand, we explore the use of data-driven generative models in managing this complex design space. We hope this work will be a starting point for addressing the design complexity of multi-material FFF parts for applications which would benefit from tailored compliance such as prosthetic devices.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Random Field Calibration with Data on Irregular Grid for Regional Analyses

Author(s): *Sena Mursel, *Lehigh University*; Daniel Conus, *Lehigh University*; Wei-Min Huang, *Lehigh University*; Javier Buceta, *Institute for Integrative Systems Biology (I2SysBio), CSIC-UV*; Paolo Bocchini, *Lehigh University*;

In engineering problems, it often occurs that geospatial data is available at an irregular grid of locations. When such data represents measurements of a random field, the calibration of its properties becomes challenging, because traditional techniques assume to have samples at regular frequencies in time and/or space. This study addresses the problem by proposing a simple, yet effective, technique and demonstrates it on a large-scale application of practical interest, covering the entire African continent.

The example application deals with understanding the population dynamics of the main reservoir of zoonotic diseases, such as bats, which is a crucial step to predict and prevent potential spillover of deadly viruses like Ebola. In this case, the estimation of the population density is largely driven by the presence of the necessary resources for survival (food, nesting areas, appropriate climate), which is called "carrying capacity". Due to the sparse data on wild animal density across Africa, this problem falls perfectly in the category described earlier. In this study, the carrying capacity of bats is studied, because they are considered the main reservoir for Ebola. The carrying capacity mean surface over the entire continent is calculated, and the fluctuations around the non-homogeneous mean are captured by a homogeneous random field. The statistics of this field are calibrated with the proposed methodology, despite the fact that the available data is unevenly spaced. In particular, the products of each pair of values in the entire dataset are used without any averaging for the estimation of the autocorrelation function, an analytical model is determined by a classical non-linear regression. This method does not require any interpolation or extrapolation of data and its use is efficient and simple. The correlation lengths along latitude and longitude are obtained as 1.78° (~200 km) and 1.40° (~150 km), respectively, and this can be interpreted in ecological terms as the correlation of resources affecting the survival of bats. Using the obtained characteristics of the random field, random realizations of the carrying capacity can be generated and fed into models of behavior and migration patterns of bats, to predict spillover of zoonotic diseases.

While the example application is in the field of bio-engineering, the proposed technique can be applied to many other topics in regional hazard analysis and catastrophe modeling, such as the calibration of hurricane wind speeds with unevenly spaced weather stations.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Reliability-Redundancy-Recoverability-Based Decision Optimization (R3-DO) for Disaster Resilience of Structural Systems

Author(s): *Seonghyun Lim, *Seoul National University*; Jungho Kim, *Seoul National University*; Junho Song, *Seoul National University*;

Structural systems should achieve a proper level of resilience to effectively secure their functionality under various disasters. Lim et al. [1] recently proposed a system-reliability-based disaster resilience analysis framework to manage the risk of system failure in the context of resilience. The framework has defined three resilience criteria – reliability, redundancy, and recoverability, which are computed based on the likelihoods of component interruptions, system-level reliability given component failures, and recovery process and mechanisms, respectively. Decision-making processes regarding design, operation and management should properly handle these criteria to assure the disaster resilience of structural systems. To this end, this study proposes a new reliability-redundancy-recoverability-based decision optimization (R3-DO) framework to achieve optimal decisions based on comprehensive understanding of component reliability, system reliability, and recoverability in the context of disaster resilience. In R3-DO, the cost function considers the structural system's recoverability by introducing a measure of an expected total cost. On the other hand, the probabilistic constraints incorporate the disaster-resilience-based limit-states that can be evaluated by the reliability-redundancy analysis [1]. The resilience indices and corresponding design parameter sensitivities are obtained using the matrix-based system reliability (MSR) method [2]. By incorporating three resilience criteria into decision optimization procedure, the disaster resilience of the structural system is effectively managed. The applicability and effectiveness of the proposed R3-DO framework are demonstrated by several numerical examples including a Daniels system, a truss structure, and a reinforced concrete bridge.

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Assessing the Vulnerability of Long-Term Deep-Space Habitats Subjected to Micrometeoroid Impact

Author(s): *Seyed Arsalan Majlesi, *The University of Texas at San Antonio*; Amir Behjat, *Purdue University*; Adnan Shahriar, *The University of Texas at San Antonio*; Arturo Montoya, *The University of Texas at San Antonio*;

With the significant developments in space traveling in recent years, the construction of long-term space habitats has become a worldwide focus. Appropriate selection of the materials used to build resilient space habitats in deep space is essential due to the limiting launch mass available for each NASA mission. Structural materials like solidified regolith, local material on the moon, and aluminum, a material with relatively high strength and low density, could be implemented to construct deep-space habitats. These structures will be exposed to harsh conditions, including the impact of micrometeoroids. This presentation will show the finite element models used to train a neural network (NN) model capable of characterizing the damage caused by micrometeoroids with different diameters and velocities on space habitats made of various structural materials. The outputs from the NN model are obtained to develop fragility curves and a vulnerability model that will be used to assess the health state transition function of the structural system. Moreover, the vulnerability model will be used to conduct trade studies that will enable researchers to identify the structural material features that are appropriate to preserve the structural integrity of long-term deep space habitats.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Multi-Scale Crystal Plasticity Approach to Simulate Creep in Superalloys

Author(s): *Shahriyar Keshavarz, *National Institute of Standards and Technology*; Carelyn Campbell, *National Institute of Standards and Technology*; Andrew Reid, *National Institute of Standards and Technology*;

This work focuses on modeling creep in superalloys utilizing multi-scale approaches to simulate and predict mechanical responses in crystal plasticity finite element platforms. The model has two major features of composition and morphology including the average size, volume fraction, shape of the precipitates. The multi-scale framework links two subgrain and homogenized grain scales. For the sub-grain scale, a size-dependent, dislocation density-based constitutive model in the crystal plasticity finite element framework is implemented with the explicit depiction of the gamma-gamma prime morphology as the building block for the next homogenized scale. For the homogenized level, a composition-dependent activation energy-based crystal plasticity model is developed with implicit effects on the morphology. The homogenized model can significantly expedite the computational process due to the parameterized representation while retaining accuracy. The glide and climb dislocation mechanisms are considered key mechanisms in the constitutive models. The composition-dependent constitutive model addresses the thermo-mechanical behavior of nickel-based superalloys for an extensive temperature domain and encompasses orientation dependence as well as loading conditions of tension-compression asymmetry aspects. The model is validated for diverse compositions, temperatures, and orientations through experimental data.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Data-Driven Nonlinear Modal Analysis with a Physics-Integrated Deep Learning Approach

Author(s): *Shanwu Li, *Michigan Technological University*; Yongchao Yang, *Michigan Technological University*;

Identifying the characteristic coordinates or modes of nonlinear dynamical systems is critical for understanding, analysis, and reduced-order modeling of the underlying complex dynamics. While normal modal transformation exactly characterizes any linear systems, there exists no such a general mathematical framework for nonlinear dynamical systems. Nonlinear normal modes (NNMs) are natural generalization of the normal modal transformation for nonlinear systems; however, existing research for identifying NNMs has relied on theoretical derivation or numerical computation from the closed-form equation of the system, which is usually unknown. We present a data-driven method with physics-integrated deep learning for identifying NNMs and reconstructing the NNM-spanned reduced-order models of unknown nonlinear dynamical systems using response data only. We leverage the modeling capacity of deep neural networks to identify the forward and inverse nonlinear modal transformations and the associated modal dynamics evolution. We discuss the performance and applicability of the method on different nonlinear systems.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Hurricane-Resilient City: Markov Decision Process-Based Problem Formulation and Machine Learning-Based Solution

Author(s): Teng Wu, *University at Buffalo*; *Shaopeng Li, *University at Buffalo*;

Representative infrastructure components (e.g., buildings and bridges) and networks (e.g., transportation and electric power systems) of a virtual city are assembled to systematically investigate effective actions for enhancement of urban resilience to hurricanes. The problem of enhancing hurricane resilience of urban built environment is first mathematically formulated as Markov decision process (MDP)-based optimization, where the unique features from the city, hurricane and their interactions are highlighted. To address issues raised by the high computational complexity, the global optimization of actions to achieve a hurricane-resilient city is partitioned into a sequence of local optimizations associated with various hurricane phases and infrastructure components/networks. Specifically, the hurricane life cycle is discretized into three phases with the assumption that their corresponding actions to enhance urban resilience (i.e., pre-hurricane preparedness, during-hurricane response and post-hurricane recovery) essentially possess different levels of interdependency. The actions considered under such an assumption are by no means exhaustive, however, they are additive to other enormous short-term and long-term actions for collectively enhancing urban hurricane resilience. For pre-hurricane phase, the component-level preparedness is implemented on individual critical hurricane-sensitive structures to enhance city robustness (e.g., intelligent morphing of tall buildings or long-span bridges to mitigate structural response under forecasted wind). For during-hurricane phase, the system-level response is performed for isolated critical infrastructure networks to enhance city operational adaptation (e.g., coordinated traffic management of a transportation infrastructure network to minimize travel time and injuries/fatalities under near real-time estimated/measured wind, rain and storm surge). For post-hurricane phase, system-of-system-level recovery is adopted for interconnected critical infrastructure networks to enhance city rapidity (e.g., cooperative repair scheduling of coupled traffic-electric power networks to reduce restoration time for hurricane damages). Solving the three subproblems for a hurricane-resilient city requires efficient simulation of the complex hurricane-city system with effective optimizations of the three-phase actions, which could be achieved by the fast-developing deep learning technology. To this end, a machine learning-based solution of the MDP-based problem is then introduced with recent efforts in representative applications, where unsupervised learning, supervised learning and reinforcement learning are respectively used for dimension reduction, surrogate modeling and decision optimization. This study could serve as a preliminary guidance for future studies on enhancing urban resilience to natural hazards using artificial intelligence tools.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Additively Graded Materials for Thermal Management

Author(s): *Sharon Park, *Johns Hopkins University*; Alex Lark, *Johns Hopkins University APL*; Arunima Banerjee, *Johns Hopkins University*; Kevin Hemker, *Johns Hopkins University*; Gianna Valentino, *Johns Hopkins University APL*;

Extreme environment applications require high temperature structural materials, such as refractory metals, but their high density, manufacturing difficulties, and limited high temperature characterization inhibit their widespread use. Advances in additive manufacturing (AM) promise to be a game-changer in the fabrication and implementation of refractory-based components via near-net-shape processing. However, the characterization of refractory high temperature properties is rare, much less for those made via AM. The majority of available high temperature data were generated decades ago and do not necessarily capture the non-uniform and highly anisotropic microstructures of AM components. Here we report on the development and optimization of AM processing parameters for tungsten and tantalum refractory alloys to obtain a deeper fundamental understanding of the AM structure-property relationships. Emphasis will be placed on characterizing the microstructure and high temperature mechanical performance, ultimately aimed at improving thermal modeling of AM refractories for high temperature applications. Although still in its infancy, a study to fabricate refractory graded materials with a diverse palette of compositions, microstructures, and form factors is ongoing and the results will be discussed for thermal management.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Artificial Neural Networks for Identifying Incoming Seismic Wave Motion into Heterogeneous Soil Columns

Author(s): *Shashwat Maharjan, *Central Michigan University*; Bruno Guidio, *Central Michigan University*; Chanseok Jeong, *Central Michigan University*;

There is a need for estimating the profile of a dynamic input motion (e.g., incident seismic wave) that shakes a domain of interest, including built environments and soils, by using vibrational measurement data on the surface of the domain. By using the reconstructed input motion, engineers can replay the seismic responses of the domain and critical infrastructure in it shaken during a strong earthquake.

The recent development on a full-waveform inversion (FWI) to reconstruct incoherent seismic input motions through a heterogeneous solid from a surface response is fairly accurate but is prohibitively time-consuming to produce results in real time. To investigate a time-efficient alternative, this paper attempts to recreate a dynamic input motion accurately through machine learning approaches that significantly reduces the processing time.

The adaptability of neural networks to learn from the provided data and the computational prowess present today has made machine learning highly desirable, especially for regression problems, such as the one presented in this paper. The two Artificial Neural Networks (ANNs) studied in this paper are Deep Neural Network (DNN) and Convolutional Neural Network (CNN). Both ANNs show promising results in the reconstruction of a seismic input motion and have reduced the reconstruction process time to a fraction of a second with high accuracy. The paper also conducts brief parametric studies on why certain parameters were chosen to construct the specific DNN and CNN models.

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Baltimore, MD, May 31 - June 3, 2022

Title: Structural Evaluation of Ledges in Shiplap Hinge Joints Using Empirical and Strut-and-Tie Methods

Author(s): *Shaymaa Obayes, *University of Delaware*; Monique Head, *University of Delaware*; Daniel Baxter, *Michael Baker International*;

Understanding how applied loads impact structural performance is important for design, especially in the presence of the in-span hinge joints (or shiplap hinge joints) that cause disruptions in the load path and can result in failure mechanisms of concrete bridges. When exceeding the limit capacity of the hinge joint region such as shear and punching capacities, the results can lead to rapid loss of the structural capacity without warning (i.e. sudden collapse), which is the worst-case scenario. This study will focus on comparing the ultimate capacity of the ledges using empirical and strut-and-tie methods. Evaluation of concrete hinge joints using the most recent American Association of State Highway and Transportation Officials (AASHTO) LRFD empirical method recommendations will be compared to strut-and-tie methods highlighting the differences, advantages, and disadvantages of each method based on the prediction of the true failure mode. The finite element model (FEM) of selected hinge joints is developed to address and evaluate the current problem of behavior versus design methods that better estimate the ultimate capacity of existing in-span hinges subjected to service load using the two methods. Addressing the consequences of using older design guidance for existing bridges to meet the current code requirements is included in this study as well. The finite element model created in ABAQUS is used to estimate the existing capacity and compared to the empirical method, revealing that the estimated horizontal forces, flexure, punching shear, hanger reinforcement, and bearing using the strut-and-tie method would be unconservative. Accordingly, corresponding capacities for all the failure mechanisms found using the empirical approach were determined to be more conservative.

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Title: Data-Based Techniques for Structure-Property Correlation in Periodic and Aperiodic Metamaterials

Author(s): *Shengzhi Luan, *Johns Hopkins University*; Enze Chen, *Johns Hopkins University*; Stavros Gaitanaros, *Johns Hopkins University*;

One of the most promising recent developments in materials science and engineering is the concept of exploiting "architecture" ? the combination of topology and solid(s) distribution ? as a means to generate materials with properties that are unattainable by traditional monolithic solids. Lightweight architected materials, such as additively manufactured micro-lattices and foams, are excellent candidates for a plethora of engineering applications ranging from space structures to battery electrodes and biomedical implants. To date, a wide range of strut- and shell-based architected metamaterials with unique effective properties have been successfully designed and synthesized. Despite their significance, however, a rigorous framework for associating specific mechanical properties of these material systems to key features of their complex microstructure remains an open challenge. We present here a data-driven framework that allows structure-property correlation for both periodic and aperiodic cellular solids. Representative lattice microstructures are first generated by solid distribution on k-uniform tilings and Laguerre tessellations with large variations of topological characteristics. A set of deterministic and stochastic morphological descriptors is used to perform microstructure quantification for all designs. Finite element simulations, validated by experiments on additively manufactured specimens, are then performed to predict the macroscopic elastic modulus for different sets of material designs. The numerical data are introduced in machine learning algorithms to develop a surrogate model with the ability to (a) predict macroscopic properties and (b) correlate them to the key morphological descriptors. Results will be presented for 2D materials, including identification of the microstructural descriptors with the largest effect on their effective stiffness. We will further show how this framework can be used to design materials with specific mechanical properties that are also imperfection-insensitive.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Parametrically Upscaled Continuum Damage Mechanics Model for Titanium Alloys

Author(s): *Shravan Kotha, *Johns Hopkins University*; Somnath Ghosh, *Johns Hopkins University*;

This talk presents the development of a Parametrically Upscaled Continuum Damage Mechanics (PUCDM) model for polycrystalline Titanium alloys such as Ti6242. PUCDM is computationally efficient, and it provides a connection between material response and the underlying microstructure. These models are developed from coupled Crystal Plasticity - Phase Field (CP-PF) simulations on polycrystalline microstructures using an integrated framework consisting of material characterization, computational homogenization and machine learning [1]. An experimentally validated crystal plasticity model accounts for elasto-plastic anisotropy, size and rate dependency in the grain-scale material response whereas a thermodynamically consistent phase field model is developed [2] for ductile crack propagation in these alloys. For the development of PUCDM, Statistically Equivalent Representative Volume Elements (SERVEs) are constructed, and a detailed sensitivity analysis is performed to identify important microstructural distributions that govern the macroscopic material response and Representative Aggregated Microstructural Parameters (RAMPs) that quantify these distributions are defined. The constitutive equations in PUCDM are then chosen to represent different up-scaled mechanical and crack propagation behaviors observed in CP-PF analyses. These include anisotropic elasticity, rate-dependent plasticity and damage which are coupled via a Helmholtz free energy density function. The proposed PUCDM model also accounts for anisotropy, tension-compression asymmetry and strain rate dependency of damage. A database of SERVEs is created, and up-scaled stress-strain responses from CP-PF simulations under a variety of loading conditions are used to calibrate constitutive coefficients of PUCDM equations as a function of RAMPs using machine learning. Finally, a non-local extension of PUCDM is implemented in Abaqus as a user material subroutine and microstructure-sensitive structural simulations are performed to demonstrate its capability.

The proposed models are necessary in the multi-scale modeling of deformation and failure in Titanium alloys which requires material microstructure dependent models such as PUCDM to predict deformation and damage behaviors. Parametric studies using PUCDMs also give insights into the role of critical microstructural features that govern the mechanical and failure response thereby enabling material design.

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Title: Material Models for Fibrous Elastomeric Biological and Bio-Inspired Materials

Author(s): *Shruti Motiwale, *University of Texas at Austin*; Christian Goodbrake, *University of Texas at Austin*; Wenbo Zhang, *University of Texas at Austin*; Michael Sacks, *University of Texas at Austin*;

We have extensively utilized meso-structural constitutive models for the normal aortic heart valve leaflets, and now present their ability to guide the design of replacement aortic heart valve biomaterials. We modeled the leaflet tissue as a hyperelastic material, wherein the total strain energy of the leaflet tissue was assumed to be given by a weighted sum of the matrix and fiber strain energies. We modeled the matrix with an incompressible neo-Hookean model. Next, we modeled the uniaxial response of an individual fiber with an Ogden model. We used a probability distribution function (PDF) to model the fiber splay and integrated the individual fiber response with this PDF to obtain the total response of all fibers. We further extended the model by assuming the interactions between fiber pairs could be modeled with a modified pseudo-invariant that depended on the fiber directions. Subsequently, we implemented the model for a hydrogel coated electrospun fiber composite biomaterial, as we had a comprehensive set of strain-controlled experimental dataset for this material. The test dataset used for parameter estimation consisted of separate extensional and shear protocols, which is a unique and important aspect of this study. To identify if our material had any interactions, we fitted the model twice, with and without including the interaction term in our model. We found that the fiber-fiber interaction term was necessary to accurately predict the fiber response under extensional as well as shear deformation modes. In the absence of the interaction term, the model consistently underpredicted shear stresses. The model was also able to predict the total composite biomaterial response using the parameters that were obtained by fitting the mesh and the gel models independently, and an additional fiber-gel interaction term was not required to predict the response under any deformation modes. As the higher accuracy of our meso-structural approach comes with a high computational cost, that makes it impractical for clinically relevant time frames. To address this issue, we have developed a neural network finite element surrogate model (NNFE) of a tri-leaflet RHV simulation model. We have compared the results of our NNFE model with previously published results and found that the NNFE can reproduce the simulation results with no loss of accuracy. A trained NNFE model only takes a few seconds for a simulation and paves the pathway for implementing highly accurate detailed structural models in extensive parametric studies. Results of extensive simulations will be presented.

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Title: An Ultra-high Speed Reproducing Kernel Particle Method

Author(s): *Siavash Jafarzadeh, *The Pennsylvania State University*; Michael Hillman, *The Pennsylvania State University*;

Meshfree methods have been developed over the past few decades to overcome the limitations of the finite element method, especially when dealing with difficult topological changes such as large deformation and fracture. The reproducing kernel particle method (RKPM) is a Galerkin weak form-based meshfree method, which employs the flexible reproducing kernel approximations that can yield both high- or low-order smoothness, as well as arbitrary-order accuracy in discretizing the field equations. Yet the computational cost of RKPM is relatively expensive compared to traditional finite element methods, owing mostly to the rational nature of the approximations and matrix operations involved [1].

Recently, a fast convolution-based method (FCBM) has been introduced for peridynamics (PD) where the convolutional structures of PD volume integrals are exploited to efficiently compute the integrals via fast Fourier transforms [2]. FCBM avoids explicitly identifying neighbors and looping over them for quadrature by transferring the burden of computations to cheap multiplications in the Fourier space. While most Fourier methods require periodicity of the domain which limit their application, FCBM uses an embedded constraint approach to enforce the desired boundary conditions on arbitrary geometries. In a similar fashion, the convolutional structures in RKPM formulations can be exploited to elevate the method's performance up to several orders of magnitude.

In this work, we introduce FFT-accelerated RKPM, where the convolution sums (arising from nodal integration of the Galerkin weak form) are efficiently computed using FFTs, and inverse FFT operations with the complexity of only $O(N \log 2N)$, where N is the total number of nodes. No prior neighbor search and storage is required, and no construction and storing of the stiffness matrix is required. Our preliminary results show CPU speedup as high as 3000 times, where computations requiring months to run on a single processor can now be carried out in a few minutes.

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Engineering Complex Energy Landscapes with Magneto-Elastic Structures

Author(s): *Sinan Keten, *Northwestern University*; Xinyan Yang, *Northwestern University*;

The Kresling truss structure, derived from Kresling origami, has been widely studied for its bi-stability and various other properties that are useful for diverse engineering applications. The stable states of Kresling trusses are governed by their geometry and elastic response, which involves a limited design space that has been well explored in previous studies. In this work, we present a magneto-Kresling truss design that involves embedding nodal magnets in the structure, which results in a more complex energy landscape, and consequently, greater tunability under mechanical deformation. We explore this energy landscape first along the zero-torque folding path and then release the restraint on the path to explore the complete two-degree-of-freedom behavior for various structural geometries and magnet strengths. We show that the magnetic interaction could alter the potential energy landscape by either changing the stable configuration, adjusting the energy well depth, or both. Energy wells with different minima endow this magneto-elastic structure with an outstanding energy storage capacity. More interestingly, proper design of the magneto-Kresling truss system yields a tri-stable structure, which is not possible in the absence of magnets. We also demonstrate various loading paths that can induce desired conformational changes of the structure. The proposed magneto-Kresling truss design sets the stage for fabricating tunable, scalable magneto-elastic multi-stable systems that can be easily utilized for applications in energy harvesting, storage, vibration control, as well as active structures with shape-shifting capability. Finally, we discuss the extension our analysis approach to other magneto-elastic structures.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Higher Order Modeling of Thin Layers in Conductivity and Elasticity

Author(s): *Sofia Mogilevskaya, *University of Minnesota*; Svetlana Baranova, *University of Minnesota*; Volodymyr Kushch, *National Academy of Sciences, Ukraine*;

Composite materials with thin coating layers (interphases) are encountered in a variety of engineering applications. As characteristic scales in such problems may vary across many orders of magnitude, their direct simulation could be, in general, challenging. To eliminate the need for such simulations, various asymptotic approaches have been proposed. They allow for modeling of layers by the jump conditions in relevant fields across some boundaries. They also represent attractive alternative to the approaches in which the layers are modeled by means of various structural elements, e.g., beams, shells, or plates, as the latter require decisions on which type of elements to use.

In this talk, we present several new results related to higher order asymptotic modeling of thin layers. We demonstrate that the modeling tools, that we recently developed, allow for straightforward derivations of explicit expressions for the higher order boundary conditions associated with the asymptotic models. For two-dimensional conductivity and elasticity problems, such conditions were derived for layers of arbitrary sufficiently smooth curvatures; for the corresponding three-dimensional problems, they were obtained for layers of spherical shapes. The results of comparative analysis of the higher order models and their testing, using available benchmark solutions and those for the limiting cases of the layer parameters, will be discussed. We demonstrate that the use of the third order models allows for accurate evaluation of all governing fields inside the layers without the need for their direct modeling.

EMI 2022
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Title: Modeling Damage for Resilience Assessment Under Natural Hazards: A Discrete Simulation Framework

Author(s): *Soolmaz Khoshkalam, *University of Massachusetts Dartmouth*; Shayan Razi, *University of Massachusetts Dartmouth*; Mazdak Tootkaboni, *University of Massachusetts Dartmouth*; Arghavan Louhghalam, *University of Massachusetts Dartmouth*;

Buildings subject to natural hazards should be considered as a system composed of structural elements and non-structural components. This is crucial for resilience assessments where the damage of both structural and nonstructural components can lead to loss of functionality and affect the robustness. Most traditional modeling frameworks only account for the behavior of structural systems or use cascaded methods to study the behavior of nonstructural elements [1]. Here we discuss the simulation framework we are developing to simulate the entire building comprising both structural and nonstructural components. The framework is based on the potential of mean force approach to Lattice Element Method (LEM), used for modeling fracture in heterogeneous materials [2]. The discrete nature of LEM is particularly advantageous for damage and failure assessment as it does not suffer from the limitations of the classical continuum approaches in modeling discontinuity. We calibrate the parameters of interaction potential for one- and two-dimensional members. The computational tool is shown to be accurate and efficient for quasi static simulations [3]. In this presentation we discuss the adaptation of LEM to account for dynamic effects. This is essential to make the simulation tool amenable to resilience assessments under natural hazards with dynamic nature such as earthquakes and hurricanes.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Inverse Analysis of Strain Distribution Sensed by Distributed Fiber Optic Sensor Subject to Strain Transfer

Author(s): *Soroush Mahjoubi, *Stevens Institute of Technology*; Yi Bao, *Stevens Institute of Technology*;

Strains measured by distributed fiber optic sensors with protective coatings can be different from the real strains in host matrix due to strain transfer effect. This study presents a novel inverse method to determine the real strain distributions in host matrix using strain distributions measured from distributed fiber optic sensors. Two different scenarios of strain distributions in host matrix are investigated, which have known and unknown types of strain fields, respectively. Three representative metaheuristic algorithms are respectively utilized in the inverse analysis, which are colliding bodies optimization algorithm, particle swarm optimization algorithm, and genetic algorithm. The performance of the proposed method was evaluated by analytical case studies and experimental testing of a prestressed concrete beam subjected to four-point bending. The results demonstrated high accuracy and efficiency of the proposed method. This study is expected to greatly advance distributed fiber optic sensing capabilities in measuring strain distributions for structural health monitoring.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Prediction and Multi-Objective Optimization of Mechanical, Economical, and Environmental Properties for Strain-Hardening Cementitious Composites (SHCC) Based on Automated Machine Learning and Metaheuristic Algorithms

Author(s): *Soroush Mahjoubi, *Stevens Institute of Technology*; Yi Bao, *Stevens Institute of Technology*; Weina Meng, *Stevens Institute of Technology*;

This study develops a framework for property prediction and multi-objective optimization of strain-hardening cementitious composites (SHCC) based on automated machine learning. Three machine learning models are developed to predict the compressive strength, tensile strength, and ductility of SHCC. A tree-based pipeline optimization method is enhanced and used to enable automatic configuration of machine learning models, which are trained using three datasets considering 14 mix design variables and achieve reasonable prediction accuracy. With the predictive models, five objective functions are formulated for mechanical properties, life-cycle cost, and carbon footprint of SHCC, and the five objective functions are optimized in six design scenarios. The objective functions are optimized using innovative optimization and decision-making techniques (Unified Non-dominated Sorting Genetic Algorithm III and Technique for Order of Preference by Similarity to Ideal Solution). This research will promote efficient development and applications of high-performance SHCC in concrete and construction industry.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Patient Specific Finite Element Analysis of the Influence of Intraocular Pressure on the Optic Nerve Head

Author(s): *Soumaya Ouhousou, *University of Pittsburgh*; Amin Pourasghar, *University of Pittsburgh*; Lucy Q. Shen, *Massachusetts Eye and Ear, Harvard Medical School*; Chhavi Saini, *Massachusetts Eye and Ear, Harvard Medical School*; Mengyu Wang, *Schepens Eye Research Institute of Massachusetts Eye and Ear, Harvard Medical School*; John C. Brigham, *University of Pittsburgh*;

Glaucoma is an eye disease that leads to irreversible vision loss and is characterized by progressive degeneration of retinal ganglion cells (RGCs) and their nerve fibers. Elevated intraocular pressure (IOP) is the only known treatable risk factor for glaucoma and has been shown in patients to directly cause damage to the optic nerve head (ONH) and RGCs. To better understand the mechanisms of glaucoma, several researchers have been investigating patient-specific mechanical models of the ONH and surrounding tissues (Sigal et al., 2005; Stitzel et al., 2002). However, several aspects around this disease remain unclear. The objective of this study is to evaluate potential mechanisms of IOP-mediated glaucomatous damage of the optic nerve, as well as the effect of high IOP on different ONH components using patient-specific finite element analysis. Swept-source optical coherence tomography (SS-OCT) imaging data of the ONH were acquired for a cohort of subjects. To create patient-specific finite element models, high-resolution 12-line radial scans for each subject were manually segmented and several regions were differentiated: sclera, neural tissue, and lamina cribrosa. Each region of the eye model was considered homogeneous with elastic and isotropic material properties, and specific material parameters were assigned to each component based on published values in the literature. Boundary conditions were set such that free body movement was restricted, which means that the outer surface was assumed fixed, and pressure was applied to the internal surface to simulate the IOP. Results that include the variations in strain and displacement distribution on each component of the eye are included in the analyses. In particular, the output parameters of different regions will be analyzed and compared in order to identify the regions that are most affected by the increase of IOP. Longer-term objectives include further improving patient-specific mechanical models of the ONH by using inverse problem solution strategies to estimate in vivo material properties.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Wave-Source Inversion for the Detection of Moving Loads

Author(s): *Stephen Lloyd, *Central Michigan University*; Chanseok Jeong, *Central Michigan University*;

In our research, we demonstrate the use of the adjoint-gradient-based source inversion method for the reconstruction of the temporal and spatial distributions of wave sources on/within a heterogeneous damped linear elastic solid given measurements of vibrations at the solid's surface. The two-dimensional finite element method (FEM) is used to obtain wave solutions with the high-resolution discretization of source functions in space and time, leading the number of inversion parameters to range in millions. Numerical experiments, in which the iterative inversion procedure begins with an initial guess of zero loading at all points in space and time, show that the presented approach is effective at reconstructing horizontal and vertical components of force, e.g., normal and shear tractions of multiple simultaneous moving dynamic distributed loads. We use experimental data obtained from lab-scale tests at a high frequency (100 kHz) to validate our inversion method.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Use of Multifidelity Training Data and Transfer Learning for Efficient Surrogate Model Construction

Author(s): *Su Jiang, *Stanford University*; Louis Durlofsky, *Stanford University*;

In subsurface flow settings, data assimilation and uncertainty quantification can be very computationally demanding because many high-fidelity models must be simulated. Various deep-learning-based surrogate modeling techniques have been developed to alleviate the simulation costs associated with these applications. However, to construct data-driven surrogate models, thousands of high-fidelity simulations may be required to provide training samples. The computation associated with these runs is one of the most expensive components of these procedures. To address this issue, in this work we present a capability that uses coarsened (upscaled) simulation models in the training step. Specifically, we develop a transfer-learning-based recurrent residual-U-Net surrogate model that is trained with multifidelity data. Training is first accomplished with flow results from a few thousand low-fidelity simulation runs. The coarsened geomodels for these runs are constructed using a global single-phase transmissibility upscaling procedure. Next, around 100 high-fidelity runs are used to retrain the output layers and fine-tune the neural networks. The transfer-learning procedure leads to about 90% savings in training simulation cost, as it avoids the need to perform thousands of high-fidelity runs. The surrogate model is applied for two-phase flow problems in 3D channelized systems. The model trained with multifidelity data is shown to be nearly as accurate as the reference surrogate (trained only with high-fidelity data) for predicting flow responses in new geomodels. The multifidelity surrogate is then applied for history matching using an ensemble-based data assimilation procedure. The transfer-learning-based framework developed here may be of applicable for a wide range of subsurface flow problems.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Coupled Crystal Plasticity Phase-Field Model for Ductile Fracture in Polycrystalline Microstructures

Author(s): *Thirupathi Maloth, *Johns Hopkins University*; Somnath Ghosh, *Johns Hopkins University*;

A wavelet-enriched adaptive hierarchical, coupled crystal plasticity - phase-field finite element model is developed in this work to simulate crack initiation and propagation in complex polycrystalline microstructures. The deformation and crack phase-field are coupled via Helmholtz free energy with contributions from stored elastic strain energy, defect energy resulting from slip and hardening of crystallographic slip systems, and the surface energy of fracture surfaces. The tension-compression asymmetry is modeled through an orthogonal decomposition of stored elastic strain energy into tensile and compressive counterparts. The crack initiation/propagation is governed by the stored tensile elastic strain energy and the accumulated defect energy with evolution of crystallographic slip. Several numerical examples are shown to demonstrate the capabilities of the proposed model to capture typical ductile fracture responses observed in polycrystalline materials. The computational model is augmented with uncertainty quantification (UQ) capabilities to quantify the uncertainty in crack propagation characteristics resulting from microstructural uncertainty considerations

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Design and Experimental Verification of Mechanical Metamaterials for Vibration Attenuation

Author(s): Weidi Wang, *University of Massachusetts Lowell*; Joshua Morris, *University of Massachusetts Lowell*; *Thomas A. Plaisted, *CCDC US Army Research Laboratory*; Bradley D. Lawrence, *CCDC US Army Research Laboratory*; Christopher Hansen, *University of Massachusetts Lowell*; Alireza V. Amirkhizi, *University of Massachusetts Lowell*;

Mechanical metamaterials (MMs) have long attracted research interest due to their capability to alter wave propagation. The internal resonance imparted by MMs creates frequency stop bands where little to no wave energy is transmitted through the material. In this work, we present the design, simulation, and experimental verification of 3D printable metamaterials for vibration attenuation purposes. The MM unit cells are first studied using eigen-frequency analysis to extract the desired band gap features. Then the overall array is assembled using graded unit cells. The graded cells are designed to have gradually overlapping stop bands so that the effective attenuation range of the array is broadened and/or deepened. Numerical simulations in the frequency and time domain confirm the wide stop band behavior under both longitudinal and shear vertical excitation. Experimental verification of the stop bands is performed under random vibration loading using a uni-axial shaker. Within the stop band frequency range, energy transmission through the sample is attenuated by two orders of magnitude compared to the source. Further numerical studies on such systems are performed to explore optimization possibilities. We show that using a staggered array design with alternately placed rows, further attenuation is achieved along with a gains in volumetric efficiency. This numerical and experimental study of MMs introduces several good design candidates and will be of particular interest for applications such as filtering and controlling of sound and vibration loading.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Characterization of Coupled Turbulent Wind Wave Flows Based on Large Eddy Simulation

Author(s): *Tianqi Ma, *Louisiana State University*, Chao Sun, *Louisiana State University*,

Wind-wave interaction involves wind forcing on wave surface and wave effects on the turbulent wind structures, which essentially influences the wind and wave loading on structures. Existing research on wind-wave interaction modeling ignores the inherent strong turbulences of wind. The present study aims to characterize the turbulent airflow over wave surfaces and wave dynamics under wind driving force. This paper develops a high-fidelity two-phase model for simulating highly turbulent wind-wave fields based on the open-source program OpenFOAM. Instead of modeling waves under uniform wind forcing, inherent wind turbulences are prescribed by imposing a temporally and spatially correlated turbulent wind field at the inlet boundary. The developed model is validated by laboratory data of wave surface under wind driving force and air structure above wave surface measured separately. Then the wind-wave interaction under extreme wind and wave conditions is analyzed. The research result shows that when the inherent wind turbulences are considered, the resultant wind turbulence is strengthened and is the summation of inherent turbulence and wave-induced turbulence. In addition, the wave coherent velocities and shelter effect are enhanced because of the presence of wind inherent turbulence. The moving waves induce wind turbulence and cause the variation of averaged wind velocities with wave phases. The regions of intense turbulence depend on the relative speed between the wind velocity and wave phase speed. Higher wind velocity induces greater turbulences, and the extreme wind forcing could increase the maximum turbulence intensity by 17%. A larger wave height also generates turbulences in a higher region above the air-water interface. The wave-coherent velocity, which represents the variation of averaged wind velocities, is nearly proportional to the wind velocity, and the influenced area mainly depends on the wave height.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: On the Use of Proper Generalized Decomposition in the Context of Topology Optimization

Author(s): *Tomas Pauwels, *KU Leuven*; Mattias Schevenels, *KU Leuven*;

In many practical topology optimization applications, a very fine mesh is desirable, either to obtain a high-resolution design, or to resolve physics in sufficient detail. As a result, the solution of the discretized state and adjoint Partial Differential Equations (PDEs) in every optimization iteration becomes computationally expensive. Model order reduction techniques allow for a mitigation of the computational cost. One such technique is the Proper Generalized Decomposition (PGD) method. In this method, the multi-coordinate state solution is approximated as a sum of products of single-coordinate basis functions. The solution thus obtained is similar to the result of a Proper Orthogonal Decomposition (POD), but in contrast to POD, the basis functions are computed on-the-fly as the problem is solved. Over the last few years, PGD has been successfully used for the solution of various types of PDEs, but it has not yet been applied for topology optimization.

In this contribution, we explore the potential of PGD in the context of topology optimization. As a proof of concept, we utilize PGD for the optimization of a two-dimensional cantilever beam for minimum compliance. The two-coordinate solution of the state equation is decomposed into products of one-coordinate solutions. After discretization, this results into systems of equations of much lower order than in the original problem. A preliminary study shows that the PGD method does allow for the solution of the optimization problem, yielding designs and compliance values that are similar to those obtained with the 88-line MATLAB code. The computation time with PGD is still about an order of magnitude longer than for the 88-line code, but we expect that it should be possible to close this gap, and to reduce computation time further, since our current code is not optimized yet, and we don't yet exploit the fact that a very similar design is analyzed in each two consecutive iterations of the optimization scheme.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: PIDynNet: An ODE-Constrained Neural Network for Nonlinear Structural System Identification

Author(s): *Tong Liu, *University of Illinois at Urbana-Champaign*; Hadi Meidani, *University of Illinois at Urbana-Champaign*;

Structural identification is of critical importance to structural resilience confronting earthquakes and other hazards. In this presentation, we proposed PIDynNet, a novel Ordinary Differential Equation (ODE)-constrained neural network framework for structural identification. This method estimates the structural parameter of nonlinear structural systems by embedding an auxiliary physics-based loss into the overall loss function accompanied by supervised loss to assist nonlinear system identification. A sub-sampling strategy and early stopping strategy are developed and implemented for more efficient learning in the identification process. Three nonlinear numerical case studies are conducted to demonstrate the advantage of PIDynNet over other competing counterparts, in problems with or without latent variables outperform. It is also shown that the ODE-constrained neural network has the generalization capability to predict nonlinear structural response encountering unseen ground excitation.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Three-Dimensional Visualization of Nondestructive Evaluation Results

Author(s): *Torin McCue, *Atkinson-Noland & Associates*; Carlo Citto, *Atkinson-Noland & Associates*;

Heritage structures provide the public with great cultural, economic, and educational benefit and are often irreplaceable. In these instances, preserving the structures is paramount and to do so in an effective and responsible manner, it is crucial to understand how the structures were originally built. Various nondestructive evaluation methods have been used for many years to investigate the composition of historic masonry buildings, which often guides the production of as-built drawings or sketches to convey how structural components were originally built or retrofitted. While simple architectural drawings are effective and often sufficient, more recent advancements in 3D modelling software have led to the introduction of reporting nondestructive evaluation results in interactive 3D formats.

New methods for combining nondestructive evaluation results with 3D models of heritage structures have been developed for a simpler and more intuitive way to visualize results from surface penetrating radar scans, ultrasonic pulse methods, infrared thermography, and various other techniques. The workflow is often started by constructing a 3D model of the structure in question using either a laser scanner or via photogrammetric methods. Then results from the nondestructive evaluations can be inserted into the 3D model independent to each investigation method or combined into one complete 3D model to easily visualize how the structure was originally built.

These new visualization techniques are beneficial when it comes to presenting investigation results to building owners or clients, but also on a wider scale to understand systematic patterns of construction methods, or even deterioration patterns that are necessary to understand during the preservation of the structures.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Connecting the History and the Future of Tall Buildings

Author(s): *Tracy Kijewski-Correa, *University of Notre Dame*;

Ahsan Kareem's work has traversed the full spectrum of wind effects on tall buildings: wind tunnel experiments that democratized access to database-assisted design, work on occupant comfort and energy dissipative devices that ensured tall buildings would be habitable, and full-scale monitoring that unlocked the mysteries of some of the world's most famous tall buildings. Even today Ahsan continues to push the frontiers of the field with respect to modeling, simulation and machine learning. Yet the value of these contributions should not be credited to the underlying mathematics and physics alone. Instead, it was Ahsan's relationships with the humans who design, construct and occupy tall buildings, as well as a deep respect for the great engineers who preceded him in this work, that inspired and guided his work. Reflecting on my over 20 years working with Ahsan, I will chronicle his career studying tall buildings, signaling the contributions and relationships that have marked key milestones in that legacy.

I will further emphasize how these contributions lay a foundation for the next generation of researchers who will study these high-value structures in a future marked by increasingly dense and complex urban wind environments, with more daring architectural concepts, and highly-efficient structural systems. And as the practice continues to push the boundaries of conventional forms and methodologies, I believe it will find even greater need to embrace Ahsan's philosophy and contributions. As such, much like Fazlur Khan provided a template for the understanding of fundamental tall building typologies and potential efficiencies, Ahsan Kareem's career has provided the template for how we can shed the rigidity of those classical forms and realize free-form geometries and heights previously unimaginable.

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Baltimore, MD, May 31 - June 3, 2022

Title: Improving Printability and Sustainability of Cementitious Mixtures Using Cellulose Filaments

Author(s): *Ugur Kilic, *University of Virginia*; Ahmed Omran, *New Jersey Institute of Technology*; Osman Ozbulut, *University of Virginia*;

Additive manufacturing of concrete, often called as 3D Concrete Printing (3DCP), has gained significant attention in construction industry due to its various advantages over conventional construction. The 3DCP eliminates the need for formwork and molds, allows the design and fabrication of many shapes and geometric features, and enables incorporation of additional functionality into a structure. As a result, it has potential to substantially reduce construction time and labor cost, enhance safety and reliability, and minimize the environmental footprint of concrete industry. However, there are several challenges that this emerging construction technology faces. One such challenge is that printable mixtures demand high cement and admixture contents to satisfy the opposing requirements of extrudability such as high flowability, and buildability such as high stability. Plant-based nano materials, as cost-effective and sustainable materials, can provide advantageous rheological and mechanical characteristics when included in printable mixtures.

This study explores the effects of nano cellulose filaments (nCF), a relatively new type of nanocellulose material, on the printability characteristics such as extrudability and buildability of cementitious mixtures. First, mortar mixtures with varying ratios of nCF are prepared. The rheology of the mixtures containing nCF is thoroughly assessed using a shear rheometer with a building materials cell and vane motor. Two testing protocol are followed: ramp test and stress growth test. A ramp test is conducted to determine dynamic yield stress and plastic viscosity using Bingham visco-plastic material model. For this purpose, a shear rate ramp-up from 0 s⁻¹ to 100 s⁻¹ is applied for 30 s followed by a shear rate ramp-down from 100 s⁻¹ to 0 s⁻¹ for 30 s. Stress growth tests, where a constant increasing strain at a constant shear rate is applied and the shear stress build-up with time is monitored, and carried out at varying resting periods to quantify static yield stress and thixotropy of the cementitious mixtures. Amplitude sweep test is carried out to determine viscoelastic properties of the mortar mixtures, including storage modulus that is found to be critical for buildability. Thermogravimetric analysis is conducted to assess the effects of nCF on hydration characteristics of the mixtures. Compressive and flexural strength tests are conducted to assess the mechanical properties. Finally, the printability of the mortar mixtures incorporating nCF is assessed using a 3D concrete printer equipped with a 10 mm diameter nozzle and screw pump.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Effect of Foundation Flexibility on the Interaction Between Elevated Light-Framed Timber Coastal Housing and Solitary Waves

Author(s): *Vasileios Kotzamanis, *University of Houston*; Dimitrios Kalliontzis, *University of Houston*;

As the population density rises in the coastal regions of the United States, the associated increase in coastline construction of light-frame timber houses raises concerns about their vulnerability to wave and storm surge loads that can be generated from tropical storms. These houses are often elevated on a pile foundation that can experience flexibility as function of the pile embedment and the soil properties. The intent of this research study is to understand and quantify the effect of soil-structure interaction in the response of elevated light-frame timber coastal houses against solitary waves. For this purpose, a prototype coastal house is modeled within a coupled eulerian-lagrangian finite element framework. The solitary waves are generated by a wave maker and vary in length and height. The pile foundation of the house is modeled with a system of p-y springs with varying constitutive properties, which simulates different foundation characteristics.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Structured Differentiable Extended Kalman Filters for Learning Nonlinear Dynamics

Author(s): *Wei Liu, *National University of Singapore*; Zhilu Lai, *ETH Zurich*; Eleni Chatzi, *ETH Zurich*;

This work leverages differentiable extended Kalman filters (EKF), a differentiable implementation of the EKF algorithm with learnable latent dynamics and measurement models, to learn the dynamics of nonlinear systems, and use this for prediction. The method is implemented under the variational autoencoders (VAEs) framework with incorporation of a structured dynamics model, where the inference is conducted via the EKF. Typically, conventional variational inference models are parameterized by neural networks independent of the actual underlying latent dynamics model. This characteristic makes the inference and reconstruction accuracy weakly based on the actual dynamics processes, resulting in inadequate training and generalization capabilities. We demonstrate the capability of the proposed method to capture the underlying dynamics of nonlinear systems for different scenario. The results indicate that leveraging EKF for performing inference essentially improves the capability to accurately learn the true underlying dynamics, thus bestowing the proposed scheme with significant predictive capabilities.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Probability-Based Seismic Hydraulic Performance Evaluation for Water Distribution Systems

Author(s): *Weinan Li, *Case Western Reserve University*; Ram Mazumder, *University of Kansas*; Yue Li, *Case Western Reserve University*;

Strong earthquake shaking often results in severely damage to components of Water Distribution System (WDS). The failures of pipelines, tanks, and pumps adversely affect hydraulic performance of WDS. Studies investigated the seismic impact on hydraulic performance of WDS, using several performance indicators (e.g., Todini's resilience, hydraulic availability, and flow entropy), are limited to system-level hydraulic performance evaluation subjected to scenario earthquake events, ignoring the uncertainty in seismic intensities. Unlike previous studies, this study performs a probabilistic approach for estimating the system-level hydraulic performance of WDS. While external corrosion increases the failure probability of water pipelines due to earthquakes, internal corrosion increases the internal roughness coefficient, therefore, decreases the hydraulic performance of WDS. Hydraulic simulation of WDS is measured by accounting for the time-dependent internal roughness growth inside the pipeline wall. WNTR is applied to execute the proposed framework. The outcomes show the existence of internal corrosion significantly reduces system-level hydraulic performance of WDS.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Joint Free-Form Model Evolution and Stochastic Parameter Estimation Using Symbolic Regression with Recurrent Neural Networks

Author(s): *Weiran Lyu, *University of Utah*; Shandian Zhe, *University of Utah*; Jacob Hochhalter, *University of Utah*; Robert "Mike" Kirby, *University of Utah*;

Conventionally, model selection and parameter estimation are two sequential steps. For example, in materials constitutive modeling, Markov Chain Monte Carlo (MCMC) has proven to be an effective approach to static parameter estimation of crystal plasticity model parameters. However, this conventional approach requires a preselection of a deterministic model form. Consequently, any inaccuracies in the preselected model form propagate forward to parameter estimates that are unreliable. To solve this issue, a more holistic approach is sought whereby model evolution and stochastic parameter estimation occur simultaneously. To this end, we develop a more holistic approach by leveraging symbolic regression, which aims to model an input data set without assuming its form. Instead, candidate models are proposed and evaluated by the algorithm, and the only assumption is that the data can be modeled by some algebraic expression. Most previous efforts have used genetic programming to evolve models within symbolic regression. Instead, to simultaneously evolve the model form and parameter estimates, we developed a reinforcement learning approach based on recurrent neural networks (RNN) and variational Bayesian inference. We used an RNN to generate the expression trees in terms of their pre-order traversal. We used policy gradient to train the RNN to evolve the tree. At each step, given the current expression, we used variational Bayesian inference to calibrate the posterior distribution of the stochastic parameters. The posterior and the expressions are then integrated to calculate a variational model evidence bound, which measures how the expression and posterior together fit the data. The bound is then used as the reward to update the RNN model. Through alternatively updating the expression model (RNN) and calibrating stochastic parameters, we jointly improve the expression and parameter estimates, with uncertainty quantification.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Mechanical Behavior and Dynamic Properties of Polymer - Clay Nanocomposites

Author(s): *Wenjian Nie, *North Dakota State University*; Yangchao Liao, *North Dakota State University*; Wenjie Xia, *North Dakota State University*;

Polymer - clay nanocomposites (PCNs) are commonly applied as multi-functional structural materials with superior thermomechanical and dynamic properties while maintaining the characteristics of lightweight and optical clarity. These nanocomposites are obtained by adding specific amount of clay nanofillers to a polymer matrix. In this study, building upon previously developed coarse-grained (CG) models of nanoclay and poly(methyl methacrylate) (PMMA), we employ molecular dynamics simulations to systematically investigate thermomechanical properties of PCNs with different microstructural features of nanoclays, i.e., exfoliated and stacked configurations, as well as varying their weight percentage. Specifically, we perform tensile and shear simulations and detailed analyses of dynamic properties to achieve an improved understanding of the influences of microstructural features in their physical properties at a fundamental level. Our findings provide molecular insights into the arrangement of the constitutive components of PCNs under deformation and highlights the importance of nanoclay and interface in the mechanical and dynamic properties of these multi-functional materials.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Solution of Bimaterial Riemann Problems in Compressible Multiphase Flow and Fluid-Structure Interaction Simulations

Author(s): *Wentao Ma, *Virginia Polytechnic Institute and State University*; Xuning Zhao, *Virginia Polytechnic Institute and State University*; Shafquat Islam, *Virginia Polytechnic Institute and State University*; Aditya Narkhede, *Virginia Polytechnic Institute and State University*; Kevin Wang, *Virginia Polytechnic Institute and State University*;

When solving compressible multiphase flow and fluid-structure interaction (FSI) problems, it is often important to account for the discontinuity of the thermodynamic equation of state (EOS) across material interfaces. One method to achieve this, known as FIVER ("Finite Volume method based on Exact multiphase Riemann solvers"), is to construct and solve an exact one-dimensional bimaterial Riemann problem between each pair of neighboring cells separated by a material interface, and use its solution to evaluate the local mass, momentum, and energy fluxes across the interface. In this talk, we present an extension of the FIVER method to handle arbitrary (convex) equations of state, and a method to accelerate the solution of bimaterial Riemann problems based on the idea of storing and reusing previous solutions. The talk will start with a summary of the FIVER framework, including the use of level set and embedded boundary methods for tracking fluid-fluid and fluid-structure interfaces. Next, the extension of popular numerical flux functions (e.g. Roe, HLLC) to handle arbitrary EOS will be presented. Then, the iterative solution of bimaterial Riemann problems will be discussed in detail, focusing on the robustness and efficiency of the solution algorithm. For an arbitrary EOS, the Riemann invariants associated with rarefaction waves involve ordinary differential equations (ODEs) that cannot be solved analytically. The numerical solution of these ODEs significantly increases the computational cost. To mitigate this issue, we propose an acceleration technique that utilizes the results of previously solved Riemann problems. Specifically, in each simulation, an R-tree is constructed to store the inputs and outputs of bimaterial Riemann problems. When solving a new Riemann problem, a nearest neighbor search is performed using the R-tree to find data points that are closest to the current one. The corresponding outputs are then interpolated to provide an accurate initial guess for the current Riemann problem, thereby reducing the number of iterations required to achieve convergence. This approach leverages the fact that multiphase flow and FSI simulations are usually compute-intensive. As a result, a large amount of random-access memory (RAM) is often available but not used. Finally, several numerical tests will be presented to demonstrate the solver's versatility in solving challenging multi-physics problems in the contexts of underwater explosion, laser lithotripsy, and hypervelocity impact. The performance of the acceleration techniques will also be assessed using these test cases.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Simulating the Mechanical Response of Chemically Active Geomaterials via Machine Learning-Generated Synthetic Microstructures

Author(s): *Winston Lindqwister, *Duke University*; Alexandre Guevel, *Duke University*; Manolis Veveakis, *Duke University*;

Porous media represent a wide range of materials that have yet to be fully understood and present a challenge in being harnessed. Among them, geomaterials, stemming from millions of years of transformations under harsh conditions, represent the most complex subclass inasmuch as processes in these media require analysis via multiphysics and multiscales. Recent advances in geosciences have found that this complexity may be resultant of the great heterogeneity and stochasticity of geomaterials' microstructures. In this work, we explore the usage of machine learning as a framework for predicting geomaterial strength from chemically active microstructures as a means to link microscale phenomenon to mesoscale effects. Through synthetically generated microstructures, we examine the influence of geometric morphometers on the simulated mechanical response of soils via finite element modeling. Furthermore, we track the chemo-mechanical evolution of material microstructures through chemical phase-field modeling. These two schemas are combined to create a framework for simulating material response under varying loading profiles and the results are critically discussed.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Efficient Global Sensitivity Analysis for High-Dimensional Outputs Combining Data-Driven Probability Models and Dimensionality Reduction Techniques

Author(s): *WoongHee Jung, *University of Notre Dame*; Alexandros Taflanidis, *University of Notre Dame*;

This presentation examines the efficient variance-based global sensitivity analysis (GSA), quantified by estimating first, total and higher order Sobol' indices, for applications involving complex numerical models and high-dimensional outputs. Two different, recently developed techniques are combined to address the associated challenges. Principal component analysis is first considered as a dimensionality reduction technique. The GSA for the original output is formulated by calculating variance and covariance statistics for the low-dimensional latent output space identified by PCA. These statistics are efficiently approximated by extending recent work on data-driven, probability model-based GSA. Extension pertains here to the estimation of covariance statistics beyond the variance statistics examined in the original formulation. Specifically, a Gaussian mixture model (GMM) is established to approximate the joint probability density function between some subset of the input vector (dependent upon the Sobol' index estimated), and each latent output, or each pair of latent outputs. The GMM is then utilized to estimate the aforementioned required statistics. The efficiency and accuracy of the proposed approach are demonstrated in two examples, the first considering the sensitivity of different peak engineering demand parameters for a nine-story benchmark building with uncertain model properties exposed to earthquake acceleration at its base, and the second examining the sensitivity of the estimated peak-surge to the storm forecast variability during superstorm Sandy. Across both examples, different settings are examined for the proposed formulation, related to the number of latent outputs considered and the dimensionality of the GMM, to offer guidance for the recommended implementation. Results show that the dimensionality reduction and transformation of output space established through PCA do not impact the overall accuracy of the probability model-based GSA, and that the proposed implementation accommodates highly-efficient GSA estimates even for applications with very high dimensional outputs.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Coupled Flow-Deformation Analyses in Creeping Landslides Catastrophic Acceleration

Author(s): *Xiang Li, *Northwestern University*; Giuseppe Buscarnera, *Northwestern University*;

Pore-water pressure transients resulting from water infiltration control the movement of creeping landslides, a widely observed type of geohazard involving porous, fluid-saturated earthen materials. While most creeping landslides move episodically over long periods of time at a velocity below 1 m/year, sudden catastrophic acceleration can occur, with consequent major infrastructure damage. This contribution discusses the implementation of a fully coupled flow-deformation framework based on critical state elastoplasticity. Such methodology enables the incorporation of deformation and failure properties of soils measurable through standard laboratory tests. Most notably, the proposed approach is able to transit automatically from drained deformation mechanisms typical of slow landslide motion to partially drained or fully undrained deformation behavior during the post-failure and active runout stage. The loss of stability of the resulting landslide dynamics is finally assessed by inspecting the structure of the coupled governing equations, eventually defining stability indices dependent on the selected constitutive law. It is shown that by simulating the slow, episodic movement of a creeping landslide, the model parameters can be constrained to capture its behavior during both the pre-failure and the runout regime. Effects from variation of hydrological condition to the coupled system can then be computed, differentiating temporarily stable creep from catastrophic motion. The satisfactory performance of the simulated real cases encourages the use of this model to support landslide monitoring and hazard mitigation.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Super-Resolution Models for Visual Structural Inspections

Author(s): Kareem Eltoumy, *University at Buffalo*; Seyedomid Sajedi, *University at Buffalo*; *Xiao Liang, *University at Buffalo*;

Visual structural inspections are entering a new era with the latest advances in sensing and computing technology accompanied by enormous progress in AI research. Unmanned aerial vehicles (UAVs) can equip the building owners and inspectors with thousands of high-resolution frames from a building façade. Effectively processing this information for autonomous inspections requires high performance and computationally cost-effective models that ultimately contribute to UAV navigation and damage identification. One of the critical tasks in this domain is semantic segmentation. The segmentation of high-resolution images using deep learning methods is significantly challenging due to high memory computational demands. The standard solution is to uniformly downsample the raw images at the price of losing fine local details, such as fine thin cracks. On the other hand, cropping smaller parts of the images can cause a loss of global contextual information. We propose a hybrid strategy that approaches the global and local semantics depending on the inspection task. A compound, high-resolution deep learning architecture equipped with learnable downsampler and upsampler modules at its outer level is designed to minimize information loss for optimal performance and efficiency. It also includes an attention-based internal segmentation model that handles low-resolution data efficiently. Another strategy is also investigated by utilizing vision transformers on a grid of crops aiming for high precision learning without downsizing. An augmented inference technique is used to boost performance and reduce possible loss of context due to grid cropping. Comprehensive experiments have been performed on 3D physics-based graphics models synthetic environments in benchmark datasets. The proposed frameworks are evaluated using several metrics on three segmentation tasks: I) component type, II) component damage state, and III) global damage (crack, rebar, spalling). TRS-Net (Task I & II) and DmgFormer (Task III) are customized deep learning frameworks that aim for computational efficiency and high-fidelity segmentation in visual structural inspections.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Generative Deep Learning for Optimal Sensor Placement

Author(s): Seyedomid Sajedi, *University at Buffalo*; *Xiao Liang, *University at Buffalo*;

Engineers deal with high-dimensional search spaces as a part of the design process. The optimization is performed manually by experienced engineers or through meta-heuristic/population-based methods relying on extensive numerical simulations. Both approaches have limitations depending on the complexity of the problem and the availability of computational resources. We propose a Bayesian AI-equipped optimization technique for expensive black-box objective functions. Conditional Variational Auto Encoders (CVAEs) are utilized to translate the high dimensional search space into a compressed latent space representation. A neural network surrogate model is adopted to construct a stochastic relationship between the latent space and the evaluation metric. CVAEs are further utilized to generate a large representative sample in the latent search space to maximize an acquisition function such as the expected improvement. After finding the next candidate in the latent space, its latent representation is translated back to the original physical definition for objective function evaluation. The surrogate model is updated, and the process is repeated until a convergence criterion is met. We will refer to this method as Deep Generative Bayesian Optimization (DGBO).

Deep learning has shown great potential to interpret signals. However, evaluating the objective function for different sensor configurations involves long training times. Optimal Sensor Placement (OSP) in data-driven Structural Health Monitoring (SHM) is a good example of this kind of optimization. A 9-story reinforced concrete moment frame subject to 10800 nonlinear seismic response simulations is considered a case study to find the OSP for the most accurate damage prediction accuracy. It is shown that DGBO compared with the popular genetic algorithm, achieves better results with equivalent objective function evaluations. Moreover, the proposed optimization method helps reduce the number of required sensors by more than 40% using the optimal configuration. While this case study is tailored to the OSP problem, DGBO can serve in other complex optimization problems in the structural engineering domain.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Using Information Fusion and Image Classification to Automatically Classify Post-Event Building Damage State

Author(s): *Xiaoyu Liu, *School of Mechanical Engineering, Purdue University*; Lissette Iturburu, *Lyles School of Civil Engineering, Purdue University*; Shirley Dyke, *School of Mechanical Engineering, Purdue University*; Ali Lenjani, *School of Medicine, Stanford University*; Julio Ramirez, *Lyles School of Civil Engineering, Purdue University*; Xin Zhang, *Lyles School of Civil Engineering, Purdue University*;

Post-event reconnaissance missions are conducted to collect valuable and perishable data to document the consequences of natural hazards. In particular, visual data (images) provide the most direct and unbiased way to store evidence that may lead to new knowledge about the best practices for the design of civil infrastructure. Visual data, when combined with state-of-the-art computer vision methods, can be a valuable tool for accelerating and automating these processes. However, information extracted from individual images that only capture one portion or one side of a building may not be adequate to provide an assessment of structural health state of buildings. To enable the full use of the visual data and a comprehensive understanding of the post-event states of buildings, we develop an automated technique to fuse the information extracted from multiple images of a single building to obtain the overall damage state of the building. The method adopts convolutional neural network-based image classifiers to extract initial classification information, a naïve Bayes fusion algorithm to combine the information, and an integrated sampling technique to reduce the computational time without compromising the quality of the results. Validation is performed using real reconnaissance images collected from several natural hazards in the past.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Statistical Learning for Nonlinear Structural Dynamics of Aircraft-UAV Collisions

Author(s): Xiao Liu, *University of Arkansas*; *Xinchao Liu, *University of Arkansas*;

The Federal Aviation Administration has identified the potential airborne collisions between aircraft and Unmanned Aerial Vehicle (UAV) as an emerging threat to aviation safety. New regulations, policies and recommendations require the collision damages to be assessed under a large number of impact scenarios (e.g., impact velocity, positions, attitudes, UAV weight, etc.). Current practice heavily relies on high-fidelity Finite Element Analysis (FEA). However, for a collision that only lasts for a few milliseconds, it takes hours or even days to complete one FEA simulation for one impact scenario. This paper proposes a physics-informed statistical approach capable of (i) learning the aircraft surface deformation processes due to aircraft-UAV collisions, by utilizing data generated from FEA (only available at sparse collision conditions) and the physics laws of nonlinear structural dynamics, and (ii) predicting aircraft surface deformation for new impact scenarios (significantly faster than existing FEA). Using the Proper Orthogonal Decomposition, the proposed statistical approach obtains the reduced-order governing physics from the full-order nonlinear structural dynamics that governs aircraft-UAV collisions. A function-to-function regression, based on multivariate Functional Principal Component Analysis, is proposed to establish the mapping between impact force (determined by collision parameters) and surface deformation. A multivariate Gaussian Process Regression is used to capture the mapping between collision parameters and impact force. In the application example, the proposed approach is applied to predict the aircraft nose skin deformation after UAV collisions with different impact attitudes (i.e., pitch, yaw and roll degrees). It is shown that the proposed physics-informed statistical model can achieve a 12% out-of-sample mean relative error, and is more than 1000 times faster than FEA for prediction. Computer code and sample data are available on GitHub.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Understanding the Size Effects on Crumpling Behaviors of Nanoribbons

Author(s): *Yangchao Liao, *North Dakota State University*; Wenjie Xia, *North Dakota State University*; Wenjian Nie, *North Dakota State University*; Zhaofan Li, *North Dakota State University*;

Understanding the complex crumpling behaviors of nanoribbons at a molecular level is of critical importance in various engineering and technological applications. Here, we report the results of a systematic coarse-grained molecular dynamics (CG-MD) simulation study of the crumpling process of nanoribbons at various aspect ratios in the case of graphene. By evaluating the evolution of potential energy and shape descriptors of the nanoribbon during the crumpling process, our results show that the increase of the aspect ratio greatly enhances the adhering effect of the nanoribbons to form a scroll configuration in quasi-equilibrium. The analyses of the sheet pressure and bulk modulus indicate that the larger the aspect ratio, the easier it is to compact the ribbon into a crumple, corresponding to a smaller bulk modulus and a softer structure. The evaluation of stress and curvature distributions of the ribbon further reveals the stress heterogeneity that decreases due to the increasing aspect ratio. Remarkably, the analysis of the effective stresses in the crumpled structure identified two aspect ratio-dependent crumpling modes, i.e., random bending compression, and adhesion-dominated self-rolling compression. Our study provides fundamental insights into the size-dependent structural behavior of nanoribbons under crumpling, which is crucial to develop the structure-property relationships towards designing and engineering crumpled matter.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: In Situ Raman Spectroscopy of Ye'elimite Clinker

Author(s): *Yangwoo Lee, *Seoul National University, Seoul, South Korea*; Hee-Jeong Kim, *University of Arizona, Tucson, AZ*; Juhyuk Moon, *Seoul National University, Seoul, South Korea*;

Ye'elimite (C₄A₃S₂) phase is an important component of calcium sulfoaluminate (CSA) cements. The driving force for these investigations is the much lower CO₂ emissions in their manufacture when compared to those of Portland cement production due to the following main reasons: lower CO₂ emission during the synthesis, lower firing temperature, and easier to grind. However, while studies on Portland cement have been conducted over a long period of time, studies on Ye'elimite-containing cement have not been conducted as much as Portland cement. Especially, studies regarding amorphous crystals and materials in early hydration of Ye'elimite have not been fully conducted thus its behavior and impact on the early age of Ye'elimite containing cement has not been comprehended. AH₃ phase, as a main gel-like hydration product of Ye'elimite, plays an important role in the density and porosity, and contributes significantly to the mechanical properties of CSA cements owing to its high indentation modulus and hardness. However, there have been no studies to date that deeply focused on the nanostructural evolution of the AH₃ phase by C₄A₃S₂ hydrated. Raman spectroscopy has been used as a probe to characterize cement, clinker minerals, and supplementary materials, revealing that this technique is a valuable tool for the identification of different phases in cements. Raman spectra also allowed the characterization of the local environment of sulfate anions and the hydrogen bond networks. A significant asset brought by Raman spectroscopy is the ability to work on hydrated cement products without specific sample preparation; i.e. without risk to damage these hydrated compounds. The recent study of the distribution hydration products in high spatial, temporal, and spectral resolution using Raman spectroscopy has revealed disordered or amorphous phases in Ordinary Portland Cement by quantifying peak positions and bandwidths of Raman spectra.[1] In this regard, this study focused on the evolution of the AH₃ by in-situ mapping Ye'elimite hydration and discovering amorphous AH₃ phase which is impossible or near impossible to assort by using other techniques such as XRD or TGA.

[1] Loh, H. C., Kim, H. J., Ulm, F. J., & Masic, A. (2021). Time-Space-Resolved Chemical Deconvolution of Cementitious Colloidal Systems Using Raman Spectroscopy. *Langmuir*.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Characterization and Simulation on the Flow of Particulate Milled Biomass

Author(s): *Yimin Lu, *Georgia Institute of Technology*; Wencheng Jin, *Idaho National Laboratory*; Jordan Klinger, *Idaho National Laboratory*; Sheng Dai, *Georgia Institute of Technology*;

Biomass material is one of the most promising energy resources because of its natural abundance and easy-to-access. However, the economic competitiveness of biomass energy is exacerbated by severe material handling issues manifested as clogging of particulate biomass materials in handling equipment, for instance, hopper arching and screw feeder jamming. Fundamentally, these issues are caused by the poor flowability of milled biomass, mainly due to the fact that in comparison to conventional granular materials (e.g., sand, bean, pill), milled biomass at the macro-scale exhibits high internal friction, high compressibility, and at the micro-scale involves large aspect ratio, high angularity, and high particle deformability. In this study, we attempt to elucidate the flow behavior of pine chips, one of the most widely used bioenergy feedstock, using multi-scale experiments and continuum-mechanics-based simulations. We first present the mechanical behavior of the pine chips via physical characterization from the Schulze ring shear test, the vibration test, and the cyclic axial compression test. We then establish a workflow to calibrate a hypoplastic model based on the critical state soil mechanics. After validating the model, it is used to simulate pine chips flowing in a wedge-shaped hopper with variable geometry and initial conditions. The qualitative comparison of flow patterns (i.e., the first-in-first-out mass flow and the first-in-last-out funnel flow) and the quantitative comparison of flow metrics (i.e., the mass flow rate, clogging) between the numerical prediction and experimental characterization show that the quasi-static constitutive model is capable of capturing the flow physics at a low shear rate. To examine whether the model can accurately capture flow behavior at a high shear rate, we further simulate an inclined plane flow test, which can vary the shear rate by changing the inclination angle. We demonstrate that the rate-independent model can realize both the quasi-static flow and the dense flow in comparison with physical measurements. This work not only promotes the understanding of the flow physics of compressible particulate materials, but also provides an advanced flow characterization scheme and insights on the application of soil mechanics constitutive models for novel granular flow characterization. This study also sheds light on the design and optimization of bioenergy material handling equipment.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Probabilistic Event Localization Using Floor Vibrations

Author(s): *Yohanna MejiaCruz, *University of South Carolina*; Juan M. Caicedo, *University of South Carolina*; Zhaoshuo Jiang, *San Francisco State University*; Jean M. Franco, *University of South Carolina*;

Methodologies for event detection using floor vibrations are becoming more popular in the literature for their multiple applications, including human detection and human gait extraction. Force estimation methods overcome limitations on some of these methodologies by using the properties of the structure while avoiding the characteristics of the wave, such as its dispersive nature when traveling across the system and multi-path fading. However, the current force estimation methods (Davis et al., 2020) establish the localization of an event as the closest calibrated location, treating space in a discrete fashion and following a deterministic methodology. The last is its most substantial limitation, especially in scenarios where an event's localization is needed with high spatial resolution, such as gait extraction. In those cases, the current force estimation methods could require a time-consuming calibration process as the number of necessary calibration points increases.

A significant portion of the literature in structural dynamics has focused on measuring the uncertainty of the dynamic systems. The purpose is to consider in the prediction the model errors, which include inexact representations of boundary conditions and incomplete data compared to the model complexity. To overcome the limitations of the current force estimation methods, we proposed a Probabilistic Force Estimation and Event Localization (PFEEL) algorithm (MejiaCruz et al., 2022). PFEEL implements a data-driven approach using a Gaussian processor to estimate the transfer functions between impact locations and response locations at random points across the system. The advantage of estimating the transfer function space, force, and event locations using a Gaussian processor is that it measures the uncertainty in these constructs.

PFEEL capabilities are showcased using an aluminum plate impacted on eighty points. The results showed that PFEEL detected the area of higher probability of the event for all cases within a spatial resolution of five cms. This shows the potential of PFEEL to be implemented in scenarios where high spatial resolution of events location is needed, such as step events localization for gait extraction.

PFEEL's can also guide calibration by implementing a Gaussian regression process using the mode shapes of the system. This formulation improves computational effort during the experimental framework and efficiently explores the system space to enhance detection accuracy.

PFEEL capabilities will be tested on the floor using a vast grid of impact points to extend the evaluation of the event detection methodology on a more complex system.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Two-Way Coupled Modeling of Rate-Dependent Deformation and Cracking in Heterogeneous Viscoelastic Solids

Author(s): *Yong-Rak Kim, *Texas A&M; University*; Santosh Kommid, *Texas A&M; University*; Jamilla Teixeira, *Federal University of Espírito Santo*;

This study presents a two-way coupled multiscale computational model to predict the damage-dependent behavior of heterogeneous natural and/or manmade materials subjected to viscoelastic deformation and cracking. Multiple length scales are two-way coupled in the model framework by linking a homogenized larger scale to a heterogeneous smaller scale representative volume element (RVE). Based on the two-way coupled multiscale and the use of the finite element technique incorporated with material viscoelasticity and cohesive zone fracture, the model approach can effectively account for the effect of geometric heterogeneity, material inelasticity, and damage accumulation due to cracks in the small scale RVE on the overall performance of larger scale bodies. In particular, the rate-dependent cracking in viscoelastic solids is modelled by an extrinsic nonlinear viscoelastic cohesive zone incorporated with the Gaussian damage evolution. Along with the theoretical model formulation, the multiscale modeling is conducted, validated and calibrated by using experimental test results available. Several example cases such as quasi-brittle infrastructure materials and heterogeneous bone tissue are presented to demonstrate capability, application, and validity of the modeling that properly captures material property-specific, loading condition-dependent, and microstructure-dependent behavior of various materials and structures. The model presented in this paper is expected to reduce time-consuming and expensive laboratory tests, which, when performed in the traditional manner, require many replicates and are limited to identify the cause of microstructural damage and failure of various heterogeneous solids. It is also expected to allow more accurate analysis-design, more appropriate use of conventional materials, development of new materials, and more sustainable materials-structural engineering.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Autonomous Classification of Road Roughness Using Deep Convolutional Neural Network Considering Environmental Conditions

Author(s): *YoungJae Lee, *Hanyang University*; Robin Eunju Kim, *Hanyang University*;

Road networks play important roles in urban expansion, impacting socio-economic growth between geographically distributed parts. In such key infrastructure, the serviceability of a road is measured from the road surface roughness, for this being highly related to driver's safety, energy efficiency, and public safety. Therefore, assessing the quality of the pavement structure is important. The extent of pavement roughness is usually represented from the International Roughness Index (IRI), which implies the road profile calculated from the accumulated responses of a mathematical model of a vehicle. In field practice, the IRIs are obtained from laser and sensor-based equipment, such as a road-profiler. Although accurate, the fact that the current approach requires a specific device limits the wide and prompt assessment. Thus, recent studies aim to use computer vision techniques in road roughness estimation. For example, images taken during IRI investigations have been used as a labeled dataset for deep learning to evaluate road conditions. While the previous studies showed the potentials of deep learning technologies in road roughness assessment, full consideration of environmental effects on the road images is essential for broader use of the technology. The present study secures speed, accuracy, and quantitative assessment of pavement by estimating and classifying the road surface roughness using numerous images considering several environmental conditions such as direction and intensity of sunlight by three dimensional (3D) rendering. 3D Road models are constructed by a road simulator using field obtained IRIs. From obtained 3D models, image datasets are constructed accounting environmental changes using V-ray functions. Then a deep convolutional neural network model is developed, which is a transfer learning model with ResNet152V2. The weights used in this model are pre-trained weights from ImageNet. As a result proposed approach showed over 90% accuracy in classifying the grade of road roughness. In summary, the presented study demonstrates the potentials of using computer vision technologies in conjunction with deep learning approach for efficiently classifying the road roughness for road structure management.

This work is supported by the Korea Agency for Infrastructure Technology Advancement grant funded by the Ministry of Land, Infrastructure and Transport (Grant 22CTAP-C164093-02).

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Autonomous Ultrasonic Thickness Measurement of Steel Bridge Members Using a Mobile Robot and the Martlet Wireless Sensing

Author(s): *Yu Otsuki, *Georgia Institute of Technology*; Son Nguyen, *University of Nevada, Reno*; Hung La, *University of Nevada, Reno*; Yang Wang, *Georgia Institute of Technology*;

This paper describes recent development in autonomous ultrasonic thickness measurement of steel bridge members using a mobile robot and the Martlet wireless sensing. The bicycle-like robot carries the Martlet ultrasonic setup, a dual element transducer, and gel couplant. The compact Martlet ultrasonic setup is capable of high-voltage excitation, filtering/amplification of the received ultrasonic signal, high-speed analog-to-digital conversions (~80 MHz), and wireless data transmission. We design a mounting/retrieving mechanism of the transducer to ensure reliable contact on steel surfaces. For better transmissibility of ultrasonic signals into specimens, a pumping mechanism is developed to apply the appropriate amount of gel couplant between the transducer and steel surfaces. We validate the accuracy of ultrasonic thickness measurement results operated by the developed mobile robot.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: DEM Study Of Two Types Of Direct Simple Shear (DSS) and Stress Tensor Computation

Author(s): *Yu-Hsuan Lee, *University of Colorado Boulder*, Beichuan Yan, *University of Colorado Boulder*, Richard Regueiro, *University of Colorado Boulder*, Zhou Lei, *Los Alamos National Laboratory*,

Two types of direct simple shear (DSS) are developed and modeled in the 3D DEM code, ParaEllip3d (<https://gitlab.com/micromorph/paraellip3d-cfd>), to explore the microscopic mechanical behavior of particles and particle-boundary interactions, as well as the macroscopic continuum response like Cauchy stress, which is aimed at further study of general bridging and upscaling between discontinuum and continuum under large deformations. One type follows the definition of solid mechanics to maintain constant volume, and the other follows the definition of geomechanics to maintain constant pressure. For both types, the DEM simulations not only present statistical information like normal and shear tractions on boundaries and average force, penetration, and stiffness, but also reveal many details in the process of DSS: for example, sub-domain relative motions, interparticle and particle-boundary contact force vectors, incremental displacement fields, velocity and angular velocity fields, force and moment fields, particle orientations and relevant statistics such as probability distribution functions, etc. Some of these details have not been well-explained before: such as the wedge-shaped non-uniform contact force vector distribution along boundaries, the sharp transients of particle forces, moments, and translation and angular velocities during shearing, and the gradual forming and reforming of force chains in one diagonal direction while absent in the orthogonal direction.

In order to compute the Cauchy stress tensor for the entire particle assembly, a new post-processing code, which computes the Cauchy stress tensor for any subscale representative volume element (RVE) with boundary grid volume change accounted for in DSS, has been developed. The general question of appropriate RVE size bridged from DEM to continuum is also studied. Applications to penetration into granular materials like sand under which both compression and shear are experienced will be investigated in future work.

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Assessing Uncertainty in Climate Forecasting with Physical-Based Probabilistic State-Space Models

Author(s): *Yuchuan Lai, *Carnegie Mellon University*; Peter Adams, *Carnegie Mellon University*; Matteo Pozzi, *Carnegie Mellon University*;

Future climate simulations provided by Global Climate Models (GCMs) serve as a valuable and informative tool to facilitate infrastructure planning, but these projections are subject to significant uncertainty. To cope with this uncertainty, one strategy is to apply a flexible scheme: processing observation data as they become available, reducing the future forecasting uncertainty, and employing engineering adaptation efforts accordingly. The main objective of this work is to develop a parametric probabilistic physic-based model, to assess the improvement of climate forecasting when additional observations become available. The GCM simulations and historical observations of global temperature anomaly starting from around 1860s are modeled by a state-space models (SSM), based on two-layers, describing the energy-balance and the global temperature response to the radiative forcings such as from greenhouse gas concentrations. The reduction of forecasting uncertainty is assessed using 39 GCMs as synthetic observations and assuming different availabilities of observations (e.g., up to 2020, 2050, or 2080). The developed model is further implemented to regional levels to examine the results for regional climate variables. The model also provides an assessment on the uncertainty of six key physical parameters, and it evaluates the performance of different GCMs based on historical observations. This probabilistic SSM can serve as a tool to facilitate decision-making for infrastructure planning.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Application of Machine Learning Algorithms in Failure Risk Analysis of Pipelines

Author(s): Ram Krishna Mazumder, *The University of Kansas*; Abdullahi Salman, *The University of Alabama in Huntsville*; *Yue Li, *Case Western Reserve University*;

Prediction of failure risk of pipelines subjected to corrosion deterioration is essential for the effective risk management of aging pipelines networks. Pipelines networks are considered the cheapest and safest mode of transportation in various lifeline systems, such as oil and gas transmission systems. Unfortunately, the rate of burst failure of aging pipelines due to corrosion deterioration has increased significantly in recent years. Pipe failure prediction to support asset management is of the utmost importance to avoid the consequences of such failures. Since pipeline networks are often large and complex, analyzing a large number of pipelines is often intensive and time-consuming. This study utilizes recent advances in machine learning algorithms to develop a viable alternative to computationally intensive analytical approaches to determine the failure risk of oil and gas pipelines. The first part of this study developed a comprehensive database of pipelines extracting information from literature, and true failure pressure is predicted considering variability between predicted burst failure pressure and actual burst test results. True burst failure pressure is estimated using widely practiced design codes in a probabilistic manner. Among burst failure prediction models, the DNV RP-F101 standard provides the lowest variability in the failure pressure prediction. Therefore, the model is used to generate the probability of failure of pipelines at a burst limit state. Pipelines are classified from low to severe failure risk groups depending on their probability of failure. Then, eight machine learning algorithms are evaluated based on the generated dataset to identify the best failure prediction algorithm. The performance of machine learning algorithms is evaluated based on a confusion matrix and computational efficiency. The outcome of the case study reveals that the XGBoost is the optimal algorithm for predicting failure and is recommended for future analysis. The computational efficiency of the machine learning algorithm is also compared to the physics-based model. Machine learning algorithms can perform a failure risk analysis of pipelines with greater computational efficiency than the physics-based approach. Even the slowest machine learning algorithm is about 12 times faster than the physics-based model.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Optimization of coastal protection amidst sea level rise, given limited resources: case studies in NYC

Author(s): *Yuki Miura, *Columbia University*; George Deodatis, *Columbia University*; Kyle Mandli, *Columbia University*;

Coastal regions are being threatened globally by storm-induced flooding. Recent hurricanes, which are some of the costliest in US history, such as Maria, Harvey, and Ida, are indicating that the disaster threat is likely to be intensified due to climate change. As resources are limited, it is critical to allocate them optimally to protect regions at risk. However, planning effectively for future hazards is a complex problem, given the lack of adequate reliable data on intense storms, the unpredictability and uncertainty of weather patterns and sea-level rise, and the vast search space over potential approaches for protection and adaptation. Prior to our work, a general optimization methodology that establishes a financially and socially sound strategy has been elusive or not robust, due to the problem's multivariate, complex, and uncertain nature. The proposed methodological framework is composed of four individual models: 1) probabilistic modeling of future storm intensity and frequency, 2) estimation of flooded areas and flood depth using physical models and geographical information systems, 3) quantification of the associated damage of every building and infrastructure component within the target region (above- and below-ground), and 4) determination of the optimal protective strategy based on cost-benefit analysis and stakeholder feedback. In order to ensure the practicality of the optimal strategy, we have interviewed stakeholders who have first-hand knowledge of the interconnected infrastructures and of emergency management, and subsequently improved our model. Eventually, the proposed methodological framework provides the optimal strategy for a selected time horizon and location, given a prescribed budget. Case studies in New York City are provided to demonstrate the capabilities of the methodology.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Unified Thermal Transport in Crystalline Cellulose I β

Author(s): *Zhiyu Liu, *University of Maryland, College Park*; Peter Chung, *University of Maryland, College Park*;

Cellulose is one of the most abundant natural polymers and is a sustainable and renewable energy source. Under delignification and densification, cellulose was found to have outstanding radiative cooling properties. Thus, phonons, the dominant heat carriers in crystalline cellulose, are significant in understanding the energy transfer mechanism. However, the phonon transport behaviors in crystalline cellulose are still unknown. The widely used particle-like propagation model failed to describe the thermal transport in several complex crystals. Recently, a unified theory of thermal conductivity was developed based on the Wigner formulation [1], which accounts for both particle-like and wave-like conduction mechanisms. In this work, we investigate the thermal transport in crystalline Cellulose I β using molecular dynamics and lattice dynamics with a tapered ReaxFF potential. Different thermal transport models, including the unified model, Green-Kubo (GK) formula, Allen-Feldman, and the ideal phonon gas models, are applied to calculate thermal conductivity. Our results indicate that the unified model that accounts for contributions from both populations and coherences shows the best agreement with GK and experiments among all the theoretical models. Compared with the phonon gas model, the leading contribution of the coherence terms to thermal conductivity indicates their predominant role in thermal transport in cellulose. Our study provides insights into the understanding of thermal transport mechanisms in complex molecular crystals.

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: A Bio-Inspired Quadrilateral Shape (BIQS) Isolation Systems for Vibration Reduction of In-Orbit Captures

Author(s): *A. Rose Thomas, *University of Oklahoma*; P. Scott Harvey, *University of Oklahoma*;

From Fibonacci spirals in shells and hurricanes to neurological pathways inspiring artificial intelligence, it is easy to find solutions to modern engineering challenges by studying phenomena in nature. One such problem revolves around the vibrations that come from spacecrafts retrieving items while in orbit, which produce unnecessary strain to the spacecraft. However, by placing a bio-inspired quadrilateral shape (BIQS) isolation system between the satellite or spacecraft and the capturing arm the vibrations can be suppressed, reducing overall strain. This BIQS system is comprised of a series of simple diamond-like shapes with two springs spanning across—one latitudinally and one transversely—the master quadrilateral unit. The combined action of these two springs allows for the system to have a low (quasi-zero) stiffness with proper parameter tuning. This system's nonlinear load-displacement relationship is analytically modeled, which can be used to determine the ideal effectiveness of designs with varying geometries. The main structural elements in the BIQS are 3D printed with PLA and the system has been tested with springs of varying stiffness and quadrilaterals of varying lengths. The system is tested quasi-statically in a universal testing machine, as well as dynamically using a shake table. Dynamic tests include both harmonic and impulse excitations, the former to characterize the system's nonlinear frequency response and the latter to emulate an impact in a zero-gravity (in-orbit) situation.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Data-Driven Identification and Modeling of Nonlinear Dynamical Systems with a Physics-Integrated Deep Learning Approach: Koopman Operators and Nonlinear Normal Modes

Author(s): *Abdolvahhab Rostamijavanani, *Michigan Technological University*; Yongchao Yang, *Michigan Technological University*;

In this study, we investigate the performance of data-driven Koopman operator and nonlinear normal mode (NNM) on predictive modeling of nonlinear dynamical systems using a physics-constrained deep learning approach. Two physics-constrained deep autoencoders are proposed: one to identify eigenfunction of Koopman operator and the other to identify nonlinear modal transformation function of NNMs, respectively, from the response data only. Koopman operator aims to linearize nonlinear dynamics at the cost of infinite dimensions, while NNM aims to capture invariance properties of dynamics with the same dimension as original system. We conduct numerical study on nonlinear systems with various levels of nonlinearity and observe that NNM representation has higher accuracy than Koopman autoencoder with same dimension of feature coordinates.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Reduced-Order Modeling for Hyper-Velocity Impact on Thin Structures

Author(s): *Adnan Shahriar, *The University of Texas at San Antonio*; Seyed Arsalan Maljesi, *The University of Texas at San Antonio*; Sterling Reynolds, *The University of Texas at San Antonio*; Arturo Montoya, *The University of Texas at San Antonio*;

The interest in space activities, including satellite launches, space tourism, deep-space exploration, and space colonization, has increased in recent years. The development of long-term deep space habitats is of interest to the engineering mechanics community. These structures will be exposed to harsh environmental loading conditions, including hypervelocity impact (HVI) caused by meteoroids or debris. Modeling HVI is not a trivial task as material nonlinearities, and large deformations are required to replicate the physics of the problem accurately. Numerical techniques to model HVI, including the Smoothed Particle Hydrodynamics (SPH) and Material Point Method (MPM), are computationally expensive, imposing limitations to risk assessment efforts. The computational time associated with these analyses can be reduced by developing multiscale or hybrid approaches that reduce the computational effort at the undamaged regions of the model's structure. This paper aims to develop a method that replicates the excitation generated by a micrometeoroid impact on thin plates through a lower fidelity finite element model. For this purpose, we modeled a high-fidelity model of a thin plate imposed to an HVI of arbitrary velocity and mass. The displacement time history, which captures the shock acoustic emission (AE) waves, was decomposed into symmetric, longitudinal, and anti-symmetric modes. For the lower fidelity model, the symmetric mode was replicated through equivalent internal stress inside the element, while the anti-symmetric mode was generated through pressure stress on the impact surface. The reduced-order model was in excellent agreement with the high-fidelity model, circumventing the need for multiscale or hybrid modeling to replicate the behavior of HVI.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Particle Damping of Floating Oscillating Surge Wave Energy Converters

Author(s): *Ahmed Shalaby, *Stevens Institute of Technology, NJ*; Alaa Ahmed, *Stevens Institute of Technology, NJ*; Raju Datla, *Stevens Institute of Technology, NJ*; Muhammad Hajj, *Stevens Institute of Technology, NJ*; Sami Masri, *University of Southern California, CA*; Jia Mi, *Virginia Tech, VA*; Lei Zuo, *Virginia Tech, VA*;

Particle Damping of Floating Oscillating Surge Wave Energy Converters

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Oscillating surge wave energy converters (OSWEC) are one of the most efficient means for converting wave energy into electricity. Because the surge component of ocean wave energy is most prevalent near the water surface, OSWEC wave capture components must be positioned near that surface to realize maximum power. This placement, however, constrains their deployment to shallow water sites. In contrast, mounting the OSWEC onto a submerged platform close to the water surface expands the deployment range to deep water locations where there is need to power observation stations, autonomous underwater robots, offshore islands, ships and submarines, among many other blue economy systems and devices. Designing the flap to attract large wave forces induced by large wave amplitudes induces significant platform motions that may adversely impact the flap's response reduce the level of generated power. Consequently, it is important to control the platform's motion.

Here, we perform experiments in a wave tank to investigate the effectiveness of particle damping in reducing the motion of the platform while increasing the flap's response as desired to enhance the energy generation. The results showed effective damping and enhanced flap oscillations under specific excitation conditions, but also increased motions under other conditions. These observations point to the complex nonlinear features of particle damping.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Studying Fluid-Structure Interactions via Real-Time Hybrid Experimental-Numerical Simulation

Author(s): *Akiri Seki, *Oregon State University*; Barbara Simpson, *Oregon State University*; Christopher Neumann, *Oregon State University*; Andreas Schellenberg, *Maffei Structural Engineering*; Pedro Lomonaco, *Oregon State University*;

Data of realistic wave-interacted structural response is very limited. In particular, structural behavior under wave-induced loads is not well understood due to: [i] limitations in traditional experimental techniques that necessitate idealized, scaled structural specimens that may not represent full-scale structural response, and [ii] difficulties and uncertainties in handling combined computational fluid and structural models, requiring validation with experimental data. Real-time hybrid simulation (RTHS) is a cost-effective cyber-physical simulation method that can be used to examine the behavior of systems too large or complex to test fully in a laboratory setting, alleviating the aforementioned constraints. In RTHS, a system is split into two portions: an experimental, physical sub-assembly and a computational, numerical sub-assembly. The physical and numerical sub-assemblies interact, in real-time, through sensors and actuators. The response of the coupled, hybrid sub-assemblies then represents the response of a complete assembly; thus, mitigating many of the similitude constraints imposed in traditional wave experiments. Hydrodynamic-RTHS, or hydro-RTHS, couples physical waves and a partial structural specimen with a computational structural model in the NHERI-EF Large Wave Flume at OSU; this choice of sub-assemblies is practical as it physically simulates the wave-structure response and leverages the complexity and similitude advantages gained through the structural numerical model.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Reliability-Based Topology Optimization via an Inverse Tangent Constraint Approximation

Author(s): *Alberto Torres, *Johns Hopkins University*; James Warner, *NASA Langley Research Center*; Miguel Aguilo, *Sandia National Laboratories*; James Guest, *Johns Hopkins University*;

A simple and effective reliability constraint is presented which allows for topology optimization subject to small target failure probabilities when leveraging simulation methods for uncertainty propagation. Designs generated by traditional deterministic topology optimization are known to be susceptible to underlying uncertainties due to the non-redundant, slender features they exhibit. The past several decades have seen rising interest in improving topology optimization algorithms with methods capable of incorporating uncertainties within the optimization framework. Monte Carlo simulations (MCS) for uncertainty propagation can be prohibitively expensive in the presence of sophisticated computational models, large random dimensions, or highly complex uncertainty structures, with cost further compounded by the iterative nature of topology optimization. Previous works have sought to mitigate the computational expense through novel perturbation techniques, spectral approaches, and reliability approximations, but few have implemented efficient simulation-based methods for the reliability constrained topology optimization problem despite the substantial amount of research performed in this area by those in the fields of probability and uncertainty quantification.

When utilizing a simulation approach for reliability-based topology optimization (RBTO), continuous approximations of the reliability constraint can lead to unstable iterations when targeting extremely small failure probabilities due to the sparsity of samples linked to these failure events. The proposed method adopts an inverse tangent Heaviside approximation of the constraint such that the derivative captures the effects of distant samples, improving stability of the optimization iterations for a broader range of target failure limits. To demonstrate, we adopt a variation of the stochastic reduced order model (SROM) to efficiently propagate large quantities of input samples at every optimization iteration. The SROM, a small sample subset that optimally defines input uncertainties, is propagated at each iteration to obtain corresponding Quantities of Interest (QoI) used in obtaining a linear surrogate of the response surface. A MCS is then propagated through the surrogate to supply the constraint approximation with enough samples to obtain a probability of failure. Results for different structures are provided and verified using direct MCS. While the work is presented in the context of the SROM surrogate, the proposed constraint is applicable to any simulation-approach capable of propagating samples directly through the model or indirectly through a surrogate. (Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.)

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Mechanics of Coarse-Grained Soils Subjected to Thermal Cycling

Author(s): *Alessandro F. Rotta Loria, *Northwestern University*; Jibril B. Coulibaly, *Northwestern University*; Yize Pan, *Northwestern University*;

Granular materials, such as coarse-grained soils, beads, and pellets, are continuously subjected to temperature variations in nature, industrial processes, and engineering applications. In all of these situations, temperature variations markedly influence the mechanics of such materials due to complex temperature effects that rule the interactions between their constituting particles, with paramount consequences for natural and engineered systems. This talk presents some of the latest experimental observations and theoretical studies of the thermo-mechanics of granular materials, analyzing the effects of cyclic temperature variations on the structure-property-behavior relationship of coarse-grained soils. Accordingly, this presentation is divided into three parts to individually address the effects of cyclic temperature variations on the structure, properties, and behavior of coarse-grained soils. Through a compendium of results deriving from temperature-controlled computerized tomography, oedometer experiments, and discrete element simulations, this undertaking analyzes the considered problem across large spatial scales: from a single sand particle to thousands of such particles. The discussed results indicate that, due to the expansion and contraction of their constituents, coarse-grained soils subjected to cyclic temperature variations undergo microstructural reorganizations. These lead to irreversible macroscopic deformations and changes in the ability of such materials to withstand mechanical loads, allow the permeation of fluids, and transfer heat. Given the relevance of these effects for various natural and engineered systems involving granular materials on the Earth system and beyond, this talk concludes with an outlook on the analyses that the developed competence can serve for the benefit of science and engineering.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Addressing Spatio-Temporal Features in Storm Surge Surrogate Modeling Through Separable Gaussian Process Implementation

Author(s): Aikateritni Kyprioti, *University of Notre Dame*; *Alexandros Taflanidis, *University of Notre Dame*; Christopher Irwin, *University of Notre Dame*; Norberto Nadal-Caraballo, *U.S Army Corps of Engineers Research and Development Center*,

Surrogate models, also referenced as metamodels, have emerged as attractive data-driven, predictive models for storm surge estimation [1]. They are calibrated based on an existing database of synthetic storm simulations, and can provide fast-to-compute approximations of the expected storm surge, replacing the (computationally expensive) numerical model that was used to establish this database. The output of the emulator is the storm surge (peak values or time-history evolution), and the input the parametric features that can be used to uniquely describe each storm within the available database, for example the parameters of the storm wind-field model. This paper discusses specifically the development of a Gaussian Process (GP) metamodel for the prediction of storm surge time-series. The spatio-temporal variability of the surge has been addressed in past studies [2] by considering that the surge at different locations or time instances corresponds to different outputs, resulting in multiple metamodels, one for each different output. To address the associated challenges at the metamodel calibration stage, principal component analysis was used in these studies as dimensionality reduction technique. This presentation examines as alternative implementation, the development of a single metamodel to predict across the augmented space that includes spatio-temporal and storm features. To circumvent computational challenges in the GP formulation, associated with factorizations for the large dimensional covariance matrix across the augmented feature space, a separable GP formulation is adopted, treating separately the kernels and associated covariance matrices across the storm, spatial and temporal spaces. This approach, that better integrates the correlation of the storm surge across the spatiotemporal domain within the model calibration stage, is compared to the traditional formulation, which leverages this correlation merely through the PCA dimensionality reduction.

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: A High-Order Generalized Finite Element Method with Adaptive Global-Local Enrichments for Structural Dynamics and Wave Propagation

Author(s): *Alfredo Sanchez-Rivadeneira, *University of Illinois at Urbana-Champaign*; Carlos Duarte, *University of Illinois at Urbana-Champaign*;

A high-order Generalized/eXtended Finite Element Method with global-local enrichments designed to solve structural dynamics and wave propagation problems exhibiting fine-scale and/or localized time-evolving features in their solution is introduced. The proposed method uses an explicit time-marching scheme together with a block-diagonal lumped mass matrix applicable to arbitrary patch approximation spaces and adopts shape functions computed numerically on-the-fly through the solution of fine-scale local problems, allowing to capture relevant localized features of the response on structural-scale meshes that are much coarser than those required by Direct Generalized Finite Element Analyses (DGFEAs) of comparable accuracy.

Due to the time-dependent nature of the problems of interest, knowledge about the existence and location of these localized features at any given time is generally unattainable. Moreover, unnecessary inclusions of global-local enrichments to patch approximation spaces lead to linear, or near-linear dependency of patch approximation bases resulting in potential numerical issues, and unnecessary fine-scale computations, which result in computational inefficiency. To overcome this, a set of low computational cost criteria is formulated on a patch-by-patch basis to determine whether to perform local scale computations and include global-local enrichments in a given patch approximation space at each time-step of the numerical simulation. Numerical examples demonstrating the performance of the method and adaptive strategy are presented.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Applying Reduced-Physics Modeling to Accelerate Depletion Planning Optimization Under Subsurface Uncertainty

Author(s): Shua He, *ExxonMobil*; Santosh Verma, *ExxonMobil*; *Alireza Sanaei, *ExxonMobil*;

Robust decision-making regarding reservoir management using model-based strategies requires a large number of evaluations which can be enormously time-consuming if incorporating the full-field simulation. This challenge becomes more acute when dealing with subsurface uncertainty represented by multiple geologic scenarios. Various reduced-physics and reduced-order models such as streamlines and upscaling are commonly applied to accelerate the optimization process by reducing the computational burden of each evaluation. In this paper we proposed an innovative integrated workflow, that applies Flow Diagnostics, a reduced-physics modelling tool, to accomplish this acceleration and the mesh-adaptive direct search (NOMAD) algorithm to efficiently optimize well count and location.

Flow Diagnostic (FD) is a reduced-physics approach that characterizes key flow behaviors and reservoir heterogeneity by combining a single-phase pressure solution with a time-of-flight estimator based on steady-state flux. The time-of-flight values for each grid cell can subsequently be combined with initial reservoir conditions to estimate saturation-weighted 3-phase production using 1D Buckley-Leverett fractional flow relationships. Our testing of this technique on a 2-phase, water flooding asset showed that, while it does not accurately predict exact volumes, there is a strong rank-order correlation with the full numerical simulator. Thus, this technique is an efficient one to assist in the decision-making and optimization process.

To demonstrate this workflow, we applied this strategy to a model of the Great White reservoir in the Gulf of Mexico. Synthetic uncertainty was added to the base case to generate multiple subsurface scenarios. Different optimization studies were then performed on these cases (optimization of each single scenario on its own and optimization across all subsurface scenarios simultaneously) to compare solutions and effectiveness. Results indicated that, when the optimized well plans were run on the simulator, optimization under uncertainty provided a solution more robust across the uncertainty space. Differential Evolution was also tested and compared against NOMAD to demonstrate the increased efficiency of that algorithm to find higher-NPV solutions. The results of the full study on Great White successfully demonstrate the efficacy of our workflow.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Probabilistic Learning on Manifolds for Liner Impedance for Design Optimisation

Author(s): *Amritesh Sinha, *Université Gustave Eiffel*; Christophe Desceliers, *Université Gustave Eiffel*; Christian Soize, *Université Gustave Eiffel*; Guilherme Cunha, *Airbus Operations SAS*;

We address the problem of noise reduction for Ultra High By Pass Ratio (UHBR) engines. This is to be done for low frequency tonal noises by means of tailored acoustic liners. In order to avoid the prohibitively high computational and experimental costs for the design optimisation of these liners, recent advances made in probabilistic machine learning and AI are used for constructing meta-models of liner acoustic impedances.

Probabilistic learning on Manifolds (PLoM) [1] is a machine-learning tool that allows a learned set to be generated from a given training set whose points are realisations of a non-Gaussian random vector whose support of its probability distribution is concentrated in a subset (a manifold). This approach preserves the concentration of the probability measure for the learned set. This approach has been developed for the case of small data in the training set as opposed to big data that are usually used for deep learning of ANN(Artificial Neural Network).

We use this probabilistic learning tool for constructing a probabilistic meta-model of a liner acoustic impedance for which a training set has been constructed with a computational model. Conditional statistics of the real and imaginary parts of the frequency dependent impedance are estimated, which allow a digital twin of the liner to be created. This digital twin is robust and has been validated through conditional statistics and measure of concentration. This surrogate model can be further improved upon by addition of physics-based impedance data from experimental and/or finite elements calculations through data fusion techniques.

Keywords: Liner acoustic impedance, Probabilistic learning on manifolds, measure of concentration, conditional probability, digital twin, data-fusion, optimisation

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: 1-D and 3-D Computational Fluid Dynamics Model Comparison of the Treatment Performance of a Full-Scale Oxidation Ditch

Author(s): Kiesha Pierre, *University of South Florida*; *Andres Tejada-Martinez, *University of South Florida*;

Wastewater treatment facilities combine biological, physical, and chemical unit processes to remove pollutants and restore wastewater to a quality that is harmless. Modeling the oxidation ditch in a wastewater treatment facility requires combining hydrodynamics, driven by mechanical aerators, with the tracking of pollutants dissolved in the wastewater as they are consumed by oxygen-dependent micro-organisms through bio-kinetic processes. This work developed two CFD models of a full-scale oxidation ditch, a three-dimensional (3-D) model and a 1-D model, to compare their predicted wastewater treatment performance. Both models incorporated bio-kinetics through the well-known Activated Sludge Model (ASM)-1, to predict the treatment performance of the ditch based on concentrations of pollutants: readily biodegradable substrate (S_S), soluble ammonium ammonia nitrogen (S_{NH}) and soluble nitrate nitrite nitrogen (S_{NO}). When comparing the time-series of the concentration of ASM-1 pollutants averaged over the ditch for 40 days, all three models displayed similar trends with slight differences in steady state values, except for S_{NO} . The steady state value of S_{NO} was greater by more than 150% for the 1-D model than the 3-D model. This difference is attributed to spatial heterogeneities in dissolved oxygen concentration predicted by the 3D model that were not captured by the 1-D model, leading the latter to under-predict the denitrification process. Specifically, the FSI occurring between the aerator blades and the wastewater resulted in a spiraling flow and an associated spatial distribution of dissolved oxygen that could not be represented in the 1-D model. This result is important to the wastewater management community, as it routinely uses 1-D oxidation ditch models in operational models of wastewater treatment facilities.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Joint Estimation of Input Loads, Structural Parameters, and Dynamic States

Author(s): Marios Impraimakis, *Columbia University*; *Andrew Smyth, *Columbia University*;

The identification of a system deterministically or probabilistically is a topic of considerable interest and importance, and a lot of real-life systems have been examined for this purpose. Many approaches, however, require the input which is not always available. Specifically, it may be impossible to know the input or, alternately, the measurement of the input is much more unreliable than the dynamic state measurement. Here, a methodology is developed to address this challenge of joint load-parameter-state estimation using a Kalman filter-based real time approach. This output-only methodology allows for a better understanding of the system compared to the standard output-only parameter identification strategies, while system identifiability characteristics are also taken into account. Applications include structural health monitoring algorithms, damage detection, and statistical linear and nonlinear system identification.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Modeling Curvature-Dependent Energetic Surfaces in Soft Polymeric Solids and Stiff Nanostructures

Author(s): *Animesh Rastogi, *The University of Texas at Austin*; Berkin Dortdivanlioglu, *The University of Texas at Austin*;

Surface stresses play a significant role in the overall mechanical response of soft solids and nanostructures. Gurtin and Murdoch [1] proposed a theory to study the solid-surface coupled mechanical behavior by incorporating a zero-thickness elastic surface bonded to the bulk. Steigmann and Ogden [2] extended their work by considering the surface to resist change in curvature. Recent studies have demonstrated that curvature-resisting surfaces can explain some anomalies observed in the mechanical behavior of nanostructures and soft solids with chemically-treated surface. Furthermore, curvature-resisting surfaces are crucial to study the mechanical behavior of biological membranes since they exhibit high bending stiffness. The growing interest in understanding complex material surface effects demands a robust computational model of their flexural-resistance. However, the calculation of surface curvature-tensor in the numerical modeling is challenging, and it requires at least C^1 continuous basis functions. Consequently, it is not possible to directly implement curvature-dependent surface energetics using the standard finite element method. In this presentation, we address this challenge by proposing a 3D computational framework of curvature-dependent surface energetics using NURBS-based isogeometric analysis [3]. NURBS basis functions are C^n (n greater than 1) continuous, and therefore can be used to directly calculate the surface curvature tensor. We demonstrate the robustness of our model using several numerical examples. First, we perform model verification using an analytical solution for a radially compressed thick hollow sphere. Next, we illustrate how endowing a thick hollow cylinder with flexural-resisting surface regularizes the deformations around line load. These examples elucidate the effects of surface energetics with only curvature-resistance and its combination with surface tension and surface elasticity. Our results show that surface curvature-resistance has a stiffening effect on the overall response of solids, introducing a bending length scale. The proposed methodology provides a robust computational foundation to help advance our understanding of the mechanics of soft solids, nanostructures, and biological membranes.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Exploring the Role of Magnesium Nitrate in Modifying Properties of Alkali-Silica Reaction Gels

Author(s): *Arkabrata Sinha, *University of Massachusetts Lowell*; Jianqiang Wei, *University of Massachusetts Lowell*;

Alkali-silica reaction (ASR), also known as “concrete cancer”, is a major concrete degradation mechanism causing significant cracking and shortened service life of concrete structures. ASR occurs when the amorphous silica dissolves from the reactive aggregates and combines with the alkalis in the pore solution of concrete to form a gel-like product that can absorb moisture, swell and exert internal stress on the surrounding aggregates and cement matrix. Traditional methods to mitigate ASR involve the incorporations of supplementary cementitious materials and lithium-based admixtures at the expense of compromising the physical and mechanical properties of the concrete, giving rise to the need for alternative additives. The current study investigates the effect of magnesium nitrate on the phase evolution and properties of ASR gel to make it harmless. To obtain a comprehensive understanding, synthetic ASR gels with a calcium to silica (Ca/Si) molar ratio of 0.3, alkali to silica ((Na+K)/Si) molar ratio of 0.8, and varying magnesium to silica (Mg/Si) molar ratios from 0.1 to 1.1 are investigated by means of thermogravimetric analysis (TGA), X-ray diffraction (XRD), Raman and Fourier transform infrared (FTIR) spectroscopy. The development of strength, dynamic vapor sorption and hygroscopic expansion behavior of the ASR gels via a novel swelling test method are also monitored. The results indicate that with increasing Mg/Si ratio less ASR phase can be formed. The ASR gel can be completely converted into magnesium silicate hydrate (M-S-H) and brucite (magnesium hydroxide) from an Mg/Si ratio of 0.7. This is confirmed by the TGA results along with the presence of silanol hydroxyl groups characteristic of M-S-H and decomposition-induced weight loss in the temperature range of brucite. Raman and FTIR spectroscopy showed a suppressed formation of silicon polymerization sites, a characteristic site in ASR gel governing the swelling behavior, with the increased Mg/Si ratio. In the presence of concrete pore solution, the incorporation of magnesium nitrate resulted in suppressed expansion, while the swelling potential of the magnesium-modified ASR gels exhibited a positive correlation with the Mg/Si ratio indicating that there exists an optimal Mg/Si ratio at around 0.1 to 0.3. The compressive strength was found to increase up to an Mg/Si ratio of 0.5, beyond which a significant strength drop was triggered.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Modeling of Wildfire Propagation: A Stochastic Level-Set Formulation

Author(s): *Armin Tabandeh, *University of Illinois at Urbana-Champaign*; Paolo Gardoni, *University of Illinois at Urbana-Champaign*;

Future perspectives of climate change tend to favor extreme drought and alter precipitations. These conditions can dramatically increase the risk of wildfires, as manifested in recent events in California and Australia. Wildfires' behavior features multi-physical processes at a wide range of time and length scales, from pyrolysis at the vegetation scale to atmospheric dynamics at the meteorological scale. Wildfires generally present a front-like geometry that propagates into unburned vegetation. The local propagation speed of the fire front, referred to as the Rate Of Spread (ROS), depends on variables characterizing vegetation properties, weather conditions, and terrain topography. The advection of firebrands also contributes to wildfire propagation, where lofted embers can initiate spot fires far ahead of the fire front. The complex physics of the problem with many sources of uncertainty renders fully physics-based models computationally infeasible, whereas empirical models are too simple to yield accurate predictions. This challenge is addressed by developing a computationally manageable physics-based formulation in which a stochastic Hamilton-Jacobi equation (or level-set equation) governs the evolution of the fire front. In the proposed formulation, the fire-front moves toward the unburned vegetation along its normal with speed determined based on existing empirical relations for the ROS. Data assimilation techniques with Bayesian inference are also proposed to update the ROS based on local data and monitored burning patterns. The Hamilton-Jacobi equation is modified to accommodate the effects of fire transport due to downwind advection and hot-air turbulence. Finally, a novel spectral representation of the solution to the formulated stochastic Hamilton-Jacobi equation is developed and numerical methods to find the probability distribution of the evolving fire front are presented.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Reliability Centered Rehabilitation Optimization for Concrete Hydraulic Structures.

Author(s): *Arslan Tahir, *Federal Waterways Engineering and Research Institute (BAW), Germany*; Claus Kunz, *Federal Waterways Engineering and Research Institute (BAW), Germany*;

Several hydraulic structures in inland navigation infrastructure are reaching their end of the life cycle. Due to deteriorated conditions, these structures need to be re-evaluated and rehabilitated based on current conditions and desired extension in service life.

Existing standards are calibrated for a service life of 50 to 100 years; its direct application would lead to uneconomical design. In case desired service life is less, a modified approach is required. Most of the aged structures are unreinforced, and it is observed in many cases that limit state verifications, and safety requirements are met through the application of an anchor system using steel reinforcements. These modifications result in a hybrid structure comprising both reinforced and unreinforced sections within the same structural component. Since hydraulic structures are in contact with varying water levels, the hydraulic pressure differential across the section develops a crack and pore-water pressure (CPWP), which must be included in the structural analysis. Moreover, the operating procedures and conditions also factor into structural system reliability.

This contribution presents an optimization scheme for an efficient reliability-centered rehabilitation strategy. The approach incorporates the three aspects. Firstly structure-specific material, loads, and failure mechanisms, secondly target reliability for desired service life extension specifically for hydraulic structures, and lastly, the influence of operations-based load events.

The proposed scheme is applied to a ship lock built in 1925 which represent 51% of German ship lock infrastructure, with gravity wall design construction philosophy, and operation conditions. The structure failed to satisfy partial safety factor-based requirements and was hence rehabilitated with steel reinforcement anchors. The authors recently developed a modified mechanical model for this structure to incorporate CPWP for sectional analysis of hybrid structures. The model's mathematical formulation is used as a modified limit state function. Appropriate probabilistic models for parameters of relevant loads (self-weight, water, earth/ groundwater pressure etc.) and materials (concrete, steel) were selected. In view of computational efficiency, First Order Reliability Method is employed for reliability analysis and coupled to Golden Section Line Search method for optimization of the reinforcement optimization.

The optimized area of steel is calculated for provided target reliabilities corresponding to different service lives and operational conditions. Additionally, the difference in reliability levels with and without consideration of CPWP is investigated, and equivalent additional reinforcement required is evaluated. The methodology could be applied to any rehabilitation technique not yet codified e.g. Steel/fiber reinforced concrete with further developed considering material deterioration modelling.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Multi-Criteria Optimal Design of Uncertain Building Systems Subject to Stochastic Wind Loads

Author(s): Thays Duarte, *University of Florida*; *Arthriya Subgranon, *University of Florida*;

The decision-making process in the design of building systems in hurricane-prone regions involves evaluating a large set of possible designs based on multiple criteria including, but not limited to, initial cost, anticipated loss, and environmental impact over the lifetime of building systems. Multi-criteria optimization can be used as a systematic method to automatically identify a set of optimal designs with different trade-offs among conflicting criteria. The optimal trade-off information can be very useful for decision-makers to holistically look at safety, cost-effectiveness, and sustainability aspects altogether. In this work, a framework for multi-criteria optimal design is presented which integrates probabilistic performance-based wind engineering (PBWE) and life-cycle assessment (LCA) with the optimization algorithms. The PBWE allows for wind-induced damage and loss estimation while the LCA allows for environmental impact assessment of building systems. To evaluate these performance criteria, Monte Carlo simulation is performed to systematically propagate various uncertainties throughout the evaluation process that entails the hazard, aerodynamics, dynamic response, damage, loss, and environmental impact models. To efficiently solve this computationally intensive problem, the epsilon-constraint method is used to transform the original multi-criteria optimization problem into a series of single-objective optimization problems, which can be solved through an approximate decoupling approach. In particular, auxiliary variable vectors (AVVs) and kriging metamodels can be constructed based on results of a single Monte Carlo simulation to estimate the second-order statistics of engineering demands and statistics of decision variables (e.g. expected loss and expected environmental impact), respectively. Within this setting, an optimization subproblem is defined in terms of the AVVs and kriging models, hence decoupling the probabilistic analysis from the optimization process. The subproblems can be solved sequentially using any gradient-based optimization algorithms until the optimal solutions of two consecutive cycles converge, ensuring the exact solution to the stochastic single-objective optimization problem. Parallel computing with GPUs is adopted to further accelerate the Monte Carlo simulation process. The applicability of the proposed framework is demonstrated with a case study involving the design of a multi-story building subject to stochastic wind loads. Three criteria are considered including initial cost, expected repair cost, and expected carbon footprint of the building system.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Enhanced Redundancy of Steel Truss Bridges Through Modular Joints

Author(s): Mirela Tumbeva, *University of Notre Dame*; *Ashley Thrall, *University of Notre Dame*; Theodore Zoli, *HNTB Corporation*;

This research investigates the load-path redundancy of a new approach for the accelerated fabrication and erection of steel truss bridges: the modular joint. Modular joints are prefabricated nodal connectors comprised of web and flanges, including a starter segment to connect to a member. These modular joints connect standard rolled wide flange members using bolted splice connections, joining the flanges and webs independently in double shear. This forms a kit-of-parts approach comprised of modular joints, wide flange members, and splice connections. Fabrication is accelerated as joints can be prefabricated and mass-produced and the wide flange members only require holes to be drilled. Erection is simplified as the same modular joints are repeated throughout a structure and only bolted connections are used. As the flanges and webs of components are joined independently, a moment-resisting connection is achieved. This, combined with the strong-axis orientation of the wide flange members, enables a truss-type structure to tolerate member loss.

This presentation investigates the load-path redundancy of a 390-ft steel bridge comprised of modular joints when subjected to the sudden loss of a diagonal member. In this evaluation, a static analysis of the undamaged structure is first performed. Elements are then removed from the fractured member. A force with equal magnitude to that which was in the undamaged member but opposite in direction is then applied to the failure surfaces. An explicit dynamic analysis - using a three-dimensional finite element numerical model comprised of shell elements - is then performed to trace the response of the structure through time. The focus is on evaluating the instantaneous behavior (~ milliseconds) of the modular joints as the high-velocity stress wave from the abrupt fracture propagates. The resulting strain rates are significantly higher than strain rates typical of live load and are associated with a reduced fracture toughness. This, combined with the reduced fracture toughness of the modular joints due to the fabrication process (i.e., welding and cold bending), warrants careful evaluation. The short-term dynamic behavior (~ seconds) and the static behavior of the faulted structure are also evaluated. Ultimately, this research demonstrates the redundancy of the modular joint system.

This presentation culminates in a discussion of how design innovations can lead to collapse-resistant infrastructure as well as the analyses that are necessary to evaluate these systems.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Linking Material Properties To Microstructure In Liquid Metal Elastomer Composites Via Machine Learning.

Author(s): Abhijith Thoopul Anantharanga, *Iowa State University*; Mohammad Saber Hashemi, *Iowa State University*; *Azadeh Sheidaei, *Iowa State University*;

Multifunctional materials have been of importance over the past decade. Since there has been a shift from unifunctional materials to multifunctional materials, there has been development in the field of computational material design to develop advanced multifunctional materials. In this study, the focus is on designing liquid metal elastomer composites (LM elastomers). These are a class of multifunctional materials in which thermal, mechanical, and electrical properties are tuned simultaneously. They have applications in wearable electronics, robotics, and biomedical engineering. These materials can handle very high strains without getting fractured and at the same time maintain high thermal conductivity. Over the last couple of years, there have been some methods developed to synthesize LM elastomers. But since they must still be refined, there is a need to develop computational methods to design LM elastomers. In this study, LM elastomers with desired properties are designed using a supervised machine learning based method. The design variables in this study are the volume fraction, aspect ratio of the ellipsoidal particles, mean and standard deviation of particle size. Sobol sequence is used to generate a database with design variables which is used to train the machine learning model. Microstructures are generated by a packing algorithm. Mechanical properties are obtained with the help of FE simulations using Abaqus subroutines. Thermal and di-electric properties are obtained with the help of FFT simulations. The machine learning model is trained over the database and a complex relationship is obtained between the material microstructure and the material properties. Inverse design is also carried out with the help of which the material microstructure design variables are predicted for a certain set of material properties. Hence the two frameworks developed link material properties and microstructure for LM elastomers.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Exploring the Interaction Between Different Instability Phenomena in Vertical Axis Turbine Blades

Author(s): *Benjamin Terry, *University of Washington*; Richard Wiebe, *University of Washington*; Michael Motley, *University of Washington*;

Wind and water turbines are quickly becoming more common as the world continues to shift towards renewable sources of energy. Concerns about the structural stability of these turbines have become more relevant as their scale continues to increase well into the megawatt range. Vertical axis turbines in particular offer an opportunity to study several different types of instability and the interactions between them.

Three main effects are considered which will govern the response of a vertical axis turbine blade: structural, fluid, and centrifugal forces. These forces can result in several instability mechanisms. First, fluid forces, even on a stationary foil, are known to give rise to static instability (divergence) as well as dynamic instability (flutter). Second, centrifugal forces on vertical axis turbine blades are dependent on blade deformation, which can result in another divergence mechanism. Third, the periodic nature of fluid loads on a vertical axis turbine as it rotates may induce both main and parametric resonance.

The goal of this work is to qualitatively explore the interactions between these instability mechanisms. Thus, instead of a high-fidelity model, we develop a low-order approximate model by expanding on Theodorsen's seminal formulation for an oscillating blade in 2D space. This is achieved using a two-element beam formulation comprised of modified bend/twist elements which can cheaply predict the response of vertical-axis turbine blades over a broad range of design space. This model serves as an ideal testbed to study how these different types of instability may interact.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Improved Finite Element Model Updating of a Full-Scale Steel Bridge Using Sensitivity Analysis

Author(s): *Bjørn T. Svendsen, *Norwegian University of Science and Technology*; Øyvind W. Petersen, *Norwegian University of Science and Technology*; Gunnstein T. Frøseth, *Norwegian University of Science and Technology*; Anders Rønnquist, *Norwegian University of Science and Technology*;

There are increasing demands in operating conditions for existing bridges with respect to traffic loads and intensity. Although many uncertainties are present for the bridges that are approaching or have exceeded their initial design life, lifetime extension is a preferred option to ensure continuous operation. A lifetime extension analysis often requires a precise numerical model, resulting in the need for model validation.

Finite element model updating can be used to calibrate the parameters of a numerical model based on vibration test data and is essential in the work of obtaining a validated numerical model. With the large number of existing bridges in infrastructure, an approach is needed to effectively establish validated numerical models from model updating.

In this work, sensitivity-based model updating is performed on a full-scale steel bridge using natural frequencies and MAC numbers. A novel procedure to obtain an optimal solution for improvement in modal properties combined with realistic parameter values by using a sensitivity analysis is proposed. The procedure is based on a structured approach. The procedure can be applied to similar case studies, irrespective of the structure under consideration and the corresponding parameterization made, to effectively obtain a validated numerical model.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Damage Localization Framework Using Physics-Based Modeling and Topology Optimization

Author(s): *Borna Rahnamay Farnod, *The Pennsylvania State University*, Wesley Reinhart, *The Pennsylvania State University*, Rebecca Napolitano, *The Pennsylvania State University*,

To ensure the reliability and safety of structures, engineers use diverse structural health monitoring tools. Obtaining information about the structure, the interior topology of its materials, and its loading history can make for more accurate estimations of the remaining service lifetime of a structure. While several Non-Destructive Testing (NDT) methods are routinely used in the field, they can exhibit high uncertainty and often require expert knowledge to interpret. To complement established NDT methods and mitigate some of their intrinsic uncertainty, we propose a hybrid physics-based and data-driven strategy based on Finite Element analysis. In this approach, we formulate the estimation of an unknown (e.g., interior) spatial distribution of material properties as a topology optimization problem. Rather than optimizing the material distribution to minimize compliance, we seek a density field that matches an observed displacement (i.e., in an existing structure). We demonstrate the approach on synthetic cantilever beams with internal structuring. We systematically evaluate the capabilities of the method using targets of varying complexity and evaluate how model hyperparameters lead to different outcomes. We believe the proposed method can scale up to larger problems and is extensible to incorporate information from a variety of NDT methods.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Upscaling Thermal and Mechanical Parameters for Second-Graded Porous Materials

Author(s): *Bozo Vazic, *The University of Utah*; Pania Newell, *The University of Utah*;

Fundamental understanding of interaction between micro-structure and underlying physical mechanisms is important, especially for development of sound multi-physics models for porous materials. For instance, understanding thermo-mechanical processes in ceramic coatings or thermo-hydro-mechanical processes in pavement structures exposed to extreme fluctuations in temperature, demand modeling techniques that rely on the underlying physics of the system to obtain reliable simulation results. In this study, we adopt a higher-order asymptotic homogenization method based on generalized continuum. The developed formulation encapsulates both physics of the problem, through determining thermal parameters and then considering thermal effects on the mechanical behavior. Similar to our previous research on influence of micro-structure morphology on mechanical properties, Vazic et al. (2021), we will employ thermo-mechanical model on a set of numerical problems with different combinations of porosity, pore shapes (i.e., circular, square, triangular, and elliptical), and with different distributions (i.e., single pore and uniform/random distribution). Developed methodology will analyze the effects of pore shape and pore distribution not only parameters associated with linear thermo-elastic model (stiffness matrix and thermal expansion stress tensor), but also higher-order parameters that are a part of generalized continuum model. This study will provide an insight into better design/analysis of porous materials under combined thermo-mechanical loadings.

Bozo Vazic, Bilen Emek Abali, Hua Yang, and Pania Newell. Mechanical analysis of heterogeneous materials with higher-order parameters. *Engineering with Computers*, pages 1–17, 2021

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: A Real-Time Hybrid Simulation Framework for Floating Offshore Wind Turbines

Author(s): *Chao Sun, *Louisiana State University*; Wei Song, *University of Alabama*; Vahid Jahangiri, *University of Nevada, Reno*;

Offshore wind farms are experiencing rapid growth globally where floating offshore wind turbines (FOWTs), which are installed in deeper marine areas and offer larger power production capacities than their fixed counterparts, have been attracting increasing research effort and industry investment. To achieve secure application, it is essential to understand the complex structural behaviors of FOWTs under the combined wind, wave, and current loading that FOWTs are exposed to. However, due to Reynolds and Froude scaling incompatibilities, conventional testing of FOWTs using scaled models becomes difficult. This research proposes a real-time hybrid simulation (RTHS) framework to study the structural performance of FOWTs under the combined wind and wave loading. In the framework, the blades (including the nacelle) and tower are numerically modeled, and the floating platform is tested in real-time via an actuation system in laboratory. The numerical and physical substructures are both simulated numerically in this study. A reduced model on a scale of 1:25 of the National Renewable Energy Lab 5MW spar-type FOWT is simulated to evaluate the performance of the proposed framework. Errors caused by representative levels of delays, noises, and wind-wave misalignments are quantified through a sensitivity analysis. Research results indicate that the delays in the RTHS framework cause the most significant discrepancy of the structural response prediction. The developed framework and associated data in the present research offer essential information for future implementation and further development of the RTHS technology for similar offshore structures.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Mesh Convergence Study for Fluid-Structure Interaction Problems Using Non-Boundary-Fitted Meshing Techniques

Author(s): *Chen Shen, *Rensselaer Polytechnic Institute*; Scott Miller, *Sandia National Laboratories*; Jesse Thomas, *Sandia National Laboratories*; Lucy Zhang, *Rensselaer Polytechnic Institute*;

In this study, we present a mesh convergence study approach for fluid-structure interaction (FSI) problems modeled using non-boundary-fitted meshing techniques. Non-boundary-fitted meshing techniques such as the Immersed Boundary method (IB), the Immersed Interface method (IIM), the Immersed Finite Element Method (IFEM), and fictitious domains, are methods where the fluid and solid are discretized independently, and they are not required to conform at the interface. These methods are emerging to be popular approaches to model multiphysics problems for their robustness in handling independent meshes and moving interfaces. However, as of now, only heuristic guidelines have been provided to ensure system solution convergence and stability. A rigorous approach in performing mesh convergence study for non-boundary-fitted meshing techniques is necessary. In this work, mesh convergence is defined as a combination of mesh compatibility and mesh sensitivity. Mesh compatibility refers to the compatibility between the mesh sizes of the overlapping domains; while given a compatible mesh size ratio, the mesh sensitivity determines the accuracy of the numerical solutions. Our study shows that the mesh compatibility test is vital to the FSI solution stability, a prerequisite for accuracy. Specifically, we show that rather than the individual solid/fluid mesh that determines convergence of the solution, it is the solid/fluid mesh size ratio that dominates solution convergence. Once the mesh compatibility range is determined, then the mesh sensitivity study can further determine the accuracy of the solution by varying either the fluid or the solid mesh size. We systematically perform both the mesh compatibility and sensitivity tests for three FSI examples using the modified Immersed Finite Element Method (mIFEM), where a solid volume is immersed in a fluid domain. Our results show that the compatibility range becomes smaller when very thin structures, e.g., one-layer thin, are immersed in fluid due to small mesh resolution requirements. As the solid structure gets thicker or occupies more volume, the coupled numerical solution has a larger compatibility region. For the first time, this work creates a paradigm to systematically study the subtlety that lies within the mesh convergence studies when using the non-boundary-fitted meshing techniques.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Simulation Free Adaptive Reliability Analysis Method for Structures Under Stochastic Loadings

Author(s): *Chi Zhang, *The Ohio State University*; Abdollah Shafieezadeh, *The Ohio State University*;

Reliability analysis of engineering problems and physical phenomena, due to their multi-query nature, often requires a very large number of simulations, which are very often at core driven by ordinary or partial differential equations (ODE/PDEs). Finite element and finite difference methods are often used for these simulations. However, performing a large number of simulations for multi-query analyses can be prohibitive. One can utilize surrogate models to reduce the required number of simulations; however, a significant amount of simulations are still required. Recently, a type of deep neural network (DNN) method, the Physics-Informed Neural Network (PINN), has gained a significant amount of attention. PINN requires no simulation data; instead, it is directly trained by using the physics knowledge informed by the formulation of the ODE/PDE.

In this study, we propose a novel simulation free method for reliability analysis based on PINN, which is called adaptively trained PINN for reliability analysis (AT-PINN-RA). We introduce a novel adaptive training (AT) sampling approach to shift the training focus to the important regions where the limit state lies. A set of anchor points are used to help sample the collocation training points with the AT sampling approach. The performance of the AT-PINN-RA is demonstrated using 2D isotropic elasticity reliability problem. It is observed that AT-PINN-RA show significantly better performance than the existing method based on PINN. AT-PINN-RA is able to make accurate predictions in all numerical examples.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Developments in Carbon Fiber Rod Analysis for Sporting Goods Applications

Author(s): *Connor Quigley, *University of Maryland, College Park;*

In sporting goods manufacturing, such as in fishing rod design, new products are created using an Edisonian process. By changing the layup and geometry of carbon fiber prepreg, a rod can be constructed to specifications that lend itself to a specific application. In this presentation, we will present an integrated computational materials engineering (ICME) approach developed for carbon fiber fishing rods. The computations are based on finite element theory, including the use of Euler-Bernoulli beam theory integrated with MATLAB, and detailed layup modelling and analysis in ANSYS. The experimental approach uses 3-point flexure test methods to gain concrete values for numerical solutions and modelling. Using data from experimental and numerical models, the physical response to deflections and vibrations of thin-walled carbon fiber rods can be better understood and analyzed in the overarching context of new fishing rod designs. Using these techniques, a rod manufacturer can create better prototypes for new products and understand the limitations of current rods. The fishing rods that can be developed from the approach show unprecedented response characteristics and control in design. This allows manufacturers to create rods that cast better and are internally tuned to specific response characteristics that create performance excelling previous rod models and design techniques.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Design Optimization of Hybrid Steel/Timber Structures for Minimal Environmental Impact and Financial Cost: A Case Study

Author(s): *Daan Van Cauteren, *KU Leuven*; Delphine Ramon, *KU Leuven*; Jorben Stroeckx, *KU Leuven*; Karen Allacker, *KU Leuven*; Mattias Schevenels, *KU Leuven*;

In the overall aim to build more sustainably, the energy performance of buildings has received a lot of attention in the past decade. In consequence, the embodied impact of buildings has become relatively more important. As the load-bearing structure is responsible for a large share of this embodied impact, it is important to design it in such a way that its environmental impact is as low as possible. Unfortunately, the best construction materials in terms of environmental impact are not necessarily the cheapest. Reducing the environmental impact of the design may therefore lead to a higher financial cost, which may exceed the available budget. In such cases, hybrid structures, consisting of two (or more) different materials, might offer a solution, as they allow the designer to finetune the trade-off between environmental impact and financial cost. In this contribution, we present a method to determine the best design of hybrid steel/timber structures in terms of environmental impact within the limits of the available budget. The method is based on the solution of a multi-objective structural design optimization problem involving environmental life cycle assessment and life cycle costing. It is applied to two test cases: a statically determinate and a statically indeterminate truss structure. The structures are optimized for three different design scenarios and typical load cases. This results in a Pareto front in the environmental and financial life cycle cost spectrum, allowing the designer to select the most appropriate solution, given the available budget. The results show that, depending on the design conditions, hybrid steel/timber structures are in some cases Pareto-optimal.

This work was recently published as a journal article [1].

[1] D. Van Cauteren, D. Ramon, J. Stroeckx, K. Allacker, and M. Schevenels. Design optimization of hybrid steel/timber structures for minimal environmental impact and financial cost: A case study. *Energy and Buildings*, 254:111600, 2022.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: A Multiscale Reduced Order Model for Polycrystalline Microstructure with Cracks

Author(s): *Damin Xia, *Vanderbilt University*, Caglar Oskay, *Vanderbilt University*;

In this work, we formulate a reduced order mathematical homogenization model for polycrystalline microstructures with the presence of microstructurally small cracks and other defects. The significance of the effect of microstructure-sized cracks on the long term performance as well as strength properties is well known. However, direct numerical simulation (e.g., using direct crystal plasticity finite element modeling, or CPFEM) of complex polycrystalline microstructures in the presence of multiple and small defects is computationally very expensive. In the current work, we propose a new reduced order model that efficiently and accurately represents the mechanical response of these microstructures.

The proposed approach employs the concepts of eigen-strain and eigen-separation to account for the plastic deformation and the presence of cracks, respectively. Reduced order approximation is applied to the plastic strain and separation to reduce the computational efforts. A linear reduced order basis function is utilized for eigen-separation field to approximate the crack opening curvatures. Specific treatment is enforced at the crack joint point to ensure the compatibility when modeling crack kinking. To capture the high stress variation around the crack tips, a clustering algorithm based on the variation of an energy measure is proposed to automatically refine the reduced order parts for those regions. The model performance is evaluated against crystal plasticity finite element model under different loading conditions and various crack configurations. Both overall and local behaviors show reasonable accuracy with only a fraction of the computational cost of the reference finite element model.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Data-Driven Reduced-Order Modeling and Response Reconstruction through A Bayesian Expectation-Maximization (BEM) Framework

Author(s): *Daniz Teymouri, *The Hong Kong University of Science and Technology*; Omid Sedehi, *The Hong Kong University of Science and Technology*; Costas Papadimitriou, *University of Thessaly*; Lambros s. Katafygiotis, *The Hong Kong University of Science and Technology*;

A new methodology, called Bayesian Expectation-Maximization (BEM), has recently been developed for joint input-state estimation problems, implemented in the physical domain of dynamical responses [1]. This methodology is an iterative algorithm, which embeds a backward-forward Kalman smoother and offers an efficient noise identification procedure. The BEM proves to be an efficient and accurate approach for estimating the state, input, and noise characteristics using incomplete vibration measurements and quantifying the uncertainties. However, its application to large-scale structures is limited as the high dimensionality of such a system imposes computational challenges. This study broadens the scope of applicability of the BEM to the vibration-based monitoring of large-scale structures, proposing a new formulation using data-driven reduced-order models. This implementation increases the computational efficiency of the proposed method by reducing the size of the state vector and system matrices using only those contributing modes necessary to describe the dynamical behavior. This framework is also advantageous to characterize the unknown spatial distribution of the input through a set of equivalent modal forces. The proposed BEM is tested through numerical and experimental examples, indicating the close agreement between the estimated and actual quantities. The quantified uncertainties well account for the errors, validating the capability of the proposed approach for uncertainty quantification.

Acknowledgements

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Computational Modeling of Time-Dependent Behavior of Laminated Timber

Author(s): Susan Alexis Brown, *Northwestern University*; *Danyang Tong, *Northwestern University*; David Corr, *Northwestern University*; Gianluca Cusatis, *Northwestern University*;

Historically, timber design has been based upon simple strength-based criteria, based on research performed from 1950-1970s. Literature shows little work was performed in the following years, and despite a renewed interest in the past decade, there still exists gaps in the broader understanding of wood behavior in structural applications. In particular, time-dependent effects are vastly understudied. Indeed, only a dozen papers have studied wood creep in constant environment with structural application, and only five of those lasted for more than 100 days [1]. There is a particular dearth of experimental testing at the structural level, most authors preferring to use small samples of clear wood.

Compare that with concrete, for which there is currently a database of 1400 creep curves, spanning over 40 years' worth of studies [2]. Additionally, due to the variation in wood properties from species to species and the lack of consistency in type of testing (tension vs bending, etc.), there is little agreement between authors regarding behavior such as asymptotic trends. Consequently, current design standards provide only a cursory treatment of creep, as a 1.5x or 2x factor on long term deflection in bending elements, and not at all in compressive elements. The following research therefore proposes a material-scale computational implementation of a wood compliance model for use in both sawn and laminated timber applications.

The authors utilized a previously work which used a compiled database to identify compliance function parameters for a variety of wood species. The model was implemented in finite-element software using a Kelvin-chain approximation. Additional elements were added to model shrinkage/swelling and mechanosorptive effects. Previous work by the authors on a hygrothermal model was also leveraged. The model was expanded for laminated wood and coupled with the mechanical model to provide complex moisture fields. This coupled model was then validated at the material level, and verified for laminated timber using existing literature. It showed good agreement with experimental data for both sawn and laminated timber.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Understanding Network-Level Asset Management Policies Enabled by Deep Reinforcement Learning

Author(s): *David Yang, *Portland State University*,

Bridges deteriorate over time due to various environmental and mechanical stressors. Deterioration poses significant risk to bridge owners (i.e., asset risk) and the traveling public (i.e., network risk). Transportation agencies carry out bridge management plans under limited resources to preserve bridge condition and control risks of bridge failure. Nonetheless, existing network-level analysis for bridge management cannot explicitly consider the effects of preservation actions on network risk, quantified usually by functionality indicators such as network connectivity and capacity. Recent advances on deep reinforcement learning allowed for truly network-level asset management that can reflect bridge importance to network functionality. However, the devised policies are usually (a) too complex to grasp by bridge managers and (b) difficult to incorporate into bridge management systems, where simple element-level Markov decision processes are still prevalent. Focusing on a classic bridge network, this study attempts to deconstruct network-level policies obtained with the proximal policy optimization algorithm. It is hoped that the investigation herein can shed light on the policies represented by neural networks, increase transparency and confidence on the obtained policies, and provide potential protocols to merge such policies with existing bridge management systems.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Tracking Sequential Particle Shape Evolution in Crushable Sand via X-Ray Tomography

Author(s): *Dawa Seo, *Northwestern University*; Giuseppe Buscarnera, *Northwestern University*;

Particle morphology is one of the key factors to determine the mechanical behavior of granular materials. Despite its importance, quantification of the particle shape and use into modeling approaches is a challenging task, especially for granular systems susceptible to changes in the morphology of individual particles. This contribution focuses on crushable sand, as a particular example of granular materials with evolving grain morphology. For this purpose, we use recent advances in non-destructive testing based on 3D X-ray synchrotron tomography. Specifically, we use digital images from X-ray scans to measure the evolving particle morphology of Ottawa sand grains subjected to high-pressure confined compression. By analyzing the digital images through a newly proposed tracking algorithm, the morphological features at particle form level were assessed with three representative fitting methods. Next, the sequential breakage history of individual grains in the tested assembly was recorded. Such image-based quantification enabled us to examine the correlation between the morphological features of original grains and fragments from each rupture event. Interestingly, we find that regardless of the fitting methods the most frequent shape of the fragments (child particles) corresponds with the modal shape of the particles from which they stem (parent particles). This phenomenon, here defined shape heritability, can be regarded as a useful indicator of the geometric trends of sequential fracture events. Further examination of the dataset shows that this phenomenon is more prevalent in finer and elongated particles, especially those which have experienced pervasive breakage. In addition, we find that the combination of this trend with the non-symmetric statistics of particle shapes leads to a moderate decrease of the average value of the aspect ratio in the assembly. These results can support the analysis of evolving shape characteristics in sand and of the role of particle-scale fractures in determining the ultimate morphology of particles in highly comminuted particle systems.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Diagnostic Criteria to Identify Delayed Strain-Localization in Viscoplastic Geomaterial

Author(s): *Dawei Xue, *Northwestern University*; Ghassan Shahin, *Johns Hopkins University*; Xilin Lu, *Tongji University*; Giuseppe Buscarnera, *Northwestern University*;

This contribution presents closed-form strain localization criteria for viscoplastic solids based on the theory of controllability. The motivation is to define constitutive indicators of strain-localization in materials susceptible to creep such as hard soils and porous rocks, to eventually use them for the detection of both quasi-instantaneous (load-induced) and delayed (creep-induced) failure. It is shown that unstable states in rate-dependent geomaterials can be detected from the inspection of the system of ordinary differential equations (ODEs) reflecting the constitutive response. For suitable choices of control conditions, such analyses can be cast in a form equivalent to traditional strain localization analyses. Analyses conducted at both material point level and system level show that these indicators can pinpoint the spontaneous propagation of deformation bands under stationary boundary conditions and the consequent growth of the visco-plastic strain rate. Notably, our analyses show that the occurrence of such delayed instabilities are marked by the vanishing of a critical hardening modulus and correspond to transient pulses of overstress, which signal the stage of strain localization in an active process zone. A number of examples are finally shown to illustrate the applicability of the proposed indicators, with emphasis to geotechnical tests (e.g., plane strain compression) and engineering applications (e.g., borehole excavation).

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Active Learning Sensitivity Analysis for a Visco-Plastic Sand Breakage Model

Author(s): *Dimitrios Tsapetis, *Johns Hopkins University*; Mohit Chauhan, *Johns Hopkins University*; Michael Shields, *Johns Hopkins University*; Aaron Baumgarten, *Johns Hopkins University*; Nilanjan Mitra, *Johns Hopkins University*; Ryan Hurley, *Johns Hopkins University*; K.T. Ramesh, *Johns Hopkins University*;

Granular materials, such as sand, constitute a key ingredient of many engineering applications ranging from geomechanics to construction. The intrinsic composition of these materials, created from finely fractioned rocks and minerals of varying sizes, introduces a large uncertainty into their mechanical behavior. This uncertainty is enhanced during dynamic deformation and penetration, especially in the presence of pore fluids. These observations motivate this work, in which we apply Uncertainty Quantification (UQ) to a mechanism-based constitutive model to compute the influence of input parameter variability on the final mechanical performance. The computational model under consideration [1, 2] is a visco-plastic breakage model and the simulation of interest involves a triaxial confining pressure stage followed by a shear deformation. Four parameter categories containing the elasticity parameters, grain size distribution, particle material parameters and particle breakage dissipation parameters are required for the model evaluation. In total there are 20 uncertain parameters which we study with our sensitivity analysis. The selection of the sensitivity analysis algorithm depends on the number of model evaluations that are required for sufficiently accurate calculation of sensitivity indices. In the case of a Monte Carlo based computation of the sensitivity indices, thousands of simulations would be required for accurate estimation. This is computationally prohibitive for problems of practical interest. Instead, a novel active learning Gaussian Process surrogate-based method is proposed which can drastically reduce the number of required simulations, while providing accurate sensitivity results and confidence intervals.

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Urban Planning and Coastal Hazards: A Future Oriented Agent-Based Model for Coastal Community Resilience

Author(s): *Dylan Sanderson, *Oregon State University*; Dan Cox, *Oregon State University*; Mehrshad Amini, *Oregon State University*; Andre Barbosa, *Oregon State University*;

Acute and chronic coastal hazards can cause damages to the built environment, which in turn disrupt daily activities, and often disproportionately impact population sub-groups. Despite these disruptions, the economy of coastal communities is often driven by their proximity to these otherwise hazardous areas. Urban planning has been identified as a means to mitigate and adapt to coastal hazards; however, unlike most hazard risk assessments which consider static, present-day conditions, urban planning necessitates a future-oriented lens of the built environment. In this presentation, we will explore how zoning and policy can be used to mitigate the impact of coastal hazards and to what extent these mitigation measures either positively or negatively impact coastal populations. A spatially explicit agent-based model (ABM) will be presented which simulates how the urban environment evolves under future scenarios. This ABM is a residential choice model in which agents, both full-time residents and visitors, search for places of residence that meet their preferences. Agent demand, zoning, and policy impact the availability and location of housing that agents are competing for, which ultimately informs how the urban landscape evolves. The ABM is coupled with IN-CORE, a modeling framework to evaluate the resilience of communities subject to natural hazards. Through this coupling, the model can be used to explore how urban planning impacts the resilience of coastal communities. To demonstrate this model, the coastal community of Seaside, Oregon is utilized as a testbed and seismic-tsunami hazards are considered.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: A Building-Block Approach to the Conceptual Design of Shape Adaptive Structures

Author(s): *Ed Wheatcroft, *University of Bristol*; Rainer Groh, *University of Bristol*; Mark Schenk, *University of Bristol*; Jiajia Shen, *University of Bristol*; Alberto Pirrera, *University of Bristol*;

Structural instabilities have traditionally been regarded as a failure mechanism; more recently, they have been exploited as a means of designing shape adaptive structures. We are designing a passively actuated morphing aerodynamic device which will utilise structural instabilities as a means of deploying. There are three main requirements of this device; Firstly, it must exhibit large elastic deflections in response to small changes in a controlling parameter. Secondly, the structure must not exhibit significant deflections until the controlling parameter reaches a critical level. Finally, it must not undergo further shape change once it has traversed this large deflection regime. In effect, this creates a 'binary' device, which is either fully stowed or fully deployed depending on the level of the controlling parameter.

These needs are partially met by a structure with a snap-through instability, which exhibits a sudden shape change when a limit point is reached. However, there will normally be significant deflections before this point, which violates the second design requirement. A super-critical branching point structure is also only partially satisfactory; whilst output deflections are initially small, out of plane deflections after the critical point occur gradually. Such structures also rapidly re-stiffen, limiting the amount of possible shape change.

Taking a building-block approach, we combine structural components with different fundamental instabilities into a morphing structure with the desired response. To aid the conceptual design of such a structure, we first explore simple analytical bar-and-spring models with limited degrees of freedom. To achieve the desired response, the output of one structure is connected to the input of a second—for example, the output deflection of a branching point structure becomes the controlling parameter for a second structure with a snap-through response. The total potential energy of the whole system is computed to identify the equilibrium paths and their stability.

Using these simple models, we demonstrate that structures which combine basic instabilities can be used to create 'binary' devices which meet our requirements. We show that these models can be used to capture the behaviour of more complex structures which operate using the principle of combining instabilities. Future work will focus on using such models as a tool for designing shape adaptive structures.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Imperfection Analysis of In-Situ 3D Measurements of Stainless Steel Unequal-Leg Angles for Computational Modeling

Author(s): *Edward Sippel, *University of Wisconsin–Madison*; Hannah Blum, *University of Wisconsin–Madison*;

Metallic structures efficiently use material resulting in structural elements that are often susceptible to buckling instabilities. To reliably model member instabilities, accurate measurements of initial imperfections are required as the imperfections influence both the strength and failure mode of the member. Traditionally, accurate measurements can be obtained through different methods such as using a series of LVDTs with a milling bed or a group of lasers which scan along discrete measurement lines in a specially built rig. A common challenge with either of these approaches is that the testing configuration works for limited cross-section sizes and member lengths and can be time consuming to reconfigure as needed. Recently, non-contact portable handheld 3D laser scanners have become readily available which have increased flexibility for scanning various structures. A 3D point cloud of any scanned object can be created by aligning the geometry and texture captured by the handheld scanner. However, the consistent geometry and surface uniformity of the structural elements can lead to difficulties accurately aligning individual scans. Once aligned, the challenge remains to reduce the dense point cloud data to useful information for computational modeling. For this study, a series of hot-rolled stainless steel unequal-leg angle specimens were scanned prior to testing. The scan data was analyzed to define the imperfections for implementation in finite element models of the experimental series. A simple, flexible scanning procedure was developed to correct scan misalignment while readily fitting members ranging from one to four meters long. The resulting scan information was processed to determine global translational and rotational imperfections for each member. Overall, the handheld 3D laser scanner proved to be an effective and efficient method to measure initial member imperfections in metallic members.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Changes in Physical Properties and Chemical Structure of Gamma and Neutron Irradiated Calcium Silicate Hydrates

Author(s): *Elena Tajuelo Rodriguez, *Oak Ridge National Laboratory*;

Calcium silicate hydrates are the most voluminous hydration phases of cement paste and responsible for most mechanical behaviour of hydrated cement (both viscous and elastic responses). The understanding of changes in physical properties and chemical structure of C-S-H with irradiation is crucial to support both new construction in the nuclear sector and the maintenance of aging structures in existing reactor fleets that are seeing their life prolonged due to subsequent license renewals. A state of the knowledge on effects of gamma rays on mechanical properties and physical properties of C-S-H, such as elastic modulus, stress relaxation and porosity, and changes on water content, basal spacing dimension, H nuclei and Si Nuclear environments will be discussed based on data on several adsorbed doses from low to 189MGy. Ongoing efforts on understanding effects of neutrons on C-S-H will also be discussed.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Augmented Reality for Feedback and Control in Vibratory Experimentation

Author(s): *Elijah Wyckoff, *University of New Mexico*; Fernando Moreu, *University of New Mexico*; Marlan Ball, *University of New Mexico*;

Human-computer interaction can assist structural monitoring and structural dynamics testing in the laboratory. In vibratory experimentation, an external force is generated to test dynamic responses of structures. One mode of generating vibration is to use electrodynamic exciters. Manual control is a common way of setting the input of the exciter by the operator. To measure the structural responses to these generated vibrations sensors are attached to the structure. If the interface between operators and the exciter controls was augmented, then operators could visualize the experiments and the exciter levels with a better awareness of the area of interest. This new information would be used to change the control input during the test based on their understanding of the experiment in real-time. This research proposes using an Augmented Reality (AR) application to provide an interface for sensor feedback and vibratory experimentation control. This method improves cognition by allowing the operator to maintain awareness of the test structure while adjusting experimental conditions accordingly with the assistance of the new real-time interface. An interface application is developed to plot sensor data in addition to voltage, frequency, and duration controls from vibration generation. This paper presents the proposed model for the new control loop and then compares the new method with a traditional method by measuring time delay in control input and user efficiency.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Investigating Shaker-System Stability for Strong and Weak Nonlinear Systems

Author(s): *Eric Robbins, *University of New Mexico*; Fernando Moreu, *University of New Mexico*;

Bifurcations are commonly encountered during stepped sine testing of nonlinear structures which leads to jumping between stable solutions. Recent research has demonstrated developments where control test strategies have been successfully applied to nonlinear structures to control the response through the unstable solutions such that the multivalued response curves can be realized. This research applies these control test strategies, namely, acceleration amplitude control and voltage control tests to a fixture-pylon structure containing a strong nonlinearity and a c-beam structure containing a weak nonlinearity. The shaker-system stability was assessed as different materials and lengths of stingers generally had an effect on the quality of the control and responses during the tests. Based on preliminary testing, inconsistencies were found between the two structures as the strong nonlinear system continued to demonstrate jumps between stable solutions whereas the weak nonlinear structure demonstrated a multivalued response. The resulting disagreement of results between the structures was examined by exploring the stability of each system under the applied test strategy. This research contributes to the field of structural control as the control of structures exhibiting strong and weak nonlinearities that result in bifurcations in sine testing is explored.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: HYBRID: HYper-Reduced Basis Reduction via Interactive Decomposition

Author(s): *Esmail Rezaei, *University of Massachusetts Dartmouth*; Yanlai Chen, *University of Massachusetts Dartmouth*; Negin Alemazkoo, *University of Virginia*; Arghavan Louhghalam, *University of Massachusetts Dartmouth*; Mazdak Tootkaboni, *University of Massachusetts Dartmouth*;

The goal of dimension reduction techniques is to transform high-dimensional data to a low-dimensional space while preserving certain properties critical to the original data. Regardless of the strategy adopted, available techniques rely heavily on computationally intensive matrix factorizations, such as Singular Value Decomposition (SVD). These techniques are, therefore, quickly becoming intractable as the world is adapting to a new norm where massive datasets have become everyday commodities. Here, we present a new dimension reduction strategy, HYBRID: HYper-reduced Basis Reduction via Interactive Decomposition that offers remarkable efficiency and an error indicator certifying the accuracy by which the properties of the original data are preserved. HYBRID draws upon the reduced basis decomposition and recent advancements in the Reduced Basis Methods (RBMs) which have garnered a lot of attention in recent years as efficient dimension reduction tools for solving parametrized partial differential equations. In particular, we propose to speed up the construction of the reduced basis by adopting the concept of "Reduced Residual" that enables measuring the error efficiently on a subset of dimensions proportional to the intrinsic dimension of the given data set. We present a few numerical examples to demonstrate the performance of the proposed HYBRID technique and its competitive edges over exiting dimension reduction techniques.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Characterization and Modeling of the Multi-Directional Behavior of Rolling Pendulum Isolation Systems for Critical Building Contents

Author(s): *Esteban Villalobos Vega, *University of Oklahoma*; P. Scott Harvey, *University of Oklahoma*; James M. Ricles, *Lehigh University*; Liang Cao, *Lehigh University*; Daleen M. Torres Burgos, *University of Puerto Rico at Mayagüez*;

The effects of an earthquake on building contents (e.g., critical equipment) can impact life safety and disrupt business operations following the event. On some occasions, the motion does not even need to be strong enough to cause significant structural damage to pose a threat to equipment. The resulting social and economic losses can be minimized by reducing the seismic forces on these non-structural components through vibration isolation. Equipment isolation systems, in particular, are a promising strategy for protecting vital building contents, facilitating and accelerating the post-event functionality of the structure to the owners and occupants. Herein is presented an overview of a series of tests conducted at the Natural Hazards Engineering Research Infrastructure (NHERI) Experimental Facility at Lehigh University, which additionally includes two rounds of real-time hybrid simulation (RTHS) tests not included in this paper. In this study, controlled-displacement characterization tests were utilized to validate mathematical models of rolling pendulum (RP) isolation bearings that incorporate large equipment loads, supplemental rolling resistance, and large deformation behavior. As the isolation system, a single full-scale (4 RP bearings) OCTO-BaseTM isolation system from WorkSafeTM Technologies was used as the prototype; each RP isolation unit is made up of two conical steel plates (upper and lower) covered by an elastomeric coating (QuakeCoatTM) and a steel ball that rolls between these. The controlled-displacement characterization tests were defined to capture the envelope performance of the isolation system subjected to a variety of multi-directional conditions, by specifying combinations of low (quasi-static) and high variable or constant velocities, different X, Y, and theta amplitudes and frequencies, and different shapes—unidirectional sawtooth and sine waves, circles, squares, T-like, and butterfly-like—with and without rotation. An in-plane multidirectional shake table driven by three actuators was used to perform the tests. Restoring forces and moments were measured by restraining the top of the isolation system from moving horizontally by struts with uniaxial load cells, accounting for large deformation transformations. These responses are additionally an opportunity to finish calibrating and fine-tuning the experimental set-up prior to the more sensitive RTHS tests. In total, 19 characterization protocol tests were defined and performed. Details of the experimental testbed and test protocols for the characterization tests are presented, along with results which focused on the effect of the rolling surface treatment for supplemental damping, and rigorous evaluation of the comparison between the experimental results and those obtained using a calibrated theoretical model.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Smart Adaptive Mesh Refinement for Finite Element Simulation of Dynamic Problems

Author(s): *Fereshteh A Sabet, *Illinois Rocstar LLC*; Alessandro Gondolo, *Illinois Rocstar LLC*; Akash Patel, *Illinois Rocstar LLC*;

Computational meshing is a key part of a finite element (FE) simulation that can significantly affect the accuracy and efficiency of the solution fields. The efficiency and accuracy of FE modeling of complicated systems governed by partial differential equations can be improved by using adaptive mesh refinement (AMR). Use of AMR will allow the software to refocus its computational budget to regions where better resolution is required. Classical AMR methods are mainly based upon instantaneous error estimation, which may not be ideal for dynamic simulations. Such methods also depend largely on experts' knowledge and thus can be subjective to the user's experience. Illinois Rocstar has developed a supervised machine learning framework to automate AMR in finite element simulations, which will save computational time and effort and obviate the need for an experienced user. Our procedure includes computing the solution fields on the current mesh, marking elements for refinement based on the estimated refinement indicator, and creating a new mesh by refining the marked elements. We used the results of more than a hundred static simulations with varying geometry, boundary conditions, and materials properties to train the artificial neural network using normalized local stress and strain fields and their gradients as our classifiers. All classifiers in the model were normalized to avoid large variations in thresholds for refinement labeling. Elements were labeled for refinement based on the error in the energy norm calculated against models with a very fine mesh, which were considered as the ground truth solution. The option for the elements to be coarsened in areas where a fine mesh is not required to improve the efficiency of the simulations has been included. We demonstrate that our model can be successfully generalized to larger, more complex, and previously unseen static test cases. The trained model was applied to dynamic simulations and AMR used at every few time steps of the simulation, resulting in lower computational and implementation costs. The refinement occurred as we expected: elements were refined in expected regions, such as in front of a stress wave, and were coarsened after the wave passed through that part of the geometry. Employing the smart AMR method developed here can result in better simulation efficiency and is independent of the user's skills.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: A Study on the Hydrodynamic Response of Hypar Thin Shell Against Waves via a Decoupled SPH-FEM Analysis and Goda's Formula

Author(s): *Gaoyuan Wu, *Princeton University*; Maria Garlock, *Princeton University*; Shengzhe Wang, *Princeton University*;

An innovative structural form that incorporates hyperbolic paraboloid (hypar) thin shell has been validated as a feasible countermeasure against hydrostatic inundation [1, 2] and hydrodynamic wave loading [3] induced by Hurricane Sandy. However, the typical wave pressure on such geometries is yet unknown, which poses questions on understanding the mechanism of hypar-wave interaction and how to design or optimize the structures. In this study, a modified decoupled technique consisting of smoothed particle hydrodynamics (SPH) and finite element method (FEM) is introduced first, which provides structural engineers with a new efficient tool to study wave-shell interaction for disaster mitigation. Implementing the technique, SPH simulations with different wave characteristics and different hypar geometries are conducted, from which the typical hydrodynamic wave pressure on hypar is studied and summarized. The results also show that the widely used Goda's formula is a good candidate of predicting the wave pressure on hypar, which can facilitate the design and optimization of such structural forms for engineering applications. Lastly, the structural efficiency of hypar against waves is further evaluated via dynamic structural analysis, validating hypar thin shell, a legacy of Félix Candela, as a feasible and sustainable alternative to traditional gravity-based coastal structures that consume lots of material.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Experimental vs. Numerical Stability Assessment of Anisotropic Laminated Web Cantilever Beams Under Tip Force

Author(s): *Garima Sharma, *Kansas State University*; Hayder Rasheed, *Kansas State University*;

Lateral-torsional buckling of thin walled composite beams is a dominant failure mode under various loading and boundary conditions. Most of the earlier studies focused on especially orthotropic and symmetric laminated layups. In this study, an attempt is made to examine the behavior of generally anisotropic laminated layups. Wet layup process is used to manufacture different web beams of identical dimensions and varying layups. These beams are tested by clamping one end and mounting a loading bucket at the other end. Loading is gradually increased by adding lead shots into the bucket while deformations are measured by mounting two laser dots at the loaded end of the beam which projects on the specially designed frame with a recording screen. Load vs. twisting angle deformations are collected throughout the experiments. Experimental assessments are conducted and the results are compared against eigen value and non-linear Riks finite element computations. These results are further validated against analytical expressions developed earlier by the same research group. The effects of varying the lamination stacking sequence and the cantilever beam dimensions, for the same L/h ratios are comparatively studied. The results show promising agreement between the experimental measurements, numerical simulations and analytical predictions. This holds promise to advance the understanding of the behavior of such complicated structural elements and shortens the gap of introducing their design rules to the state of the art of engineering calculations.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: A Dislocation-Based Crystal Plasticity Finite Element Simulation for the Micropillar Compression

Author(s): Juyoung Jeong, *Louisiana State University*; *George Voyiadjis, *Louisiana State University*;

A new crystal plasticity model based on the dislocation mechanism is developed to study the mechanical behavior of face-centered cubic (FCC) single crystals under heterogeneous inelastic deformation through a crystal plasticity finite element method (CPFEM). The main feature of this work is generalized constitutive relations that incorporate the thermally activated and drag mechanisms to cover different kinetics of viscoplastic flow in metals at a variety of ranges of stresses and strain rates. The constitutive laws are founded upon integrating continuum description of crystal plasticity framework with dislocation densities which is relevant to the geometrically necessary dislocation (GND) densities and the statistically stored dislocation (SSD) densities. The model describes the plastic flow and the yielding of FCC single-crystal employing evolution laws of dislocation densities with mechanism-based material parameters passed from experiments or small-scale computational models. The GNDs evolve on account of the curl of the plastic deformation gradient where its associated closure failure of the Burgers circuit exists. A minimization scheme termed L1-norm is utilized to secure lower bounds of the GND densities on slip systems. The evolution equations of SSDs describe the complex interactions between two distinct dislocation populations, mobile, and immobile SSDs, relying on generation, annihilation, interactions, trapping, and recovery. The experiments of a micropillar compression for the copper single crystal are compared to the computational results obtained using the formulation. The physics-based model clarifies the complex microstructural evolution of dislocation densities in metals and alloys, allowing for more accurate prediction.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: A Data-Driven Bayesian Crack Nucleation Model for Fatigue in Ni-Based Superalloys

Author(s): *George Weber, *Johns Hopkins University*; Maxwell Pinz, *Johns Hopkins University*; Somnath Ghosh, *Johns Hopkins University*;

A data-driven Bayesian approach is developed to identify the underlying mechanics that drive crack nucleation in Ni-based superalloy Rene88-DT. Experimental 2D micrographs containing crack nucleation sites after undergoing low cycle fatigue are virtually replicated and simulated within an automated crystal plasticity finite element framework, providing mechanical state variable values at each material point of the microstructures. The virtual representations of these microstructures are embedded within a homogenized constitutive model to alleviate inherent boundary condition errors and provide an accurate simulation of the microstructure. A Bayesian classification method is applied in order to optimally select the most informative state variable predictors of crack nucleation and construct a near-pareto frontier of models with varying complexity. The paradigm of this Bayesian approach is to allow the micro-mechanical state variables responsible for causing crack nucleation events to arise naturally from existing data. This method allows the experimental data to inform a theory of crack nucleation, rather than generating a theory to test against data. The final Bayesian model highlights specific mechanistic features of crack initiation in superalloys, such as parallel slip and thermodynamic driving forces. The result is a model capable of predicting the probability of nucleating a crack at a microstructural position, given the mechanical state of the material.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: High Rates and Temperature Effects in Nanoindentation Testing on Hardness in SLM INC718

Author(s): *George Z. Voyiadjis, *Louisiana State University*; Reem Abo Znemah, *Louisiana State University*; Paul Wood, *Derby University*;

The aim of the current research is to study the effect of the scanning process parameters in selective laser melting (SLM) process, a powder bed fusion additive manufacturing process where the power source is a laser beam, on the mechanical properties of Inconel 718 (INC718) parts when the final external dimensions approach few multiples of the laser spot diameter. This size range represents the element size found in most cellular structures in engineering applications. While considerable research in the past decade aimed to characterize the material behavior of INC718 specimens cut from a larger bulk ingot or the nominal (effective) behavior of cellular structures. The research field is still short of accurate material characterization at such length scale built to the net shape when coupled with the process parameters of SLM.

For this purpose, hexagonal INC 718 honeycomb structures with three different cell wall thicknesses (0.4, 0.6 and 0.8 mm) were examined. The microstructure corresponding to the three wall thicknesses was scanned using Electron Channeling Contrast Imaging (ECCI), and the results revealed a variation in the average grain size among the three studied dimensions. The average grain size was observed to increase as cell wall thickness decreased. Furthermore, location dependency of the grain size and elongation was observed on the scanning planes compared to uniform elongation pattern in the lateral planes. The wall areas were scanned by an array of nanoindentations 50 μm apart in both directions to detect subtle changes in hardness. The hardness readings revealed a consistent drop in hardness readings in the contour area ($\sim 150 \mu\text{m}$ width on both sides) compared to the internal scanning area for each specimen. This was a combined by an anisotropy in the hardness readings between the top and lateral planes. Comparing the hardness results in the intermediate areas for the different dimensions revealed a reduction in the average hardness as the cell wall thickness was reduced. Increased hardness reduction sensitivity was pronounced as the element thickness was reduced from 0.6 mm to 0.4 mm. In addition, the different specimens and plans showed different hardness strain rate sensitivity that was related to the change in the average grain size.

A temperature and strain rate indentation size effects (TRISE) model developed earlier by Voyiadjis and his co-authors was modified to include the effects of the average grain size and specimen width on the hardness. Following this, a variable material length scale that gives a measure of the extent of the strain gradient field in the vicinity of the studied point that will add to its effective strain was evaluated by comparing the experimental results with the TRISE model for each specimen.

Another aspect will be studied for SLM-manufactured INC718, is the mechanical behavior under high strain rates ($\dot{\epsilon} = 10^2 - 10^4 \text{s}^{-1}$). Cylindrical specimens with different printing orientations are tested using split Hopkinson pressure bar. Evaluation of the material damage using electron microscopy and nanoindentation will be performed.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Design of Force-Limiting Deformable Connections in High-Performance Earthquake-Resilient Buildings

Author(s): *Georgios Tsampras, *University of California, San Diego*; Richard Sause, *Lehigh University*;

Novel force-limiting deformable connections reduce the seismic induced horizontal forces transferred from the floor-diaphragms to the seismic force-resisting systems in high-performance earthquake-resilient buildings with base flexural yielding mechanisms (e.g., reinforced concrete shear wall buildings) or base rocking mechanisms (e.g. precast rocking shear walls, self-centering concentrically braced frames) [1, 2, 3]. The force-limiting connections act as a seismic response modification mechanism and their use mitigates the contribution of the second and higher mode responses in the dynamic response of these buildings [2]. This presentation focuses on a force-based design method of force-limiting deformable connections. The proposed design method determines the limiting forces at each floor of the building based on a modified version of the ASCE/SEI 7-16 alternative seismic design force method for diaphragms. Results from numerical earthquake simulations of twelve-story, eight-story, and four-story reinforced concrete shear wall example buildings and a nine-story self-centering special concentrically braced frame building show that the proposed method enables the preliminary design of force-limiting deformable connections in buildings with reduced magnitude and variability in their seismic response compared to conventional buildings.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Hierarchy of Structural and Mechanical Length Scales in Granular Systems

Author(s): *Ghassan Shahin, *Johns Hopkins University*, Ryan Hurley, *Johns Hopkins University*,

The length scales governing structural and mechanical properties of granular materials are fundamental variables affecting constitutive laws and numerical modeling. Despite progress in quantifying length scales related to packing structure, shear bands, and force chains, a rigorous analysis of length scales governing various other properties has yet to emerge. In this work, we study representative volume element sizes governing structural and mechanical properties of granular solids by applying geostatistics to in-situ X-ray tomography and 3D X-ray diffraction data obtained during compression of samples with rigid and flexible confinement. Our results suggest that length scales are arranged in a hierarchy, with those governing structural variables such as fabric and packing fraction being the shortest, those governing mechanical variables such as mechanical fabric and stresses being intermediate, and those governing energy dissipation being the longest. These length scales and their ordering are insensitive to boundary conditions. Numerical simulations support the use of geostatistics to calculate these length scales in samples smaller than the length scales themselves, suggesting that they can be studied from high-fidelity in-situ experiments on small systems.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Experimental and Numerical Analysis of an Additively Manufactured Ti-6Al-4V Panel Subjected to Blast Loading

Author(s): *Gillian Schiffer, *United States Military Academy*; Brandon Escamilla, *United States Military Academy*; Cole Chappell, *United States Military Academy*; Kevin McMullen, *United States Military Academy*; Benjamin Simonson, *United States Military Academy*;

Since the early 2000s, buried improvised explosive devices (IEDs) have killed over 3,000 American soldiers in Iraq and Afghanistan.¹ The significant threat imposed by IEDs prompted the U.S. Army to focus on improving the level of protection provided for the next-generation combat vehicles as one of six priorities in the 2019 Army Modernization Strategy.² The goal of the new design is to minimize the mass, allowing the vehicle to maintain its maneuverability capabilities, while minimizing deflection to prevent the panel from penetrating into the body of the hull and inflicting lower-extremity injuries upon vehicle occupants. Current designs for underbody protective panels, such as the monolithic plates and V-Shaped hulls, are inefficient at protecting vehicle occupants. The United States Military Academy is investigating the design of a lightweight, modular protective panel for the underbody of combat vehicles. The structural designs are optimized to minimize the mass and deflection of panels by providing passive energy dissipation mechanisms. Fifteen alternatives were generated, including auxetic structures, sandwiched panels, Gaussian curves, and tubular interiors. Each alternative design was modeled and meshed in a high-fidelity finite element modeling software. The loading was simulated through analytical impulse time histories derived to represent the radial flow field of an equivalent buried blast event. The main criterion used to evaluate the alternative designs was the maximum deflection of the panel compared to a monolithic plate of equivalent areal density. The highest performing design consisted of a Gaussian curvature underbody. The design was refined to include tubular interior supports to further reduce the maximum deflection. A small-scale prototype of the final design was additively manufactured from a sintered titanium alloy Ti-6Al-4V. The panel was experimentally tested at a small-scale blast facility at the Army Research Laboratory. The experimental deflection data was collected using high-speed digital image correlation and compared to the finite element simulations. The results of the experimental test were used to validate the modeling methodology including the boundary conditions, material model, and loading conditions. Based on the refined model, two additional designs will be additively manufactured and experimentally tested to further improve the performance. The results of this study have the potential to advance the level of protection provided by the U.S. Army next-generation combat vehicles, ultimately saving soldiers' lives.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Tough Nacre-Like Cement Paste-Silicon Architected Composites

Author(s): *Hadi Shagerdi Esmaeeli, *Princeton University*; Reza Moini, *Princeton University*;

Biological materials offer an unparalleled combination of two competing material properties, strength and toughness. For instance, the brick-and-mortar architecture of biological nacre made of mineral tablets held together by organic protein interfaces gives rise to several toughening mechanisms. These biological composites comprise a trace quantity of organic interface material that toughens the inorganic tablets in a three-dimensional assembly. This brick-and-mortar arrangement leads to deformable and tough characteristics, owing to the microscopic tablet sliding followed by the crack deflection and branching mechanisms. In particular, strain hardening at the interface, pull-out of platelets from the interface, chain unfolding, and cross-link breakage are among the primary mechanisms likely to contribute to energy dissipation and enhanced toughness nacre-like composites. This work focuses on designing and fabricating three-dimensional nacre-like cement paste-silicon composite assemblies through multi-stage depositing of silicone material in-between hexagonal cement paste tablets. The aspect ratios and arrangement of tablets and their effect on fracture toughness and ductility were investigated. We hypothesize that introducing the highly deformable and compliant silicon material adhered strongly to hard cement paste tablets with a high aspect ratio and structural arrangement mimicking those of the natural counterparts, can lead to large-scale tablet sliding mechanism, crack deflection and ultimately enhanced fracture and damage tolerance. The resultant multi-layered cement paste composite is a tough and deformable composite material while maintaining a high stiffness and flexural strength, compared to the monolith brittle cement paste material.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Conditional Neural Network-Based Parameter Estimation for Non-Gaussian Wind

Author(s): *Haifeng Wang, *Lehigh University*; Paolo Bocchini, *Lehigh University*; Jamie Padgett, *Rice University*;

The simulation of non-Gaussian wind pressure fields on building envelopes is critical for the accurate evaluation of building vulnerability under wind hazards or coastal multi-hazards, where time-domain response analyses need to be conducted considering structural and aerodynamic nonlinearities. Existing simulation methods typically rely on specific wind tunnel test data. Specifically, for each target building, the parameters of the pressure field models [e.g., probability distribution function (PDF), power spectral density (PSD), and coherence] need to be obtained from specific wind tunnel tests. However, in practice, significant variation in building geometries, design details, and wind hazard exposure may exist, thus posing a challenge to extrapolate the case-specific derived pressure field models to support regional risk and resilience quantification. To address this issue, a conditional neural network-based parameter estimation is proposed in this study to estimate model parameters based on existing wind tunnel test data.

In the proposed framework for wind pressure field generation, the conditional neural network is composed of two parts: (1) the weight-generation sub-network (WGSN) and (2) the parameter-estimation sub-network (PESN). The conditional neural network essentially leverages a two stage model to interpolate existing test data for a certain building and across different buildings. Specifically, the WGSN takes the condition vector (e.g., building geometry, wind direction, and terrain roughness) as input and provides as output the weights for the PESN. The PESN takes the coordinates of sensors across a given building configuration as input and provide as output the model parameter vector. In this way, the complex relationship between the wind pressure and wind condition vector is captured, allowing efficient estimation of the non-Gaussian and non-homogeneous pressure field for subsequent probabilistic response analyses.

In this study, the University of Western Ontario Boundary Layer Wind Tunnel dataset is used for training and validating the proposed conditional natural network, which is implemented with PyTorch. A novel four-parameter coherence model is proposed to describe the wind pressure field together with existing parametric PDF and PSD models. The trained network shows good performance in estimating the model parameters for wind conditions in the validation data. The resulting model can pave a path toward fragility modeling of a diverse set of buildings exposed to wind and coastal multi-hazards, supporting risk and resilience assessment in such coastal settings.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Efficient Phase Field Fracture Calculations: Domain-Decomposition Solvers and Adaptive Re-Meshing

Author(s): *Haim Waisman, *Columbia University*,

I will present two recent approaches that have been used to expedite the phase field method when solving fracture problems: Domain Decomposition preconditioner and adaptive mesh refinement.

First, I will discuss a novel updating domain decomposition preconditioner for parallel solution of dynamic thermo-mechanical fracture problems. Using an Additive Schwarz Method, the key idea is to decompose the computational domain into two subdomains, a localized subdomain that includes all localized features of the solution and a healthy subdomain for the remaining part of the domain. In this way, one can apply different solvers in each subdomain, i.e. focus more effort in the localized subdomain. Excellent performance of the proposed updating preconditioner is reported in serial and parallel computers.

Second, I will present a novel adaptive remeshing strategy with applications to quasi-static crack propagation in brittle materials. The adaptive refinement is based on the stability analysis which is combined with the quadtree decomposition. The stability analysis is based on a linear perturbation method that is used herein to determine the onset of fracture initiation on the fly. The approach does not require any post processing techniques for adaptive refinement and yet is shown to be effective.

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- [1] L. Berger-Vergiat and H. Waisman, An overlapping Domain Decomposition preconditioning method for monolithic solution of shear bands, *Computer Methods in Applied Mechanics and Engineering*, 318:33-60, 2017.
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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: A Novel 3D Discrete Beam Lattice Model: from Mesostructure to Macroscopic Behaviors of Wood

Author(s): *Hao Yin, *Northwestern University*; Erol Lale, *Istanbul Technical University*; Gianluca Cusatis, *Northwestern University*;

A 3D discrete lattice model to simulate the mechanical behaviors of wood materials (such as wood panel, ply-wood, CLT, etc.) at the mesoscale level is currently developed. The basic elements of such a lattice model are 3D curved beams characterized by (a) a general geometrical curvature and torsion of the axis as well as (b) an irregular cruciform cross-section. The various branches for the cross-section represent the walls of the wood cellular structure and the beam axis is the line at which various cell walls meet. The Isogeometric Analysis (IGA) techniques are employed in order to describe the beam geometries accurately. The connections between neighboring beams are characterized by the cohesive fracture laws for quasi-brittle materials in both normal and shear directions. The aim of this model is to simulate the orthotropic nature, as well as the fracture behaviors of the wood materials. The relationship between the mesostructure and the macroscopic properties of the material can be also investigated with the help of this model.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Virtual Distributed Real-Time Hybrid Simulation for Floating Wind Turbine Under the Coupled Wind and Wave Loads

Author(s): *Hezha Sadraddin, *Western Michigan University*; Bilal Alhawamdeh, *Western Michigan University*; Xiaoyun Shao, *Western Michigan University*;

Clean energy has become a main topic around the world and wind energy is one of the major resources that could be fossil energy alternatives. Limited land and near coast spaces led to the development of floating wind turbine (FWT) farms in unlimited space of deep water with steady winds to produce clean energy. Design, construction and safe operation of FWTs considering coupled wind and wave loads require a deep understanding of their dynamic responses. Experimental studies have been widely adopted to evaluate this complex dynamic evaluation. However, due to the size limitations of water tanks and wind tunnels used in FWT experiments, realistic FWT responses are difficult to be replicated on scaled-down test specimens. Moreover, the scaling conflicts between the Froude and the Reynold numbers exist in the coupled wind-wave loading tests of FWT. Real-time hybrid simulation (RTHS), combining the full-scale numerical simulation and the testing of large-scale substructure specimens in real-time, might overcome the aforementioned scaling conflicts in coupled FWT tests. Furthermore, RTHS can be executed to leverage the available large-scale wind tunnels and water tanks that are geographically distributed, leading to distributed RTHS (dRTHS). In this research, a dRTHS testing method is proposed for realistic dynamic response evaluation of FWT structures and numerical simulation of the proposed dRTHS method, namely virtual dRTHS (vdRTHS), is presented. First, the equation of motion (EOM) of a rigid-body prototype FWT structure under the coupled wind-wave loads was established. The FWT structural parameters in the EOM were then partitioned to represent the wind turbine tower and the platform substructures, based on which substructural formulation was derived for the vdRTHS. Two distributed real-time controllers were used during vdRTHS to simulate the physical testing of the two substructures tested in the wind tunnel and water tank, respectively, with interface data communicating to each other through the network in real-time. The vdRTHS test results were compared with the numerical simulation of the whole FWT and substructured FWT structure responses. Good agreements were achieved among these results, confirming that the substructuring method and the testing platform used in vdRTHS are applicable for the proposed dRTHS testing method for FWT, which pave the road for future development of physical dRTHS validation.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Multiscale Condition Assessment of Concrete Plates Using Impulse-Response Test

Author(s): Sikandar Sajid, *McGill University*; Luc Chouinard, *McGill University*; *Hizb Ullah Sajid, *Federal Highway Administration*;

This research introduces a procedure for obtaining both local material deterioration information and global structural damage detection in concrete plates using the impulse-response test as a single non-destructive test method. The impulse-response test has been widely used in practice for the detection of delamination, honeycomb and cracking in concrete elements. Given that standing waves form the basis of detection with the test, the latter provides the means to estimate structural level dynamic properties of the test element. A 3D finite element model of a reinforced concrete slab on elastic foundation is first developed in Abaqus® and validated with experimental data. The impulse-response test is then simulated with the numerical model over grid at the surface of the plate to obtain acceleration frequency response functions (FRF) at each point. The Accelerance of each dominant frequency peaks for each point is used to derive corresponding deflection shapes. The deflection shapes are shown to match closely the eigenvectors and eigenvalues obtained using the Lanczos algorithm in Abaqus®. Experimental impulse response tests are performed over a grid pattern on two concrete plates with and without defects to obtain FRFs using the methodology of ASTM C1740. The amplitudes of the dominant modes at each grid point are plotted to generate mode shapes at respective frequencies. The near surface delamination and debonding are delineated by the deflection shapes and represents a new approach for detecting local defects with the impulse-response test.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Residual Strength Assessment of a Heat-Straightened Steel I-Section Member Exposed to a Fire Event: A Case Study of a Brent Spence Bridge Stringer

Author(s): *Hizb Ullah Sajid, *Federal Highway Administration*; Ryan Slein, *Federal Highway Administration*;

The Brent Spence Bridge serves as a major crossing of the Ohio River, carrying I-71 and I-75 over the between Covington, KY and Cincinnati, OH, supporting an average daily traffic count of 180,000 vehicles. In November 2020, an accident between two semi-trailers resulted in a fire that acutely damaged adjacent deck stringers. The bridge owner consulted with the Federal Highway Administration (FHWA) as part of a National Transportation Safety Board investigation. Options of either replacement or heat straightening were proposed. Ultimately, the owner decided to replace the damaged stringers to ensure mobility of the bridge and to avoid risk associated with structural performance. FHWA secured one of the severely distorted stringers from the event to provide future stakeholders with an assessment of the viability of heat-straightening. Post-fire investigations, conducted by different researchers over the past decades, have shown that fire exposure can cause considerable loss in the residual mechanical properties. Beyond the event itself, additional heat is applied to the member during the straightening process, potentially further modifying the mechanical properties. This study aims to 1) independently observe heating patterns and bounds of the working temperature of the steel during heat-straightening conducted by a prominent commercial contractor, and 2) evaluate residual mechanical behavior at zones of maximum heat-induced distortion representative of both the fire event and the repair. Measured mechanical properties including yield strength, ductility, toughness, and hardness are tested in accordance with ASTM specifications. To support the findings, metallographic investigations are also conducted at the critical zones of maximum distortion. The obtained stringer is restrained in three-point bending with fork boundary conditions such that camber is removed, simulating discrete bracing at a uniform elevation. All external forces are monitored to ensure that mechanical straightening is not occurring. Results obtained from this experimental investigation will provide an assessment regarding the safety and structural performance of heat-straightened steel I-section bridge member damaged during a fire event.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Crack Cooling During Dynamic Crack Propagation in Thermo-Visco-Elastic-Plastic Solids

Author(s): *Jacob Thiesen, *University at Buffalo*; Jiaoyan Li, *University at Buffalo*;

In continuum mechanics, the number of balance laws in Lagrangian description can be condensed into two: balance of linear momentum and conservation of energy. In principle, one may perform a finite element analysis of any material provided that we have the constitutive equations of stress tensor, heat flux, and internal energy density. During the process of formulating a constitutive theory, if internal variables are introduced, then correspondingly for each internal variable a governing equation has to be derived. In this talk, we will formulate a set of generalized constitutive relations, including strain-based return mapping formula, for thermo-visco-elastic-plastic (TVEP) solid. During the process of formulating a theory of plasticity, a set of internal variables, including plastic strain tensor, were introduced. Then, for those internal variables, a set of governing equations, i.e., strain-based return mapping formula, was derived. A generalized finite element computer code for large strain thermomechanically coupled material system was developed. For illustrative purpose, we will concentrate on Poly(methyl methacrylate) (PMMA), which is a typical TVEP solid. We will solve a dynamic crack propagation problem to show the temperature variation, especially in the wake and in the front of the advancing crack tip, during the crack propagation process. An interesting cooling phenomenon around crack tip will be discussed.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Discovering Dynamical Equations Using a Denoised State-Variable Transformation

Author(s): *Jacqueline Wentz, *University at Colorado Boulder*; Alireza Doostan, *University at Colorado Boulder*,

Recent advances in data-driven techniques allow researchers to learn a system's dynamical equations using data. One method, known as Sparse Identification of Nonlinear Dynamics (SINDy), assumes the dynamics are sparse within a predetermined basis. As an example, the basis might contain monomials of the system states, up to a specified degree. The dynamical equations are learned by solving an l_1 -regularization problem, with a measurement matrix that contains the basis elements evaluated at the time-dependent state measurements. However, the measurement matrix may be ill-conditioned and the measurements may contain noise, leading to inaccurate results. To address these challenges, we developed new methods to account for measurement noise and poor conditioning of the measurement matrix. First, we introduce a denoising approach that uses estimators of the state moments to determine optimal smoothing parameters. We then apply a learned state-variable transformation to the denoised states. This transformation is optimized to reduce the correlations between state variable monomials and, thus, improve the conditioning of the measurement matrix. We demonstrate our approach on the Duffing and Van der Pol oscillators and find that we obtain reduced coefficient and prediction error as compared with existing approaches.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Performance-Based Structural Fire Design and Constructability of Tall Concrete-Filled HSS Columns

Author(s): *Jenny Sideri, *Thornton Tomasetti*; Pierre Ghisbain, *Thornton Tomasetti*; Luciana Balsamo, *Thornton Tomasetti*; Ali Ashrafi, *Thornton Tomasetti*;

Performance-based structural fire engineering (PBSFE), as opposed to traditional prescriptive fire resistance, is an approach based on quantified behavior of a structural system under realistic fire scenarios. As a rational design approach, PBSFE may offer improvements in safety, economy, construction schedule, aesthetics, design flexibility, and carbon footprint.

Fire resistance rating of concrete-filled hollow steel (HSS) columns has been quantified in AISC Design Guide 19. This document is based on experiments showing that concrete-filled HSS columns without any external protection can effectively sustain ASTM E119 fire loads to meet a fire resistance rating of up to two hours. These fire ratings are limited by the column geometry and the concrete compressive strength. These applicability limits are quite narrow (e.g. column height is limited up to 13 feet, and for round sections the diameter is limited up to 16 inches), and many real structures fall outside these limits. When designing a structure with taller and larger columns or a non-straight geometry, PBSFE is the only alternative method to meet the code intent without external passive fire protection.

This presentation will discuss practical implementation of PBSFE for structures with tall concrete-filled hollow steel (HSS) columns, along with potential design considerations regarding load path during realistic fires, connections, erection, detailing, constructability, and building straight versus bent columns. Example applications from different projects including Pittsburgh International Airport (PIT) are presented.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Time-Domain Linear Sampling Method for In-Situ Ultrasonic Imaging

Author(s): *Jian Song, *Department of Civil, Environmental & Architectural Engineering, University of Colorado Boulder*; Xiaoli Liu, *INRIA, Center of Saclay Ile de France, CMAP, Ecole Polytechnique*; Fatemeh Pourahmadian, *Department of Civil, Environmental & Architectural Engineering, University of Colorado Boulder*; Housseem Haddar, *INRIA, Center of Saclay Ile de France & UMA, ENSTA Paris Tech, Palaiseau Cedex, FRANCE*;

We present a theoretical, computational, and experimental application of the time-domain linear sampling method (TLSM) to laser ultrasonics for in-situ reconstruction of interfacial anomalies in safety-sensitive materials and components. Originally formulated for inverse electromagnetic and acoustic scattering, the TLSM is first rigorously adapted to elastic-wave imaging of cracks and dislocations in solids. The resulting indicator is then put to test both synthetically and experimentally in a laboratory setting. In the former case, we make use of the FreeFEM software to simulate 2D wave motion in an elastic plate in both pristine and damaged states. In our experiments, ultrasonic shear waves are generated in a prismatic slab of granite featuring a discontinuity interface whose interaction with the incident waves gives rise to transient velocity responses measured on the specimen's boundary by a laser Doppler vibrometer. Thus-obtained (synthetic and experimental) scattering signatures are then used to compute the TLSM indicator in a suite of sensing configurations. For completeness, a comparative study will be conducted with the LSM indicator maps obtained from the associated spectra of the computed and measured waveforms.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Deep Reinforcement Learning for Fish Fin Ray Control

Author(s): Xin-yang Liu, *University of Notre Dame*; Dariush Bodaghi, *University of Maine*; Qian Xue, *University of Maine*; Xudong Zheng, *University of Maine*; *Jian-xun Wang, *University of Notre Dame*;

For ray-finned fishes, the ray-fin structure is a highly sophisticated control system enabling versatile locomotion in complex fluid environments. Although the kinematics and hydrodynamics of fish fin locomotion have been extensively studied, the complex control strategy is still poorly understood. In this work, we develop a deep reinforcement learning (DeepRL) solution coupled with multi-fidelity fluid-structure interaction (FSI) models to decipher the control strategy and understand the underlying mechanism of ray-fin locomotion. In particular, we will leverage state-of-the-art off-policy RL structures, including Twin Delayed Deep Deterministic Policy Gradient (TD3) and Soft Actor Critic (SAC), to learn the complex ray-fin control strategies for different swimming needs. To accelerate the training process, the DeepRL agent interacts with virtual environments built upon the FSI models of different fidelities, where a transfer learning strategy is adopted for efficient learning. We also combine both the model-based DeepRL and model-free fine-tuning methods to improve the sample efficiency and learning performance.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: An Upwind Reproducing Kernel Collocation Method for Convection-Dominated Problems

Author(s): *Jiarui Wang, *The Pennsylvania State University*; Michael Hillman, *The Pennsylvania State University*;

Traditional Bubnov-Galerkin methods have proved immensely successful in modeling the problems which are self-adjoint such as heat conduction, elasticity, and so on. However, numerical instability arises in the Bubnov-Galerkin or central finite difference methods when strong convection in problems is present. The non-self-adjoint feature due to the convection term leads to spurious oscillations, but nevertheless can be handled by the class of Petrov-Galerkin methods. In particular, the upwind-type schemes and their variational and subgrid descendants have been developed substantially over the years for an effective weak-form Galerkin solution which precludes these instabilities. Nevertheless, these methods are immature for the class of strong-form collocation methods which utilize the high-order smoothness of approximations such as meshfree and isogeometric analysis, where numerical oscillations are observed when they are straightforwardly applied to convection-dominated problems.

In this work, an upwind meshfree collocation method is proposed to model convection-dominated problems. The connection between the upwind finite difference scheme and the gradient smoothing technique in meshfree methods is built. It turns out that in the collocation framework, selecting the collocation points as meshfree nodal points is not optimal. The second order diffusion term is approximated by using a finite-volume type approach, while the first-order convection term is treated by properly selecting the collocation points according to the flow direction. The upwind effect is achieved without introducing artificial parameters and it is trivial to generalize for multi-dimensional cases. Cross-wind diffusion is also not observed in the solution. An error analysis is presented, and the effectiveness of the proposed methodology is well demonstrated by the 1D and 2D numerical examples.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Coarse Grained Modeling of Nanostructure and Asphaltene Aggregation in Asphalt Binder Using Dissipative Particle Dynamics

Author(s): *Jin Tang, *Rutgers University*; Hao Wang, *Rutgers University*;

This study aims to develop coarse grained models of asphalt binders and study nanostructure and aggregation behavior of asphalt binders using Dissipative Particle Dynamics (DPD). The coarse-grained models of asphalt binders with different SARA (asphaltene, aromatic, resin and saturate) fractions were built with the mapping of bead groups and the calculation of forcefield parameters. The simulation results were validated through the calculated molecular structure parameters including interlayer distance and diffusion coefficient of asphaltene. The ordered stacking structures (T shape, face–face, and offset face–face stacking) were observed and the aggregation patterns of asphaltene were more obvious between the same type of asphaltene molecules due to self-similarity. The aggregation rates of asphaltene of three asphalt binders were found positively correlated with the mass fractions of asphaltene, which can be used to better predict relative viscosity of asphalt binders. The colloid structure of coarse-grained asphalt binders was observed on the mesoscale platform with small variations of localized nanostructure in three asphalt models. On the other hand, asphaltene showed the lowest diffusion coefficient that was similar among different asphalt binders. The analysis findings indicated that coarse grained modeling with DPD enables large-size model asphalt systems for observation of morphology and aggregation of asphaltene, providing a foundation to study complex molecular interaction in polymer modified asphalt binder.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Friction Modified Size Effect Law and Analysis for the Transverse Compressive Failure of Fiber Composites

Author(s): *Jing Xue, *Stony Brook University*; Kedar Kirane, *Stony Brook University*;

This work presents a numerical analysis of the effect of friction on the size effect in the transverse compressive strength of unidirectional composites. The model employed is based on the fixed crack concept, and combines friction and damage effects. The model is calibrated and verified using available test data on transverse compression of a carbon-epoxy T700/MTM57 unidirectional composite. Then it is used to predict the failure of geometrically scaled notched specimens of different sizes, each subjected to transverse compression. All specimens are predicted to fail in a geometrically similar fashion, by an inclined shear crack with prominent crack face friction starting from the notch-tip. The modeling results reveal a marked increase in quasi-brittleness due to inclusion of the friction effect. This reflects in a higher overall strength, increased by a roughly constant, size independent value, interpreted as the residual stress due to friction. It is also found that the size effect predictions must now be fitted by a modified form of the size effect law, that includes this constant friction stress term. Then this new friction modified size effect law is derived here by using energy balance and superposition principles.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Multi-Physics Modeling of Additive Manufacturing Processes via a Mixed Interface-Capturing/Interface-Tracking Approach

Author(s): *Jinhui Yan, *University of Illinois at Urbana-Champaign*; Qiming Zhu, *University of Illinois at Urbana-Champaign*;

High fidelity multi-physics simulations are in much demand to reveal the multiscale and multi-physics phenomena in metal additive manufacturing (AM) processes, yet accurate and robust predictions remain challenging. In this talk, we present a novel computational framework by mixing interface-capturing/interface-tracking methods for simulating the thermal multi-phase flows in metal AM applications, focusing on better handling the gas-metal interface, where AM physics, such as phase transitions and laser-material interaction, mainly takes place. The framework, built on level set method and variational multi-scale formulation (VMS), features three major contributions: (1) a simple computational geometry-based re-initialization approach, which maintains excellent signed distance property on unstructured meshes, re-constructs an explicit representation of gas-metal interface from the level set, and facilitates the treatment of the multiple laser reflections during keyhole evolution in AM processes; (2) a fully coupled VMS formulation for thermal multi-phase governing equations, including Navier-Stokes, level set convection, and thermodynamics with melting, solidification, evaporation, and interfacial force models; and (3) a three-level recursive preconditioning technique to enhance the robustness of linear solvers. We first compare the geometry-based re-initialization with the Eikonal partial differential equation (PDE)-based approach on two benchmark problems on level set convection and bubble dynamics. The comparison shows the geometry-based approach attains equivalent and even better performance on key criteria than the PDE-based counterpart. We then apply the developed framework to simulate two AM experiments, which Argonne National Laboratory has recently conducted using in-situ high-speed, high-energy x-ray imaging. The proposed framework's accuracy is assessed by thoroughly comparing the simulated results against experimental measurements on various quantities. We also report important quantities that experiments can not measure to show the modeling capability.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Multiscale Modeling of Microtextured Region (MTR) Effect on the Fatigue Nucleation of Titanium Alloy Using Parametrically Upscaled Constitutive Models

Author(s): *Jinlei Shen, *Johns Hopkins University*; Somnath Ghosh, *Johns Hopkins University*;

Abstract:

Titanium alloys have been prevalently used in high-performance aerospace industries, attributing to their excellent mechanical properties, e.g., high strength-to-weight ratio and good corrosion resistance. On the other hand, it is well-known these near α and β Ti alloys are prone to exhibit earlier fatigue failure under dwell loading, where the peak applied stress is held fixed for a considerable portion of the period of the loading cycle. While the researchers have revealed such cold dwell sensitivity stems from the underlying microstructural behavior, and more recently, the experimental observations showed the existence of microtextured region (MTR), which is defined as a cluster of grains with similar crystallographic orientations, serves a critical role in determining the fatigue life, it is still unclear how the various microstructure features affect the fatigue performance at the structural level. In this work, to investigate the microstructural effect, specifically with the inclusion of MTR, on the dwell fatigue nucleation of the two-phase Ti-6Al-4V (Ti64), a multi-scale modeling framework is developed, utilizing Crystal Plasticity FEM (CPFEM) at grain scale and Parametrically Upscaled Constitutive Model (PUCM) at macroscopic scale. Firstly, a variety of synthetic microstructures explicitly modeling the different aspects of MTR, e.g., intensity, size, shape etc. are generated, and the corresponding CPFEM simulations under stress-controlled cyclic loading are conducted to obtain the predicted crack nucleation cycles. The global sensitivity analysis with advanced interpolation technique is then employed to identify the importance of microstructural parameters with respect to the fatigue crack initiation. A novel representative aggregated microstructural parameter (RAMP) for MTR is proposed, and it is further incorporated into the development of Parametrically Upscaled Crack Nucleation Model (PUCNM) which bridges the microstructure to the structural fatigue performance explicitly and computationally efficiently, with the assist of machine learning tools. Finally, an innovative matrix integrating important RAMPs is constructed, aiming at better understanding of microstructural dependency on fatigue life of Ti64, and hence contribute to further improvement of material design.

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Title: Probabilistic Performance Assessment of Tunneling-Induced Structural Damage

Author(s): *Jinyan Zhao, *University of California, Berkeley*; Matthew DeJong, *University of California, Berkeley*;

Probabilistic prediction of structural damage is a promising technique to assist tunnel design and construction in urban areas. Due to the complexity of the tunnel-soil-structure system, the current modeling methods (predominantly finite element methods) are difficult to apply in probabilistic performance assessments, where an extensive number of model evaluations are typically required.

In the presented research, a fast yet accurate 3D model is developed to predict structure performance due to tunnel construction beneath. The surface structures are modeled with the finite element method and the soil structure interaction effects are modeled with a two-stage elastoplastic approach [1]. A customized computer program was created to implement the proposed model; the program was first validated through comparison with results from a commercial computer software [2]. The customized computer program was then optimized with a high-performance linear solver and distributed computation strategy, which makes Monte-Carlo based uncertainty propagation possible. The program is demonstrated through a case study. After quantifying the uncertainty caused by soil variation, loading and tunnel construction uncertainties, the probability of structure damage at each stage of tunnel construction was computed, and damage mitigation procedures are suggested accordingly. Computation is done with the high-performance computer Savio at UC Berkeley. To further understand how structure damage is affected by each uncertain input, variance-based sensitivity analysis (i.e., Sobol's sensitivity analysis) is conducted. The uncertainty propagation and sensitivity analysis follow the framework first proposed in [3].

The significance of the presented research is the creation of a method of simulation-based probabilistic tunnelling-induced structural performance assessment without employing surrogate models. The presented research also demonstrated that the 3D effect and progressive modeling are important to achieve accurate assessment, although they are generally neglected in engineering practice. Further, the approach also enables regional simulations of tunneling scenarios, where the probability of structural damage for a proposed tunnel drive could be evaluated.

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Quantitative Multi-Hazard Community-Level Hurricane Risk Assessment Approach

Author(s): Omar Nofal, *Colorado State University*; *John van de Lindt, *Colorado State University*;

Hurricanes result in significant damage to coastal communities which lead to disruptions to other physical and socio-economic systems. The hazards induced by hurricanes drive different types of loads on coastal buildings affecting their safety and functionality. A number of past studies have investigated the impact of these hazards solely or collectively including surge, waves, and wind. While these studies provided a novel contribution, the analysis resolution used in these studies did not enable a vulnerability analysis at the component-level or subassembly-level (group of components) and predict building vulnerability. Several existing modeling drawbacks, some resulting from data scarcity, are the complexity of the combined impact of hurricane-induced hazards made it difficult to develop high-resolution multi-hazard hurricane vulnerability models and provide validation for these models; and propagation of uncertainties in the damage models made it a challenge to develop and validate these models. Therefore, in this study, a high-resolution multi-hazard hurricane risk assessment approach was developed to account for the combined impact of hurricane-induced hazards on the building system after propagating the inherent uncertainties in the building's components resistance including structural and nonstructural components along with the interior contents. This approach account for the combined impact of surge inundation depth, surge inundation duration, significant wave height, and wind speed. The developed approach was extended to be used at the community-level after using the concept of building portfolio to model the vulnerability of different building typologies. The developed approach was then applied to Galveston County, TX to show the applicability of the developed model at large spatial scales. The developed multi-hazard hurricane risk assessment model can leverage many community resilience analysis studies and provide policymakers with better risk-informed decisions.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Permeability and Diffusivity Simulation Based on Gray Lattice Boltzmann Method Using 3D Microtomography of Cement Composites

Author(s): *Jongmin Rim, *Seoul National University*; Juhyuk Moon, *Seoul National University*;

Assessment of durability for concrete structures are one of the foremost problems faced by the construction industry. Determination of permeability and diffusivity coefficients is widely used methods to assess durability of concrete structures nowadays. Field tests and Lab tests have different limitations for the determination. Therefore, simulation based methods are proposed to consider various environments affecting structures. FE, FV schemes for the simulation consumes long time and have difficulties with treating complex geometries. Lattice boltzmann method can be conducted on complex geometries easier and have advantages in parallel computing. In this paper, determination of the permeability and diffusivity coefficients is conducted with lattice boltzmann method based simulation on 3D microtomography of cement composites. Simulation using 3D microtomography has limitation with difference between resolution and pore sizes. To be specific, cement matrix defined from microtomography should be treated as permeable solid. Therefore, gray lattice boltzmann mehtod is used to deal with the permeable solids in cement composites. In this paper, Gray lattice boltzmann method was tested for complex real geometry of cement composites and compared with experiment results,

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: UAV-Deployable Vibration Sensing Nodes

Author(s): *Joud Satme, *University of South Carolina*; Corinne Smith, *University of South Carolina*; Austin Downey, *University of South Carolina*; Nikos Vitzilaios, *University of South Carolina*; Rizos Dimitris, *University of South Carolina*;

As bridges, railroad networks, power transmission towers, and more existing infrastructure continue to age, the necessity to accurately quantify deterioration and damage becomes more important. A structure's vibration signature holds information about the health and operating conditions. Manual methods of sensor deployment for vibration-based structural health monitoring (SHM) can be time-consuming, cost-ineffective, or even limited in safety-critical situations. Strides in wireless communication, energy harvesting, and power management have made high mobility small footprint sensors in SHM applications a viable option. This work reports on recent advances in a UAV-deployable sensor package for measuring structural accelerations coupled with a frequency response filter algorithm to aid in noise reduction. Utilizing electro-permanent magnets (EPMs), sensor packages can easily be mounted to any ferrous surface on the test structure with minimal interference. This type of magnet was chosen due to its favorable power requirements, where power is only supplied when the magnet switches states. To further reduce power constraints, the developed UAV-deployable sensor node has implemented load-sharing solar panels as a strategy to extend the sensors package's lifespan, up to one week, contributing to more accurate data sets for analysis and damage quantification. The effect of measurement transmissibility through the sensor package has been addressed by implementing a transfer function-based filter that results in a signal to noise ratio improvement of over 1 dB, a 6.69% improvement over the range of 0-20 Hz, the bandwidth typically found in the vibration signature of large structures. Moreover, the proposed filter results in a sensor package with excellent accuracy between 6 and 15 Hz. A wireless system was also integrated into the package for various uses such as IO commands to control the sensor package parameters, data transfer, and relaying package status (charge and memory capacity) to the operator. The UAV deployment systems include a deployment and retrieval mechanism mounted onboard a delivery UAV to further improve the autonomous rapid-deployment of large-scale sensor networks. During deployment, the system employs two EPMs, one on the UAV and one on the package, each controlled by the UAV flight controller. The magnets are toggled, establishing contact with the structure and releasing from the UAV simultaneously. The sensor node presented in this work, in combination with the UAV-deployment mechanisms, lays the groundwork for the rapid-deployment of large-scale networks of vibration-based sensors for SHM.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Topology Optimization with Bilinear Elastic Material Models

Author(s): *Justin Unger, *Johns Hopkins University*; Alberto Torres, *Johns Hopkins University*; Andrew Gaynor, *DEVCOM U.S. Army Research Laboratory*; Matthew Vaughn, *Johns Hopkins University*; Brandon McWilliams, *DEVCOM U.S. Army Research Laboratory*; Kevin Hemker, *Johns Hopkins University*; James Guest, *Johns Hopkins University*;

Stress-dependence of a material's stiffness and strength is a common characteristic in the domain of engineering design such as with applications of certain additively manufactured components and materials. Automated and conventional design methods using isotropic material and uniaxial yield surface models do not properly account for this stress-dependent behavior. We consider the case of materials and applications with tension-compression asymmetry of elastic moduli and yield criterion and propose a topology optimization scheme that incorporates new advances on stress-dependent constitutive material model inspired by ideas in [1,2]. Tension and compression elastic moduli and yield stress limits are material or application-dependent and controllable as initial input variables. This optimization scheme is demonstrated on canonical topology optimization problems for minimum compliance with volume constraints as well as minimum mass with displacement (stiffness) and stress constraints with all solutions satisfying minimum length scale. Various perturbations of tensile and compressive properties in both stiffness and strength regimes, along with extensions of stiffness model framework to global stress-dependence (i.e. build-direction), illustrates the potential of the method for design of stress anisotropic components and materials. [1] A. Gaynor, J.K. Guest and C. Moen. Reinforced concrete force visualization and design using bilinear truss-continuum topology optimization. *Journal of Structural Engineering*, 139(4): 607-618, 2013. [2] Yang Y., Moen C.D., and Guest J.K. (2015). Three-dimensional force flow paths and reinforcement design in concrete via stress-dependent truss-continuum topology optimization. *ASCE Journal of Engineering Mechanics*, 141(1): 04014106.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Analytical Stress Intensity Factor for Shear In-Plane Load in Reflective Cracking Model

Author(s): *Kairat Tuleubekov, *Applied Research Associates*; David Brill, *Federal Aviation Administration*;

The Federal Aviation Administration (FAA) developed a two-dimensional model of its full-scale, indoor, reflection cracking test equipment at the National Airport Pavement Test Facility (NAPTF), William J. Hughes Technical Center, Atlantic City International Airport, NJ. The analytical model represents two jointed concrete slabs and a continuous hot mix asphalt overlay with a single, preexisting vertical crack centered on the joint. Mode II stress intensity factors (SIF) were derived from superposition of the linear elastic solutions of two separate problems having different domains. The first problem considers the uncracked domain with the same prescribed vertical displacements at the bottom as the original problem. The second problem considers the cracked domain, where vertical displacements at the bottom boundary are prescribed to be zero. The sum of the solutions of these two problems in the linear elastic domain gives the desired Mode II solution at the vicinity of the crack tip. By applying Schapery's theory of crack propagation in viscoelastic materials, this model can be used to determine the energy release rate (ERR) in and asphalt overlay subject to Mode II cracking caused by repeated aircraft traffic loads. The model was used to compute Mode II SIFs at the crack tip for a series of incremental crack lengths, using assumed properties. Computed SIF values showed good agreement with SIF values computed by a finite element model (ABAQUS).

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Bounds of Relaxation Functions for Aging Composites

Author(s): *Kairat Tuleubekov, *Applied Research Associates*; Lev Khazanovich, *University of Pittsburgh*;

Determination of deformation properties of composite materials from properties of their components is an important problem. This presentation concentrates on the micromechanics of particulate composite materials of which the components may exhibit creep properties and these properties may depend on the time of load applications. Eshelby's theorems for elastic materials and Hashin's approach for homogenization of elastic properties was generalized to obtain the bounds for the relaxation functions. For Hashin's assemblage, further simplifications of the bounds are developed. An approach for determination of effective shear relaxation function that can be interpreted as a generalization of the Mori-Tanaka scheme is also proposed.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Quantification of Seismic Energy Demand and Capacity of Nonlinear Structures

Author(s): *Kevin Wong, *National Institute of Standards and Technology*;

Building structures constructed in the seismic regions are vulnerable to earthquake activities and are designed with the anticipation of suffering significant damage without collapse during a major earthquake. To design these structures the classical seismic design procedure uses a force-based approach where reduced seismic force demands are evaluated and compared to the corresponding seismic capacities. An improved performance-based seismic design procedure recently developed uses a displacement-based approach, where the maximum nonlinear deformations of the structure are evaluated and compared with the corresponding acceptance limits to ensure ductile behavior of the structures. However, neither of these procedures considers the effect of cyclic behavior that is typically observed in the seismic response of nonlinear structures.

On the other hand, energy is the product of force and displacement, which captures both monotonic and cyclic behavior of the structures. At the same time, structures suffering damage from a major earthquake is an energy transfer process. Earthquake ground motion transfers part of the energy to individual structures as input energy that induces vibrations in the structure and its contents, resulting in potential energy, kinetic energy, and damping energy. Quantifying these energy demands is often difficult, particularly in the calculation of potential energy, where earthquake often causes both material inelasticity and geometric nonlinearity in the structure. Since the potential energy relates to the stiffness of the structure, it consists of three components: (1) Strain energy associated with the elastic portion of the material; (2) Higher-order energy associated with geometric nonlinearity of the structure; and (3) Plastic energy associated with material inelasticity of the components.

In this research, an analytical method is used to quantify the potential energy demand of fully nonlinear framed structures. A moment-resisting steel frame will be used to demonstrate the method. The result will show that plastic energy dissipated at each plastic hinge is a positive scalar quantity that can be calculated uniquely, and the sum of individual plastic energy at each plastic hinge is exactly equal to the overall plastic energy of the structure. Once the plastic energy demand is quantified uniquely, the structural performance and damage can be assessed by comparing this plastic energy demand with the corresponding plastic energy capacity, which can be obtained based on cyclic testing of the members. Through this process of quantifying the seismic performance of structures, higher level of confidence can be achieved in the design over the current force-based or displacement-based methods.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Modeling Microscale Solidification and Residual Stresses of As-Built Additively Manufactured Materials

Author(s): Lukasz Kuna, *National Research Council Postdoctoral Associate at the US Naval Research Laboratory*; *Kirubel Teferra, *US Naval Research Laboratory*;

Laser powder bed fusion (L-PBF) additive manufacturing (AM) fabricates materials through a layer-by-layer deposition process, where a concentrated heat source follows a scanning pattern to build successive material cross sections according to computer-based geometry specifications. The primary advantage to this fabrication process is the ability to have highly tailored and optimized geometries for a particular application. However, the fabrication process imparts high thermal gradients (on the order of 107 K/m) and cooling rates (on the order of 105 K/s), which leads to unique solidified microstructures as well as high residual stresses. In order to achieve performance reliability of built parts, the residual stress must be quantified and its effect evaluated.

This work is aimed toward developing models to predict the residual stress distribution at the polycrystalline length scale due to laser scanning history in order to improve modeling capabilities linking material processing to material microstructure and material properties. In prior work, an implementation of the cellular automata finite element (CAFE) model optimized for AM processing has been developed and validated for bulk material regions for powder bed fusion 316L in terms of polycrystalline grain morphology and crystallographic texture. This model is utilized as input geometry for crystal plasticity finite element thermomechanical analysis. This model assumed a one-way coupling between temperature and mechanical deformation through material coefficient of thermal expansion, computing thermally driving stress development during solidification. A simplified method of a sequence of static analyses is compared with a time domain analysis that includes element birth and death to model solid material be removed during melting. The model is applied to thin-walled structures and struts as these are very common geometric features in AM components. Through the use of this model, build condition parameters, such as strut angle with respect to build condition, can be assessed without resorting to costly trial and error experimental testing.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Damage Estimation and Condition Monitoring in Structural Systems Using Parametric Reduced Order Models and Limited Output Measurements

Author(s): *Konstantinos Vlachas, *ETH Zurich*; Konstantinos Tatsis, *ETH Zurich*; Anthony Garland, *Sandia National Laboratories*; Carianne Martinez, *Sandia National Laboratories*; Eleni Chatzi, *ETH Zurich*;

Structural and mechanical systems are oftentimes subjected to damage or rapidly evolving deterioration and degradation processes, which impel the vibration response beyond the normal operational regime. Apart from challenging the system serviceability and integrity, these events pose a limit to the versatility and applicability of structural health monitoring strategies. The present works aims to address the challenges associated with the response prediction and damage or parameter identification of systems subjected to such events in the context of vibration-based structural health monitoring. The proposed approach relies on projection-based Reduced Order Models (ROMs) for the representation of system dynamics, which are tailored to an inverse engineering framework that aims to estimate characteristic traits of the system's state and features of the induced damage. To assess the evolution of damage and capture the changes of system parameters over time, the ROMs are used as predictors in the context of a sequential Bayesian inference problem, whereby the physics are fused with vibration response measurements. This approach allows recursive state or damage-related parameter estimation through a bank of filters and an evolution strategy that captures the parametrized states' dynamics.

By continuously monitoring damage-related features and tracking the system's traits, the proposed framework aims to provide an indirect evaluation of the system's condition, while quantifying the induced damage. In turn, the estimated features and the condition monitoring information are utilized to choose a proper reduced-order basis enrichment scheme from a pool of Gaussian Process Regressors (GPR). Each GPR-based scheme encodes response information from different damage effects and utilizes the limited monitoring data to reconstruct the current state of the whole system in an online manner. This approximation, in turn, serves as a damage-related enrichment mode for the ROM and potentially allows for accurate response prediction under extreme events. Thus, the suggested approach enables the potential of deriving an adaptive reduced representation while serving as a warning framework in the case of potentially irreversible or even catastrophic consequences.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Subsurface Void Detection of Subgrade Around Culverts with Dual-Frequency Ground Penetrating Radar (GPR)

Author(s): *Koosha Raisi, *University of Massachusetts Lowell*; Nimun Nak Khun, *University of Massachusetts Lowell*; Aiyad Alshimaysawee, *University of Massachusetts Lowell*; Tzuyang Yu, *University of Massachusetts Lowell*;

The objective of this paper is to establish and assess the efficacy of dual-frequency (300 and 800 MHz) ground penetrating radar for the early detection of subsurface voids in culverts. Ground penetrating radar is a well-established and dependable nondestructive evaluation technique for locating and mapping subsurface anomalies such as voids and cracks. In this study, a 12 by 14 ft grid was placed on the surface of a road right above a culvert suspected of having subsurface voids in Townsend, Massachusetts, and the operation was conducted on wet pavement on a snowy day. It is crucial to discover subsurface voids early, particularly in the subgrade surrounding culverts, because moisture can penetrate the soil's capillaries and accumulate in the forming voids. If these voids are not detected in time, the section loss in the soil will result in stress redistribution within the subgrade, eventually leading to settlement and collapse of the surrounding soil, without prior warning. Multiple B-scans along the x and y axes were conducted on the marked grid using a dual-frequency (300 and 800 MHz) GSSI UtilityScan DF GPR; Additionally, various image processing techniques such as contrast adjustment, noise reduction, the wiener spatial filtering, and background removal algorithms were applied to the scans to isolate and analyze the size, severity, and moisture retention of the subsurface voids. Moreover, the voids' existence was validated by analyzing and comparing the signal amplitude fluctuations along the depth of the soil at both void and intact cross-range locations. Finally, the homogeneity of the subgrade soil was determined by computing the dielectric constants of selected elements of small thicknesses. The results verified the existence of multiple voids of varied dimensions around the culvert with suspected water retention. It was established that the GPR is capable of accurately detecting early-stage voids in culverts, even on wet surfaces.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Application of Probabilistic Learning on Manifolds (PLoM) for Performance-Based Seismic Assessment of Reinforced Concrete Moment Frame

Author(s): *Kuanshi Zhong, *Stanford University*; Javier Navarro, *Universitat Politècnica de Catalunya*; Sanjay Govindjee, *University of California, Berkeley*; Gregory Deierlein, *Stanford University*;

Structural seismic response analysis is an essential component in performance-based seismic assessment. For example, nonlinear response history analysis is conducted using selected ground motions at selected ground shaking intensities to generate sets of engineering demands (e.g., peak story drift ratios, etc.) which are used to develop statistics including medians, standard deviations, and correlations between demand parameters. High-fidelity models are usually computationally expensive, and it is common to have trade-offs between the model efficiency and resolution. While recent advances in surrogate modeling methods offer promising solutions to this problem, one key challenge is how to consistently propagate uncertainty in high-dimension problems which involve both ground shaking intensity measures and structural response demands.

Probabilistic Learning on Manifolds (PLoM) provides a powerful approach to generate realizations of a set of variables whose statistics are inherited from training data. This presentation will introduce the use of PLoM for developing surrogates from nonlinear response analyses of a reinforced concrete moment frame. A 12-story reinforced concrete moment frame in downtown Los Angeles is used as the archetype structure. Conventional multiple stripe analysis is first conducted to provide a comparison baseline. Ground motions are selected per intensity level to match the site's target conditional spectrum and significant duration. The selected ground motions are used for analyzing an OpenSees model of the 12-story moment frame. The structural response demands (peak story drift ratios and floor accelerations) sampled from the multiple stripe analysis along with key ground motion intensity measures are used as the dataset to train PLoM surrogates. New realizations of structural response demands are generated and compared with the baseline case. This process is repeated under different training data sizes and prediction/training ratios.

From the comparison, the median, dispersion, and correlation of generated response demands are found comparable to the baseline. Decreasing the training data size is found to increase the error of dispersion, but PLoM and baseline statistics remain in good agreement with 11 or more training data points per intensity level. The prediction accuracy is found to be insensitive to the prediction/training ratio.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: A Layout Optimization Framework of Large-Scale Wind Farms Based on Machine Learning

Author(s): *Kun Yang, *The University of Hong Kong*; Xiaowei Deng, *The University of Hong Kong*;

This paper proposes a layout optimization framework of large-scale wind farms based on machine learning. A validated ANN-based standalone wind turbine wake model, in conjunction with the superposition models, provides accurate power prediction for large-scale wind farms. Computational Fluid Dynamics (CFD) simulations are applied to generate reliable datasets for ANN training. The ANN model is tested to be as accurate as CFD simulation with an error smaller than 5% in power prediction. On the other hand, gradient-free and gradient-based optimization algorithms are compared in this problem. When under the same condition, gradient-free algorithms are capable of reaching better solutions when compared with gradient-based ones. However, the computational costs of the gradient-free algorithm are much higher. The accuracy and efficiency of the proposed optimization framework are justified by a virtual test wind farm and a real large-scale wind farm. By comparing with an analytical model, the results from the ANN-based framework show better agreement with CFD simulation results and Horns Rev wind farm measurement data. The proposed framework is proved to be about 7% more accurate than the analytical model. Considering the wind rose data of Horns Rev wind farm for the past three years, the optimal solution can produce extra 5% power production if the layout is optimized by using the layout optimization framework.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: EPRI's Battery Storage Fire Safety Roadmap

Author(s): Dirk Long, *Electric Power Research Institute*; *Lakshmi Srinivasan, *Electric Power Research Institute*;

Energy storage deployment is accelerating, and there are safety incidents drawing attention to hazards of battery energy storage systems. (Link to EPRI managed database below). This presentation discusses the results of a large industry collaborative research project of electric utilities and industry experts. The project, through several comparative site hazard mitigation analyses, developed a Battery Storage Fire Safety Roadmap to organize and prioritize work needed to advance the state of BESS safety throughout the industry. (Ref public link below). The roadmap provides necessary information to support proactive fire risk mitigation through battery system design, construction, operation, and maintenance. The proposed research will identify, assess, and address battery storage fire safety issues to help avoid safety incidents and loss of property. These research efforts are expected to increase battery energy storage system safety and reliability and improve confidence in future energy storage deployments. This presentation will also introduce current projects and available resources to address the identified industry gaps.

https://storagewiki.epri.com/index.php/BESS_Failure_Event_Database

<https://www.epri.com/research/products/000000003002022540>

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: A Fourth-Order Phase-Field Fracture Model: Formulation and Numerical Solution Using a Continuous/Discontinuous Galerkin Method

Author(s): *Lampros Svolos, *Los Alamos National Laboratory*; Hashem Mourad, *Los Alamos National Laboratory*; Gianmarco Manzini, *Los Alamos National Laboratory*; Krishna Garikipati, *University of Michigan*;

Modeling crack initiation and propagation in brittle materials is of great importance to be able to predict sudden loss of load-carrying capacity and prevent catastrophic failure under severe dynamic loading conditions. Second-order phase-field fracture models have gained wide adoption given their ability to capture the formation of complex fracture patterns, e.g., via crack merging and branching, and their suitability for implementation within the context of the conventional finite element method. Higher-order phase-field models have also been proposed to increase the regularity of the exact solution and thus increase the spatial convergence rate of its numerical approximation. However, they require special numerical techniques to enforce the necessary continuity of the phase field solution.

In this talk, we present the derivation of a fourth-order phase-field fracture model in two independent ways; namely, from Hamilton's principle and from a higher-order micromechanics-based approach. The latter approach is novel, and provides a physical interpretation of the higher-order terms in the model. In addition, we present a continuous/discontinuous Galerkin (C/DG) method for use in computing the approximate phase-field solution. This method employs Lagrange polynomial shape functions to guarantee C0 continuity of the solution at inter-element boundaries, and enforces the required C1 regularity with the aid of additional variational and interior penalty terms in the weak form. The phase-field equation is coupled with the momentum balance equation to model dynamic fracture problems in hyper-elastic materials. Two benchmark problems are presented to compare the numerical behavior of the C/DG method with mixed finite element methods.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Parallel Buckling Constrained by Adjacent Members

Author(s): *Lawrence Virgin, *Duke University*;

This paper exploits the accuracy and versatility of additive manufacturing to display interesting buckling behavior in slender elastic columns. A set of parallel columns were 3D-printed to relatively high precision, and then subjected to uniform axial loading. The load-deflection behavior and load-carrying capacity are influenced by the post-buckled mutual contact between adjacent columns. The role of initial geometric imperfections has an important role to play in this behavior. Given the capability of incorporating prescribed (but small) initial geometric imperfections using additive manufacturing it is feasible to seed post-buckling behavior, effectively tailoring stiffness. The final part of the paper focuses on extending the basic system to include a very large number of buckling columns, in which a statistical description might be useful.

L.N. Virgin (2018) 'Tailored buckling constrained by adjacent members', *Structures*, 16, pp.20-26.
<https://doi.org/10.1016/j.istruc.2018.08.005>

L.N. Virgin (2021) 'Simultaneous Buckling, Contact and Load Carrying Capacity', *Engineering Mechanics*, 147(5), 04021023. [https://doi.org/10.1061/\(ASCE\)EM.1943-7889.0001926](https://doi.org/10.1061/(ASCE)EM.1943-7889.0001926)

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Linear System Identification of the UC San Diego Geisel Library Building

Author(s): *Lin Sun, *UC San Diego*; Joel Conte, *UC San Diego*; Michael Todd, *UC San Diego*; Jose Restrepo, *UC San Diego*; Yehuda Bock, *UC San Diego*;

This paper focuses on linear dynamic system identification of the UC San Diego Geisel Library Building, an 8-story (5 above ground and two underground) landmark and iconic building of brutalist architecture, using different sources of dynamic excitation (i.e., seismic excitation and ambient excitations) under the assumption that the structure is linear elastic, linear viscously damped, and fixed at its base. The building was instrumented with an array of ten tri-axial high-resolution accelerometers installed on different floors and one weather station mounted on the penthouse (roof).

Five state-of-the-art state-space-based system identification (SID) methods, consisting of two input-output and three output-only methods, were used to extract the modal parameters, namely natural frequencies, damping ratios and mode shapes, from the vibration data recorded during a small (M5.3) earthquake. The lowest three identified modes are the global first torsional and first translational (flexural) modes in the two principal directions of the building, and the remaining identified modes are coupled translational and torsional higher modes. The modal properties of the building were also identified by using an output-only method together with the continuously recorded ambient vibrations (AV) during a 15-day monitoring period. The modes which could be identified from the AV data (subdivided into 10 min long back-to-back time data windows) are higher modes compared with those identified from the seismic vibration data. It is observed that the time-varying identified modal parameters vary periodically with a 1-day cycle due to human activity and changes in environmental conditions such as wind velocity and temperature.

The state-space model identified using input-output seismic data was also used to predict the response of the structure to the M5.3 earthquake, compare it to the measured response, and to study the modal contributions to the building response. Additionally, a linear elastic detailed finite element (FE) model of the building was developed and used to predict the natural frequencies and vibration mode shapes of the structure. The lowest three natural frequencies and mode shapes from the FE model show good agreement with the identified ones. This study provides a unique opportunity to apply linear system identification to a real-world full-scale civil structure under different types of dynamic excitation and to investigate the effects of changes in environmental conditions on the identified modal properties. It also lays the foundation for updating/calibrating the FE model in the modal and time domains using the modal identification results and recorded input-output seismic data, respectively.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Impulse Response Testing for Evaluation of Heritage Structures

Author(s): *Linda Seymour, *Simpson Gumpertz & Heger*;

Impulse Response (IR) is a non-destructive technique that can be used to help assess concrete structures for construction defects and deterioration. IR works by impacting the concrete surface with an instrumented hammer and measuring the surface's response with an accelerometer. Differences in response indicate changes in material condition or support and can thus identify a component's structural condition. The testing is typically performed on a grid, so that the processed data can be used to develop contour maps that indicate potential areas of concern or to monitor the structures response over time. In this talk, we use real project examples to describe how IR technology informed assessment of heritage structures. We show how the spatially resolved mapping can be applied locally, over a focused area of interest, or over an entire structure to inform sampling locations, repair strategies, and determine the efficacy of previous maintenance projects. Our case studies range from a small pedestrian bridge in New England to the entirety of a historic football stadium's seating area. Each case study provides insight into the breadth of IR applications, how the data correlate to other techniques, and the role that IR plays in decision making during repair and rehabilitation.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Collapse Reliability of High-Rise Reinforced Concrete Structures Under Extreme Winds

Author(s): *Liuyun Xu, *University of Michigan*; Seymour Spence, *University of Michigan*;

With the introduction of performance-based wind engineering, the estimation of collapse of structures subject to extreme wind loads is gaining growing attention. To prevent wind-excited structural collapse and improve structural reliability, various research efforts are under way with the aim of predicting the nonlinear behavior and failure mechanism during extreme wind events. The continued development of computational methods has led to numerical simulations being widely used as an economical and reliable technique to investigate collapses. Notwithstanding, material and geometric nonlinearities associated with the complex behavior of reinforced concrete can lead to various convergence problems making accurate collapse simulation challenging. Moreover, another key challenge emerges from the need to treat uncertainty in the in the structural system (e.g., model uncertainties associated with material parameters, degradation, and damping) as well as wind load uncertainties (e.g., record-to-record variability, wind speed and direction, duration). In this work, stratified sampling schemes are combined with high-fidelity finite element modeling of reinforced concrete (RC) systems for the estimation of collapse reliability under extreme winds. In particular, the uncertainty in the wind climate is model through a Copula-based approach that captures the affect of wind directionality. The record-to-record variability in the dynamic wind loads is captured through stochastic models based on the spectral proper orthogonal decomposition of directional data collected in specific boundary-layer wind tunnel tests. To ensure the results of the study are consistent with reliabilities used in calibrating modern codes, a comprehensive set of model uncertainties are included. To model the nonlinear response of the structural system, the stochastic simulation scheme is integrated with the finite element modeling environment OpenSees with large-displacements modeled through a corotational transformation and material nonlinearity captured through fiber models and hysteretic constitutive laws that capture material degradation, fatigue failure of the reinforcing, and concrete crushing. The framework is illustrated on an archetype 45-story RC building located in New York, NY. The collapse reliability of the structure is estimated and the failure mechanism of the system is investigated. Important insight into the modeling and extreme nonlinear response, including collapse, of RC high-rise structures subject to extreme winds is gained.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: A Fast Solver to Peridynamic Models of Pitting Corrosion Damage

Author(s): *Longzhen Wang, *University of Nebraska Lincoln*; Siavash Jafarzadeh, *Pennsylvania State University*; Florin Bobaru, *University of Nebraska Lincoln*;

We introduce a fast convolution-based method (FCBM) for peridynamic (PD) models of pitting corrosion damage. Based on passivation, salt-layer, and passive-film rupture mechanisms [1], the PD corrosion model simulates pitting corrosion damage as well as autonomous formation of lacy covers. The meshfree method previously used to discretize PD corrosion models scales as $O(N^2)$, where N is the total number of discretization nodes. For realistic problems involving hundreds or thousands of corrosion pits, spanning centimeter-scales and long duration, this becomes too costly. In order to simulate realistic problems (engineering-relevant length and time scales), faster algorithms are needed. By structuring the spatial integrals in the PD formulation in terms of convolutions and using the fast Fourier transform (FFT) to compute them, the computational complexity of the PD corrosion model is reduced to $O(N \log N)$. This approach also has significantly lower memory allocation needs: $O(N)$, instead of $O(N^2)$ for other methods. By using an “embedded constraint (EC)” approach, this method is applicable to bounded domains of arbitrary shapes and satisfying arbitrary given boundary conditions.

We verify and validate the model against previous simulations which used the meshfree discretization [2] and against experimental results [3]. The efficiency gains are impressive: computation time is reduced from days to hours and from years to days. This, together with massive reduction in memory allocation, allow for simulating pitting corrosion in a 3D cylinder with hundreds of pits growing simultaneously. This is the first demonstration of predicting pitting corrosion damage in samples of engineering relevance. Future steps include coupling the model with the PD fracture model to simulate stress corrosion cracking (SCC) [4].

Keywords: peridynamics, spectral methods, nonlocal model, corrosion, pitting corrosion

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Understanding Structure-Creep Relationships in Colloidal Glasses: Insights from Molecular Dynamics Simulations and Machine Learning

Author(s): *Luis Ruiz Pestana, *University of Miami*;

Concrete is the most widely used man-made material worldwide and is responsible for a large fraction of anthropogenic CO₂ emissions. Under the action of sustained loads and over long-time scales, concrete undergoes irreversible deformations that can severely restrict the lifetime of infrastructure. This process, known as aging creep, arises from the relaxation of the nanoporous and disordered network of colloidal particles that forms the nanostructure of cement, the “glue” in concrete. A direct and effective strategy to mitigate the environmental impact of concrete is to lower its consumption by extending the lifetime of infrastructure. However, our understanding of the mechanisms that govern aging creep in nanoporous colloidal glasses is incomplete and the relationship between the static structure of the glassy gel and its mechanical response remains poor. Here, we use extensive data from molecular dynamics simulations of glass model systems subjected to constant stress, together with deep learning models, to gain insight into local structural metrics that are predictive of the non-affine displacements of individual colloidal particles, as well as global system metrics that can explain the overall creep response of the glass. We also use this computational framework to further assess the effect of polydispersity and nanoporosity on the overall creep response of the glass. Our ultimate goal is to use our trained models for the rapid evaluation of the creep response of different nanoporous colloidal architectures, which will ultimately allow us to identify durable cement nanostructures that could most effectively resist creep.

Title: Micromechanics of Non-Embedded Spruce Wood: Novel Polishing and Indentation Protocol

Author(s): *Luis Zelaya-Lainez, *TU Wien*; Giuseppe Balduzzi, *Augsburg University*; Christian Hellmich, *TU Wien*; Josef Füssl, *TU Wien*;

The material properties, such as the reduced elastic modulus and the hardness, of wood can be determined by nanoindentation protocols and resulting unloading displacement curves [1]. There are several indentation campaigns performed in wood [2,3]. Nevertheless, most of them use embedding substances, such as resin, to stabilize the material for surface polishing protocols [4]. Thus, we propose a novel polishing protocol without the need of an embedding medium. This will be complemented by an extensive number of indents and a statistical nanoindentation technique [5,6] to identify the phase with non-mechanical damage, which is a probable result of preparation.

The nano-indentation protocol was performed in displacement control mode by means of a Triboindenter (Hysitron Inc., USA), equipped with a three-sided pyramid-shaped tip (Berkovich type). Conditions inside the indenter chamber were kept constant at 21 centigrade and 35 % RH. Three probability distribution functions work adequately for our resulting reduced elastic modulus. The mechanical undamaged phase (cell wall) is the mean of the distribution with the highest mean elastic modulus and hardness. [7] documented around 17 GPa for embedded samples. Meanwhile, we obtained around 15 GPa for the mean late wood undamaged phase. The phenomenon of an increase of 15% was observed for embedded compared to non embedded pine specimens [8].

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EMI 2022
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Title: A Novel Discrete, Mesoscale Modeling Framework for the Simulation of the Damaging and Fracturing Behavior of Composites

Author(s): *Marco Salviato, *University of Washington*; Sean Phenisee, *University of Washington*; Antonio A. Deleo, *University of Washington*; Daniele Pelesson, *ES3 Inc*; Mark Flores, *Air Force Research Laboratory*;

Unidirectional (UD) and 2D/3D textile composites are increasingly being employed in systems across many industrial sectors including aerospace, automotive, and wind energy. This is due to the excellent specific mechanical properties and tailorability of composites, paving new avenues for structural optimization and weight savings.

One of the challenges with the simulation of the mechanical response of composite materials is that their damage mechanisms depend strongly on the material micro- and mesostructures. Phenomena such as fiber micro-buckling and kinking in compression or fiber scissoring and matrix microcracking in shear in UD composites are only a few examples. Homogenized continuum models that describe these mechanisms are extremely mathematically complex, lack generality, and can only be used to fit experimental data. In fact, the constitutive equations compensate for not modeling fibers and matrix explicitly by introducing several complex equations and fitting parameters of unclear physical meaning. This makes model calibration extremely cumbersome and limits the predictive capability of the model.

In reality, the modeling of damage and fracture in composite materials does not have to be complex if the physics of the micro- and mesostructures is simulated explicitly. This is the goal of the Discrete Model for Composites (DM4C), a novel discrete mesoscale modeling framework that simulates the mechanical behavior of UD and textile composites. Specifically, this framework is only based on physical laws and does not depend on element erosion to simulate fracture. As it will be shown in this presentation, in DM4C, fibers, groups of fibers, and tows are simulated explicitly as Timoshenko beam elements while the matrix is described by vectorial constitutive laws defined on the facets of a tetrahedral mesh anchored to the nodes of the beam elements. These vectorial laws describe both the elastic and inelastic behavior of the matrix, including the traction-separation laws governing the fracture process and the friction between facets governing the compressive behavior. Thanks to the facet-based formulation, fracture is modeled in a discrete way and the need for element erosion can be avoided. Furthermore, since fibers and matrix are now simulated explicitly, the constitutive laws of each material can be physics-based, simple, and with clearly defined material parameters.

To demonstrate the predictive capability of the proposed framework, simulations of several typical damage mechanisms in composites will be compared to experimental data such as shear band formation in transverse compression, fiber micro-buckling and kinking in longitudinal compression, and sub-critical matrix microcracking in off-axis layers.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Learning Constitutive Relations in Multiscale Viscoelastic Materials

Author(s): Kaushik Bhattacharya, *California Institute of Technology*; Burigede Liu, *University of Cambridge*; Andrew Stuart, *California Institute of Technology*; *Margaret Trautner, *California Institute of Technology*;

The macroscopic behavior of materials is governed in part by small-scale rapidly-varying material properties. Fully resolving these features within the balance laws thus involves expensive fine-scale computations which need to be conducted on macroscopic scales. The theory of homogenization provides an approach to derive effective macroscopic equations which eliminates the small scales by exploiting scale separation. An accurate homogenized model avoids the computationally-expensive task of numerically solving the underlying balance laws at a fine scale, thereby rendering a numerical solution of the balance laws more computationally tractable.

In simple settings the homogenization produces an explicit formula for a macroscopic constitutive model, but in more complex settings it may only define the constitutive model implicitly. In these complex settings machine learning can be used to learn the constitutive model from localized fine-scale simulations. In the case of one-dimensional viscoelasticity, the linearity of the model allows for a complete analysis. For this case, we derive a homogenized constitutive model and develop a theory to prove that the model may be approximated by a recurrent neural network (RNN) model that captures the memory; this may be thought of as discovering appropriate internal variables. Simulations are presented which validate the theory, and additional numerical experiments demonstrate extension of the methodology to higher dimensions and to nonlinear viscoplasticity.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Mechanics of Origami Bellows

Author(s): Mengzhu Yang, *University of Bristol*; Fabrizio Scarpa, *University of Bristol*; *Mark Schenk, *University of Bristol*;

Origami bellows have been shown to offer a rich mechanical response, including deployability, multistability and tailorable stiffness. Applications range from robotic manipulators and deployable structures, to impact absorption devices and mechanical memory materials.

Its fold pattern dominates the mechanical response of an origami bellows; in fact, multistability can be predicted from pattern geometry alone. Most origami bellows, however, are not rigid-foldable and their axial compression or extension therefore also requires deformation of the facets.

In this work we investigate the structural response of origami bellows with Kresling and Miura patterns, and compare detailed finite element simulations against experimental results. Our results show that manufacturing details must be captured accurately in the numerical models, and we show new routes for tailoring the nonlinear stiffness of origami bellows.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Multifunctional Zirconia-Reinforced Metal-Matrix Composite for Energy Dissipation and High Temperature Applications

Author(s): *Marwa Yacouti, *Virginia Tech*; Maryam Shakiba, *Virginia Tech*;

This study investigates the behavior of zirconia-reinforced metal matrix composite under mechanical and thermal loading through finite element simulations. Zirconia-based ceramics belong to a class of smart materials that are characterized by two properties: superelasticity and shape memory effect. These features are achieved by virtue of a reversible phase transformation from a high-temperature tetragonal phase to a low-temperature monoclinic phase. The applications of zirconia faced major limitations due to its brittle failure at low strains. Nevertheless, recent studies showed that zirconia cracking can be suppressed using microscale zirconia structures. This encouraging result contributes to the resurgence of zirconia reinforcing particles as strengthening agents and one of the promising materials for energy dissipation applications. Compared to other widely used shape memory materials, zirconia-based ceramics are distinguished by higher stresses and a wider transformation temperature range (0°C-1200°C). The objective of this study is to exploit the shape memory actuation and the superelastic behaviour of zirconia to develop a composite designated for elevated temperature usage with an improved strength and energy dissipation. The composite consists of zirconia particles embedded in copper matrix. Microstructural simulations are performed to characterize the response of the composite and investigate the effect of zirconia volume fraction on the strength and the energy dissipation capacity as well as the strain recovery upon heating. This work provides insights into the promising potential of zirconia-reinforced copper-matrix composite for damping devices and artificial muscle applications such as robotics, aerospace and medical devices.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: 3-D Microstructural Modeling of Damage Propagation in Additively Manufactured Discontinuous Fiber-Reinforced Composites

Author(s): *Maryam Shakiba, *Virginia Polytechnic Institute and State University*; Reza Sepasdar, *Virginia Polytechnic Institute and State University*;

This presentation discusses a micro-mechanical framework for finite element simulation of progressive damage and failure in additively manufactured discontinuous fiber-reinforced composites under tensile loading along the fibers' axis. A numerical framework is proposed which includes accurate constitutive equations to explicitly simulate the fibers, matrix, and fiber/matrix interfaces within a representative volume element of the microstructure. The representative volume element is generated randomly, based on a target distribution for the fibers' aspect ratios, measured experimentally. The accuracy of the micro-mechanical framework is verified versus the experimental results of one of the recently developed additively manufactured aligned discontinuous fiber-reinforced composites as the composite of interest. It is shown that the proposed framework can accurately simulate various aspects of the mechanical response, including the failure pattern and stress-strain behavior. By simulating several randomly generated representative volume elements with various dimensions, an optimal representative model size for accurate and reliable investigation of the mechanical response is computed. Subsequently, the composite of interest is further studied by investigating the sensitivity of the mechanical response to a few constitutive equation-related parameters, including strength and fracture toughness of the fiber/matrix interfaces and the matrix strength. The correlation between the studied parameters and the composite's strength and failure pattern is also analyzed and the observed trends are presented and discussed.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: High-Order Implicit Shock Tracking for High-Speed Flows

Author(s): *Matthew Zahr, *University of Notre Dame*; Tianci Huang, *University of Notre Dame*; Charles Naudet, *University of Notre Dame*;

Shock tracking, as an alternative method to shock capturing, aims to generate a mesh such that element faces align with shock surfaces and other non-smooth features to perfectly represent them with the inter-element jumps in the solution basis, e.g., in the context of a finite volume or discontinuous Galerkin (DG) discretization. These methods have been shown to enable high-order approximation of high-speed flows and do not require extensive refinement in non-smooth regions because, once the non-smooth features are tracked by the mesh, the solution basis approximates the remaining smooth features.

In this talk, we introduce an implicit shock tracking framework that re-casts the geometrically complex problem of generating a mesh that conforms to all discontinuity surfaces as a PDE-constrained optimization problem. The optimization problem seeks to determine the flow solution and nodal coordinates of the mesh that simultaneously minimize an error-based indicator function and satisfy the discrete flow equations. A DG discretization of the governing equations is used as the PDE constraint to equip the discretization with desirable properties: conservation, stability, and high-order approximation (both solution and geometry). By using high-order elements, curved meshes are obtained that track curved shock surfaces to high-order accuracy. The optimization problem is solved using a sequential quadratic programming method that simultaneously converges the mesh and DG solution, which is critical to avoid nonlinear stability issues that would come from computing a DG solution on an un-converged (non-aligned) mesh. We use the proposed framework to solve a number of relevant inviscid, steady and unsteady, transonic and supersonic, inert and reacting flows in two and three dimensions, and demonstrate the potential of the method to provide accurate approximations to these difficult problems with local features on extremely coarse, high-order meshes.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Artificial Intelligence Based Digital Twinning Framework for Structural Cyber Physical Systems

Author(s): *Mehrdad Shafiei Dizaji, *University of Virginia*; Zahra Zhiyanpour, *University of Virginia*; Aya Yehia, *University of Virginia*; Devin Harris, *University of Virginia*;

This research investigates a high-risk/high reward scheme to technologize infrastructure systems by employing artificial intelligence-informed digital twins. The digital twinning of an infrastructure system establishes a collaborative feedback loop between the measurable data of the physical world and simulated processes in the virtual world, providing a domain-specific adaptation of the broader CPS framework necessary to inform decision-making. Applied to the domain of large-scale structural systems, this research evaluates the conjecture that immersive engagement using a digital twin representation of these structural systems will permit participants to observe, interact, and contextualize the complex behavior mechanisms associated with these systems in their operational environment. The research design investigates a series of technology innovations to assessing the hypothesis, incorporating AI models to imitate both simulation-based results and experiment-based measurements. The model-based simulation and experimental characterization reformulations within the proposed digital twin framework require adapting simulation behavior and experimental measurements within a real-time collaboration environment. Therefore, to achieve a real-time collaboration environment, an AI model is formulated to substitute the finite element modeling (FEM) computations by creating a model of the FEM outcomes and learning the highly complex mapping using deep learning neural networks. Moreover, re-formulating a computationally expensive process using DIC is investigated to calculate structural deformation fields from image sequences using a deep learning neural network. While the base formulations (i.e., FEM and DIC) of these results are computationally expensive, the AI formulations generate the foundation for real-time interconnection between these results and also establish novel opportunities for integration within a visualization platform that is necessary for decision-making for large scale structural systems. After training the AI models, a client-server-based architecture will be developed where a user can interact and calibrate with a finite element model of a structure in a computational server in a physical environment to diagnose, prognoses, and forecast the behavior of the structure based on alternative scenarios.

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Baltimore, MD, May 31 - June 3, 2022

Title: Vibration-Based Assessment of Local Damage in Prestressed Concrete Beams Based on Joint Acceleration and FBG Strain Data

Author(s): *Menno Van de Velde, *KU Leuven*; Edwin Reynders, *KU Leuven*; Geert Lombaert, *KU Leuven*;

Vibration-based Structural Health Monitoring (SHM) is a widely used non-destructive approach for monitoring civil infrastructure. Changes in modal characteristics (natural frequencies, mode shapes, modal strains) are used for the detection and localization of damage. These dynamic characteristics are related to the stiffness of the structure. Natural frequencies are sensitive to the global stiffness of the structure but are found to be relatively insensitive to local damage. Modal strains are more sensitive to local changes in structural stiffness [1] and might thus be better suited for the detection of the local deterioration of prestressed strands, but experimental validation is still needed.

Therefore, an experimental set-up is constructed in order to study the effects of local damage on the modal characteristics of prestressed concrete beams. The set-up consists of a concrete beam with a length of five meters, prestressed with five prestressing strands. The damage consists of locally cutting one of the five prestressed strands, simulating the reduction in cross-section caused by pitting corrosion. Pitting corrosion is caused when chlorides, coming from e.g. contaminated aggregates or de-icing salts, destroy the passive layer of the steel prestressed strand. It is an important cause of deterioration for prestressed concrete structures [2]. Before and after the cutting of the strand, dynamic measurements are conducted. The response of the beam is recorded with accelerometers and three chains of Fiber-optic Bragg Grating (FBG) strain sensors. The modal characteristics (natural frequencies, mode shapes and modal strains) are identified using combined subspace identification. The effect of the local damage of the prestressed strand on these different modal characteristics is investigated, where the detection of this local damage is feasible if it causes a local change in the dynamic stiffness of the structure.

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EMI 2022
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Title: Problems of the Coupled Theory of Thermoelasticity for Materials with Double Porosity

Author(s): *Merab Svanadze, *Ilia State University*;

In the last two decades, intensive research has been carried out in the theory of materials with double porosity, which has led to the widespread use of such materials in civil and geotechnical engineering, technology, hydrology, geomechanics and biomechanics. Moreover, many engineering problems have a coupled physical nature and it is necessary to consider several coupled mechanical concepts simultaneously (for details, see [1, 2]).

In this work, the linear model of thermoelasticity for materials with double porosity is introduced in which the coupled phenomenon of the concepts of Darcy's law and the volume fraction of pore network is presented. Then, the basic internal and external boundary value problems of steady vibrations are investigated. Namely, the radiation conditions are established and Green's identities are obtained. The uniqueness theorems for the classical solutions of the internal and external boundary value problems are proved. The single-layer, double-layer and volume potentials are constructed and the basic properties of these potentials are given. The boundary value problems are reduced to the always solvable singular integral equations for which Fredholm's theorems are valid. Finally, the existence theorems for classical solutions of the above mentioned boundary value problems of steady vibrations are proved by means of the potential method (boundary integral equation method) and the theory of singular integral equations.

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Title: Machine Learning Enabled Offline Multiscale Aggregating Discontinuity Method for Elastoplastic Composites Undergoing Strain Localization

Author(s): *Mian Xiao, *Columbia University*; Nikolaos Vlassis, *Columbia University*; WaiChing Sun, *Columbia University*;

We propose a deep learning based multiscale aggregating discontinuity (MAD) method that circumvents the loss of material stability when modeling elastoplastic composites. To replicate the elastoplastic material behavior homogenized from microscale representative volume element (RVE) simulations before the localization point, we apply Sobolev training techniques to learn multiple smoothed neural networks functions predicting different components of an elastoplastic material model, including the stored energy function, the yield function and the plastic flow potential. Strong ellipticity check is performed at each constitutive evaluation in order to identify the onset of weak discontinuity. To solve the ill-posedness issue after the localization point, we adopt an assumed enhanced strain finite element method that embeds the weak discontinuity inferred from the acoustic tensor into the macroscale elements. Numerical experiments are conducted using a database created from layered-structure RVE simulations with the Cam-Clay model at the microscale, and the implementations of each component of the models are individually verified.

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Baltimore, MD, May 31 - June 3, 2022

Title: A Multi-Scale Computational Model of Ventricular Myocardium

Author(s): David Li, *The University of Texas at Austin*; Emilio Mendiola, *The University of Texas at Austin*; Reza Avazmohammadi, *Texas A&M University*; Frank Sachse, *The University of Utah*; *Michael Sacks, *The University of Texas at Austin*;

Modeling the tissue-level mechanical behavior of normal and pathological right ventricular free wall (RVFW) myocardium has highlighted the integral role of mechanical interactions between myofibers and extracellular matrix (ECM) collagen fibers in determining bulk tissue properties, as well as their structural alterations in response to diseases such as pulmonary hypertension. However, because these approaches have remained necessarily continuum-level, functional descriptions of how micro-scale interactions between myofibers and ECM drive meso-scale mechanics remain largely unexplored. Thus, a multi-scale modeling framework linking myocardial micro-anatomy to tissue-scale myocardial mechanical behavior is needed. To this end, we developed a 3D micro-anatomically realistic finite element model of myocardium, leveraging high-resolution imaging of myocardial microstructure and supercomputer-based modeling, to model a localized representative tissue element (RTE) of ventricular myocardium. From a confocal fluorescence microscopy dataset of a 204x204x40- μm myocardium sample, we defined the RTE domain and generated a 1.1-million element tetrahedral mesh of myofibers embedded in collagenous ECM. We then modeled their material behaviors by specializing well-established hyperelastic anisotropic constitutive forms derived from previous structurally-based models. Utilizing the open-source software FEniCS and the Stampede2 supercomputer at the Texas Advanced Computing Center, equibiaxial and non-equibiaxial loading conditions were simulated to compute the mechanical stress-strain response of the RTE (at the sub-tissue-scale). We then used the myofiber and collagen fiber composition and orientation distributions measured in the RTE to simulate a "top-down" localized biaxial response with our previous extended structurally-based (tissue-scale) model, and the material parameters of the RTE model were fitted to reproduce the resulting stress-strain behavior. Next, we developed a multi-scale approach to predict the tissue-level (5x5x0.7-mm) RVFW biaxial behavior via a "bottom-up" homogenization of the RTE model, according to histologically measured myofiber and collagen orientation distributions and biaxial experimental data. The combination of fitting constitutive parameters at the RTE level, along with the multi-scale homogenization approach, successfully reproduced the tissue-level mechanical behavior of our previous studies in all biaxial deformation modes, suggesting that the 3D micro-anatomical arrangement of myofibers and ECM collagen is indeed a primary mechanism driving myofiber-collagen coupling at the tissue level. This work establishes the feasibility of incorporating micro-anatomical information into high-fidelity supercomputer-based modeling of myocardium to better understand remodeling of the cardiac microstructure in response to disease and identify mechanical attributes critical to heart disease therapies.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Manifold-Based Surrogates: Towards Breaking the Curse of Dimensionality in Black-Box-Type Problems with Uncertainty Sources

Author(s): Katiana Kontolati, *Johns Hopkins University*; Dimitris Loukrezis, *Siemens AG, Technology*; Dimitris Giovanis, *Johns Hopkins University*; Somdatta Goswami, *Brown University*; George Karniadakis, *Brown University*; *Michael Shields, *Johns Hopkins University*;

The process of constructing accurate surrogate models for partial differential equations (PDEs) (e.g., describing complex spatio-temporally varying physical processes) is a challenging task. Especially when these models are associated with stochastic high-dimensional inputs (e.g., forcing terms, boundary conditions, initial conditions) constructing a surrogate can be intractable. The so-called "curse of dimensionality" can be addressed with manifold learning (nonlinear dimension reduction) techniques used as a pre-processing tool to encode inputs onto lower-dimensional subspaces while retaining as much as possible the local structure and variance. In this work, we propose a unified framework based on manifold learning and polynomial chaos expansion, known as manifold PCE or m-PCE, for addressing the curse of dimensionality and learning the solution of nonlinear PDEs under uncertainty. We discover two separate lower-dimension embeddings of both inputs and quantities of interest and use non-intrusive polynomial chaos expansion to map data on the reduced spaces. Despite being low, the dimensions of the resulting embeddings, lead to the construction of overparameterized surrogates capable of constructing accurate mappings for even models exhibiting highly non-smooth response. An inverse manifold learning procedure is employed to transform predicting samples back to the physically interpretable space. To demonstrate the capabilities of the proposed approach, we compare its performance with state-of-the-art neural operator models, namely the DeepONet (Deep Operator Network) and FNO (Fourier Neural Operator) to model the Brusselator reaction diffusion system, describing an autocatalytic chemical reaction between two species. We show the computational advantages and limitations of the proposed model and test its performance on interpolation, extrapolation and robustness to noise.

EMI 2022
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Title: Exploring Permeability-Porosity Relations in Architected Materials

Author(s): *Michael Vladimirov, *Johns Hopkins University*; Stavros Gaitanaros, *Johns Hopkins University*; James Guest, *Johns Hopkins University*;

Permeability-porosity relationships have been studied for a range of porous media. Analytical and empirical models have been proposed for structures taking on specific topological forms, such as fiber beds, foams and granular media, and within these studies there is a reported upper bound for the permeability at a given porosity given the topological form. Motivated by the rise of additive manufacturing and its ability to create more complex geometries, we employ topology optimization to design architected materials with maximized permeability across a broad range of porosities to study this relationship and estimate a maximum permeability independent of material architecture – a class of bounds often referred to as micro-structure independent. Both density-based and level set approaches to topology optimization were used to populate the property space. A one-parameter mathematical model based on the conventional and modified Kozeny-Carman equation is then proposed that fits our results well. We compare our predicted maximum permeabilities with those achieved with realistic and numerical architecture-dependent materials and confirm the prediction of maximum magnitude holds for these cases.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: The Curious Case of 166 TMDs in One Building

Author(s): *Michael Wesolowsky, *Thornton Tomasetti*; Melissa Wong, *Thornton Tomasetti*; Hannah Kim, *Thornton Tomasetti*; Rabih Alkhatib, *Thornton Tomasetti*;

Tuned Mass Dampers (TMDs) are devices that oppose the motion of a floor which has been excited by occupant footfalls. They have been demonstrated to be effective when considered during the design process or in mitigation situations. If designed and implemented properly, they achieve three goals: (1) maintain structural motion levels below commonly accepted criteria, (2) optimize the size and configuration of the structural system in order to provide more useable space in a building, and (3) reduce the cost of construction due to fewer and/or smaller structural elements. Traditionally, TMDs have only been used to control perceptible and excessive motions from wind loading and crowd movement. As such, they have not been used in laboratory and other sensitive spaces due to equipment criteria which specify vibration levels far below perceptibility.

This presentation illustrates the case study of a 45,000 sm steel-framed structure originally designed as a core and shell office building with 3 levels of below grade parking, 12 above grade levels of tenant space and 2 mechanical penthouse levels. As construction was beginning, a single pharmaceutical firm chose to lease the entire building, and required that more than half of the floor plate of each floor meet the strict VC-A criterion (with some areas requiring VC-C). As the building had been designed for typical office occupancy vibration criterion, major last-minute modifications would be required to stiffen the structure to meet the new criterion. Several options were explored, with the final solution incorporating a combination of stiffening of primary structural members, tying floor masses together using interstitial posts and installing 166 tuned mass dampers (TMDs) within the depth of the floor framing to counteract floor footfall vibrations. Dynamic characterization tests were completed on every area of each floor during construction in order to tune the TMDs in-situ as construction was progressing. Final testing conducted once the structure was complete and the TMDs were tuned indicated that the VC-A criterion was achieved in all relevant areas.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Adaptive Sequential Sampling for Polynomial Chaos Expansions of Vector-Valued Response Quantities

Author(s): Lukáš Novák, *Brno University of Technology*; *Miroslav Vorechovský, *Brno University of Technology*;

It is well known that the construction of a surrogate model is highly dependent on experimental design. One of the most efficient approaches is adaptive sequential sampling, which iteratively selects the new sampling points according to a specific criterion while updating the surrogate model. Recently, the authors have proposed a novel variance-based adaptive sequential sampling for non-intrusive Polynomial Chaos Expansion (PCE) [1]. The algorithm is based on a novel criterion for the selection of sampling points from a pool of candidates. The criterion takes into account specific properties of PCE approximation and optimally balances between exploration of the design domain and exploitation of the available information. In the present, we generalize the approach for vector-valued outputs.

The pool of candidates containing a large number of realizations of the input random vector can be generated by any sampling scheme. Once the pool of candidates is generated, it is necessary to select the best candidate. Exploitation in the variance-based sampling is achieved by using the variance density, which can be obtained analytically as a by-product of the PCE. The analytical derivation of variance density makes the evaluation of the criterion very efficient. However, in the case of vector-valued quantity of interest (QoI) approximated component-wise by separate PCEs, the original criterion for the selection of the best candidates must be generalized in order to exploit all PCEs. This contribution describes the generalization of the variance-based adaptive sequential sampling for an arbitrary number of PCEs.

The generalized criterion prefers candidate points in parts of multidimensional space associated with higher contribution to the product of local variances derived from all PCEs. The proposed generalization leads to the optimal coverage of the design domain for all approximated outputs of an original mathematical model. The exploration part of the proposed criterion prefers candidates in locations without sampling points in the existing experimental design. Note that the exploration part is independent of all PCEs, since we assume that the experimental design domain is identical for all PCEs. The performance of the proposed approach will be demonstrated on numerical examples.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Quantifying the Long-Term Effects of Climate Change on Sea Conditions and Fatigue Deterioration in Ship Hulls Across the Atlantic Ocean

Author(s): *Mohamed Soliman, *Associate Professor, School of Civil and Environmental Engineering, Oklahoma State University*; Mohammad Tamimi, *Graduate Research Assistant, School of Civil and Environmental Engineering, Oklahoma State University*; Omid Khandel, *Oklahoma State University*;

Civil and marine structures are subjected to various deterioration mechanisms due to aggressive environmental effects or mechanical loads. These loading and environmental conditions can lead to strength failure (e.g., yielding or buckling) or gradual deterioration due to fatigue and corrosion. Fatigue is one of the most critical deterioration mechanisms that may influence the safety of civil and marine structures. Accurate prediction of the fatigue crack growth under service loading forms the basis for essential inspections and repair planning throughout the service life of the structure. Marine structures in particular are prone to fatigue deterioration due to aggressive sea conditions and the large number of welded connections within the structure. The significant randomness of sea conditions and loading sequences adds to the challenges associated with crack growth prediction in ships. This presentation discusses an innovative simulation-based framework for predicting the failure probability of ships under growing cracks in light of climate change. The presentation also discusses the impact of climate change on wave parameters and storm characteristics across the Atlantic Ocean and principal shipping routes. Global Climate Models (GCMs) are employed to predict the effect of climate change on the characteristics of waves and storms and the associated wave-induced loading. A three-dimensional nonlinear finite element (FE) model is established and used to extract essential parameters used to model crack propagation under variable sea loading. An analytical crack advancement rule is used in conjunction with the FE analysis to quantify the crack propagation characteristics. Monte Carlo simulation is used to quantify the probability of fatigue failure under the projected load profiles. The results show that the effect of climate change highly depends on the navigation route and location across the ocean. While some routes displayed an increase in the fatigue service life, others showed a significant decrease in the expected fatigue life with more aggressive sea conditions.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Experiments and Multiphysics Computational Modeling of Desiccation Behavior in Inorganic Microfiber-Reinforced Engineered Barrier Materials for Geological Repository of Nuclear Spent Fuel

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The use of nuclear power plants in generating electricity is growing rapidly in today's world. Each nuclear power reactor generates 20-30 tons of highly radioactive waste annually. Secure long-term storage of nuclear waste is a great concern for public health and safety. A preferred long-term solution for highly radioactive waste disposal is containment in geological repositories. Canisters filled with radioactive waste are placed in tunnels, with one or more engineered barrier systems (EBS) encapsulating them. A material like bentonite clay, which is physio-chemically compatible with both natural rock and nuclear waste, can be used in EBS. However, heat-induced desiccation cracking of bentonite can cause radiation in EBS. In this study, inorganic microfiber-reinforcement was examined to reduce desiccation cracking in bentonite EBS, for enhancing repository performance and safety. Shrinkage was observed for bentonite clay samples with randomly oriented basalt microfibers drying from an initial moisture content near the liquid limit. Digital image correlation (DIC) method was employed to capture the evolution and propagation of cracks in the bentonite-microfiber specimens when subjected to desiccation. Free and restrained shrinkage tests were carried out for both plain and microfiber-reinforced specimens. The restrained shrinkage tests were implemented using the restrained ring test method. The DIC method effectively helped determine the evolution of radial and circumferential displacement and strains of the microfiber-reinforced and plain bentonite specimens during the drying process. The results show that plain and microfiber-reinforced bentonite exhibited similar free shrinkage behavior (i.e., similar displacement, strains, and moisture loss over time), however desiccation cracking behavior was significantly influenced by fiber inclusion. Microfiber-reinforcement was shown to be effective in "bridging" the cracks, preventing complete separation of the material. Thus, basalt microfiber-reinforced clay bentonite can be an effective approach to limit desiccation cracking in geological repositories and improve nuclear waste management and safety. A hydro-mechanical finite element method integrated with cohesive zone fracture was then implemented to model the desiccation process followed by initiation-propagation of cracks. The DIC data from the experimental tests were used in an inverse problem to back-calculate core material properties including the shrinkage coefficient, moisture-dependent stiffness, and cohesive zone fracture parameters.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Decentralized Actor-Critic Deep Reinforcement Learning Approach for Optimal Life-Cycle Management of Transportation Networks

Author(s): *Mohammad Saifullah, *The Pennsylvania State University, University Park, PA, USA*; Charalampos Andriotis, *Delft University of Technology, Delft, The Netherlands*; Kostas Papakonstantinou, *The Pennsylvania State University, University Park, PA, USA*; Shelley Stoffels, *The Pennsylvania State University, University Park, PA, USA*;

Efficient life-cycle management of civil infrastructure is of ever-increasing significance in view of an aging built environment. According to ASCE, the US infrastructure is in 'fair'/'bad' condition, with components approaching the end of their service life. Pavements and bridges are characteristic examples, with 20% of pavements in poor condition and 7.5% of bridges structurally deficient. Optimal management of such systems relates to finding a strategy for inspection and maintenance actions that minimize long-term risks and various cost metrics. Decision-making in complex and stochastic settings, however, comes with various challenges, such as heterogeneity of different asset classes, a large number of components resulting in intractable state and action spaces, uncertain observations, limited resources, and disparate performance constraints. Currently, age- or condition-based maintenance techniques, as well as risk-based or periodic inspection plans have been mainly used to address this class of challenging optimization problems. Albeit simple and practical, these methods most often lead to suboptimal solutions. Addressing this matter, in this work an advanced methodology is developed within the framework of Partially Observable Markov Decision Processes, which provide a comprehensive mathematical approach for stochastic sequential decision settings under observation data uncertainty and limited resources [1-3]. The used Deep Decentralized Multi-agent Actor Critic (DDMAC) reinforcement learning method, developed in [2] and modified in [3], can accommodate large state and action spaces. The modified algorithm assigns an agent per infrastructure component, through actor neural networks, estimates a single value function for the entire system, through a critic neural network, and newly employs a Centralized Training and Decentralized Execution (CTDE) approach. The efficiency of the DDMAC-CTDE framework is demonstrated based on a large, existing transportation network in Virginia, that includes several bridge and pavement components with nonstationary degradation, considers traffic delay costs, various risks, and agency-imposed constraints. Comparisons with traditional management practices showcase that the DDMAC-CTDE solution significantly outperforms its counterparts.

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Probabilistic Investigation on the Behavior and Reliability of Steel Connections Combining Slip-Critical Bolts and Fillet Welds

Author(s): *Mohammad Tamimi, *Graduate Research Assistant, School of Civil and Environmental Engineering, Oklahoma State University*; Omid Khandel, *Oklahoma State University*; Mohamed Soliman, *Associate Professor, School of Civil and Environmental Engineering, Oklahoma State University*;

Combining welds and bolts may be an appealing practical solution to improve the capacity of an existing steel connection. In many situations, it may be desirable to add welds to a bolted connection to resolve construction errors or to retrofit existing connections. However, the reliability of these connections has not been previously investigated. Furthermore, data needed to properly quantify the behavior and reliability of steel connections is generally scarce. The presented research discusses a probabilistic approach for evaluating the reliability of connections made with slip-critical bolts and longitudinal fillet welds in combination. The approach uses detailed finite element analysis, meta-modeling, and Monte Carlo simulation to quantify the reliability of the investigated connections. Large-scale experiments were conducted to collect the required data for improving the accuracy of the numerical models and establishing proper probabilistic models of underlying random variables. The finite element models are validated using the results of large-scale laboratory experiments. The validated numerical models are then integrated into a low-rank tensor approximation process to conduct variance-based sensitivity analysis aiming at identifying the effect of variability of different random variables on the load-carrying capacity of the combination connections. The sensitivity analysis indicated that the load-deformation behavior is strongly influenced by the variability in weld geometry, bolt pretensioning forces, and the condition of the faying surfaces. The variables that significantly affect the connection behavior are treated as random variables in the probabilistic simulations. The descriptors of these random variables are obtained from the results of the large-scale laboratory experiments conducted in support of this research. Finally, the selected variables and the validated numerical models are used to perform reliability analysis through accelerated kriging Monte Carlo simulation. The proposed approach is applied to multiple combination welded-bolted connections with different weld dimensions, bolt patterns, and faying surface conditions to evaluate their long-term reliability based on current design specifications. Best practices for modeling the load-deformation behavior of welds and bolt for reliability evaluation are also discussed.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Digital Twinning for Offshore Wind Turbine Drivetrain Using Bayesian Model Updating Method

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Failures in wind turbine drivetrain systems including gearbox, bearings, and generator account for more than 60% of total wind turbine downtime. The dynamic demands in wind turbine drivetrain systems often vary from values used in the design phase, which leads to unexpected and unpredictable failures. Therefore, it is important to develop remote monitoring techniques for damage identification purposes in the wind turbine drivetrain systems. In this study, a physics-based digital twin technology is proposed for the wind turbine drivetrain system, which can be used to predict the remaining useful life and failure points of different components. For this purpose, a time-domain sequential Bayesian model updating approach is proposed for model calibration, which can jointly estimate the drivetrain parameters including shaft stiffnesses, gear, and generator inertias, etc., and the time-history of unknown input forces such as aerodynamic loading. Implementation of this technique provides stress-strain time history of drivetrain components which can be used to update the failure models and estimate the remaining useful life of drivetrain components including gears, shafts, and bearings.

Title: PRISMS-Plasticity and PRISMS-Fatigue: ICME Frameworks to Advance Boundaries of High-Fidelity Simulations

Author(s): *Mohammadreza Yaghoobi, *University of Michigan*; Krzysztof S. Stopka, *Georgia Institute of Technology*; Aaditya Lakshmanan, *University of Michigan*; Duncan Greeley, *University of Michigan*; Zhe Chen, *University of Michigan*; John E. Allison, *University of Michigan*; David L. McDowell, *Georgia Institute of Technology*; Veera Sundararaghavan, *University of Michigan*;

Meeting design requirements of the next generation of high-performance structural systems requires the discovery and development of new structural materials with enhanced properties. High-performance computational ICME frameworks are an integral part of any design and development platform for next-generation structural materials. In this work, highly scalable ICME frameworks of PRISMS-Plasticity [1, 2] and PRISMS-Fatigue [3] are presented as part of an overarching PRISMS Center integrated framework. First, an open-source parallel 3-D crystal plasticity finite element (CPFE) software package PRISMS-Plasticity [1, 2] is presented here. Highly efficient rate-independent and rate-dependent crystal plasticity algorithms are implemented. Additionally, a new twinning-detwinning mechanism is incorporated into the framework based on an integration point sensitive scheme. The integration of the software as a part of the PRISMS Center framework is demonstrated. This integration includes well-defined pipelines for use of PRISMS-Plasticity software with experimental characterization techniques such as electron backscatter diffraction (EBSD), Digital Image Analysis (DIC), and high-energy synchrotron X-ray diffraction (HEDM), where appropriate these pipelines use popular open-source software packages DREAM.3D and Neper. The parallel performance of the software demonstrates that it scales exceptionally well for large problems running on hundreds of processors. In the next step, a novel open-source framework PRISMS-Fatigue [3] is presented that enables simulation-based comparisons of microstructures with regard to fatigue resistance of polycrystalline metals and alloys. The framework uses the crystal plasticity finite element software PRISMS-Plasticity as its microstructural analysis tool. This framework provides a highly efficient, scalable, easily modified, and easy-to-use ICME community platform. The performance and flexibility of this framework is demonstrated with various examples, including effects of crystallographic texture, grain morphology, strain state, free surface effects, and choice of parameters to represent mesoscopic driving forces for fatigue crack formation. The integration of PRISMS-Plasticity and PRISMS-Fatigue results with the PRISMS Center information repository, the Materials Commons, will be presented.

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: A Comprehensive Experimental Program of Concrete Notched Beams Using Digital Image Analysis to Identify Concrete Fracture Parameters

Author(s): *Mohammad Minhajur Rahman, *Case Western Reserve University*; Zahra Ameli, *University of Maine*; Christian Carloni, *Case Western Reserve University*;

Every physical theory deals with the problem of size effect. The well-known size effect formula for quasibrittle materials is given by Z. Bažant and it has been implemented in ACI 318 code. The size effect of concrete notched beams has been studied extensively in the literature. However, the largest possible size of the specimen tested often suffers from some limitations due to difficulties associated with test setup. This study includes three point bending tests of the largest plain concrete notched beams ever attempted. The depth of the specimens explored are, 75 mm, 150 mm, 250 mm, 500 mm, and 1000 mm. The net span of the specimens is three times the depth and the notch length is one-fourth of the depth. In total four different test setups are used to accommodate different sizes of the specimens. To tackle the problems related to testing large specimens vertically, specimens with 500 mm and 1000 mm depth are tested horizontally. An innovative horizontal test setup is designed to make the beams float on top of the floor by using plexiglass balls and steel plates. The 500 mm-depth specimens are also tested vertically to compare the responses with the 500 mm-depth specimens that are tested horizontally and verify that the horizontal test setup does not introduce any discrepancy. The nominal stress is plotted against the depth of the specimen in logarithmic scale to evaluate the size effect. The parameters of the size effect law proposed by Z. Bažant are determined and critically discussed.

Digital image correlation (DIC) is also used on all 5 different sizes of specimens to identify the fracture process zone, and to determine the critical crack opening value for concrete. Results of the DIC analysis show that the load versus load point displacement can be erroneously determined when external sensors are used. In addition, DIC analysis indicates that the width of the fracture process zone is size dependent.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Role of Subscale Heterogeneities on Local Stresses and Strains in Concrete Using X-Ray Computed Tomography and Mesoscale Simulations

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The prediction of mechanical properties of concrete is challenging due to the material and structural heterogeneities. The use of X-Ray Computed Tomography (XCT) in combination with Finite Element Modeling (FEM) is a powerful approach to predict mechanical properties directly from the microstructure. Several studies in the past used this approach to predict macroscopic stiffness and strength; however, the influence of subscale heterogeneities on local stress and strain fields remains under-explored with no experimental validation. The present work utilizes experiments based on Digital Volume Correlation (DVC) and mesoscale finite element modeling to study the role of subscale heterogeneities on local stress and strain fields. The results shed light on the influence considering subscale heterogeneities in the cement matrix has on mesoscale simulation accuracy. The issues related to the segmentation of phases in XCT images of concrete and mesh discretization are considered. Furthermore, a comparison between the experiments and numerical model is provided both in terms of macroscopic and microscopic response.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Agent-Based Unmanned Aerial Vehicle in Simulated Environment for Collaborative Inspection

Author(s): *Muhammad Rakeh Saleem, *The Pennsylvania State University*; Rebecca Napolitano, *The Pennsylvania State University*;

The use of unmanned aerial vehicles (UAVs) for building inspection tasks requires users to understand flight patterns and their interaction with the environment, to detect potential damage for structure assessment and documentation, and to capture expert knowledge train drones for informed decision making. While most UAV inspections are based on either pre-programmed flight paths or remote-controlled UAVs, each mode has its own downside. Pre-programmed UAV-based inspection can miss key details or damage indicators that require zooming or comparative assessment. Remote-controlled UAV inspection has limited knowledge transfer between the human and the UAV which can lead to suboptimal communication amongst human-UAV inspector teams. To achieve autonomous inspections, a comprehensive end-to-end framework must be proposed, incorporating both expert knowledge and decision-making. This work seeks to develop a holistic framework using reinforcement learning (RL) and eye tracking data for more detailed UAV-based inspection in a simulated environment. The overall system involves a multi-agent approach: 1) a macro agent that is used to perform damage detection and localization using eye tracking data, and 2) a micro agent that is responsible for drone autonomy and control for reactive decision-making using feedback control loop. The developed algorithm will be implemented in a 3D virtual environment to validate the autonomy and efficiency of the system and tested on real-world case scenarios for post-disaster inspection.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Analysis of Eye Tracking Metrics for Facade Inspection to Understand Human-Infrastructure Interactions in Built Environment

Author(s): *Muhammad Rakeh Saleem, *The Pennsylvania State University*; Rebecca Napolitano, *The Pennsylvania State University*;

With the aims of ensuring public safety and decreasing maintenance costs, previous studies in built environment research have worked to elucidate damage indicators and understand their correspondence to structural deficiency. Understanding how damages occurred and their presence on a built structure is one part while the data analysis and dissemination is another critical part. To understand human perception and assess human-infrastructure interaction for salient feature extraction, eye tracking can be significant. This work seeks to capture how an expert interacts with a structure during a façade inspection so that more detailed and situationally-aware inspections can be done automatically. Eye tracking can accurately map where an inspector is looking at and what they are focusing on while doing the structural inspection to recognize and infer human implicit attention. To this end, experiments will be performed on building façade for damage assessment to analyze key visually-based, intent features that are important for understanding human-infrastructure interaction. For data collection and analysis, experiments will be conducted to assess an inspector's behavioral changes while performing an assessment of a real structure. These eye tracking features provide the basis for the inspector's intent prediction and will be used to understand how humans interact with the structure for assessing damages during inspection processes. By enabling a sense-making UAV through AI support, this method will facilitate information sharing and decision-making during the inspection processes.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: On the Emergence of 3D Printable Engineered Cementitious Composites: Extrudability and Buildability Evaluation

Author(s): *Muhammad Saeed Zafar, *University of New Mexico*; Amir Bakshi, *University of New Mexico*; Maryam Hojati, *University of New Mexico*;

3D printing technology has gained the attention of researchers and industry to a great extent in the field of civil engineering due to its potential of improving the current construction practices. Novel 3D-printing technology would provide relatively economical construction solutions to reduce the labor requirement, formwork cost, construction wastages, safety risks, construction time by speeding up the overall construction process and enhancing energy efficiency. Furthermore, as more automation is involved, there is flexibility to achieve an optimized design and complex geometries due to architectural requirements. However, there are numerous challenges in implementing it at practical scales and adjusting its properties considering the 3D printing requirements. Some of the major challenges include the inappropriate rheology and incompatibility of conventional reinforcing techniques with 3D printing. 3D printable engineered cementitious composites (ECC) can be an effective reinforcing approach to minimize the requirement of conventional steel reinforcement. However, there are several issues involved in the 3D printing of ECC such as nozzle blockage, inadequate rheology, and insufficient printing quality. Previous studies indicated that the rheological parameters such as plastic viscosity, yield stress, and thixotropy have some major contributions towards the printability of 3D printable concrete. Moreover, several researchers have utilized different reinforcing techniques; yet, there is a dire need for an effective reinforcing approach in the 3D printing of concrete. This study focused on investigating the several properties of engineered cementitious composites (ECC), including rheological evolution and printability. The rheological evolution was studied for 0, 15, 30, 45, and 60 minutes. The printability of these ECC mixes was examined in terms of extrudability, buildability, and shape retention. The initial results depicted an unsatisfactory printing quality which was further modified by utilizing a viscosity modifying admixture (methylcellulose). In addition, several other factors such as printing speed, extrusion speed, interlayer time gap, and water to binder ratio were also considered to evaluate the printability of the ECC. The average increase in rheological parameters was 392.46%, 92.82%, 528.39%, and 617.94 for plastic viscosity, static yield stress, dynamic yield stress, and thixotropy with the incorporation of methylcellulose. This improvement leads to superior printing quality in terms of dimension conformity, dimension consistency, surface quality, buildability, and shape retention. The thickness and the width of filament showed a decreasing trend as the printing speed was increased from 1 cm/sec to 5 cm/sec. Furthermore, due to the interlayer time gap, the filament deformations were reduced; however, the interlayer bond was weakened.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Estimating Physical Parameters of Linear Dynamic Systems in the Presence of Model Form Uncertainty

Author(s): *Mukesh Ramancha, *University of California San Diego*; Joel Conte, *University of California San Diego*; Matthew Parno, *Dartmouth College*;

Model form uncertainty (also referred to as modeling uncertainty, model discrepancy, model bias, or uncertainty about model structure) arising from model inadequacies due to simplifying assumptions, hypotheses, and unmodeled physics is a significant source of uncertainty in model calibration. However, its formal treatment is traditionally ignored in structural engineering. If not appropriately accounted for, the model discrepancy can lead to biased estimates of the unknown physical parameters of the model, thereby hindering the predictive capability of the calibrated model. The state-of-the-art Kennedy and O'Hagen (KOH) framework to account for modeling uncertainty is directly applicable only for systems under static or quasi-static loading. An extension of the KOH framework to account for modeling uncertainty in linear systems under dynamic loading is presented in this paper. The proposed extension is based on the theory of random vibrations. The validity of the proposed approach is demonstrated by calibrating structural engineering benchmark problems (using simulated data) in the presence of modeling uncertainty when subjected to dynamic loading (e.g., white noise excitation, wind loading, and earthquake loading). Bayesian model updating leads to highly confident biased parameter estimates when performed without adequately accounting for the model discrepancy. Conversely, using the proposed approach to account for model discrepancy leads to a posterior probability distribution of the parameters whose support contains the true parameter values.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Accelerating Bayesian FE Model Updating via Surrogate Models: Application to a Miter Gate

Author(s): *Mukesh Ramancha, *University of California San Diego*; Manuel Vega, *Los Alamos National Laboratory*; Joel Conte, *University of California San Diego*; Michael Todd, *University of California San Diego*; Zhen Hu, *University of Michigan-Dearborn*;

Simulation-based Bayesian inference methods often require repeated evaluations of the model to be calibrated, which makes updating high-fidelity FE models of large-scale structural systems a highly computationally expensive endeavor. This study considers Bayesian model updating of a miter gate structural system using a high-fidelity FE model considering three predominant damage modes occurring in such systems. Model updating is first performed using direct FE model evaluations using transitional Markov chain Monte Carlo (TMCMC) sampling. The TMCMC algorithm allows for the model evaluations within each stage to be run in parallel, which is more suitable than MCMC methods which require sequential model evaluations. Then, two global surrogate models of the FE model are constructed using polynomial chaos expansion (PCE) and Gaussian process regression (GPR) techniques to accelerate the model updating process. Next, model updating is repeated using surrogate model evaluations in the updating process. Finally, the loss of accuracy in the model updating results and gain in computational time (which includes the training time of the surrogate models) are investigated and compared when model evaluations are performed using trained surrogate models instead of FE models in model updating. The posterior distribution of the FE model parameters obtained using the trained surrogates are sufficiently accurate with respect to the posterior distribution obtained utilizing the direct FE evaluations. In addition, a four-fold reduction in the computational time was observed when using surrogate model evaluations instead of direct FE evaluations for model updating of the miter gate.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: A Contribution to Lowering Concrete-Related Emissions: Realization of Mass-Optimized Concrete Girders

Author(s): *Nadine Stoiber, *University of Natural Resources and Life Sciences, Vienna*; Benjamin Kromoser, *University of Natural Resources and Life Sciences, Vienna*;

Global environmental challenges of our time reveal the urgency to reappraise construction material consumption, with structural concrete being responsible for a major share of worldwide greenhouse gas emissions. In this context the European Cement Association introduced the 5C Approach, listing a variety of levers to push resource efficiency in the concrete construction sector. In the presented study, the strategy of topology optimization is used as a guide to find geometries for optimized concrete girders that are characterized by the same load-bearing capacity but require less construction material than the equivalent full girders. The research aims at advancing practical investigations in the field of topology optimization in concrete construction, with the respective need carved out in [1]. As part of the study, various optimization software applications were investigated and applied to a specified design domain. The girders have a rectangular cross section with a thickness of 60 mm, a height of 0.2 m and a span of 2 m loaded with an asymmetrically applied point load. The final mass-optimized geometry was found by gradual layout adjustment, incorporating both the findings from the optimization tools and state-of-the-art structural concrete design considerations. Following the optimization process, the organic-looking concrete specimens were manufactured, with the load-bearing capacity verified in subsequent full-scale experiments. The parameter variations included the consideration of different geometry layouts, two reinforcement types (stainless reinforcement bars, laser-cut reinforcement) and varying concrete cover thicknesses. For comparison purposes, full concrete girders with optimized as well as conventional reinforcement layout were also tested. The measurement data obtained from the experiments allowed an elaboration of the subtleties in structural behaviour of full girders versus optimized girders, with bending and truss effects being identified. This study proves the feasibility of optimized concrete girders with less material use than full pendants, but with an equal load-carrying capacity and, thus, a more resource-efficient design approach in concrete construction.

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Title: Shift in the Natural Frequencies of Structures with Multiple Variable Inertia Flywheels

Author(s): Anika Sarkar, *University of Tennessee*; *Nicholas Wierschem, *University of Tennessee*;

Rotational inertial mechanisms, most prominently inerter-based passive control devices, have gained popularity in academia and industry because of their potential to mitigate the dynamic response of structures. Rotational inertial mechanisms can transform linear motion to the rotational motion of a flywheel and produce a significant mass effect while utilizing only a small physical mass. The majority of the research in this field has primarily considered rotational inertial mechanisms as linear mechanisms, known as inerters, that generate constant equivalent mass; nevertheless, there is growing interest in nonlinear rotational inertial mechanisms that can generate variable equivalent mass. One kind of nonlinear rotational inertial mechanism features a variable inertia flywheel (VIF), a flywheel with masses that can move and alter the rotational inertia of the flywheel. The VIF can be utilized in vibration control strategies as it can cause significant passive changes to the dynamics of the attached structure. Although it has potentially advantageous behavior, very few studies have considered the VIF as a passive control device. Most of the current VIF research uses it as an active or semi-active device that requires input energy and complex hardware. Furthermore, few studies have considered the attachment of single or multiple VIFs in multi-degree-of-freedom (MDOF) systems. This work investigates the effects provided by the variable rotational inertia of multiple passive VIFs when attached to a MDOF system considering free vibration or subjected to forced excitation. The mechanism and dynamic model of the proposed device in a MDOF system are presented in this study, and numerical simulations are carried out to investigate the behavior and effectiveness of this device. The results of this study show that the addition of the VIFs can provide a significant shift in the instantaneous and pseudo-natural frequencies of the structure that depends on the response amplitude of the system while also adding higher frequency dynamics to the system. Moreover, the results show that the effect of the distribution of the VIF in an MDOF system can be significant and that the distribution has the potential to be used to beneficially tailor the frequency response behavior of the structure.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Graph Embedding Plasticity for Granular Solids

Author(s): *Nikolaos Napoleon Vlassis, *Columbia University*; WaiChing Sun, *Columbia University*;

Macroscopic constitutive responses of granular assemblies are dictated by the evolution of particle connectivity and the topology of the force chains that lead to different types of contractive and dilative plastic behavior upon shear. While conventional modeling efforts often focus on introducing relationships among physical descriptors such as porosity, fabric tensor, and void distribution, precise and accurate predictive models often require information that is not available in these traditionally derived descriptors from the literature. In this work, we introduce a deep geometric learning meta-modeling approach that deduces physically interpretable encoded feature vectors directly from high-dimensional microstructural non-Euclidean data that double as plastic internal variables. We then formulate a variational plasticity problem that yields thermodynamics compatible constraints that lead to a robust return mapping algorithm. Our results reveal that this augmented intelligence approach supplies additional material response history information that is otherwise missing in classical descriptors and therefore yield more consistent forward predictions, especially for events such as strain localization and static liquefaction where topological changes (e.g. buckling of force chain, particles re-arrangement due to rotation inside shear band) are significant. Methods to enforce material frame indifference, material symmetry, and control of ellipticity are also discussed.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: A Study of the Effects of Oxide Films on the Cold Spray Behavior of Aluminum and Titanium Alloy Powders

Author(s): Mobin Vandadi, *Worcester Polytechnic Institute*; Arvand Navabi, *Worcester Polytechnic Institute*; Trevor Bond, *Worcester Polytechnic Institute*; Ridwan Ahmed, *Worcester Polytechnic Institute*; John Obayemi, *Worcester Polytechnic Institute*; Joseph Oghenevweta, *Worcester Polytechnic Institute*; *Nima Rahbar, *Worcester Polytechnic Institute*; Winston Soboyejo, *Worcester Polytechnic Institute*;

Deformation and cracking phenomena are investigated for the cold spray of nanoscale surface oxide layers on Aluminum and Titanium alloy powders. Using Focused Ion Beam (FIB), Transmission Electron Microscopy (TEM), and X-ray Photoelectron Spectroscopy (XPS), the oxide layer was studied and shown to have been crystalline γ -Al₂O₃. Phenomena associated with surface contacts, contact-induced elastic-plastic deformation, heating, and cracking are then studied using a combination of analytical models, Finite Element Analysis (FEA) and Molecular Dynamics (MD) simulations. It is shown that the powder impacts result in localized splat deformation and heating, along with the cracking of the oxide layers that expose fresh metallic surfaces to high-temperature surface contacts (at temperatures above the recrystallization temperature for metal) that can give rise to bonding and mechanical interlocking. Additionally, it is shown that a small portion of the oxide layer stays between the two metals, and the difference in this amount is studied under different impact velocities, oxide thickness, and powder size.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Evaluation and Construction of Microstructural Data Distributions for ICME Applications.

Author(s): *Noah Wade, *Johns Hopkins University*, Lori Graham-Brady, *Johns Hopkins University*,

Many of the modern advances in computational material engineering have come through the incorporation of detailed material microstructural characterization. Within the ICME community many researchers are starting to use more detailed material characterization in their models. Microstructural data is routinely being used not just for the measurement of grain size, but also aspect ratios, shapes properties, perimeter measurements and the spatial distribution of objects. In addition many computational models are being to incorporate parameter distributions in place of average values. However, measurement standards for many of these metrics have not been established and numerous methods exist for their evaluation. The process of reporting a full parameter distribution typical requires the use of extensive statistical tools for data processing. The communication and reporting of these processes and the possible errors and bias associated with them is important. Uncertainty quantification tools to evaluate the accuracy of these measurements will be important to their continued incorporation into advanced material modeling.

In this work a tool for the evaluation of error associated these measurements is proposed. Using a numerical simulation of the microstructural data collection process, the distributions of possible true values given a measurement value is computed. This distribution is constructed using a Bayesian framework, which integrates over a wide range of possible grain shapes, sizes, and orientations, until a converged posterior distribution is obtained.

These distributions of possible true values allow for the effective communication of the variability of a measurement with minimal assumptions. Results showing how the variability associated with the resolution at which the data is collected are presented. Results are also shown for various different measurement metrics, such as grain size, aspect ratio, and perimeter measures. This method also provides a direct means for evaluation of the efficacy of many different measurement algorithms. Furthermore, it allows for the easy construction of property distributions without the need for data fitting algorithms. Results are presented for the construction of several different property distributions. Finally, the context in which these tools can be used to better integrate the variabilities associated with experimental data collection into computational models is explained.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Evaluation of Event-Based Camera for Structural Dynamic Measurement and Control

Author(s): *Odey Yousef, *University of New Mexico*; Fernando Moreu, *University of New Mexico*;

Structural dynamic testing of systems is an experimental necessity in many fields such as automotive manufacturing, aerospace engineering, and seismic design. Such experiments typically rely on lab-scale representations of a larger system with physical vibration measurement instruments. However, physical sensors modify the properties and behavior of the system, increasingly with respect to the size of the modelled structure. Furthermore, they collect data at discrete locations. Frame-based video cameras may be used to solve both issues, as they offer full-field, contact-free displacement estimation. These traditional cameras collect a large amount of redundant background data, reducing the efficiency and processing speed of a system reliant on them. Neuromorphic event-based cameras offer a solution. Instead of collecting full frames of pixels at predefined sampling windows, event-based cameras asynchronously store information from pixels in the scene with sufficient change in luminosity at far greater sampling speeds than traditional cameras. Such data acquisition devices allow for efficient data collection and real-time processing at orders of magnitude greater efficiency. This work demonstrates a novel data processing algorithm and compares its performance in accuracy and latency. This evaluates the applicability of neuromorphic cameras in real-time, contact-free experimental control of dynamic structures

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Peridynamics Computations at the Exascale

Author(s): *Pablo Seleson, *Oak Ridge National Laboratory*; Sam Reeve, *Oak Ridge National Laboratory*;

Peridynamics is a nonlocal reformulation of classical continuum mechanics suitable for material failure and damage simulation, which has been successfully demonstrated as an effective tool for the simulation of complex fracture phenomena in many applications. However, the nonlocal nature of peridynamics makes it highly computationally expensive, compared to classical continuum mechanics, which often hinders large-scale fracture simulations. In this talk, we will present ongoing efforts to develop a GPU-enabled, performance portable, and exascale-capable peridynamics code designed to run on U.S. Department of Energy supercomputers, in particular Summit (currently ranked #2 in the TOP500 list) and Frontier (to be deployed later this year), both at Oak Ridge National Laboratory.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Architected Material Analogs for Shape Memory Alloys

Author(s): Yunlan Zhang, *Purdue University*; Kristiaan Hector, *Purdue University*; Mirian Velay Lizancos, *Purdue University*; David Restrepo, *UT San Antonio (former Purdue)*; Nilesh Mankame, *General Motors*; *Pablo Zavattieri, *Purdue University*;

We analyzed a new periodic architected materials with building blocks that are capable mimicking both salient behaviors exhibited by shape memory alloys namely, superelasticity and the shape memory effect. We develop an analytical model that explains how the block works. This model is then used to generate a phase diagram that captures the complex relationship between the stress on the material, its temperature and the various phases that can be produced. We then develop a design space map that enables a material designer to select key material parameters based on a desired thermo-mechanical behavior. In this talk we will show how this map can be used to design architected material analogs for shape memory alloys (ASMAs) for free recovery (i.e. shape recovery in the absence of an external resistance) as well as constrained recovery. A sample comprising three building blocks of an ASMA, that is designed for free recovery, is fabricated and tested. The experimental results show good agreement with those from finite element models and the analytical model. A couple of alternative ASMA block designs inspired by the complex thermo-mechanical behavior of a naturally-occurring material with shape effect will be also discussed.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Predicting Dynamic Response of Slender Structures in Windstorms

Author(s): *Partha Sarkar, *Iowa State University*;

Slender or flexible structures or their structural components in civil engineering are flexible ($f < 0.5$ Hz) and hence vulnerable to wind-induced vibration. Examples of such structures are plenty such as long-span bridges, high-rise buildings, stay-cables, power-line cables or transmission towers, wind-turbine blades, etc. Traditional methods to estimate wind effects (buffeting, VIV and flutter) for design of these structures require building scaled models of the prototype and testing them in a wind tunnel for straight-line wind and possibly testing them in a tornado or downburst simulator for non-synoptic winds, where the latter is not currently prescribed. Aeroelastic models are expensive to model physically and difficult to model numerically, and to some degree limited in what they can capture. As height of tall structures (>300 m) or span of horizontally spanned structures like long-span bridges (>2000 m) increase in the future, it will be increasingly expensive and more challenging to perform physical tests in boundary-layer wind tunnels and tornado/microburst simulators whose size is mostly limited. Further, traditional linear frequency-dependent models of aerodynamic loads are not valid for large-amplitude motions and non-stationary and transient wind excitation that can occur during hurricanes, thunderstorms, and gust fronts. In this paper, a time-domain method to estimate the wind-induced buffeting, vortex-induced vibration (VIV), and near-flutter response or flutter speed of slender structures is reviewed. The proposed method is based on numerically predicting the upstream wind of a specific characteristics and experimentally identifying the sectional- aerodynamic properties of the structure and then solving the governing equations of motion for wind-excitation in time domain. It is demonstrated to predict the wind response of example structures such as a tall building, a stay-cable, a signal-light structure, and a wind-turbine blade in straight-line ABL wind and a long-span bridge in a microburst and gusty wind using its sectional-aerodynamic and structural dynamic properties, where the load parameters of the example structures were identified using section model tests in a wind tunnel. The estimated wind-induced vibration response of the prototype structures compared well with other wind tunnel and full-scale studies. A case study of comparison of the vibration response of a tall building measured in laboratory simulated ABL and tornado winds shows that the characteristics of the tornado-induced excitation are different, and its magnitudes are much more severe from those of the conventional straight-line wind. This makes a case for considering non-conventional wind for design of tall structures located in specific regions.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Impact of Spine Strength and Stiffness on the Seismic Response of Strongback Frames

Author(s): *Peter Talley, *University of Tennessee*; Mark Denavit, *University of Tennessee*; Nicholas Wierschem, *University of Tennessee*;

Many structural systems are susceptible to soft story mechanisms during earthquakes. These mechanisms are life-threatening and lead to damage that is too costly to repair. One way to mitigate damage and eliminate the potential for soft story mechanisms is through the introduction of an elastic spine, sometimes called a strongback, which distributes drifts across the height of a structure. Strongbacks introduce unique design challenges and opportunities. Significant demand on the spine is generated by forces related to higher modes, which are not accounted for by the most common analysis methods, and the design criteria for the spine are unclear. A few design methods have been proposed for these systems. They focus on novel analysis methods to capture the seismic demand on the elastic spine, and then using those demands within existing design paradigms. Important questions remain open, however. How does overall performance of the structural system vary with the strength and stiffness of the strongback? What level of stiffness and strength is required to achieve strongback design goals? Previous work has focused on strength requirements for the strongback to prevent it from yielding; does allowing limited yielding in the strongback prevent achieving the goals? To evaluate these questions, a wide variety of strongback braced frames of different heights, plans, design seismic demands, etc. were investigated using a simplified model with three main components: (1) the strongback spine, abstracted into springs with explicit strength and stiffness, (2) buckling-restrained braces as the main energy-dissipating elements, and (3) continuous gravity columns, which provide a baseline level of continuity between stories. Incremental dynamic analysis was performed to examine the impact of varying the strength and stiffness of the strongback spine. Performance measures included peak story drift, maximum residual story drift, and story drift concentration (a heuristic for detecting soft stories). The results of the analyses show that the stiffness and strength of the strongback impact the overall response of the structure over a broad range, and identified the level at which increases in strength and stiffness provides only a marginal benefit. The results will help guide the further development of design recommendations and encourage the use of this innovative structural system.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Bayesian Calibration of a Cluster Dynamics Model

Author(s): *Pieterjan Robbe, *Sandia National Laboratories*; Tiernan Casey, *Sandia National Laboratories*; Khachik Sargsyan, *Sandia National Laboratories*; Habib Najm, *Sandia National Laboratories*;

We perform Bayesian inference of the parameters in a cluster dynamics computational model, where observed data summaries are available as mean values with associated error bars. Our calibration strategy uses synthetic data to match the uncertainty in the pushforward posterior to the given measurement errors. In doing so, the measurement error is reflected in the inferred uncertain parameters. To keep the approach computationally tractable, we replace the cluster dynamics model with a prebuilt polynomial surrogate model. The data used in our calibration effort is comprised of sets of diffusivity measurements for fission gas in uranium dioxide fuel, performed under different conditions, and thermodynamic measurements of uranium dioxide non-stoichiometry. We investigate how the contribution of these different data sets, taken from multiple sources available in the literature, can be weighted in the final likelihood function, in order to reflect associated confidence. We discuss the performance of the algorithm, and compare the results to those available from approximate bayesian computation inference.

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Baltimore, MD, May 31 - June 3, 2022

Title: Parametrically Upscaled Coupled Constitutive Model (PUCCM) for Nonuniform Unidirectional Multifunctional Composites from Micromechanical Analysis

Author(s): *Preetam Tarafder, *Johns Hopkins University*; Saikat Dan, *Johns Hopkins University*; Somnath Ghosh, *Johns Hopkins University*;

This work develops a finite deformation Parametrically Upscaled Coupled Constitutive Model (PUCCM) for structural scale electromechanical response of structures with nonuniform piezocomposite microstructures undergoing progressive damage. The microstructure consists of unidirectional piezoelectric fibers distributed nonuniformly in a passive epoxy matrix. The PUCCMs are thermodynamically consistent, reduced order continuum models [1, 2] with explicit representation of microstructural descriptors and evolving material variables. The upscaled constitutive model incorporates the nonuniform microstructural morphology in the PUCCM coefficients through representative aggregated microstructural parameters or RAMPs. Optimal expressions for RAMPs are determined through principal component analysis of the two-point correlation functions. The PUCCM coefficients in terms of the RAMPs are determined using machine learning tools operating on data generated by micromechanical analysis. The PUCCMs represent damage anisotropy at the structural scale through a second order damage tensor that contributes to the evolution of a damage surface in the space of damage work conjugate. The damage surface characterizes the initiation and evolution of damage in the multifunctional composites. The developed PUCCM is used for structural analysis of multifunctional composites for understanding concurrent damage and failure at multiple scales.

[1] X. Zhang, D. O'Brien and S. Ghosh, "Parametrically homogenized continuum damage mechanics (PHCDM) models for composites from micromechanical analysis", *Computer Methods in Applied Mechanics and Engineering*, Vol. 346, No. 1, pp. 456-485, April 2019.

[2] X. Zhang and S. Ghosh, "Parametrically homogenized continuum damage mechanics (PHCDM) Models for unidirectional composites with nonuniform microstructural distributions", *Journal of Computational Physics*, Vol. 435, Art. 110268, March 2021.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Leveraging Machine Learning to Predict the Structural Capacity of Slender Steel Members at Elevated Temperature

Author(s): *Qi Tong, *Johns Hopkins University*; Carlos Couto, *University of Aveiro*; Thomas Gernay, *Johns Hopkins University*;

Evaluation of the elevated temperature capacity of steel members is important to design structures that can perform adequately in the event of a fire. However, for slender steel members, current methods of evaluation are hindered by the complex interaction between stability and thermal effects on the response. Finite element modelling is computationally expensive, while analytical methods err on the side of overconservativeness. In this presentation, we describe the application of machine learning techniques to predict the resistance of slender steel columns and beams at elevated temperatures. Machine learning appears as a promising approach to overcome the limitations of finite element models and analytical design methods, as attested by the fact that it has been increasingly adopted in many engineering fields to solve a variety of nonlinear problems. We adopt machine learning techniques including artificial neural networks (ANN), support vector regression (SVR), polynomial regression (PR), and random forest (RF), to assess the elevated temperature resistance of slender steel columns and beams at minimal computational cost. The machine learning models are trained and tested based on an extensive dataset of numerical results obtained through parametric finite element simulations. The finite element simulations use shell element models in the thermal-structural software SAFIR and are validated against experimental data on steel columns and beams at elevated temperatures. The results show the excellent performance of the machine learning models in terms of agreement with the numerical results for the tested range of slender steel beams and columns. Parametric analyses are also conducted to discuss the ability of the machine learning models to provide reasonable assessment when changing the loading and boundary conditions outside the range considered in the training dataset, and insights based on the structural mechanics response are formulated. Finally, the results of the machine learning models are compared against existing design codes and show the benefits of using these data-based approaches to calculate the resistance of slender steel columns and beams at elevated temperatures.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Dispersion and Dissipation Behavior in a Pre-Strained Shape Memory Alloy Periodic Beam

Author(s): *Qianlong Zhang, *Purdue University*; Hongfei Zhu, *Purdue University*; Fabio Semperlotti, *Purdue University*;

Shape memory alloys (SMAs) exhibit significant energy dissipation capacity that is associated with either their temperature-induced or stress-induced phase transformations. This ability to tune the damping capacity has been exploited to attenuate structural vibrations and stress waves in mechanical systems. In this paper, the dispersion behavior as well as the energy dissipation properties of a superelastic periodic SMA beam are studied under the simultaneous effect of material and geometric nonlinearities. The dispersion relations do not show significant alterations as a result of the pre-strain levels, hence indicating that the damping capacity of SMAs has a weak effect on the wavenumbers; this latter observation is consistent with the behavior of elastic lattices with general material damping. In terms of the attenuation characteristics, an increase in the pre-strain can appreciably reduce the amplitude of propagating waves when only material nonlinearity is considered. When both material and geometric nonlinearities are considered, it is found that under constant pre-strain the amplitude of propagating waves remain practically unchanged while increasing the excitation amplitude. These results suggest that the SMA lattice can effectively attenuate large amplitude waves. Another interesting phenomenon that was observed concerned the effect of periodicity. By comparing the displacement amplitude of the periodic SMA beam with its non-periodic counterpart (while maintaining the same global mass properties), the periodic design was capable of enhancing the energy dissipation capacity. These results suggest that periodicity can be exploited to further tailor and enhance the energy dissipation capabilities of SMA structures. Overall, this study provides several important guidelines for the design of periodic SMA structures for vibration and wave suppression.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Mechanics of Bioinspired Living Materials

Author(s): *Qiming Wang, *University of Southern California*;

The US infrastructure is continuously aging and failing during service or under unpredictable hazards such as hurricanes, earthquakes, and terrorist attacks. One of the NAE grand engineering challenges in the 21st century is to restore and improve urban infrastructure (www.engineeringchallenges.org/challenges/infrastructure.aspx). Living organisms typically exhibit extraordinary resilience to hazards, thus becoming continuous sources of inspiration for designing engineering materials and structures. Living organisms are typically different from engineering materials in two aspects: First, living organisms typically feature sophisticated microstructures and architectures that are challenging to reproduce in traditional engineering practice. Second, living organisms consist of living cells to support their metabolisms, such as growth, regeneration, and remodeling, which are typically impossible in traditional engineering materials. In this talk, we present the design of bioinspired living materials by integrating living components (e.g., living chemistry, microorganisms, and plants) into engineering materials using modern manufacturing technologies. The vision is that these bioinspired living structures can imitate both architectures and metabolisms of living organisms to enable self-growing, self-remodeling, self-strengthening, and self-healing in resistance to aging, fatigue, and natural hazards. For example, assisted by living chemistry, 3D-printed structures can self-heal large-scale impact damages and fractures. Assisted by living microorganisms, 3D-printed polymers can self-grow into structural composites with pre-designed delicate microstructures. Assisted by living chloroplasts, 3D-printed artificial trees can harness photosynthesis to self-remodel into multifunctional materials.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: A Two-Step Deep Learning-Based Surrogate Model for Pressure on Low-Rise Buildings

Author(s): *Qiming Zhu, *University of Illinois at Urbana-Champaign*; Ze Zhao, *University of Illinois at Urbana-Champaign*; Jinhui Yan, *University of Illinois at Urbana-Champaign*;

Digital models are important parts of digital twins, however fast and accurate model remains challenging. In this paper, we present a new two-step deep learning-based framework for fluid field surrogate modeling and pressure sensor location optimization in typical wind engineering problems. Our framework features two major contributions: (1) Our surrogate model is able to do fast fluid field prediction and update its state by using sensor data. The surrogate model builds a mapping between sensor information and full fluid field by combining previous unbalanced high-fidelity data (field velocity and sparse structure surface pressure) and physical conservation laws. (2) Pressure sensors can be redistributed efficiently by utilizing the first-step surrogate model and second-step pressure sensor location optimization. Fewer sensors are required while still maintaining the high accuracy of surface pressure predictions.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Performance of Various Inflow Turbulence Generation Methods for Wind Engineering Applications

Author(s): *Rathinam Selvam, *University of Arkansas*; Zahra Mansouri, *University of Arkansas*; Arindam Chowdhury, *Florida International University*;

If buildings are not strong enough to resist winds, they can be damaged. Recent years wind flows have higher intensity compared to those in the past and it is expected to be higher in the future (Woods, 2019). Hence, it demands a better understanding of wind loads on buildings considering in designing structures. For component and cladding, the maximum peak pressure coefficient (C_p) obtained from ASCE 7-16 is -3.2 for a low-rise building. However, field measurements have reported that the maximum C_p on a low-rise building can be lower than -8.

A well-validated computational fluid dynamic (CFD) provides more flow field details at lower costs compared to field measurements. To incorporate turbulence effects in wind, turbulence modeling methods are used in CFD. Large Eddy Simulation (LES) is more reliable and applicable in the industry compared to other methods. However, in LES simulations, a proper turbulent flow field at the inlet as inflow boundary condition is required to apply and predict C_p correctly. Hence, the turbulent flow behavior in the computational domain is extremely dependent on the type of inflow generators. In this work, the performance of synthetic turbulence generators is evaluated by plotting the velocity, pressure, and wind spectrum at the inlet and building location without building. The flow domain is a channel flow with inflow and outflow boundary condition (BC) in the stream wise direction, noslip and slip wall at the bottom and top of the domain and periodic or symmetric BC on the sides. The considered methods are a) Digital Filter Methods (DFM), b) Synthetic eddy methods (SEM), c) Divergence Free Synthetic Eddy Method (DFSEM), d) Anisotropy Turbulent Spot Methods (ATSM) and e) Random Fourier Method RFM). Other than RFM all the other methods are computed using TInF software available from SIMCenter and CFD calculation were done using OpenFOAM and inhouse research programs.

All the methods produced spurious pressures at the building location. There is also difference in the wind spectrum at the inlet to building location in the high frequency range. The high frequency wind spectrum cut off at the building location depends on the largest grid spacing used in CFD. Many of the methods doesn't have proper way to control the frequency range of the wind spectrum. The reason behind these issues will be discussed and few methods of improvement are also suggested for inflow turbulence generation.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Convolutional Autoencoders for Compressing and Decoding Metal Microstructures

Author(s): Dharanidharan Arumugam, *North Dakota State University*; *Ravi Yellavajjala, *North Dakota State University*;

Computer Vision is now widely used to characterize, and analyze metal microstructures from digital micrographs. The accuracy of the Computer Vision algorithms will depend on the quantum of data available and the quality of images used. The material science community can benefit by safe and secure sharing of micrographs which is often hampered by large volumes of data and lack of understanding of what visual features are important for compact representation of microstructural information. The objective of this study is to compress the metal microstructure data and identify the features important for the compact representation of the micrographs. To this end, we use convolutional autoencoders to compress the image data to a compact representation and develop a new pixel attribution method that identifies the regions of the micrographs that are important for the reconstruction of images from lower-dimensional vectors.

Convolutional autoencoders (CAE) have an encoder that compresses the inputs to dimensionally reduced latent variables and a decoder that reconstructs the original inputs with an acceptable loss in the information. Since the trained weights of the decoder network are necessary to reconstruct the original images, the decoder network also acts as a key to securely decompress the image data into its original form. In this study, we compressed microstructural images of ASTM A36, A572, and A992 of size 256×256(65,536 pixels) into a latent dimension of size 2048 using a convolutional autoencoder. This input image dataset of size 6.15 Gb is reduced to 278 Mb with a compression ratio of 22.1 without losing necessary information in reconstruction. The encoder network of the autoencoder has 4 convolutional layers alternated with max pool layers, whereas the decoder network has 4 convolutional layers alternated with upsampling layers. The number of kernel filters in the convolutional layers is decreased from 64 to 8 in the encoder and increased again to 64 in the decoder. We also analyzed the importance of input pixels to the latent space of the trained network using a new complex step derivative approximation-based pixel attribution approach. Pixel attribution contours outlining the importance of the pixel regions to its reconstruction are generated. The generated contours consistently indicate that the grain boundaries and minor metallurgical phase regions of the microstructure are important for the reconstruction of metals with multiple phases. Data compression, sharing, and a novel pixel attribution method to identify important regions of the microstructure will be discussed in this talk.

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Baltimore, MD, May 31 - June 3, 2022

Title: Quality Control of Low-Cost Nitrate Sensors Using a Scalable and Resource-Efficient Artificial Intelligence Based Approach

Author(s): *Rih-teng Wu, *National Taiwan University*; Ye Mi, *Purdue University*; Xihui Wang, *Purdue University*; Sotoudeh Sedaghat, *Purdue University*; Kerry Maize, *Purdue University*; Nicholas Glassmaker, *Purdue University*; Mohammad Jahanshahi, *Purdue University*; Rahim Rahimi, *Purdue University*; Ali Shakouri, *Purdue University*; Jan Allebach, *Purdue University*; Elisa Bertino, *Purdue University*;

The real-time assessment of soil conditions using nitrate sensors has a variety of applications in Agriculture Engineering and Environmental Engineering. Current commercial sensors are quite expensive, which prevents them from being deployed for large-area monitoring with many sensors. Therefore, there is an urgent need to develop new low-cost sensors with a reliable roll-to-roll manufacturing system. In this study, a printed thin-film sensor is fabricated to measure the concentration of nitrates using the recording of potentiometric responses when the sensor is placed in a nitrate solution. Also, an artificial intelligence (AI) based framework is proposed to enhance the quality control of the sensors during the manufacturing process. We first build a deep auto-encoder (DAE) using only a few amounts of images of the sensors for automatic feature extraction. Next, the features are trained with neural networks to predict the potentiometric responses of the sensors, as well as the physical properties (e.g., thickness of the film) of the sensors. Once the training is finished, the networks are able to quickly identify the sensors of inferior performances, and the estimated physical properties can be served as a reference for adjustments in the manufacturing system. The proposed framework is scalable and resource-efficient, in that the feature extractor built using very limited training data works decently on the sensors made on other fabrication dates. Results from lab characterized nitrate sensors have demonstrated the robustness of the proposed approach.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Effect of the Pore Fluid Compressibility on the response of Crushable Sands Subjected to High Strain Rate Compression

Author(s): *Ritaja Ray, *Northwestern University*; Giuseppe Buscarnera, *Northwestern University*;

The interstitial pore fluid of multiphase porous solids plays a major role in the stress-deformation behavior. It has been observed both in experiments and natural events that drainage often act as the key controlling factor. Geomechanical analyses typically target two end members of fluid flow, i.e., drained or undrained. However, in real applications the response is likely to be intermediate between these regimes. In this research we use a lumped modelling approach to examine partially drained processes in conjunction with a constitutive model for dry sand capturing grain crushing and dilation. The model results are validated against available measurements. Further, a parametric analysis is performed to examine the effect of the loading rate, soil permeability, and confining pressure. Finally, the effect of the fluid compressibility is incorporated, to examine the emergence of coupled flow-deformation feedbacks even in dry sand beds subjected to rapid dynamic forcing, such as impact, penetration, and comminution. The simulated model responses are then compared, with emphasis to the difference between water-saturated and air-saturated systems characterized by the same packing density and confinement. The results show that the model is able to capture the response of sand for varying combinations of packing density, loading rate, degree of saturation, and hydraulic conductivity.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Comparison of Graded and Thin-Shell Models for the Interfacial Transition Zone

Author(s): *Robert Zimmerman, *Imperial College*;

Many composite materials, in particular cementitious materials, contain interphase zones that surround each inclusion. In concrete, this zone is referred to as the interfacial transition zone (ITZ). Analysis of backscattered electron images reveals that the porosity in the ITZ varies smoothly, from a uniform value corresponding to the bulk cement paste, to a higher value near the aggregate particles. This gradient in porosity would be expected to lead to a local gradient in physical properties such as the elastic moduli, fluid permeability, ionic diffusivity, etc.

Broadly speaking, two types of models have been developed to model the influence of the ITZ on overall macroscopic physical properties. In one type of model (Lutz et al., *Cement and Concrete Research*, 1997), the local physical properties in the ITZ are assumed to vary smoothly, usually according to a power law. In these models, there is no clearly defined boundary between the ITZ and the bulk cement paste. Another family of models (Hashin and Monteiro, *Cement and Concrete Research*, 2002) treats the ITZ as a clearly-defined thin shell-like zone within which the local properties are distinct from those of the bulk cement paste.

Graded ITZ models are clearly more “realistic” with regards to their treatment of the ITZ, but generally lead to more complicated expressions for the effective macroscopic properties. Thin-shell models lead to simpler expressions for the macroscopic properties, but do not accurately reflect the local property variations within the ITZ. An obvious question, but one which has not yet been well explored, is whether the two types of models can be made to coincide, by some rational choice of the shell thickness and the local value of the physical property that is used within the thin shell. This question will be investigated in detail in this talk.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Machine Learning Models for Prediction of Single and Multiple Concrete Properties with SHAP Method Interpretation.

Author(s): *Rodrigo Teixeira Schossler, *Case Western Reserve University*; Xiong (Bill) Yu, *Case Western Reserve University*;

Using statistical and machine learning models to predict the properties of concrete from its mixture proportions has received great attention considering that concrete is the most widely used construction material in the world. A reliable ML model for accurately predicting the compressive strength (CS), slump, and flow of concrete can contribute to construction decisions such as framework removal and road opening, that ensure performance, reduce risk while saving time, energy, and cost. The results of ML models in predicting high-performance concrete properties are affected by the input variables and characteristics of the model. More than that, interpretations of results are vital towards the development of efficient materials design methods for enhanced materials performance. For this reason, four ML predictive models, including random forest (RF), decision tree (DT), deep artificial neural network (DANN), and XGBoost (XGB) are developed to investigate the relationship between the mixture design variables and their characteristics. In addition, the notion of SHAP (SHapley Additive exPlanations) value that comes from cooperative game theory, which is also popular in machine learning, was used. The SHAP method was used to analyze the relative importance of the factors affecting the best model. This investigation provides the reader with theoretical results, basic examples, and attribution of comparative analysis of flow, slump, and compressive strength that included mixtures of concrete found in the literature with unique properties and curing methods. The trained models allow it to estimate properties such as flow, slump, and compressive strength of concrete. Also, with the use of Shapley values analysis on the data is it possible to obtain useful value ranges for individual features (as well as their different combinations) for developing improved compressive strength, slump, and flow models identifying which ones are relevant and need to be considered when producing a specific mixing. This work can be used as an initial point toward the design of optimized and enhanced mixtures.

Title: Numerical/Experimental Study of Self-Healing Under Sustained Loadings in Concrete

Author(s): *Roman Wan-Wendner, *Ghent University*; Giovanni Di Luzio, *Politecnico di Milano*; Salam M.J. Al-Abaidi, *Politecnico di Milano*; Yilin Wang, *Ghent University*; Marco Davolio, *Politecnico di Milano*; Liberato Ferrara, *Politecnico di Milano*;

In the construction industry field, the challenge must be faced of building sustainable resilient structures and infrastructures able to guarantee the safety of people while reducing the impact due to maintenance works and overall life cycle costs. These goals are also achieved with the healing of micro-cracks and defects: self-healing and self-curing admixtures are employed to seal small cracks, in case also guaranteeing recovery of material properties. However, for real structures under service loading the time-dependent behavior is also of extreme importance, especially in presence of cracks which can lead to a nonlinear creep behavior that might cause the structural failure [1-2]. Now the new challenge is to study and quantify the effect of healing on the nonlinear creep behavior. This study aims at the following goals: 1) to characterize with experimental investigations the effect of the healing in tests in which the specimens, along the exposure time and under controlled environmental conditions, are under sustained load, the expected service load, determined as a fraction of the pre-cracking load; 2) develop a comprehensive numerical framework for the interpretation and simulation of the experimentally observed results. To this purpose an experimental investigation is currently ongoing at Politecnico di Milano with reference to a Ultra High Performance Concrete developed in the framework of the H2020 ReSHEALience project for exposure to extremely aggressive environments [2,3]. 30 mm thin beam specimens have been pre-cracked in 4-point bending up to a prescribed serviceability crack width level and then, thanks to a tailored test set-up, subjected to a sustained load equal to the recorded pre-cracking load. While undergoing such a conditions the specimens have been exposed to the intended healing environment (water with different levels of aggressiveness) and cured for a time period ranging from one to twelve months (still on going). At the end of each scheduled period, besides measuring by means of optical microscopy the crack sealing, the post-cracking and post-healing mechanical performance has been assessed by 4-point bending tests as well. The numerical framework is based on the recent developments of the multiphysics lattice particle model [4,5,6]. The numerical framework is framed into a coupled hygro-thermo-chemo-mechanical numerical framework, resulting from pairing the mesoscale Lattice Discrete Particle Model (LDPM) and the Hygro-Thermo-Chemical (HTC) model [7,8]. The experimental investigation has been performed at Politecnico di Milano.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Gaussian Process Subspace Prediction for Parametric Studies of Structural Systems

Author(s): *Ruda Zhang, *Duke University*;

Parametric studies of complex civil engineering systems require repeated simulations of large-scale computational models at various model parameters, for purposes of optimization, design, and control, to uncertainty quantification. Such tasks are computationally expensive and oftentimes infeasible. Previous efforts to speed up such computations build parametric surrogates by interpolating subspace or models of low dimensions. These methods can be inaccurate and slow. Here we propose a novel Bayesian nonparametric model for surrogate modeling: the Gaussian process subspace (GPS) model. It combines physics-based reduced order models and data-driven, machine-learning based surrogates to construct fast and accurate models for parametric studies. As an innovative use of Gaussian processes, the GPS adopts a simple yet general correlation structure, and a principled approach for model selection. Its predictive distribution admits an analytical form, which allows for efficient prediction over the parameter space. For parametric studies, the GPS provides a probabilistic prediction at a new parameter point that retains the accuracy of local reduced models, at a computational complexity that does not depend on system dimension, and thus is suitable for online computation. We apply our method to emulate the dynamics of a multilevel structure for spent nuclear fuel. Compared with the state-of-the-art methods, our method is more data efficient and computationally efficient, and gives smooth predictions with uncertainty quantification.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Vision-Based Measurements for Dynamic Evaluation of Structures

Author(s): *Sajjad Safari, *University of Delaware*; Shaymaa Obayes, *University of Delaware*; Wael Aloqaily, *University of Delaware*; Monique Head, *University of Delaware*;

Computer vision and other vision-based sensing are being used for remote monitoring of structures such as bridges and buildings. Digital imaging technologies allow for remote structural monitoring of locations that may be deemed unsafe to access or merely inaccessible for mounting sensors. For this study, a vision-based monitoring system is used to validate remote measurements during full-scale, multidirectional shake table tests subjected to predefined motions such as sine waves and scaled recorded ground motions. The system consists of video cameras to validate dynamic displacement and acceleration structural responses in real-time through processing the captured images. The displacements of the images of the conventional target panel attached to the structure can be captured at a stationary point away from a structure but within the field of view. In addition to monitoring displacements, acceleration time histories were compared to the feedback traces from the actuators and Raspberry pi units interacting with a commercially available low-cost MEMS accelerometer. The data from the shake table output and Raspberry pi units shows the robustness of the vision-based measurement system and its suitability for remotely monitoring displacements and accelerations with significant accuracy.

Therefore, the use of vision-based measurements of various types of structures in different conditions subjected to real-time service loads provides a feasible alternative and flexibility to monitor different points simultaneously along the structure compared to conventionally mounted discrete sensors as evident from the data obtained in the case study presented.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Efficient Adaptive Design of Experiments Methods for Global Surrogate Modeling Based on Approximated Mean Squared Error and Multi-Criteria Search Technique

Author(s): *Sang-ri Yi, *University of California, Berkeley*; Alexandros Taflanidis, *University of Notre Dame*;

Design of experiments (DoE) plays a prominent role in global surrogate modeling applications by allowing us to identify the most informative simulations experiments to improve the computational accuracy of the developed metamodel. For example, recent work by Kyprioti et al., (2020) has showcased the importance of combining concepts related to both variance and bias reduction in adaptive DoE. Considerable research effort has been made to identify and apply optimal DoE strategies for global surrogate modeling; however, there is still room for improvement. For example, the computational cost of DoE is often non-trivial for the benefit it provides. Furthermore, choosing the arbitrary weight factor between the variance and bias measures is often not straightforward. To address such challenges, this work proposes two new adaptive DoE algorithms for training the global Gaussian process model. The first approach approximates the traditional variance criterion, integrated mean square error (IMSE), to increase the computational efficiency. In particular, the classic IMSE, during its integration process, required repeated inversion of the covariance matrix of which the computational demand increases as the number of the DoE stages increases. Instead, we introduced a decaying shape function of influence that surrounds each experiment to approximate the reduction of mean squared error after adding the experiment. By numerically integrating the area under the function, approximated IMSE is obtained with lesser computations. On the other hand, the second approach considers the adaptive DoE selection as a multi-objective optimization task, where the objectives are the variance and bias measure, and utilizes the Pareto optimal points to select a set of optimal DoE points. Once the Pareto front samples are identified, they are sorted in descending order in a greedy way by multiplying the two objective values and truncated at a given number of the batch simulation limits, e.g. number of parallel CPU cores. In light of the non-dominated search strategy, the proposed approach naturally balances the exploitation and exploration without introducing an additional tuning parameter, leading to more robust training when a highly localized nonlinear response is presented.

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: A Long Short-Term Memory-Based Algorithm for Seismic Response Prediction Using Structural and Material Parameters

Author(s): *SangHoon Song, *Hanyang University*; Ali Tabish, *Hanyang University*; Robin Enju Kim, *Hanyang University*;

Earthquakes are one of the catastrophic hazards that may impact our lives bringing physical and/or potential damages on built structures. Therefore, to assure the sustainability of those structures, predicting their responses through successful computational implementations under seismic load has been a task for civil engineers. Classical physics-based computational methods, for example a finite element method (FEM) costs vast amount of computing effort to conduct nonlinear time history analysis. To overcome its computationally intensive workload and incertitude of calculation, artificial intelligence (AI) technology became a promising approach in response prediction. Recently, several researchers carried out deep learning methods for computationally cost-effective tool for predicting structure response adopting nonlinear functional modelling. This paper proposes a long short-term memory (LSTM) algorithm for response prediction incorporating nonlinear characteristics and responses of a structure. LSTM is a class of recurrent neural network (RNN) that overcome the major drawbacks of the RNN, which is gradient vanishing and exploding: It connote the ability to memorize the prior data within given time history, which allows the network to yield precise prediction in longer time series data [1]. Herein, LSTM reveals great performance in modelling aforementioned data that involve nonlinearity at the response. The developed algorithm has been evaluated for multi input single output (MISO) case together with multi input multi output cases (MIMO): the inputs are ground motion (GM) and diverse variables such as yield strength (f_y), damping ratio (?) and additional units that related with designed model then output as storey displacement, velocity, and acceleration in MISO and additionally, restoring force for MIMO. Datasets are produced using MATLAB including the restoring force that is calculated using the Bouc-Wen hysteresis model [2] which is an efficient way of modelling hysteretic response of structural systems. Generated datasets are divided into sets for training, validation, and prediction in specific ratio. In conclusion, proposed algorithm will play significant role in modelling dynamic response with various essential parameters that will raise the level at structural health monitoring (SHM) area.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Bench-Scale Laboratory Experiments and Coupled Thermo-Hydro-Mechanical-Chemical Modeling for Understanding the Behavior of Bentonite Under High Temperature Heating and Hydration

Author(s): *Sangcheol Yoon, *Lawrence Berkeley National Laboratory*; Sharon Borglin, *Lawrence Berkeley National Laboratory*; Chun Chang, *Lawrence Berkeley National Laboratory*; Chunwei Chou, *Lawrence Berkeley National Laboratory*; Liange Zheng, *Lawrence Berkeley National Laboratory*; Yuxin Wu, *Lawrence Berkeley National Laboratory*;

In geological repository for high-level radioactive waste, the bentonite buffer that is emplaced between the waste package and the wall of the emplacement tunnel plays a crucial role in the long-term safety of the repository. The bentonite buffer is exposed to heating from the waste and hydration from the existing geological formation, which leads thermo-hydro-mechanical-chemical (THMC) changes over their life span. In most repository design concepts, temperature within the bentonite at the vicinity of canister is managed under 100 °C, and subsequently most studies were conducted under 100 °C. However, understanding the THMC behavior of bentonite under higher temperatures (up to 200 °C) could open different design concepts and improve the predictability of numerical models for assessing long-term performance of bentonite buffer. In this paper, we present bench-scale laboratory experiments with heating up to 200 °C and the corresponding THMC modeling results.

The bench-scale laboratory experiments include two test columns, with the non-heated control column undergoing only hydration, and a heated column experiencing both heating in the center up to 200 °C and hydration from a sand-clay boundary filled between the bentonite and the vessel. X-ray CT images were examined frequently to check the spatio-temporal evolution of THMC due to heating, hydration, bentonite swelling/compression, and mineral precipitation. Chemical analyses of the effluent fluid were also conducted during the test.

Aligned with the experiment setup, 2-D axisymmetric grid system was used for hydraulic simulation and the mechanical changes were investigated in full 3-D with a sequential method. The model was investigated with step-wise temperature boundary conditions at the heater and fixed pressure at saturated sand layer. After calibrating the properties such as thermal conductivity, specific heat, relative permeability curve, soil water retention curve, and mechanical properties, the model considers the combined impact of saturation, fluid pressure, and porosity change due to swelling/compression on the spatio-temporal distribution of bulk density and movement of the thermocouple modules. In the model, three approaches were employed to model the swelling behavior: a linear elastic swelling model, state surface approach, and the Barcelona Expansive Clay Model. A geochemical model was added to the THM model to understand the changes in the concentration of major ions in the effluent fluid and precipitation of minerals close to the heater. Deliverables from this study will help to interpret experimental complexities and improve our understanding of bentonite THMC processes.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Environmental Application Potential of FRP-Reinforcement in Concrete Infrastructure Engineering: LCA Data and Two Application Examples

Author(s): *Sara Reichenbach, *University of Natural Resources and Life Sciences, Vienna*; Philipp Preinstorfer, *TU Wien, Vienna*; Nadine Stoiber, *University of Natural Resources and Life Sciences, Vienna*; Tobias Huber, *TU Wien, Vienna*; Benjamin Kromoser, *University of Natural Resources and Life Sciences, Vienna*;

Fibre-reinforced polymer (FRP) reinforcement, with its positive attributes in regard to low required concrete cover, high tensile strength, light weight and high corrosion resistance, has become a serious alternative to conventional steel reinforcement within the search for more resource-efficient and durable concrete constructions. In order to evaluate the construction material as a whole, not only the mechanical characteristics but also the environmental footprint has to be considered when designing such structures.

In the first part of the presentation a cradle-to-gate assessment (LCA) for the production of non-metallic reinforcement (carbon CFRP, glass GFRP, basalt BFRP) based on products found on the European market will be presented. The environmental data (global warming potential, acidification potential, potential for abiotic depletion of fossil resources, and potential for abiotic depletion of non-fossil resources) were evaluated for the individual components of the fibre composites as well as the finished reinforcement (1D rebars and 2D textiles). With regard to the fibres, carbon, basalt and glass fibres were investigated, while vinyl ester resin, epoxy resin, polyester resin, styrene-butadiene rubber and acrylates were considered on behalf of the matrix materials. Within the second part the data will be applied for the material-specific design of a railway platform barrier and a retaining wall, which are reinforced with textile CFRP reinforcement and GFRP reinforcement, respectively. This is done in accordance with the current state of data availability and standardisation. Subsequently the environmental impact of those two examples was evaluated and compared to ordinary steel-reinforced structures to assess the application and sustainability potential of the FRP-reinforced alternative design.

The results of the assessment in regard to mass show a much higher environmental impact of carbon fibres, in comparison to basalt or glass fibres and steel. Such differences are not evident with regard to the matrix material. The results change when not only the reinforcement but the whole structure and its design is taken into consideration. The comparison on a structural level proves an environmental potential when using FRP reinforcement for the chosen construction elements based on a material specific design.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Fire Resilience of Steel-Concrete Composite Floor Systems: Experimental Evaluation

Author(s): *Selvarajah Ramesh, *National Institute of Standards and Technology*;

Steel-concrete composite system is a commonly used floor construction for multi-story steel framed buildings. Structural integrity of composite floor assemblies in the event of a fire relies heavily on the passive fire protection applied to exposed steel surfaces determined from prescriptive fire testing methods. The standard fire testing, however, has inherent limitations because of the use of small-scale specimens and idealized boundary conditions which are not commonly seen in real buildings. Therefore, this method seldom provides useful information regarding the overall fire resilience of a real-scale composite floor including connections. With these recognized limitations in the present fire testing method, a series of landmark compartment fire tests is being conducted on the 9.1 m × 6.1 m composite floor systems to measure their behavior and fire resilience using a full-scale two-story and two bays by three bays steel gravity frame at the National Fire Research Laboratory of the National Institute of Standards and Technology.

In this talk, the effect of the test variables on the structural behavior and integrity of the composite floors will be presented. The first experiment (Test #1) aimed to create baseline data for the real fire resistance and behavior of the full-scale composite floor system designed to achieve a 2-hour fire resistance rating used in the US practice. The second experiment (Test #2) was conducted to study the fire resilience of the composite floor system with the slab reinforcement of larger area and ductility, designed incorporating tensile membrane action. The first two tests demonstrated that the appropriate slab reinforcement scheme can maintain the structural integrity at large vertical displacements over a longer duration of fire exposure. The third test (Test #3), currently in progress, aims to evaluate the structural integrity of the composite floor with no fire protection on the secondary beam. The data from these experiments will be essential to explore engineered solutions that could optimize the passive fire protection and slab reinforcements used in the steel-concrete composite floor systems, a necessary step in the performance-based design of steel framed buildings subjected to fire.

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Baltimore, MD, May 31 - June 3, 2022

Title: Post-Fire Stability and Performance of Tall Steel Buildings

Author(s): *Serdar Selamet, *Bogazici University*; Aykut Onursal, *Bogazici University*; Yusuf Özer, *Bogazici University*;

Fire poses high level of risk for the structural integrity of tall steel buildings. Therefore, it is crucial to understand the performance of such structures under fire conditions for proper design. Steel members subjected to elevated temperatures weaken in terms of stiffness and strength, which causes the structural systems to undergo large deflections and rotations. Permanent deflections may cause a change in the modal and dynamic characteristics of steel structures and thereby decrease their seismic performance. This study investigates the changes in earthquake response of a tall steel building after a multi-story fire event. As a case study, a 42-story tall residential building with 960 m² floor area is modeled using finite element software. Fire load is estimated from surveys of commonly used combustible items in residential apartments. A parametric study with fire scenarios occurring in lower-height, mid-height and upper-height of the building on multiple floors is performed. Fire modeling is performed using fire dynamics simulator. Modal response and non-linear time history analyses are performed to estimate the earthquake resistance before and after the fire event. Results suggest that fire spread to multi-floors causes permanent deformations on structural members, which significantly alters the relative floor drifts of the tall building under study. Fire on the lower levels is the most critical scenario because it leads to a soft-story response.

Title: Accurate Wildfire Prediction by Geostationary Orbit Satellites and Rate of Spread Adjustment Factor

Author(s): *Seungmin Yoo, *Seoul National University*; Junho Song, *Seoul National University*;

Wildfires tend to spread rapidly and inflict widespread damage using various natural materials in the mountains including trees and plants as fuels. In order to reduce such damage, rapid predictions of wildfire spread are essential. However, regional-scale wildfire spread simulators used in near-real-time wildfire spread prediction have low accuracy. In order to improve the prediction accuracy, real-time wildfire perimeter observation data is generally used. Various methods have been proposed to increase the prediction accuracy through data assimilation between observation data and spread prediction data [1]. Real-time wildfire perimeter observation data are generally obtained using drones, but this option is often infeasible due to stiff winds or thick forests. One of the most effective methods to consistently obtain real-time wildfire observation data regardless of the external conditions is to use geostationary orbit satellites (GSO) [2]. However, the spatial resolution of GSO is exceedingly low due to the high altitude. In addition, since new wildfire observation data can be obtained from only one pixel at a time, it is difficult to assimilate with the wildfire perimeter observation data.

This study proposes a new algorithm that indirectly improves the prediction accuracy of the regional-scale wildfire spread simulator by updating the Rate of Spread (ROS) adjustment factor in near-real-time through the observation data of GSO. The ROS adjustment factor aims to empirically calibrate the initial ROS obtained based on weather, terrain, and fuel dataset. This determines the ROS which will be used by wildfire spread simulators. In order to assimilate the ROS adjustment factor using the GSO wildfire observation data, the relationship between the ROS adjustment factor and the initial wildfire observation time difference of adjacent pixels is defined. Data assimilation of the ROS adjustment factor uses Ensemble Kalman Filter. To represent the actual spread of wildfires, different ROS adjustment factors are applied to each fuel model. The proposed algorithm is tested and demonstrated through the actual wildfire spread dataset of the 2020 Creek Fire. The results confirm that the ROS adjustment factor can drastically increase the wildfire spread prediction accuracy.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Past, Present and Future of Performance-Based Wind Engineering

Author(s): *Seymour Spence, *University of Michigan*;

Wind engineering is undergoing a period of rapid change. From a traditionally prescriptive discipline, the theoretical and practical advances of recent years is shifting the profession towards performance-based procedures. The motivation for this change stems from the enormous losses that can be generated by severe wind storms. It is estimated that over \$300 billion were lost to severe hurricanes alone between 2017 and 2018. These losses are generally accompanied by significant societal disruption that can take a community many years, if not decades, to overcome. This situation was the motivation behind many of the early attempts to bring performance-based design concepts to wind engineering. Early frameworks were often inspired by the successful work carried out in the field of seismic engineering in transitioning from a predominantly prescriptive discipline to a pioneer of performance-based engineering. Commencing from these early contributions, this work will discuss the advances that have led to the recent development of a series of frameworks that encapsulate what is generally termed performance-based wind engineering (PBWE). The key characteristics of the wind loading chain that require special attention in developing successful PBWE frameworks will be identified as will recent modeling approaches for capturing them. Special attention will be placed on frameworks that take a holistic view of PBWE and recognize the fundamental role played by the building envelope together with the structural system in dictating performance of buildings subject to extreme winds. The need to comprehensively treat uncertainty in both the model and loads (stochasticity of the wind excitation) will be discussed as will a number of recent models that enable the efficient propagation of uncertainty in both linear and nonlinear systems in estimating probabilistic performance metrics associated with rare events and that aid decision making. The role of wind tunnel informed non-stationary/-straight-/Gaussian stochastic wind models will be discussed in the context of envelope performance evaluation and path-dependent nonlinear dynamic analysis potentially leading to collapse. Finally, a vision for the future of PBWE will be outlined.

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Baltimore, MD, May 31 - June 3, 2022

Title: Double-Layer Machine Learning Framework for Cooperative Wind Farm Control

Author(s): *Shanghui Yang, *The University of Hong Kong*; Xiaowei Deng, *The University of Hong Kong*;

An appropriate cooperative yaw control strategy can mitigate the significant power loss owing to the wake interference of multiple turbines in the wind farm, where two key issues should be addressed involving the accurate power prediction of the wind farm and efficient optimization method. The present study develops a novel double-layer machine learning framework combining a novel ANN (artificial neural network) yawed wake model and Bayesian machine learning algorithm, where the former coupled with some superposition models undertakes the power prediction as the 1st layer to feed the optimization system based on the latter in the 2nd layer. Using CFD simulation results as accurate values, the performance of the proposed framework in power prediction and enhancement for a simplified 5-turbine row is evaluated compared with the framework based on the analytical wake model. In addition, parametric studies have been conducted on the inflow conditions with the focus on the suitability of the proposed framework for the wind farm under various inflow velocity and turbulence. To further promote the applicability of the proposed framework in large-scale wind farm, a new row-based steering strategy is proposed for a 16-turbine layout and then compared with the independent steering strategy in terms of optimization effect and efficiency. The results show that the proposed framework is capable of realizing more accurate power prediction and notable power enhancement than one based on the analytical model. Moreover, its superiority becomes more obvious under relatively low inflow velocity and turbulence intensity. On the other hand, the row-based steering strategy can realize the power enhancement comparable to the independent steering strategy using the relatively short computational time under the aligned and staggered layout of wind farm.

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Baltimore, MD, May 31 - June 3, 2022

Title: Multiscale Modeling of Metal-Ceramic Spatially Tailored Materials via Gaussian Process Regression and Peridynamics

Author(s): *Shaoping Xiao, *University of Iowa*;

A micro-to-macro multiscale approach with peridynamics is proposed in this work to study metal-ceramic composites. Since the volume fraction varies in the spatial domain, these composites are also called spatially tailored materials (STM). At the microscale, microstructure uncertainties are considered when conducting peridynamic modeling and simulation. The collected dataset is used to train a probabilistic machine learning model via Gaussian process regression, which can stochastically predict material properties. The machine learning model plays a role in passing the information from the microscale to the macroscale. Then, at the macroscale, peridynamics is employed to study the mechanics of STM structures with various volume fraction distributions.

A recent work by the author [1] employed a similar approach to study the mechanics of metal-ceramic STM structures via finite element simulations. However, only deterministic predictive models were trained to pass material properties from the microscale to the macroscale. Although the effects of microstructure uncertainty on material failure were also considered in the previous study [1], there was difficulty generating and meshing STM microstructure configurations at volume fractions close to 50% for finite element simulations. Consequently, only composites with volume fractions less than 25% or greater than 75% were modeled and simulated at the microscale to collect the dataset. This issue is resolved by using peridynamics in this work. In addition, porosity and its uncertainty at the microscale are uniquely considered in the proposed multiscale approach.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Cascade Control Method to Conduct Hybrid Simulation with Stiff Test Specimens

Author(s): *Shawn You, *MTS Systems*; Shawn Gao, *MTS Systems*; Brad Thoen, *MTS Systems*; Catherine French, *University of Minnesota*;

Hybrid simulation is an innovative method that integrates an analysis model of a structural system with physical tests of one or more substructures. The analysis model is typically a finite element analysis (FEA) model that outputs displacements applied to the physical substructure using a control system operated in displacement control. For stiff specimens, the displacement commands can be so small that the control system has difficulty imposing the command displacements accurately. To do hybrid simulation with this type of specimen, force control is desirable. Cascade control is proposed to address this issue. Cascade control features two layers of closed loop control. The inner control loop has force control mode that provides accurate control for hybrid tests with stiff specimens. The outer control loop is in displacement control mode for accepting displacement commands from an FEA model. The effectiveness of the cascade control method in conducting hybrid simulation of stiff test specimens was evaluated with three sets of tests in which the results of both cascade and displacement control methods were compared. The three test cases covered a wide range of variation from specimen size, test equipment, model type (2-D vs. 3-D), experimental element type (beam-column vs. truss), and test speed (slowdown 10 times in Test Case 1 and 2 versus 100 times in Test Case 3). In all cases, cascade control proved to be an effective method for conducting hybrid simulation with a stiff specimen. In two of the cases, cascade control showed clear advantage over displacement control in terms of smoothness and wave shape of the force signals. In the third case where system noise was very low and the displacement sensors had high resolution, displacement control generated nearly identical results to the cascade control. The third test series was conducted at the University of Minnesota Multi-Axial Sub-assembly Testing (MAST) facility. Its unique actuator hydrostatic bearing design enables ultra-low friction, making the system ideal to perform high performance hybrid simulation. Friction could be a major challenge for multi-axial loading system of such size, which could easily cause hybrid system instability if not properly managed. For test systems with relatively high levels of system noise, cascade control is expected to have greater advantage over displacement control when conducting hybrid simulation with stiff specimens because fundamentally, cascade control is a force control method. It is more sensitive than displacement control when specimen deformations are minute.

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Baltimore, MD, May 31 - June 3, 2022

Title: A Potential of Mean Force-Based Lattice Element Method for Modeling Response of Structures

Author(s): *Shayan Razi, *University of Massachusetts Dartmouth*; Mazdak Tootkaboni, *University of Massachusetts Dartmouth*; Arghavan Louhghalam, *University of Massachusetts Dartmouth*;

Examining the functional integrity of civil infrastructure, e.g., buildings and bridges, subject to natural hazards play a crucial role in risk mitigation and resilience assessment. Such assessments thus requires an accurate yet computationally efficient framework to model the failure of buildings composed of structural and nonstructural components. To this end, we leverage a potential-of-mean-force (PMF) approach to Lattice Element Method (LEM), a class of discrete methods demonstrated to be particularly advantageous for modeling fracture in heterogeneous materials (1), to simulate the response of structures. The premise of the proposed framework is to discretize a structure into a set of particles that interact with each other through prescribed potential functions representing the mechanical properties of a building's components. Lending itself to failure and damage assessment due to its discrete nature, PMF-based LEM transcends the limitations of continuum mechanics approaches in modeling discontinuity.

Harmonic and non-harmonic potentials are adopted to capture respectively linear and nonlinear behavior of different components. Non-harmonic potential is also adapted to model failure through breakage of bonds between particles based on energy-based failure criteria. We explore the efficiency and accuracy of the proposed method through its application to quasi-static simulations of large-scale buildings. The buildings are composed of one- and two-dimensional components. The calibration procedure for the potential parameters of these components is thus carried out via a handshake with continuum mechanics theories, i.e., the Timoshenko beam and Kirchhoff-Love plate theories and experimental results. The simulation framework is then used to model the response of several structures. The results obtained from the LEM simulations are found to be in close agreement with their finite element counterparts.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Temperature Effects on the Diffused Double Layer Using Molecular Dynamics

Author(s): *Shijun Wei, *Virginia Polytechnic Institute and State University*; Sherif Abdelaziz, *Virginia Polytechnic Institute and State University*;

This study identifies the thermally induced changes in the diffused double layer (DDL) around a kaolinite particle using molecular dynamics (MD) simulation. Although the effect of various factors (e.g., soil water content, valency, and cation concentration) on the thickness of DDL have been studied, the temperature dependency of the diffuse double-layer has been questionable over the past decades. The modified Boltzmann equation suggests that the DDL thickness is proportional to the square root of temperature. However, other contradicting arguments exist in the literature. The MD simulation considers a three-dimensional (3D) kaolinite clay specimen using Large-scale Atomic/Molecular Massively Parallel Simulator (LAMMPS). A two-layer kaolinite system is built using modified structures suggested by Grim and CLAFF intermolecular force fields with Particle-particle Particle-mesh (PPPM) solver. SPC/E extended simple point charge, water model is implemented to build the clay-water electrolyte system facing the silicon tetrahedral basal surface. Simulations are proceeded under different temperatures ranging from 273 K (about 0 C°) to 363 K (about 90 C°) to capture the behavior of DDL. Radial distribution function is applied under multiple thermal conditions to perform quantitatively studies. VMD is used as a visualization tool to monitor the progress of the movement of particles and a descriptive method to observe the evolvement of DDL. The results first show that temperature changes have a significant impact on the energy of the clay-water system. The positions of the first peaks and the furthest distances in which water interacts with the kaolinite surface remain relatively unchanged under thermal effect. Hence, the DDL thickness is not sensitive to the temperature variations for this study. The value of the first peak decreases as the temperature raises between atom interactions for quantitatively analyses, which implies a more intense effect of the DDL on the kaolinite-water system at lower temperatures.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: AI-Enhanced Advanced Algorithms for the Micromechanical Modeling and Design of Materials with Complex Microstructures

Author(s): *Soheil Soghrati, *The Ohio State University*; Pengfei Zhang, *The Ohio State University*; Mohamad Mohamadsalehi, *The Ohio State University*; Mingshi Ji, *The Ohio State University*; Salil Pai, *The Ohio State University*; Abhijit Kale, *The Ohio State University*; Balavignesh Vemparala, *The Ohio State University*;

We present a set of new algorithms for the automated modeling of materials with complex microstructures, including various composites and biomaterials. The proposed framework relies on virtual microstructure reconstruction and non-iterative, parallel mesh generation algorithms coined CISAMR for creating realistic geometrical models and converting them to high-fidelity finite element (FE) models, respectively. We present new algorithmic aspects pertaining to both methods, including a combination of animation-inspired packing and physical simulation for synthesizing composite material microstructures with very volume fractions (e.g., chopped fiber composites). The CISAMR algorithm is also expanded to enable modelling problems with sharp edges/corners, including polycrystalline materials. Further, a novel staggered algorithm is introduced for direct numerical simulation of structures, allowing incorporating the material microstructure within the simulation. Finally, we also combine the algorithms discussed above with deep learning techniques such as the convolutional neural networks (CNN) to enhance the computational design process.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Shape-Fitting Origami with Curved Creases and Pinches

Author(s): *Steven Woodruff, *University of Michigan*; Evgueni Filipov, *University of Michigan*;

When determining the functional properties of a structure (e.g., stiffness, mass, volume), the location of material and its orientation in the system play an enormous role. Folding thin sheets can allow engineers to intentionally re-distribute and re-orient material. However, placing multiple folds on a sheet can lead to convoluted designs, overly flexible structures, and complex system actuation. In this talk, we introduce a novel method for folding thin-sheet structures by using continuous curved creases and applying pinches at specific points along the length of the structure. With this method, we can transform a flat sheet into specified, three-dimensional target shapes, while minimizing the number of folds and the number of points requiring actuation. The underlying principles of our method rely on newly discovered relationships between the geometry of a crease pattern and the amount of bending and twisting generated from a pinch. We use a mechanics-based bar and hinge model to simulate the deformed shape of the pinched sheets and optimize the initial design until a target geometry is achieved. We also explore how the sheet surfaces can be re-oriented in space to tailor the stiffness characteristics of the target three-dimensional structure. We conclude our presentation with a discussion on potential applications of this technology, including robotic mechanisms that meet specified configurations for gripping, assembly of lightweight three-dimensional structures from flat sheets, and metamaterials with variable mechanical properties.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Autoregressive Surrogate Models of High-Dimensional Time-Dependent Wind Turbine Simulations for Uncertainty Quantification

Author(s): *Styfen Schär, *ETH Zurich*; Stefano Marelli, *ETH Zurich*; Bruno Sudret, *ETH Zurich*;

Global adoption of wind as a renewable energy source has increased dramatically over the past decades. With the growing number of wind turbines being installed worldwide, safety concerns and the need to reduce turbine installation and maintenance costs, especially in large wind farms, have become more and more relevant. Wind turbine design is primarily driven by climatic conditions such as wind speed, turbulence, and for offshore turbines waves, all of which are subject to large aleatory uncertainties. Consequently, current design standards recommend stochastic design approaches that often require the evaluation of a large number of expensive aero-servo-elastic simulations.

Surrogate models are well established in robust design optimization of engineering structures, and have shown remarkable performance in mimicking the behavior of real world systems and numerical models. However, they suffer from the curse of dimensionality, which makes them unsuitable for emulating wind turbine simulators that require high-dimensional, time-dependent turbulence boxes as inputs and produce load time-series as outputs.

To overcome these limitations, we propose a surrogate modeling strategy based on combining a spectral representation of spatial variability in the input wind turbulence box, and an autoregressive approach to exploit the temporal coherence between inputs and outputs.

The performance of our approach is benchmarked on the well-known NREL 5 MW reference onshore wind turbine (Technical Report NREL/TP-500-38060).

We demonstrate that we are able to accurately replicate the aero-servo-elastic simulator performance over a wide range of wind conditions, including controller-dominated regimes, while reducing the related computational costs of a typical 10-minute simulation from several minutes to a fraction of a second.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Investigation of the Compressive Response and Failure of Novel Nano-Reinforced Epoxy Foaming Systems

Author(s): Katerina Loizou, *AmaDema – Advanced Materials Design & Manufacturing Ltd*; Katerina Sofokleous, *AmaDema – Advanced Materials Design & Manufacturing Ltd*; Orestes Marangos, *Cyprus University of Technology*; *Stylianos Yiatros, *Cyprus University of Technology*; Vassilis M. Drakonakis, *AmaDema – Advanced Materials Design & Manufacturing Ltd*;

The demand for multifunctionality is driving the development of lightweight polymer composite structures that contain reinforcement at the nano-scale in order to tailor for specific properties. For instance, epoxy foaming material systems are gaining traction in transport, sports and energy sectors due to their low weight and ability to absorb energy at a given compressive strength but might suffer mechanical property degradation due to the inherent thermal conductivity and flammability. By reinforcing the epoxy foams with nanoparticles, both thermal conductivity and flammability are sought to be reduced while keeping or improving the compressive strength and stiffness of the material.

The work presented herein investigates the compressive behaviour and failure of PB250 epoxy foams, each reinforced with a different type of nanoparticles. The nanoparticle types utilized in this investigation were (a) 4% halloysite nanoclays, (b) Graphene, and (c-d) Multiwall Carbon Nanotubes in two different concentrations (1% and 0.1%). The specimens were observed and characterised using a Scanning Electron Microscope. Cuboid specimens were then tested in compression according to ASTM D1621 and their mechanical response was compared to the mechanical response of plain PB250 Epoxy foam. The experimental results exhibit consistency within different specimen groups. Between the different nanoreinforcement systems the 4% halloysite nanoclay specimens exhibit superior performance in comparison to Graphene and MWCNT specimens, having limited deviation with the control specimens of plain PB250 on compressive stiffness, strength and energy absorption. Two different groups of MWCNT with concentrations 0.1% and 1% had non-significant reductions in stiffness and peak strength. However, the energy absorption capacity of the specimens in both cases was reduced, with the larger concentration exhibiting more brittle behaviour and loss of cohesiveness. Graphene specimens also exhibited a mostly brittle behaviour, close and beyond peak stress, while the behaviour was prone to imperfection sensitivity reducing the capacity of some specimens before the peak stress could be reached.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Unsupervised Image to Image Translation of Structural Damage

Author(s): *Subin Varghese, *University of Houston*; Vedhus Hoskere, *University of Houston*;

In the aftermath of earthquakes, structures can become unsafe and hazardous for humans to safely reside. Automated methods that detect structural damage can be invaluable for rapid inspections and faster recovery times. Deep neural networks (DNNs) have proven to be an effective means to classify damaged areas in images of structures but have limited generalizability due to the lack of large and diverse annotated datasets (e.g., variations in building properties like size, shape, color). Given a dataset of paired images of damaged and undamaged structures supervised deep learning methods could be employed, but such paired correspondences of images required for training are exceedingly difficult to acquire. Obtaining a variety of undamaged images, and a smaller set of damaged images is more viable. We present a novel application of deep learning for unpaired image-to-image translation between undamaged and damaged structures as a means of data augmentation to combat the lack of diverse data. Unpaired image-to-image translation is achieved using Cycle Consistent Adversarial Network (CCAN) architectures, which have the capability to translate images while retaining the geometric structure of an image. We explore the capability of the original CCAN architecture, and propose a new architecture for unpaired image-to-image translation (termed Eigen Integrated Generative Adversarial Network or EIGAN) that addresses shortcomings of the original architecture for our application. We create a new unpaired dataset to translate an image between domains of damaged and undamaged structures. The dataset created consists of a set of damaged and undamaged buildings from Mexico City affected by the 2017 Puebla earthquake. Qualitative and quantitative results of the various architectures are presented to better compare the quality of the translated images. A comparison is also done on the performance of DNNs trained to classify damaged structures using generated images. The results demonstrate that targeted image-to-image translation of undamaged to damaged structures is an effective means of data augmentation to improve network performance.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: A Hybrid MLP-CNN Model for Estimating Buckling Strength of Corroded Plates

Author(s): *Tao Zhang, *University of Connecticut*; Arash Zaghi, *University of Connecticut*,

Corrosion damage is one of the most common factors affecting the strength of structural members. However, it is difficult to accurately model the corrosion damage in finite element analysis (FEA) due to the complex and random geometry of the corroded surface. Most of the studies that have investigated the effects of corrosion damage on structure capacity have simplified irregular corrosion patterns to a uniform section loss. Some studies have shown that simplification may introduce considerable errors. To address this problem, this paper evaluates a machine learning (ML) approach to capture the effect of complex geometric features in estimating residual buckling strength of a plate element. A hybrid Multilayer Perceptron and Convolutional Neural Network (MLP-CNN) model was trained with a dataset of 10,000 synthetic, but realistic, corrosion geometries and the buckling capacity of plates obtained using a non-linear finite element model. The plate dimensions and boundary conditions are presented as an input vector to the MLP layers, and the thickness maps of the corroded plates are presented as 2D arrays to the convolutional layers. The synthetic thickness maps were generated based on the features of real-world corroded surfaces, including the standard deviation and correlation length of the corrosion depths. The output of the MLP-CNN model in the training dataset is the full load-displacement relationship obtained from FE simulation of the plate. The predictive accuracy of the trained MLP-CNN model was evaluated by comparing the results of 2,000 test samples with those of the FE models. The error of the MLP-CNN model was less than 5% in the validation set. The results showed that the proposed MLP-CNN model is promising to estimate the strengths of structure members with random corrosion damage.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Damage Assessment Methods For Rapid Post-Fire Tunnel Inspection

Author(s): *Thomas Vitalis, *University of Massachusetts Amherst*; James Viglas, *University of Massachusetts Amherst*; Simos Gerasimidis, *University of Massachusetts Amherst*; Scott Civjan, *University of Massachusetts Amherst*; Nicholas Menz, *University of Massachusetts Amherst*; John Czach, *MassDOT*; Joseph Rigney, *McMillen Jacobs Associates*;

Tunnel structures are an essential part of the United States' transportation infrastructure, and recent fire incidents delineate the necessity for additional, comprehensive, and tunnel-specific post-fire inspection guidelines. It is well documented in the literature that concrete and steel mechanical properties degrade after exposure to high temperatures present in a fire. Fire-induced residual damage on structural tunnel elements should be assessed after a tunnel fire incident before the structure is back to its fully operational state. Elevated temperatures in reinforced and prestressed concrete affect the residual capacity of such cross-sections, thus creating uncertainty when inspectors must rapidly make decisions on the structural integrity, safety, and re-occupancy of infrastructure. Additionally, overhead equipment and structural elements can threaten incoming traffic if their design strength deteriorates due to fire exposure. To aid tunnel inspectors in making decisions with a higher degree of confidence, post-fire tunnel inspection methods are discussed. Emphasis is given to visual inspection that can provide a quick way to determine severely fire-damaged areas. Both structural and non-structural tunnel components are experimentally heated, and their visual response is documented at various elevated temperatures. Experimental heating tests and finite element computational simulations are employed for structural tunnel elements such as precast tunnel ceiling panels and wall panels.

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Baltimore, MD, May 31 - June 3, 2022

Title: Continuous Modeling of Creased Annular Strips with Tunable Bistable and Looping Behaviors

Author(s): *Tian Yu, *Princeton University*; Francesco Marmo, *University of Naples Federico II*; Sigrid Adriaenssens, *Princeton University*;

We study the mechanics of a novel origami structure, namely creased annuli, made by introducing radial creases to annular strips with variable overcurvatures, which measure the number of loops the annular strip would cover in its rest configuration. We found generic bistable and looping behaviors in creased annuli, determined by geometric parameters such as the crease angle, number of creases, and overcurvature.

We combine tabletop experiments and numerical modeling to investigate the nonlinear mechanics. In experiments, creases are first annealed in an oven to relax the residual stress and then glued together with circular strips to construct creased annuli [1-2]. We further propose a continuous description of creases in anisotropic rods using Dirac-delta-like functions, modeling the spike of curvature at the crease [3]. Together with numerical continuation, we systematically investigate the influences of geometric parameters on the bistable and looping behaviors, which are summarized in phase diagrams and could be controlled by tuning geometric parameters. Our numerical results match well with the tabletop experiments, demonstrating the robustness of our numerical method. The novel continuous framework for modeling crease mechanics could be applied to study slender structures with different types of material and geometric discontinuities. The creased annuli are promising candidates for designing structural systems with tunable mechanics, which could find broad applications in deployable structures and soft robots.

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: A Self-Consistent Approach to Interfaces of Variable Stiffness in Polycrystalline Materials Subject to Pressure Solution

Author(s): *Tingting Xu, *Georgia Institute of Technology*; Chloé Arson, *Georgia Institute of Technology*;

We present a new self-consistent formulation to predict the mechanical behavior of polycrystalline materials that contain grain-to-grain bonds of variable stiffness. The crystal-plasticity behavior of spherical inclusions is coupled to that of elastic-visco-plastic interfaces. In addition to those imperfectly bonded crystals, we assume that the microstructure also contains spherical voids. The mechanical stiffness of the interfaces is mapped on a rectangular grid that covers the spherical inclusions ("cubed-sphere" discretization). A numerical method is developed to calculate the Eshelby tensor of the spherical crystal inclusion with interface embedded in an anisotropic matrix.

Pressure solution is modeled within a thermodynamic framework that considers viscoplastic deformation at the inter-particle interfaces. The mass dissolved from grain contacts by pressure solution is considered to be equal to that of the solid volume precipitated on the pore walls, plus that of the solid mass stored in the interfaces. The evolution of grain boundaries affects the effective diffusivity and can explain the reduction in pressure solution strain rates. The visco-plastic interface properties evolve with the microscopic stress field and the boundary connectivity. Elastic interface debonding is characterized by a nonlinear cohesive law, which depends on the interface cohesive strength, hardening modulus and softening modulus.

The proposed model is calibrated against creep experiments conducted on halite. We perform a set of numerical simulations to examine the relative influence of grain boundary healing vs. in-pore precipitation for various mass transfer scenarios. The model can capture the increase of the effective elastic stiffness due to decreasing porosity as well as the onset of the tertiary creep stage, in which the creep rate accelerates and terminates upon rupture of the material. An extensive parametric study is conducted for different statistical distributions of interface orientations.

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Baltimore, MD, May 31 - June 3, 2022

Title: Artificial Crack Depth Determination of Concrete Specimens Using Ground Penetrating Radar and Synthetic Aperture Radar Images

Author(s): *Tzuyang Yu, *University of Massachusetts Lowell*;

Cracking in concrete structures is a common phenomenon caused by various reasons such as curing and loading. Importance and criticality of a crack in concrete structures depends on its severity against the functionality and durability of concrete structures. For example, distributed surface hair cracks are less severe than single structural crack for their impact on protecting subsurface steel reinforcing bars in concrete structures. In general, crack depth is the most important parameter to assess the criticality of cracks. In this paper, contact ground penetrating radar (GPR) and non-contact synthetic aperture radar (SAR) imaging sensors are used to determine crack depth in artificially cracked concrete specimens. Four 30cmX30cmX4cm concrete panel specimens (one intact and three artificially cracked) were manufactured in the laboratory, with three artificial cracks (10cmX0.5cmX0.5cm, 10cmX0.5cmX1.5cm, 10cmX2cmX0.5cm) considered. A 1.6-GHz GPR sensor (GSSI StructuralScan) and a 10-GHz SAR sensor were used in this research. Comparison between GPR and SAR crack detection mechanisms was made. From the result, it is found that SAR imaging provides more information about concrete cracking, due to its nature of integration on multi-angular scattering responses. SAR imaging can also provide the scattering response of background concrete, even without the presence of cracks.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Impedance Matching Control Design for Real-Time Hybrid Simulation

Author(s): Sai Sharath Parsi, *University at Buffalo*; *Vidhi Solanki, *University at Buffalo*; Mohit Verma, *CSIR - Structural Engineering Research Center*; Mettupalayam Sivaselvan, *University at Buffalo*; Andrew Whittaker, *University at Buffalo*;

Model-in-the-loop (MIL) testing, commonly referred to as real-time hybrid simulation, involves physical testing of an equipment or component, with its surrounding environment represented virtually by computer models, and loading devices (actuators) controlled to simulate realistic boundary conditions of the virtual environment on the test article. This paper presents a novel strategy for designing such controls, referred to as impedance matching control design, wherein the actuator is not merely viewed as a device imposing prescribed boundary conditions between the virtual and the physical systems but is rather viewed as a dynamic system that is controlled in a such a way that the impedance of the actuator at the boundary interface matches as closely as possible to that of the virtual system it is representing. Put differently, the controller is designed by posing the question "what should the control command to the actuator be such that for the same feedback measurement (force/displacement) at the interface, the actuator responds in a way the virtual system would have responded?". The key features of the impedance matching approach are (i) it does not explicitly require a tracking controller, (ii) control design is decoupled from the test article - improves versatility (iii) the controls are simple, easy to implement, and robustly stable. This new strategy, developed and being nurtured at the University at Buffalo, has found its application in designing MIL controls for different dynamic systems. Some specific examples are hybrid testing of soil-foundation-structure system (Stefanaki and Sivaselvan, 2018), flexible conductors interconnecting substation equipment, flexible bridges under aerodynamic loads, steel column under fire loadings (Qureshi et al., 2020), and horizontally isolated equipment under seismic loadings (Parsi et al., 2022). The presentation at the EMI conference focuses on demonstrating the robustness and versatility of the impedance matching approach using results from the above mentioned benchmark tests.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Metamaterials with Independently Tunable Mass, Damping, and Stiffness

Author(s): *Vinod Ramakrishnan, *University of California San Diego*; Michael Frazier, *University of California San Diego*;

Over the past decades, metamaterials – whose engineered internal architecture grants unusual or extraordinary macroscopic response – have garnered increasing attention from researchers as the desire to shape material behavior beyond natural limitations (e.g., chemistry) arises within several areas of materials science and engineering. For acoustic metamaterials, the clever design of the small-scale architecture – which regulates the propagation of supported mechanical waves – has elicited such exotic properties as negative effective mass, stiffness, and refractive index, and made plausible such fantastic applications as sub-wavelength imaging, cloaking, and topological insulation in addition to wave focusing, filtering, and guiding.

The bulk of reported acoustic metamaterial architectures are passive such that their properties and functions are fixed at fabrication. Nevertheless, a tuning capacity is desirable, not only to allow for adaptation in the face of potentially changing service requirements, but also to expand the range of response, in general. Several strategies have been proposed to tune acoustic metamaterials post-fabrication: piezoelectric controllers, precompression, hydration, geometric instability and multi-stability, etc. Nevertheless, despite the diversity of approach and the significance of inertial and dissipative effects in elastodynamics, most studies realize tuning via modifications to the stiffness parameter alone, often requiring significant metamaterial distortion. Moreover, the use of special, stimuli responsive constituents necessarily restrict metamaterial architectures to specific compositions.

In this presentation, we present a novel implementation of unit cell (geometric) bi-stability and kinematic amplification to independently tune the value and distribution of the effective mass, stiffness, and viscous damping within metamaterial architectures by purely geometric means (and without distortion) which impacts the dynamic response. We demonstrate the effectiveness of our strategy through analytical and numerical investigations of the dynamics of a 1D system (readily extended to 2D/3D). We show that the frequency band structure depends on the specific configurations of the bi-stable elements: opening, sifting, and closing band gaps. As the number of bi-stable elements per unit cell increase, so to do the number of unique dynamic responses from which to choose. The proposed strategy significantly expands the property set available for tuning acoustic metamaterial performance post-fabrication.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Influence of Lateral Surface Vibrations on Drop Contact Line Dynamics: A Numerical Study

Author(s): *Vishal Sivasankar, *University of Maryland*; Siddhartha Das, *University of Maryland*; Balakumar Balachandran, *University of Maryland*;

Controlling solid-liquid interactions by manipulating the wettability of the solid substrate has been widely studied due to the prominent role these interactions play in a plethora of applications including coating, adhesion, additive manufacturing, electronic paper, chemical synthesis, biological and chemical screening etc. Many mechanisms, such as the application of a temperature gradient, an external electric field, or surface chemical modification, have been proposed for adjusting the wettability of the solid surface. Amongst them, however, only a few are capable of ensuring a reversible and dynamic wettability control, such as the vibration induced or photo (UV-radiation) induced wettability control. A number of studies have investigated the effect of frequency and amplitude of vibration, impact speed, and other factors on the dynamics of droplets in interaction with solid surfaces. However, hitherto, a deep understanding of the contact line dynamics (including possible contact line slippage) in the presence of the surface vibration has remained elusive. In this study, as a step towards furthering this understanding, the authors employ direct numerical simulations (DNS) and probe the dynamics of a stationary, sessile, micron-sized, three-dimensional (3D) water droplet placed on substrates subjected to a lateral vibration. Substrates with different wettability characteristics (i.e., both hydrophilic and hydrophobic substrates) are considered and the results obtained are discussed. First, when subjected to a lateral vibration, the obtained findings reveal a stick-slip behavior of the droplet, which is usually witnessed on rough surfaces. The results reveal an interesting alteration in the vibration induced slip behavior for different surface wettability attributes. Second, the authors observe a significant change in the apparent wettability induced by lateral vibrations, showing enhanced wetting or de-wetting depending on the initial substrate wettability. It is argued that the present findings will be fundamental for designing systems that enable droplet-based 3D printing on hydrophobic substrates and fabrication of self-cleaning surfaces and surfaces that enable easy ejection of drops overcoming drop-substrate sticky interactions.

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Baltimore, MD, May 31 - June 3, 2022

Title: A von Kármán-Type Model for the Elastic Buckling Behavior of Two-Layer Laminated Glass Plates and its Finite Element Approximation

Author(s): *Viviane Setti Barroso, *University of Coimbra*; Anísio Andrade, *University of Coimbra*; Noël Challamel, *University of Bretagne Sud*; Paulo Providência, *University of Coimbra*;

Laminated glass consists of two or more glass layers, not necessarily of equal thickness, bonded together by an adhesive interlayer to form a composite member. Such laminates have long been used in aircraft and automotive production. Their use as a structural material in the building industry has become increasingly popular over the past three decades. The number of individual glass layers that make up the laminate differs widely according to application, but in building structures the most common arrangement consists of only two layers. Lamination is essential for the structural use of glass – a brittle material –, as it dramatically improves the post-breakage behavior. But the presence of the interlayer (whose thickness typically ranges from 0.38 mm to 6.0 mm) has also a significant influence on the mechanical response of laminated glass members prior to failure. Because of the deformability of the interlayer, there is not full interaction between consecutive glass plies, i.e., the member does not behave as a monolithic, though inhomogeneous, unit. On the other hand, the assumption of zero interaction (no shear transfer between the glass plies) may be overly conservative in general. Indeed, the interlayer does restrain to some degree the relative movement of the glass plies, leading to what is commonly referred to as partial or incomplete shear interaction.

In terms of their spatial character, many structural applications of laminated glass occur in the form of plates. Because of their characteristically high slenderness, they are prone to instability phenomena. The aim of the present work is to derive and implement numerically a layerwise von Kármán-type model specifically tailored to describe the elastic buckling behavior of two-layer laminated glass plates under bi-axial compression and shear loads. In view of the additional kinematic structure associated with the description of the slip between layers, particular attention will be paid to the definition of appropriate edge conditions.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Vibration of Two-Layer Laminated Glass Plates with Initial In-Plane Loads

Author(s): *Viviane Setti Barroso, *University of Coimbra*; Anísio Andrade, *University of Coimbra*; Noël Challamel, *University of Bretagne Sud*; Paulo Providência, *University of Coimbra*;

Laminated glass plates consist of two or more glass layers, not necessarily of equal thickness, bonded together by an adhesive interlayer to form a composite member. The number of individual glass layers that make up the laminate differs widely according to application, but in building structures the most common arrangement consists of only two layers. Because of the deformability of the interlayer, laminated glass plates exhibit what is commonly referred to as partial or incomplete shear interaction. Their characteristically high slenderness also makes it mandatory to account for geometrical non-linearities.

In this paper, the dynamic version of a layerwise von Kármán-type model is used to investigate the effect of initial in-plane loads on the flexural natural frequencies and vibration mode shapes of two-layer laminated glass plates with various edge conditions. The relevance of the inertia associated with the rotational motion of the transverse fibres of the two layers and with the relative motion between them is also assessed.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Manifold Embedding Data-Driven Elasticity

Author(s): Bahador Bahmani, *Columbia University*, *WaiChing Sun, *Columbia University*,

We introduce a new data-driven approach that leverages a manifold embedding generated by the invertible neural network to improve the robustness, efficiency, and accuracy of the constitutive-law-free simulations with limited data. We achieve this by training a deep neural network to globally map data from the constitutive manifold onto a lower-dimensional Euclidean vector space. As such, we establish the relation between the norm of the mapped Euclidean vector space and the metric of the manifold and lead to a more physically consistent notion of distance for the material data. This treatment in return allows us to bypass the expensive combinatorial optimization, which may significantly speed up the model-free simulations when data are abundant and of high dimensions. Meanwhile, the learning of embedding also improves the robustness of the algorithm when the data is sparse or distributed unevenly in the parametric space. Numerical experiments are provided to demonstrate and measure the performance of the manifold embedding technique under different circumstances. Results obtained from the proposed method and those obtained via the classical energy norms are compared.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: A Combined Phase Field and Variational Multiscale Approach for Modeling Thermomechanical Frictional Cracks

Author(s): *Wan Wan, *Penn State University*; Pinlei Chen, *Penn State University*;

A thermomechanical coupled phase field method is developed for modeling cracks with frictional contact. Compared to discrete methods, the phase field method can represent arbitrary crack geometry without an explicit representation of the crack surface. The two distinguishable features of the proposed phase field method are: (1) for the mechanical phase, no specific algorithm is needed for imposing contact constraints on the fracture surfaces; (2) for the thermal phase, formulations are proposed for incorporating the phase field damage parameter to accommodate different thermal conductance conditions. While the stress is updated explicitly in the regularized interface regions under different contact conditions, the thermal conductivity is calculated under different conductance conditions. In particular, we consider a pressure-dependent thermal conductance model which is fully coupled with the mechanical phase, along with the other three thermal conductance models, i.e., the fully conductive model (FCM), adiabatic model (ACM) and uncoupled model (UCM). The potential of this formulation is showcased by several benchmark problems. We gained insights into the role of the temperature field affecting the mechanical field. Several 2D boundary value problems are addressed, demonstrating the capabilities of the model to capture cracking phenomena with the effect of the thermal field. We compare our results with the discrete methods as well as other phase field methods, and a very good agreement is achieved.

Keyword: Thermo-mechanical coupled problems, Frictional contact problems, Stabilized and variational multiscale method, Discontinuous Galerkin, Interfaces, phase field method

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Probabilistic Digital Twin for Component Stress-Aware Rotorcraft Control

Author(s): *William Sisson, *Vanderbilt University*; Pranav Karve, *Vanderbilt University*; Sankaran Mahadevan, *Vanderbilt University*;

A digital twin is a virtual replica of a system built by incorporating the most up-to-date information (sensor data and physics/ data-based models) regarding the system. Since a digital twin is built and updated individually for each asset, such as a particular car, aircraft, or rotorcraft in the fleet, and is not simply a computational model for a class of assets (e.g., fleets of UH60 rotorcraft or A320 aircraft), it can be used for well-informed operational and maintenance decision making during the individual asset's useful life. Quantification and propagation of aleatory and epistemic uncertainty from sources such as measurement noise, model uncertainty, and diagnosis uncertainty are important tasks underlying the construction of the digital twin. In this work, we build a stochastic digital twin for a rotorcraft component for stress-aware control. The proposed digital twin structure incorporates probabilistic Bayesian diagnosis using noisy sensor data and a physics-based diagnostic model to estimate the health state and associated uncertainty for the component. Then this health state estimation, along with a prognosis model and its associated uncertainty are used to estimate probability distribution of the stress in the component for potential future mission profiles. Next the optimal mission profile is determined, which minimizes the expected stress on the component, by performing optimization under uncertainty. We thus build and demonstrate the probabilistic digital twin framework for component stress-aware, or damage-adaptive operational control for mechanical systems, using a rotorcraft mission and maneuver design example.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Inverse Design of Multimaterial Structures for Realization of Arbitrary Programmed Mechanical Responses

Author(s): *X. Shelly Zhang, *University of Illinois at Urbana-Champaign*; Weichen Li, *University of Illinois at Urbana-Champaign*; Fengwen Wang, *Technical University of Denmark*; Ole Sigmund, *Technical University of Denmark*;

Programming structures to realize a prescribed mechanical response under large deformation is highly desired for various functionalities, such as actuation and energy trapping. Yet, the use of a single material phase may lead to restricted design space and potential difficulty to achieve specific target behaviors. Here, through an inverse design approach, multiple hyperelastic materials with distinct properties are optimally distributed into composite structures to precisely achieve arbitrary and extreme prescribed responses under large deformations. The digitally synthesized structures exhibit organic shapes and motions with irregular distributions of material phases. We present several design scenarios in which we design multi-material structures that achieve a variety of programmed load-displacement curves, some of which are physically unattainable with single materials.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Performance-Based Structural Fire Design of a Prototype Metal Building

Author(s): *Xia Yan, *Johns Hopkins University*; Thomas Gernay, *Johns Hopkins University*;

Performance-based design for fire conditions has been increasingly adopted for different structural systems over the last decade. However, for cold-formed steel structures, this fire design approach has rarely been applied in the US, and there lacks guidance in standards. This presentation will describe the application of a performance-based structural fire engineering approach to cold-formed steel assemblies of a metal building. The procedure that is used follows the newly proposed Appendix 4 to AISI S100 on 'Structural Design for Fire Conditions'. The study focuses on the protected load-bearing cold-formed steel column assemblies at the end walls of a prototype one-story warehouse metal building. The evaluation of the performance of the column assemblies in fire conditions is conducted step-by-step by analysis including the definition of performance objectives, design-basis fires, thermal analysis, and mechanical analysis.

The performance objective for the end wall columns, selected after discussion with industry stakeholders considering the occupancy and size of the building, is to maintain stability for one hour in case of an uncontrolled fire inside the warehouse. Different assemblies are considered for the cold-formed steel columns based on single C-shaped and double C-shaped sections protected by two layers of Type X gypsum board. In addition to the ASTM E119 standard fire curve, a series of design-basis fires are generated from physically based zone models that consider the fuel load, opening conditions, geometry, and properties of the compartment. Heat transfer analysis of the protected cold-formed steel columns are conducted with the finite element software SAFIR. Results show that the steel temperatures for the protected cold-formed steel columns subjected to ASTM E119 fire range between 600-930 °F (315-500 °C) after 60 minutes and are much higher than for those subjected to the other design-basis fires. The failure time and failure temperature of each column are evaluated using both the AISI S100 Direct Strength Method (DSM) and finite element analysis with shell elements in SAFIR. The finite element analyses confirm the results from the DSM. Both methods demonstrate that the required performance can be achieved for the end wall columns in fire conditions. As several of the studied assemblies do not correspond to qualified UL assemblies, the study illustrates how analysis methods can be used to study variations of qualified assemblies to determine appropriate adjustments in fire protection and propose solutions that are innovative and optimized for a specific project.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Nonlinear Material Design with Reduced-Order Modeling

Author(s): David Brandyberry, *University of Illinois at Urbana-Champaign*; *Xiang Zhang, *University of Wyoming*; Philippe Geubelle, *University of Illinois at Urbana-Champaign*;

Recent progress in multiscale modeling and sensitivity analysis, together with advancement in additive manufacturing, allow us to develop an integrated workflow to design and manufacture the microstructure geometrical features and constituent properties to deliver a desired stress-strain response. During this process, the prohibitive computational cost associated with multiple optimization iteration and costly evaluation of a single microstructure problem still limits the application of this workflow, especially for the cases that involve complex microstructure and nonlinear constituent behaviors. Here we present a multiscale reduced-order optimization method for efficient nonlinear microstructure material design. This method builds on the recent development on Interface-enriched Generalized Finite Element Method (IGFEM) based reduced-order modeling [1], to formulate a reduced order model (ROM) of the microstructure problem. Model order reduction is achieved by partitioning the microstructure volume and interface into a number of subdomains called parts, where a series of influence function problems based on the elastic properties of the microstructure are solved a priori to obtain the interaction coefficients between different parts and between each part and the microstructure. Based on these coefficient tensors, and the assumption that the response in each part is uniform, a ROM system that contains a set of linear algebra equations is derived to replace the microstructure problem with part-wise response as unknowns. In addition, the material sensitivities are further derived within the ROM. Since the influence function problems are solved based on the elastic properties of the microstructure, the coefficient tensors hence do not change during the material optimization process as we optimize the nonlinear material properties. The reduced-order microstructure problem evaluation and reduce-order sensitivity analysis allow us to efficiently optimize the microstructure material properties with multiple initial states, from which we choose the best optimization results and further conduct a full IGFEM-based optimization to obtain the final optimization result [2]. This two-step optimization process is demonstrated to deliver satisfactory results on 3D particulate composites with the presence of both volumetric and interfacial damage

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Large Eddy Simulation of Wind Loading on Elevated Low-Rise Buildings

Author(s): *Xiangjie Wang, *Louisiana State University*; Chao Sun, *Louisiana State University*; Steve Cai, *Southeast University / Louisiana State University*;

Residential buildings in coastal communities are usually elevated to a certain level to avoid flooding and wave-surge impacts. As a result, the local wind speed increases and the aerodynamics vary. Post-event reconnaissance data show that roofs, walls, and floors of elevated residential buildings suffered from serious structural damage during extreme hurricanes. However, the aerodynamic pressures on elevated buildings are poorly understood and the corresponding design specification is limited. In this paper, the Large Eddy Simulation (LES) techniques are adopted to simulate the wind effects on critical structural components of elevated buildings. The inflow is generated by an improved Discretizing and Synthesizing Random Flow Generation (DSRFG) method. Different wind attack angles and elevation heights are simulated and validated using experimental data from the Florida International University Wall of Wind Experimental Facility. With the verified model, comprehensive simulations are performed to study the influences of roof angle, wall height and stilt number on the distribution of the pressure coefficients on building surfaces, especially on the floors. Research results indicate that the peak negative pressure coefficients on the floors are significantly influenced by the stilt number and layout, while the wall height and roof angle have less influence on it. The present study shows the necessity of engineering design of the floor of elevated buildings and provides references for real application and revision of relevant design specifications.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: An Explicit Weighted Shifted Boundary Method for Euler Equations in Deforming Domains

Author(s): *Xianyi Zeng, *The University of Texas at El Paso*; Guglielmo Scovazzi, *Duke University*;

We present a new computational approach for embedded boundary simulations of the compressible Euler equations of gas dynamics. It belongs to the class of surrogate/approximate boundary algorithms and is based on the idea of shifting the location where boundary conditions are applied from the true to a surrogate boundary. Specifically, we focus on the imposition of normal velocity conditions on the boundary of an embedded/immersed domain, which is typical in fluid-structure interaction applications. To prevent pressure oscillations that usually occur when the surrogate boundary sweeps across mesh vertices, we enhance the stability of the method by utilizing a test functional space that is weighted by the fluid mass fraction. Lastly, we present numerous computational experiments to demonstrate not only the accuracy, stability, and robustness of the proposed method, but also its capability to improve accuracy comparing to standard weak boundary conditions imposed at curved geometries when a conformal computational grid is employed.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Crack Detection, Location, Quantification, and Visualization Using a Distributed Fiber Optic Sensor Based on Optical Frequency Domain Reflectometry

Author(s): *Xiao Tan, *Stevens Institute of Technology*; Yi Bao, *Stevens Institute of Technology*;

Cracks affect the mechanical performance and durability of engineering structures. In steel structures, cracks may significantly reduce the functionality of the structures, due to reduction of load-carrying capacity, stiffness, and resistance to leaking. In concrete structures, cracks may compromise the durability by accelerating steel corrosion and freezing-thawing deterioration. Early detection and monitoring of cracks may improve the safety and save the costs of engineering structures. The overarching goal of this study is to develop an effective method to detect, locate, trace, quantify, and visualize strains and cracks using a distributed fiber optic sensor based on optical frequency domain reflectometry (OFDR). This study has three main objectives: (1) to improve the measurement accuracy of crack width with a high spatial resolution based on the OFDR; (2) to investigate the effects of three key parameters of distributed fiber optic sensors, which are the coating thickness of optical fiber, the spatial resolution of strain measurement, and the spacing between adjacent cracks; and (3) to develop an effective and efficient method to visualize cracks in typical structures for autonomous condition assessment. To achieve the above objectives, first, a customized specimen was designed to manipulate cracks under precise displacement control. An optical fiber was attached on the specimen and served as a distributed sensor which measured strain distributions along the fiber based on OFDR. An algorithm was presented to quantify crack width based on the measured strain distribution. The calculated crack widths are calibrated with an extensometer. Parametric studies were conducted and revealed that the coating thickness of optical fiber, the spatial resolution of strain distribution, and the spacing of cracks had significant effects on the measurement of cracks using the distributed sensor. Finally, the presented method was implemented to a prestressed concrete beam instrumented with distributed sensors, which was under four-point bending. The measured strain distributions were then used to quantify and map cracks for visualization of the condition of the beams. This research is expected to promote the capability of distributed fiber optic sensing technology for crack and damage assessment in real-life practices.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Data-Driven Parametrically-Upscaled Continuum Damage Mechanics (PUCDM) Model for Composites

Author(s): *Xiaofan Zhang, *Johns Hopkins University*; Somnath Ghosh, *Johns Hopkins University*;

Damage in composites exhibits multi-scale phenomena - microscopic damage mechanism such as fiber-matrix interfacial debonding and micro-cracks subsequently leads to macroscopic material behaviors such as structural stiffness degradation and crack propagation. The multi-scale phenomena in heterogeneous materials make their macroscopic constitutive behaviors strongly influenced by the underlying microstructures. Parametrically-Upscaled Continuum Damage Mechanics (PUCDM) model is developed for composites to manifest the microstructure-dependent multi-scale deformation and damage phenomena. PUCDM represents a class of thermodynamically consistent multiscale constitutive models that bridge length-scales through explicit incorporation of characteristic microstructural descriptors and evolving damage variables. The microstructural descriptors are optimally identified as representative aggregated microstructural parameters (RAMPs), which are incorporated into the functions of PUCDM coefficients. Synthetic microstructural response database (MRDB) for the calibration of PUCDM coefficients is generated from micromechanical simulations of various microstructures and loading conditions. Machine learning algorithms, including symbolic regression, gradient-based optimization and artificial neural networks, are operated on the MRDB to identify the functional representation of PUCDM coefficients in terms of RAMPs and evolving material damage states. The calibration of PUCDM coefficients satisfies the principle of energy equivalence across different material hierarchical levels, such that the PUCDM model can reveal multiscale damage phenomena in structural analysis. The developed PUCDM model explicitly accounts for the effects of important microstructural features on material constitutive behaviors, meanwhile it is computationally efficient and convenient for structural analysis in any commercial FEM packages through user-subroutines (UMAT/VUMAT). These advantages, demonstrated by numerical and experimental validations, significantly facilitate the materials-by-design process and make the PUCDM model a very important tool for integrated structure-material design.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Topology Optimization of Conformal Thermal Control Structures on Free-Form Surfaces: A Dimension Reduction Level Set Method (DR-LSM)

Author(s): *Xiaoqiang Xu, *State University of New York at Stony Brook*; David Gu, *State University of New York at Stony Brook*; Shikui Chen, *State University of New York at Stony Brook*;

In this talk, the speaker will introduce a dimension reduction level set method (DR-LSM) for shape and topology optimization of heat conduction problems on general free-form surfaces utilizing the conformal geometry theory. The original heat conduction optimization problem defined on a free-form surface embedded in the 3D space can be equivalently transferred and solved on a 2D parameter domain utilizing the conformal invariance of the Laplace equation along with the extended level set method (X-LSM). The reduction of dimension can not only significantly reduce the computational cost of finite element analysis but also overcome the hurdles of boundary evolution on free-form surfaces. The equivalence of this dimension reduction method rests on the fact that the covariant derivatives on the manifold can be represented by the Euclidean gradient operators multiplied by a scalar with the conformal mapping. The proposed methodology is applied to the design of conformal thermal control structures on free-form surfaces. Specifically, both the Hamilton-Jacobi equation and the heat equation, the two governing PDEs for boundary evolution and thermal conduction phenomena, are transformed from the manifold in 3D space to the 2D rectangular domain using conformal parameterization. The objective function, the constraint, and the design velocity field are also computed equivalently with FEA on the 2D parameter domain with properly modified forms. The effectiveness and efficiency of the proposed method are systematically illustrated using a number of numerical examples of heat conduction problems on the manifolds.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Stochastic Reduction and Efficient Bayesian Analysis for High-Dimensional Parameter Space and High-Dimensional Quantity of Interest Problems

Author(s): *Xiaoshu Zeng, *University of Southern California*; Roger Ghanem, *University of Southern California*; Bora Gencturk, *University of Southern California*; Olivier Ezvan, *Université Gustave Eiffel*;

The present work deals with an efficient inverse analysis, in particular by using Bayesian methods, for problems both with a high-dimensional parameter space and a high-dimensional quantity of interest (QoI). In the Bayesian framework, the probability distributions of the parameters are inferred from observed data of the QoI, which is almost always noisy and uncertain. The Monte Carlo Markov Chain (MCMC) methods are usually used for posterior sample generation, which poses a significant challenge because the forward model must be evaluated numerous times. We address this challenge by proposing a polynomial chaos expansion (PCE) surrogate model to replace the model in evaluation. However, the construction of the PCE model for high-dimensional parameter space and high-dimensional QoI is challenging and at the forefront of uncertainty quantification (UQ) research. To account for that, it is first proposed to approximate the QoI by a truncated Karhunen-Loeve (KL) expansion, which reduces the dimension to a limited number of KL terms. Then a dimension reduction technique, the basis adaptation method, in the framework of PCE is applied independently to each of the KL terms to reduce the dimension of the parameter space. Next, the PCE models of the KL terms are substituted back into the KL expansion of the QoI to construct the surrogate model. Lastly, a block-update MCMC method is applied for posterior sampling to accelerate the exploration of the high-dimensional parameter space. The method is applied to a sealed spent nuclear fuel canister model with a fine-meshed finite element model. It is demonstrated that the KL expansion has reduced the QoI dimension from 691 to 20, and the basis adaptation method has reduced the dimension of the parameter space from 204 to 3. In addition, the accuracy of the surrogate model is verified. The efficient Bayesian method has successfully identified the location and level of damage inside the sealed canister.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Acceleration of Basis Adaptation Method for High-Dimensional Uncertainty Quantification Problems

Author(s): *Xiaoshu Zeng, *University of Southern California*; Roger Ghanem, *University of Southern California*;

Uncertainty quantification (UQ) is crucial for risk and reliability analysis due to inevitably randomness in engineering structures. The randomness could originate from the structures themselves, for example, the uncertainties of material properties, and/or external sources such as random excitation like strong winds and earthquakes. The advancement in computational science enables models of high fidelity that can precisely describe complex structural behaviors. However, to match the high resolution of the computation results, the parameter space must also be increased to a significant dimension. In such circumstances, the efficient stochastic analysis tool, polynomial chaos expansions (PCE), suffers from the curse of dimensionality. The basis adaptation method was proposed to circumvent this issue. The method is based on rotating the input Gaussian random variables properly such that the quantity of interest (QoI) has concentrated information in a low-dimensional polynomial subspace composed of the first several rotated variables. Once the rotated space is constructed, the dimension to be kept in the computation is determined by convergence analysis. One challenge posed in the basis adaptation method is that the convergence can be slow in some applications. The present study proposes two approaches to accelerate the convergence of the basis adaptation method. The first one corrects the zero and first-order coefficients of the adapted PCE by the information computed via a first-order pilot PCE. The pilot PCE is necessary for constructing the rotation matrix; thus, no additional effort is required. The second method updates the rotation matrix while sequentially increasing the dimensions of the adapted variables. The wealthiest information available will be used to improve the rotation matrix. These two methods are applied to a borehole water flow function, a space model, and a spent nuclear fuel canister model. The applications show that the methods can reduce the dimension of complex problems from hundreds to only a few.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: A Computational Nonlocal Poromechanics Model for Unguided Cracking in Unsaturated Porous Media

Author(s): Shashank Menon, *University of Florida*; *Xiaoyu Song, *University of Florida*;

In this study we present a computational multiphase periporomechanics model for unguided fracturing in unsaturated porous media. An energy-based criterion for arbitrary crack formation is formulated using the effective force state for unsaturated porous media. Unsaturated fluid flow in the fracture space is modeled in a simplified way in line with the nonlocal formulation of unsaturated fluid flow in the bulk. The formulated unsaturated fracturing periporomechanics is numerically implemented through an implicit fractional step algorithm in time and a two-phase mixed meshless method in space. The two-stage operator split converts the coupled periporomechanics problem into an undrained deformation and fracture problem and an unsaturated fluid flow in the deformed skeleton configuration. Numerical examples are presented to demonstrate the efficacy of the proposed multiphase periporomechanics model for unguided cracking in unsaturated porous media.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Machine-Aided Bridge Deck Condition Evaluation Analysis

Author(s): *Xin Zhang, *Purdue University*; Benjamin Wogen, *Purdue University*; Shirley Dyke, *Purdue University*; Julio Ramirez, *Purdue University*; Randall Poston, *Texas Department of Transportation*; Xiaoyu Liu, *Purdue University*; Lissette Iturburu, *Purdue University*;

According to FHWA requirements, bridge inspection teams must evaluate every bridge and its elements to assess their condition at least every 24 months. Bridge inspectors are deployed to each bridge to collect information. The information to be collected includes the bridge and its element profile, damage state, etc. Inspectors need to analyze collected information to determine the bridge and its element's condition. The majority of this analysis is determining the severity of each damage and fuse these damage's information to give an evaluation of condition. This process takes inspectors a lot of time to record this bridge information in the field. Besides, inspectors' evaluation of condition can be influenced by their subjective opinion. Thus, it is necessary to develop a method to improve the efficiency and accuracy of this process. Usually, information related to the visual condition is recorded through images. Thus, using machine learning algorithm to extract useful information from these images can be a powerful tool to accelerate and assist in this analysis process. However, the images collected by human inspectors are not specially taken for machine learning algorithm, which may cause difficulties in directly applying machine learning algorithms to these images. Thus, this paper focuses on developing effective and efficient method and utilize machine learning algorithm to extract damage information directly from images collected in inspectors' daily work. The proposed method requires preprocessing of these images and then adopts image classification and semantic segmentation to extract information about the condition of the elements of the bridge. In this work, bridge deck element and its images are selected to illustrate the workflow and the potential of this machine-aided approach. The damage information of each deck images is extracted, analyzed, and fused through proposed method to evaluate bridge deck condition.

Keywords: Bridge Inspection, Condition Evaluation, Machine Learning Method

EMI 2022
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Title: Structural Topology Optimization Using an Enhanced and Robust Genetic Algorithm

Author(s): *Xingjian Wang, *Lehigh University*; Clay Naito, *Lehigh University*; John Fox, *Lehigh University*; Paolo Bocchini, *Lehigh University*;

Topology optimization is gaining popularity in recent years due to increased interest in minimizing material waste and the growing availability of large scale 3D printing. Genetic algorithms (GA) provide an effective means of achieving optimization. GAs possess high flexibility on the expression of objective and constraints and have been seldomly applied to topology optimization. GAs mimic the biological concept of survival of the fittest, by analyzing generations of individuals (i.e., sets of trial solutions) and their ability to minimize the objective(s). The most successful individuals are recombined to form the next generation, through operations called “crossover” and “mutation”, which involve an element of randomness. In topology optimization, the random crossover and mutation tend to generate a large number of redundant individuals, slow down the convergence, and result in unstable (i.e., not robust) output. To address these issues, an improved GA, specifically tailored to topology optimization through the use of a strong shape constraint and enriched information obtained from inline finite element analyses is proposed in this study. The strong shape constraint adds a filter to all the individuals at the beginning of each iteration in order to prevent redundant calculations. The utilization of the enriched information serves as specific guidance to the mutation and reproduction process, which results in a high convergence rate to the optimal shape. Three case studies are considered to investigate the performance of the proposed algorithm compared to conventional GA and the SIMP (solid isotropic material with penalization) method, which is the most widely used topology optimization algorithm in both academia and industry. The first study investigates the robustness of the optimization process. With the utilization of the proposed algorithm, high robustness is achieved and the probability of convergence to impractical shapes is reduced to almost zero. The second study indicates that the proposed algorithm expedites convergence and reduces the computational cost to one half. The third case study showcases the performance and superiority of the proposed algorithm in reaching optimized shapes which can be manufactured in the industry.

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Predicting Wildfire Ignition Induced by Conductor-Vegetation Contact Under High Winds

Author(s): *Xinyue Wang, *Lehigh University*; Paolo Bocchini, *Lehigh University*;

Under fire weather conditions that feature high winds, electric power systems have been shown to be a rising source of catastrophic wildfires. The utility-related wildfires are mostly attributed to conductor-vegetation contact which can then lead to flashover (or sparkover) and subsequent ignition. Decision making, such as proactive power shutoffs and vegetation management, can be informed by wildfire risk analysis, in which the ignition probability analysis is a key component. This study focuses on the ignitions caused by the conductor swinging out to nearby vegetation under high winds. The problem is formulated in the context of proactive de-energization with a focus on the transmission system. Specifically, the failure (or limit state) is defined as the conductor encroaching into the prescribed minimum vegetation clearance and is examined through quantifiable distances. The stochastic properties of the dynamic displacement response of transmission conductors are derived from spectral analysis in the frequency domain. The probability of encroachment, proposed as the proxy for the probability of ignition, is estimated by solving a classical first-excursion problem based on random vibration theory. The impact of conductor dynamics on encroachment probability is investigated considering varied wind intensities and vegetation clearances. A numerical example featuring a two-span transmission line is given, and an example application at the transmission system level is presented. It is found that the conductor exhibits appreciable variations in its displacement response under turbulent high winds. Neglecting this uncertainty can underestimate the wildfire risk from power systems. In addition to the durations of wind events, the results show the importance of vegetation clearance and wind intensity, by quantifying their effects on the encroachment probability. These findings provide evidence of the value of high-resolution data on these quantities. While flexible in accommodating various combinations of wind loading, structures and vegetation, the presented methodology provides a potential avenue for accurate and efficient ignition probability prediction.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Bio-Inspired Adaptive Building Envelope for Energy Efficiency

Author(s): *Xiong Yu, *Case Western Reserve University*; Jianying Hu, *Case Western Reserve University*;

The climate change leads to extreme weathers that potentially increase the building operation cost. We explore adaptive infrastructure strategies that dynamically modulate the environmental loads to reduce the environmental stress on the infrastructure. The concept is demonstrated on an adaptive building envelope which features solar reflectance that are modulated by environmental temperature. Consequently, it makes the building cooler during hot weather and warmer during cold weather. Both aspects improved the durability and also reduces the energy consumption.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: An Efficient Seismic Reliability Method Accounting for Stochastic Earthquake Model Parameters.

Author(s): *Xuanli Sun, *University of Oxford*; Martin Williams, *University of Oxford*; Manolis Chatzis, *University of Oxford*;

The reliability analysis of structural systems under earthquakes is important to finalizing the design of a new structure or investigating if an existing structure requires reinforcement. This requires that the structure is subjected to a number of earthquakes. A means to achieve this is through adopting a stochastic seismic model, often referred to as a filter as they operate on an underlying white noise excitation. The parameters of such a filter can themselves follow a probabilistic distribution, e.g., in the case where the filters are described in terms of seismological properties, such as the magnitude and source-to-site distance of a seismic event, as in 1. In this case of interest to this work, an effective method for reliability analysis must account for the probabilistic distributions of the parameters of the model, as well as the realizations of the white noise.

Sampling methods, such as Monte Carlo, is a common way to evaluate reliability. However, a large number of samples would be required due to the two sources of randomness that must be sampled: the stochastic filter parameters and the white noise excitation. Reliability methods, such as the Design Point Excitation (DPE) method, offers a more computationally efficient alternative. The DPE method utilizes the First Order Reliability Method, which requires finding the most probable point, named the Design Point, satisfying a failure curve. This is achieved by solving an optimization problem which in turn requires calculations of various gradients. While this idea is promising, existing implementations only allow for evaluating the reliability of structures subjected to simple earthquake models where the parameters of the filter are deterministic. This is not directly applicable to the case of interest where the seismic model is described in terms of seismological properties.

This paper introduces an extension of the DPE method capable of dealing with the latter case. To achieve that, the parameters related to the seismological properties are added to an augmented Design Point vector. Analytical derivatives are obtained recursively by using an Euler approximation for the time derivatives, the Chain Rule and the Implicit Theorem. These are then used in the optimization procedure to estimate the reliability of the system. Examples of structural systems with nonlinearities are presented to demonstrate the accuracy of the suggested method versus the standard Monte Carlo approach.

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Optimization of Concrete Plate Thicknesses Using a Feature Mapping Approach

Author(s): *Yakov Zelickman, *Johns Hopkins University*; James Guest, *Johns Hopkins University*; Oded Amir, *Technion - Israel Institute of Technology*;

Concrete plates constitute a significant fraction of the total concrete volume in buildings. Therefore, reducing their mass would have significant contribution to the global effort to reduce concrete consumption. Existing methods for optimization of plates' thickness are based on the classical SIMP approach and result in organic-shaped thickness distribution, which is not practical for concrete slabs. Moreover, the majority of studies considers only global structural measures such as the compliance or the principal frequency, whereas some local measures such as the bending moments and transverse shear have not been considered yet.

In this study we optimize the thickness of plates ensuring designs that are simple enough for construction while including the fundamental requirements from concrete plates. Thus, we use feature mapping approach, that offers implicit control over the optimized shapes, and include local performance constraints. The optimized designs have discretely varying thickness over rectilinear domains that meet the major requirements and therefore can be used as initial design of concrete plates in buildings. The results indicate that the optimized thickness distribution is not trivial and that concrete savings of more than 30% can be achieved by increasing the total structural depth by less than 10%.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Thermo-Mechanical Characterization of Concentrated Complex Alloy Building Blocks Using Nanoindentation

Author(s): *Yanbo Wang, *The University of Utah*; Hayden Johnson, *The University of Utah*; Pania Newell, *The University of Utah*; Jay Tiley, *Oak Ridge National laboratory*;

Complex concentrated alloys (CCAs) are typically designed by multi-components to generate improved alloys. We are interested in studying the formation and evolution of intermetallic within classic CCA materials. CCAs can have exceptional mechanical properties such as lightweight, corrosion resistance, creep resistance, high hardness values, and excellent fracture toughness. Adaption of multi-component designs to include multi-phase structures have further expanded material capabilities. These properties have received great interest for various applications, including automotive structures, medical devices, and aerospace structures. In addition, the research involving deformation mechanisms of these materials has demonstrated unique strengthening combinations, allowing co-design of materials under competing criteria. For example, propulsion materials must provide both creep resistance and high strength while resisting crack growth at elevated temperatures. In this study, we characterize the thermo-mechanical properties of two model alloys targeted for CCA alloys (i.e., 70Ti-AlTa, 70Ti-AlZr). First, scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), and electron backscatter diffraction (EBSD) techniques were used to characterize element distributions, phase evolution, and crystal orientation/structure. We then use nanoindentation at elevated temperatures to obtain the mechanical response at 25?

250? and 500?. The results show the impact of Ta and Zr additions on hardness and phase evolution, including thermal oxidation resistance. This study sheds light on the use of these model alloys for CCA high-temperature applications, including the relative evolution of strengthening phases. Results are compared to CALPHAD based thermodynamic predictions.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: A New Anisotropic Elasto-Plastic-Damage Model for Quasi-Brittle Materials Using Strain Energy Equivalence

Author(s): George Z. Voyiadjis, *Louisiana State University*; *Yaneng Zhou, *Louisiana State University*; Peter I. Kattan, *Louisiana State University*;

An anisotropic elasto-plastic-damage model is developed for quasi-brittle materials within the thermodynamics framework. The anisotropic damage is characterized by second-order damage tensors that are different under tensile and compressive loadings. The hypothesis of strain energy equivalence is adopted with two components, including the hypothesis of elastic strain energy equivalence and the hypothesis of plastic strain energy equivalence. The hypothesis of plastic strain energy equivalence is extended from metals to quasi-brittle materials so as to derive the relations of hardening stresses, which are previously assumed between the undamaged and damaged configurations for quasi-brittle materials. A plastic yield criterion is adopted simultaneously with a damage criterion to account for the coupled elasto-plastic-damage behavior under different loadings. The damage criterion can capture larger axial damage in uniaxial tension and smaller axial damage in uniaxial compression as compared with the lateral damage. The Helmholtz free energy functions are derived for three components: elastic, plastic, and damage. The constitutive laws are derived for three scenarios: the elastoplastic behavior without further damage evolution, the damage behavior without further plasticity evolution, and the coupled elasto-plastic-damage behavior. The anisotropic elasto-plastic-damage model is implemented in ABAQUS as a user material (UMAT) subroutine. The coupled constitutive laws in the continuum domain are implemented in an uncoupled way in the discrete domain with three steps, elastic predictor, plastic corrector, and damage corrector. The UMAT is validated in different conditions, including uniaxial, biaxial, and three-point bending tests. The advantage of considering the plastic free energy in anisotropic damage is illustrated through the strength envelope in biaxial loadings. The numerical results generally agree with experimental results, including the stress-strain curves in uniaxial tests, strength envelope in biaxial tests, and load-deflection curves in three-point bending tests.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Finite Element Model Updating with Vibration Testing Data: A Non-Convex Optimization Perspective

Author(s): *Yang Wang, *Georgia Institute of Technology*; Yu Otsuki, *Georgia Institute of Technology*;

The past two decades have witnessed burgeoning advances of wireless sensing as a promising alternative to cable-based structural sensing systems. This presentation will first introduce a latest wireless sensing platform collaboratively developed between three university labs, and a few large-scale applications on civil structures. Growing popularity of low-cost wireless sensors provides larger and larger quantity of field data. One common data processing is modal analysis that provides modal properties of an as-built structure. Based on the modal properties extracted from field sensor data, finite element (FE) model updating can be performed to fine-tune parameter values of an FE model so that the model has properties matching these from field measurements. To this end, an optimization problem is usually formulated to minimize the difference between the simulated and the measured modal properties. When an optimization problem is non-convex, solution algorithms in general cannot guarantee finding the global optimum. A local minimum is usually taken as the solution, without providing any knowledge on how close the local minimum is to the global minimum. This lecture will demonstrate a few structural examples for studying the nonconvexity in FE model updating problems.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Physics-Informed Neural Networks for Ultrasonic Elastography

Author(s): *Yang Xu, *University of Colorado Boulder*, Fatemeh Pourahmadian, *University of Colorado Boulder*,

We present an application of the recently developed Physics-Informed Neural Networks (PINN) for wave-based learning of elastic properties from full-field measurements. The key idea is to incorporate the basic principles of solid-state physics as soft constraints in loss functions which would otherwise be only a measure of discrepancy between the model predictions and observations. The model training i.e. minimization of the loss function will then follow using the available tools of machine learning. First, we formulate the loss functions pertinent to the plane-stress mode of wave propagation in an elastic plate, corresponding to our laser ultrasonic experiments. Then, a suite of MLP-based multi-network models are implemented for accurate approximation of the displacement field over the designated scanning grid. The training process entails identification of the elastic moduli. PINN's performance in predicting the material properties and their spatial distribution in an elastic plate is put to test using both synthetic and experimental data in time and frequency domains. For completeness, a comparative study is conducted between the PINN-predicated wavefields and their synthetic (and experimental) counterparts to shine light on the PINN's capability for forward modeling.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Extrapolation of Wind Pressure Coefficients for Low-Rise Buildings at Different Scales Using Meta-Learning

Author(s): *Yanmo Weng, *Texas A&M; University*; Stephanie Paal, *Texas A&M; University*;

For low-rise buildings, large-scale models are needed for wind tunnel tests because it is hard to simulate a high enough Reynolds number to neglect the scale effects in a small-scale model. Sometimes, even at larger scales, the Reynolds number can cause deviations from real wind pressure measurements. Therefore, it is important to find an approach to accurately simulate full-scale performance based on small-scale wind tunnel test results. Machine learning (ML) can potentially be utilized to address this challenge. However, traditional ML algorithms (e.g., decision tree, support vector machine, artificial neural network) can typically only solve interpolation problems. Therefore, an efficient method to extrapolate to full-scale wind pressures for low-rise buildings based on existing wind tunnel test data needs to be developed.

In this work, we propose a few-shot learning approach to solve the scale extrapolation problem. Few-shot learning is a machine learning technique requiring the machine to learn a new object (e.g., full-scale data) with only a limited number of samples. We used the Wall of Wind (WOW) dataset containing scaled wind tunnel experiments and the Texas Tech University (TTU) dataset containing full-scale measurement results. Meta-learning, used in this research, is a common framework for few-shot learning. In the proposed meta-learning algorithm, the training set only contains model scale data from the WOW dataset. A special set, named the 'shot set', is used in the proposed algorithm which only contains 6% of the full-scale data (TTU dataset), and the remaining 94 % forms the testing set. The proposed meta-learning algorithm is trained on the training set to obtain good initial model parameters. With only a few gradient descent updates based on the data from the small 'shot set', the trained model can achieve good prediction performance for the testing set data. The meta-learning algorithm can guarantee that the maximum amount of full-scale data used in the training set is limited to the size of the shot set (e.g., 6% of full-scale data used) while the traditional ML model cannot guarantee adequate performance with a similarly small dataset size.

The overall results show that with only 6% of the TTU dataset in conjunction with the model scale data, the mean wind pressure coefficients for the remaining 94% of the TTU full-scale dataset can be predicted with a coefficient of determinant value equal to 0.755 and MSE loss equal to 0.071 for the testing set.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Topology Optimization of District Heating Networks Using a SIMP-Like Multi-Material Penalization

Author(s): *Yannick Wack, *KU Leuven / Vito / Energyville*; Robbe Salenbien, *Vito / Energyville*; Tine Baelmans, *KU Leuven / Energyville*; Maarten Blommaert, *KU Leuven / Energyville*;

Due to the ability of District Heating Networks to connect a multitude of different renewable heat sources to provide carbon free heat to districts and entire cities, it is considered one of the core technologies to enable carbon-neutral space heating. The design and optimal routing of these heat networks poses a challenging topology optimization problem, that is proving to be hard to solve for classic combinatorial optimization approaches for relevant network sizes. To solve this problem efficiently, this contribution presents a novel topology optimization approach using a multi-material 'Solid Isotropic Material with Penalization' (SIMP)-like penalization for the topology optimization of District Heating Networks. The optimization problem is formulated around a non-linear heat transport model and minimizes a detailed net present value representation of the total cost of the heat network. For District Heating Networks, the upfront investment cost is a crucial factor for the roll-out of this technology, and emphasizes the importance of cost-optimal pipe routing and accurate choice of discrete available pipe diameters.

This discrete network topology and near discrete pipe design is achieved with a SIMP-like multi-material penalization approach. On a realistic and medium-sized test case, it is shown that a discrete network topology and near discrete pipe sizes are achieved with the presented SIMP-like multi-material penalization approach, while outperforming simple post-processing steps. On this test case, it is shown that higher total network cost improvements can be achieved through topology optimization for scarcer available set of pipe diameters.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Solver Selection and Complexity Analysis for the Meshfree Methods

Author(s): *Yanran Wang, *The Pennsylvania State University*; Michael Hillman, *The Pennsylvania State University*;

Meshfree methods are generally formulated under two frameworks: the Galerkin weak form and strong form collocation [1]. Meshfree methods have significantly eased mesh-distortion and mesh-dependence problems in the finite element method. However, quadrature and kinematic constraints require special treatment in the Galerkin weak-form formulations due to the rational, non-interpolatory nature, along with misalignment of supports and integration cells. Therefore, considerable effort has gone into researching efficient, stable, and accurate Galerkin solutions, and several successful techniques have been proposed, such as strain-smoothing, variational consistency, various stabilizations, and modification of approximations or variational principles in one way or another to recover the ability to impose essential boundary conditions [2].

Meshfree approximation functions also offer the unique ability to solve boundary value problems directly in the strong form by collocation leveraging the flexible properties of meshfree approximations, which can obtain arbitrary-order smoothness effortlessly. In addition, collocation methods can bypass both quadrature issues and the additional techniques needed to enforce essential boundary constraints. Nevertheless, collocation methods require computations of high-order derivatives since they are directly based on the strong form, which is more computational demanding for constructing the meshfree approximations [3]. Moreover, a larger number of collocation points than the number of nodes in the system is needed to ensure the optimal converging rates, which is analogous to the necessity of higher-order quadrature rule in the Galerkin weak-form based methods.

As a result of these issues, both Galerkin and collocation-based meshfree methods and their variants will result in different types of linear systems to be solved. Therefore, it is important to provide an in-depth analysis of the efficiency of both types of methods. In this work, a comparison of the complexity of different types of linear solvers is given. Furthermore, operation counts are derived and compared for select methods, and their convergence and efficiency are examined numerically.

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EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Uncertainty-Quantified Parametrically-Upscaled Continuum Damage Mechanics (UQ-PUCDM) Model for Plain Weave Woven Composites

Author(s): *Yanrong Xiao, *Johns Hopkins University*; Somnath Ghosh, *Johns Hopkins University*;

Uncertainty-quantified parametrically-upscaled continuum damage mechanics (UQ-PUCDM) models for plain weave woven composites are developed. The PUCDM models are thermodynamically consistent, micro-/mesostructure-integrated constitutive models that bridge length scales through explicit incorporation of lower-scale descriptors into coefficients. The PUCDM models explicitly incorporate constitutive material properties and micro/meso-structural features, characterized by representative aggregated meso-structural parameters (RAMPs). The level-1 PUCDM model features homogenized intra-yarn constitutive response of unidirectional composite SERVEs, while the level-2 PUCDM model reflects the upscaled effect of mesostructural RVE response. The functional forms of the coefficients are established through machine learning algorithms operating on a micro-/mesostructural response database. The 2-level PUCDM model is validated by experimental results. The UQ-PUCDM framework addresses sources of uncertainty that accrue at the model development and response prediction stages: constitutive material properties and microstructural variability. A Taylor-expansion based uncertainty propagation method is developed to propagate the uncertainty among the PUCDM constitutive parameters and evolving macroscopic response variables. Numerical examples demonstrate the accuracy of UQ-PUCDM.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: AI-Enabled Drone Image Processing for Rapid Bridge Inspection and Management

Author(s): *Yelda Turkan, *Oregon State University*; Donghoon Ji, *Oregon State University*; Paolo Calvi, *University of Washington*;

The mobility of people and goods is highly dependent on the health of a nation's transportation system. Timely inspection and effective maintenance and management of bridges is crucial to avoid any issues that may have a negative impact on public mobility. However, current bridge inspection practice inhibits the collection and analysis of information regarding the status of bridges in an efficient and timely manner. This problem is further exacerbated by the large number of bridges in the U.S. and the limited number of inspectors available. Therefore, in this study, we propose a framework that will make it more convenient and faster to inspect and manage bridges, which can improve the current practice significantly in terms of efficiency and safety, thus helping to improve public mobility.

To overcome the challenges associated with the current bridge inspection and management approaches, several researchers have implemented a variety of technologies including drones, and lidar for as-is rapid and accurate bridge data collection. However, processing this data is not fully automated and persists as an extremely time consuming and challenging task. Drones enable safe and rapid collection of visual bridge inspection data in the form of digital images and have been used for bridge inspections. However, these efforts have primarily focused on taking photographs and videos that are used for onsite evaluation or subsequent virtual inspection by engineers. The ability to convert images or videos automatically and robustly into actionable information such as extraction and quantification of inspection data is still a challenge.

Bridge Information Models (BrIM) is another technology that has been investigated in the context of bridge inspections. BrIM is an object-oriented database that enables storing all bridge data, including 2D drawings and 3D models, inspection notes, images, and maintenance information. Recent research efforts have focused on implementing BrIM for bridge structural condition assessment and concluded that it is a suitable technology that can be used to improve current bridge inspection practice.

Therefore, in this study, we applied Convolutional Neural Networks (CNN) to drone images to automatically identify cracks and other defects on concrete bridges. In the next step, we implement skeletonization technique to measure crack dimensions including their length and width. In the final step, all relevant crack information is mapped onto 3D BrIM. In summary, the proposed framework has the potential to improve the current bridge inspection and management practice significantly in terms of efficiency and safety, thus improving public mobility.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Detecting Delamination in Composites Using Planar Electrical Capacitance Tomography and Machine Learning

Author(s): *Yening Shu, *University of California, San Diego*; Xinlun Zhao, *University of California, San Diego*; Kenneth Loh, *University of California, San Diego*;

Composites are extensively used for aircraft, automotive, and civil infrastructure systems because of their high strength- and stiffness-to-weight ratios. However, defects such as porosity and delamination could occur and propagate, especially when they are subjected to unpredictable impact, service, and/or environmental loads. To prevent these damage features from propagating and causing catastrophic structural failure, there is an urgent need to localize and evaluate the extent of these subsurface damage features. Conventional nondestructive evaluation and structural health monitoring systems, which require the use of discrete sensors and estimation of structural response, can be time and economically inefficient. In contrast, direct damage detection methods such as electrical capacitance tomography (ECT) could be used in a noncontact manner to directly visualize these subsurface damage features. The hypothesis is that delamination results in a localized change in dielectric property (i.e., permittivity) in the composite, which can be mapped using ECT. To test this hypothesis, the planar ECT method was used in this study in order to develop a portable, handheld nondestructive inspection system for carbon fiber-reinforced polymer (CFRP) composites. In short, planar ECT utilizes capacitance measurements of planar electrodes to reconstruct the volumetric permittivity distribution of the scanned object. Localized changes in permittivity correspond to cracks or delamination. However, the conventional planar ECT reconstruction algorithm suffers from intensive computational demand and low-resolution because of the ill-posed nature of the inverse problem. For inspection accuracy and time-efficiency, a supervised machine learning method that utilizes an artificial neural network was employed in the planar ECT solver. The results showed that high-resolution and real-time permittivity reconstruction could be achieved. Both numerical simulations and experimental results are presented in this work to verify the delamination damage mapping in CFRP composites.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Simulation of Thermo-Mechanical Coupling in Origami Assemblages

Author(s): *Yi Zhu, *University of Michigan*; Evgueni Filipov, *University of Michigan*;

Origami assemblages provide a novel method to build metamaterials and active structures that have unique thermal and mechanical properties. However, current simulation methods cannot capture the complex thermo-mechanically coupled behaviors resulting from large folding motions of the origami, so these systems are currently designed based on trial-and-error approaches. This talk introduces a novel simulation framework to capture the thermo-mechanical coupling within origami assemblages to resolve the above-mentioned challenges [1]. The proposed simulation method uses a rapid bar-and-hinge model to represent the origami geometry and to simulate the large deformation mechanical behaviors of the origami systems. A new reduced order model is introduced to capture the heat-transfer characteristics within origami assemblages as well as the heat loss from the origami to the surrounding environment. Finite element models are used to validate the proposed origami heat transfer simulation for different system geometries, materials, and surrounding environments. This framework provides the much-needed simulation method for origami-inspired thermal mechanical metamaterials and allows future research to explore the optimization and inverse design of these origami structures.

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EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: A Multiphysical Surface-Force Based Fracture Theory for Subcritical Crack Growth in Surface-Reactive Environments

Author(s): Mehdi Eskandari Ghadi, *University of Colorado Boulder*; *Yida Zhang, *University of Colorado Boulder*;

This work proposes a surface-force based theory for quantitative modeling of the non-linear multistage subcritical crack growth (SCG) by considering the underlying physiochemical processes. In surface-reactive environments, a strength reduction is commonly observed in the form of stable crack growth at finite velocity at stress intensity factors significantly lower than the intrinsic fracture toughness. The crack propagation rate increases with increasing stress intensity up to a transport-rate limited stage. With the stress intensity exceeding the fracture toughness, rapid blow-up of crack velocity associated with in-vacuum conditions occurs. Current hypotheses for strength reduction are adsorption-induced surface energy reduction and chemical attack of crack tip material. Surface phenomena such as sorption, hydration, and crystallization and the induced repulsive forces behind the crack tip, however, are largely neglected.

To fill this gap, we proposed a mechanistic theory and implemented in a partitioned implicit scheme to couple the cohesive fracture theory with surface mechanics and fluid transport. For a homogenous material in vacuum, simulated crack tip profiles are indicative of sharp closure for equilibrium cracks and parabolic closure under higher levels of applied tension, based on the surface force-separation relation intrinsically determined by the decohesion of the material bonds. A model of thermally activated debonding of crack tip bonds is adopted for the kinetics of crack propagation. Considering that surface-reactive species are not necessarily uniformly distributed along the crack, the local force-separation relation varies as a function of position away from crack tip. The fluid distribution profile is dictated by transportation models of viscous flow and surface diffusion along the crack. Thus, it is coupled with the relative speed that the crack tip travels with respect to the environment, the ambient concentration, and the crack opening profile. The proposed theory operates at a scale larger than the atomic level without relying on the chemistry of crack-tip bonds and smaller than the macroscopic energy analysis by requiring the full resolution of crack opening profile and stress fields near the crack tip. We therefore refer it to as the Surface-Force based Fracture Theory (SFFT). A feature of this theory is the capability to inject different surface force and transportation mechanisms in a multiphysical setting and the natural transition between all three stages of SCG. The model is validated by calibration against experimental data for the system of glass in moist air to quantitatively capture the stages of SCG with smooth transitions under different levels of humidity.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Investigating Structural Performance of the Elevated Slab Residential Buildings in the Coastal Regions

Author(s): *Yong Yoo, *Texas A&M; University*; Maria Koliou, *Texas A&M; University*; Nur Yazdani, *University of Texas at Arlington*; Cedric Ling, *University of Texas at Arlington*;

A number of natural disasters have continuously occurred in the United States and around the world. Near-coastal structures are exposed to multi-hazard events such as earthquakes, tsunamis, tropical cyclones, and coastal flooding. Especially, the total number of hurricane occurrences classified as Category 3 and higher has increased. To mitigate the damage from multi-hazards to residential buildings in the vulnerable regions, various retrofit strategies and methods were studied and suggested. Elevating a home slab is one of the methods to retrofit an existing house foundation to reduce the potential flood damage. Experimental testing of elevated slab specimens was performed at the University of Texas at Arlington (UTA) and data were used to validate/calibrate slab-level numerical models. Then, building models of typical residential buildings were developed in the ABAQUS to evaluate the response of those elevated structures subjected to combined wind and flood loads, typical of coastal loading conditions. To investigate the structural demand of the elevated slab residential building, simulated time-series data (wind speed, flood depth, and significant wave height) at Bolivar Peninsula for Hurricane Ike were utilized to calculate hazard load conditions. The analyses targeted buildings located in three different locations along the Gulf coast. This study might contribute to code developers, design professionals, insurers, portfolio managers, researchers, and government planners because wood-frame residential buildings in coastal areas in the United States might suffer hurricanes or tropical cyclones-induced wind, surge, and wave.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Robust Output-Only Modal Identification with Unsupervised Learning of Full-Field, High-Spatial-Dimensional Video Measurements

Author(s): *Yongchao Yang, *Michigan Technological University*; Charles Dorn, *California Institute of Technology*;

High-fidelity characterization of structural dynamics has recently been made possible by the emerging full-field, high-spatial-resolution vibration measurement (i.e., very dense spatial measurement points) techniques using optical methods such as photogrammetry and laser vibrometers. However, a significant obstacle to tackle is output-only identification of high-spatial-resolution modal parameters, especially the determination of physical modes from spurious, because many modes are only weakly present in the noisy vibration measurements. In this study we present our recent work in developing a new non-parametric, unsupervised learning approach for robust output-only identification of high-spatial-dimensional modal parameters, by exploiting the full-field, high-spatial-resolution response measurement data from digital video cameras. We present experimental study about the performance of the new method and comparisons with a few existing methods and observe encouraging results. We also discuss its applicability and limitations for more complex dynamic structures.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: A Meshfree Peridynamic Model for Brittle Fracture in Randomly Heterogeneous Materials

Author(s): *Yue Yu, *Lehigh University*; Yiming Fan, *Lehigh University*; Huaiqian You, *Lehigh University*; Xiaochuan Tian, *University of California, San Diego*; Xiu Yang, *Lehigh University*; Xingjie Li, *University of North Carolina at Charlotte*; Naveen Prakash, *Corning Incorporated*;

In this work we aim to develop a mathematically unified framework and a reliable computational approach to model the brittle fracture in heterogeneous materials with variability in material microstructures and properties, and to provide statistic metric for quantities of interest, such as its fracture toughness. To model the material responses and naturally describe the nucleation and growth of fractures, we consider the peridynamics model. In particular, a stochastic state-based peridynamic model is developed, where the micromechanical parameters are modeled by a finite-dimensional random variables or a truncated combination of random variables with the Karhunen-Loeve decomposition or the principle component analysis (PCA). To solve this stochastic peridynamic problem, probabilistic collocation method (PCM) with sparse grids is employed to sample the stochastic process. On each sample, the deterministic peridynamic problem is discretized with an optimization-based meshfree quadrature rule. We present rigorous analysis for the proposed scheme and demonstrate convergence for a number of benchmark problems, showing that it sustains the asymptotic compatibility spatially and achieves an algebraic or sub-exponential convergence rate in the random coefficients space as the number of collocation points grows. Finally, to validate the applicability of this approach on real-world fracture problems, we consider the problem of crystallization toughening in glass-ceramic materials, in which the material at the microstructural scale contains both amorphous glass and crystalline phases. The proposed stochastic peridynamic solver is employed to capture the crack initiation and growth for glass-ceramics with different crystal volume fractions, and the averaged fracture toughness are calculated. The numerical estimates of fracture toughness show good consistency with experimental measurements.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Let's Continue to Share This Path Together to Build an Even Better Future

Author(s): *Yukio Tamura, *Chongqing University*;

I am very honored to be invited to this mini-symposium to celebrate the 75th birthday of my best friend, Prof. Ahsan Kareem. Ahsan and I first met in Fort Collins at the 5th International Conference on Wind Engineering (ICWE) chaired by Prof. Jack E. Cermak, who was then Ahsan's supervisor. However, we did not have the opportunity to converse there. That was my first experience of overseas travels and international conferences, as well as a memorial event for the wind engineering community. The term "Wind Engineering" was first used as the name of the quadrennial conferences. We met again at the 6th ICWE in Gold Coast, Australia, in 1983, and later, I heard from Ahsan that he acted as rapporteur of a session where I presented a mathematical model of vortex-induced oscillation of circular continuous cylinders. His impression was that my paper was full of equations. Our Japanese group established the International Wind Engineering Forum (IWEF) in 1994, and Ahsan joined as a member of the International Advisory Board. He gave some invited lectures at the forums, including IWEF on Damping in Buildings held in September 1995 in Atsugi, and he has participated in the US-Japan Natural Resources (UJNR) Panel Workshops on Wind Effects since 1997. Ahsan has invited me almost every year to the ASCE Structures Congress since 1989. He collaborated with us as a member of the Academic Frontier "Wind Engineering Research Center" of Tokyo Polytechnic University (TPU) from 2000 to 2005. From 2003 to 2008, I served as the Director of the TPU 21st Century Center of Excellence (COE) Program and Ahsan strongly supported us as a member of the Advisory Board. Ahsan also contributed to the TPU Global COE (GCOE) Program on which I served as Director from 2008 to 2013. In the ten years of COE and GCOE Programs, we collaborated to establish the database enabled design (DED) system and the Engineering Virtual Organization "VORTEX-Winds". I created the Japanese Damping Database (2000) and the TPU Aerodynamic Database (2007) for research, education and practical applications. Ahsan established the analytical cyber infrastructures to efficiently integrate and utilize knowledge bases and databases. Ahsan has always been at the forefront of wind engineering research and has brilliantly created many innovative methods in the wind engineering field.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Advanced In-Situ Fabrication of Nanofibers via a Modified Wet Electrospinning Method to Yield Advanced Polymer-Ceramic Nanocomposites

Author(s): *Yunzhi Xu, *Northwestern University*; Ping Guo, *Northwestern University*; Ange-Therese Akono, *Northwestern University*;

This project develops an innovative method for manufacturing nanofiber-reinforced ceramic composites with the advantages of high-efficiency and low-cost by electrospinning polymer fibers directly to a reactive ceramic precursor gel. The electrospinning method consists in using an electric force to draw a charged jet of polymer solution into fibers with diameters ranging from nanometer to micrometer scale. The liquid gel becomes an inorganic ceramic matrix upon curing. Consequently, the adoption of a liquid gel as the collector during electrospinning enables the direct infusion of nanofibers in an inorganic ceramic matrix at the same time when they are generated, which significantly reduces the time and effort required in conventional composite manufacturing methods.

We demonstrate the viability of our method by producing a 0.5 wt% electrospun PEO fiber reinforced geopolymer composite. We performed microstructural and mechanical characterization of the geopolymer nanocomposite through scanning electron microscopy and micro-indentation, respectively. The fabricated fiber-reinforced polymer-ceramic composite shows a random distribution of the PEO fibers with individual fiber well blended in the matrix, suggesting great bonding between the fiber and matrix. The micro-indentation tests reveal that 0.5 wt% electrospun PEO fibers are sufficient to yield a substantial increase of 29% and 22% in the indentation modulus and indentation hardness, respectively. This enhancement can be attributed to the fact that PEO fibers served as a catalyst during the ceramic precursor gel reaction due to their high surface area, meanwhile, the fibers toughen the ceramic matrix through crack-bridging mechanisms.

Our approach allows in-situ fabrication of nanofibers and incorporates the nanofiber production in the process of ceramic synthesis. This method leads to a potentially scalable manufacturing approach of organic/inorganic nanocomposites. It also provides significant potential in designing multifunctional and architected polymer ceramic composites.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Fracture Toughness of Electrospun Nanofiber-reinforced Geopolymer Composites Using Scratch Tests

Author(s): *Yunzhi Xu, *Northwestern University*; Ping Guo, *Northwestern University*; Ange-Therese Akono, *Northwestern University*;

We investigate the fracture response of advanced electrospun nanofiber-reinforced geopolymer composites using scratch tests. We created a novel geopolymer nanocomposite using a highly efficient and low-cost fabrication technique based on electrospinning. We integrated electrospun nanofibers into geopolymer as a reinforcing phase. The nanofibers were first generated using electrospinning and infused in the ceramic matrix by employing water glass as a liquid bath collector during electrospinning. Next, the fracture properties were characterized using scratch tests. The principle of scratch testing is to push a sharp probe across the surface of material under a linearly increasing vertical force while recording the horizontal force and penetration depth. In our tests, a microscopic scratch tester was used along with a Rockwell C diamond probe. Afterward, the fracture toughness was calculated by application of a nonlinear fracture mechanics model. Furthermore, we explored the fracture micro-mechanisms using high-resolution environmental back scattered scanning electron microscopy. We will present our results and examine the potential of advanced manufacturing methods coupled with nanomaterials to toughen geopolymer composites.

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Title: Relation Between Void Ratio and Contact Fabric of Granular Soils

Author(s): *Yuxuan Wen, *University of Colorado Boulder*; Yida Zhang, *University of Colorado Boulder*;

Void ratio is one of the key engineering properties of granular soils. It reflects how well the grains are packed and hints whether the soil is contractive or dilative upon shearing. On the other hand, fabric tensor has been at the center of experimental and theoretical granular mechanics research over the past decade for its intimate relation with the material's anisotropy and critical-state behaviour. However, despite both void ratio and fabric tensors are quantitative descriptors of soil internal structure, their interconnections are seldomly studied. A specific question is, can the fabric data be used to deduce the void ratio of granular materials?

We have thus investigated the relation between void ratio and the fabric tensor of granular soils. The fabric tensor is defined on contact normals and with their spherical component preserved such that the information of coordination number Z can be carried. Through discrete element method, a series of isotropic/anisotropic consolidation tests and monotonic triaxial compression and extension tests are conducted. The obtained void ratio data is found to collapse onto one unique surface, namely the fabric-void ratio surface (FVS), when plotted against the first two invariants of the contact-based fabric tensor. The robustness of this relation is confirmed by testing samples with different initial void ratios under various consolidation and monotonic triaxial stress paths. An additional undrained cyclic triaxial test followed by continuous shearing to critical state is performed to further examine the fabric-void ratio relation under complex loading paths. It is found that the previously identified FVS from monotonic tests still attracts the states of these specimens at critical state, although their fabric-void ratio paths deviate from the FVS during cyclic loading. The newly discovered FVS provides a refreshing perspective to interpret the structural evolution of granular materials during shearing and can serve as an important modelling component for fabric-based constitutive theories for sand.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: An Enriched Immersed Boundary Method for Thermo-Fluid-Structure Systems with Large Property Discontinuities.

Author(s): *Ze Zhao, *University of Illinois Urbana Champaign*; Jinhui Yan, *University of Illinois Urbana Champaign*;

Conjugate heat transfer problems exist in a wide range of industrial applications. Many numerical studies have been conducted to reveal the mechanism behind the phenomena. However, the traditional boundary-fitted method becomes challenging when the geometry of solid parts grows complicated. On the other hand, many immersed boundary methods relax the geometric requirement but get trapped in violation of temperature and flux continuity due to the inherent limitations, which results in an energy-unconservative system.

We propose an immersed boundary method with the enriched linear finite element to overcome the above issues. The DOFs dwelling on the cut cells are duplicated to represent the velocity and temperature fields on both sides. Across the interface, the quantity fields from solid and fluid regions are connected via additional interfacial integral terms. Expressly, for the momentum equation, the weak boundary condition guarantees the compatibility of velocity and traction across the fluid-structure interface. The augmented Lagrange method is enforced to eliminate the temperature and flux discontinuity.

Evaluations from multiple aspects justify the outstanding performance of the proposed method. The case "heat conduction in the concentric sphere" compares the accuracy against other popular approaches. Then we simulate that cold flow passes around a hot sphere to show the agreement of thermofluid behaviors with DNS results. Other cases focusing on moving structures are investigated to demonstrate flexibility.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Modeling Cracks in Clay at the Nanoscale Through Full-Scale Molecular Dynamics

Author(s): *Zhe Zhang, *University of Florida*; Xiaoyu Song, *University of Florida*;

In this study, we investigate the mechanism of nucleation and growth of cracks in clay at the nanoscale through full-scale molecular dynamics simulations. The clay adopted is pyrophyllite, and the force field is CLAYFF. The crack formation in a pyrophyllite clay layer is evaluated under uniaxial tension and simple shear. The numerical results show that cracks in the nanoscale pyrophyllite clay layer are brittle and strain-rate dependent. Small strain rate results in low ultimate tensile/shear strength. As strain rate increases, clay crack shifts from a single-crack pattern to a multiple-crack one. The cracking mechanism is investigated from bond breakage analysis at the atomic scale. It is found that the first bond breakage occurs in the silicon-surface oxygen bond. As a crack propagates, the relative percentage of broken silicon-surface oxygen bonds is the smallest compared to other types of metal-oxygen interactions, demonstrating that the atomic interaction between silicon and surface oxygen atoms is the strongest. To understand the propagation of cracks, we also study the stress intensity factor and energy release rate of pyrophyllite and their size dependence at the atomic scale.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Performance-Based Optimization of Structural Fire Mitigation Strategies for Roadway Tunnels

Author(s): *Zheda Zhu, *Lehigh University*; Aerik Carlton, *Lehigh University*; Spencer Quiel, *Lehigh University*; Clay Naito, *Lehigh University*;

Several technologies such as forced ventilation, active fire-fighting systems, and passive fire protection systems are used in current practice to mitigate fire-induced structural damage and increase resilience for roadway tunnels. Decisions about the cost-benefit of each strategy will be based on a tunnel's geometry, traffic load, and reparability; however, there are few available performance-based tools that account for the comparative impact of each strategy on reducing post-fire downtime and cost. This presentation will outline a new decision-making approach to optimize fire mitigation strategies for roadway tunnels by minimizing the investment and maximizing the protection efficiency. First, the damage assessment tool for the concrete liner with and without passive fire protection is developed to account for realistic uncertainties of the thermal properties for both the passive protection material and concrete liner. Second, the investment, as well as the economic loss due to stochastic vehicle fire hazards, are quantified for a single mitigation strategy or a combination of strategies. The economic loss includes the direct repair cost and the functionality loss due to tunnel closure, which is determined by the extent and severity of concrete liner damage and the corresponding repair procedures. The thermal impact of the fire on the tunnel liner is calculated with the Confined Discretized Solid Flame (CDSF) model, which is computationally efficient and therefore well suited for stochastic analyses that account for additional uncertainties associated with fire intensity, combustion energy, and the effect of active fire mitigation methods such as longitudinal ventilation and Fixed Fire-Fighting System (FFFS). Third, a genetic algorithm is used to perform a multi-objective optimization, resulting in a Pareto front as the reference for the decision-making process. The objectives and constraints of the algorithm can be readily modified based on practical engineering requirements. The proposed approach is then used to evaluate the sensitivity of fire protection selection to tunnel geometry, traffic volume and composition, and detour length during closure.

EMI 2022
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Title: Fractal Lattices Lead to Improved Energy Dissipation

Author(s): *Zhennan Zhang, *University of Louisville*;

Lattice metamaterials exhibit remarkable mechanical properties and novel functionalities, such as high specific stiffness, fracture toughness, tunable vibroacoustic properties, and energy absorption. This study explores a group of lattice metamaterials with fractal cuts that feature energy dissipation via structural sliding friction mechanisms and intrinsic material damping. Lattice metamaterials with three types of fractal cut patterns were designed and fabricated using additive manufacturing. Three-point bending tests and numerical analysis have been combined to investigate their bending behavior. Experimental results show that the structural bending compliance of the metamaterials can be sharply enhanced by increasing the fractal orders, while at the same time keeping the shape recoverability during cyclic loading. Loss factors associated with the cyclic bending of these metamaterials are almost independent of the fractal order used, which is attributed to the synergistic effect between friction and viscoelasticity. It is further demonstrated via validated finite element models that the sliding friction plays a critical role by investigating the effects of the bending displacement and sample thickness on the flexural behavior. Results suggest that the magnitude of the maximum bending displacement has a negligible effect on the loss factors, and a power scaling law exists between bending stiffness and sample thickness. This study suggests that fractal lattice metamaterials have unique energy dissipation properties, with potential applications in many industrial sectors such as defense, energy, and transportation

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Simulation-Based and Risk-Informed Assessment of the Effectiveness of Tsunami Evacuation Routes Using Agent-Based Modeling

Author(s): *Zhenqiang Wang, *Colorado State University*; Gaofeng Jia, *Colorado State University*;

Abstract: Typically, tsunami evacuation routes are marked using signs in the transportation network and the evacuation map is made to educate people on how to follow the evacuation route. However, tsunami evacuation routes are usually identified without the support of evacuation simulation, and the route effectiveness in the reduction of evacuation risk is typically unknown quantitatively. This study proposes a simulation-based and risk-informed framework for quantitative evaluation of the effectiveness of evacuation routes in reducing evacuation risk. An agent-based model is used to simulate the tsunami evacuation, which is then used in a simulation-based risk assessment framework to evaluate the evacuation risk. The route effectiveness in reducing the evacuation risk is evaluated by investigating how the evacuation risk varies with the proportion of the evacuees that use the evacuation route. The impacts of critical risk factors such as evacuation mode (for example, on foot or by car) and population size and distribution on the route effectiveness are also investigated. The evacuation risks under different cases are efficiently calculated using the augmented sample-based approach. The proposed approach is applied to the risk-informed evaluation of the route effectiveness for tsunami evacuation in Seaside, Oregon. The evaluation results show that the route usage is overall effective in reducing the evacuation risk in the study area. The results can be used for evacuation preparedness education and hence effective evacuation.

Keywords: Agent-based model; Risk-informed evaluation; Route effectiveness; Simulation-based framework; Tsunami evacuation risk; Tsunami preparedness education

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Impact of Detailing on the Lateral Performance of Cold-Formed Steel Framed Walls.

Author(s): *Zhidong Zhang, *Johns Hopkins University*; Matthew Speicher, *National Institute of Standards and Technology*; Amanpreet Singh, *University of California, San Diego*; ?Tara Hutchinson, *University of California, San Diego*; Benjamin Schafer, *Johns Hopkins University*;

The main objective of this study is to investigate the impact of structural and non-structural detailing that is not directly accounted for in conventional lateral strength and ductility design of wall-lines constructed of cold-formed steel (CFS) framed steel sheet shear walls. A key structural detail that commonly occurs in wall-lines, but not in shear wall testing, is the presence of a heavy ledger track attached along the top of the wall, as this facilitates connection of the floor system with the wall. A key non-structural detail, which will impact the wall-line's lateral performance, is the presence and type of finish system (e.g., gypsum board). Herein, a numerical study employing OpenSees is validated and exercised on wall-line models with or without ledger tracks as well as with or without finish. Modeling results predict the degree by which both strength and ductility of wall-lines increase due to the presence of a ledger track and/or finish system. The strength increase can be attributed to the engagement of ledger track-to-stud connection moment resistance and additional direct shear resistance provided by an applied finish layer. The developed OpenSees model is able to capture the impact of detailing and can be incorporated into building-level simulations.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Extended Polynomial Chaos Expansion-Based Framework for Sensitivity and Reliability Analysis Under Uncertainty and Modeling Errors

Author(s): *Zhiheng Wang, *University of Southern California*; Roger Ghanem, *University of Southern California*;

Abstract: We provide a novel procedure that simultaneously accounts for parameter uncertainty, statistical error (lack of data), and model inadequacy. We first present a coherent and efficient formulation, namely the “extended polynomial chaos expansion”, to characterize and propagate these distinct uncertainties to various quantities of interest (QoI). We focus our attention on QoI that pertains to tails of probability distributions. The approach is grounded in polynomial chaos formalism, and relies on the formulation of the polynomial chaos coefficients themselves as random variables. By combining KDE approximations of probability density functions with directional derivatives in Gaussian spaces, we propose sensitivities that connect these QoIs with the various sources of uncertainty. The approach is useful both for prognosis and for design and resource allocation. We demonstrate our approach on several problems of interest in science and engineering.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Geometric Influence on the Bending Stability of Thin-Walled Corrugated Tubes

Author(s): *Zhongyuan Wo, *University of Michigan*; Evgueni Filipov, *University of Michigan*;

Thin-walled corrugated tubes that have bending multi-stability, such as the bendy straw, allow for variable orientation over the tube length. Compared to the long history of practical applications, the mechanics of the multi-stable tube bending remain unknown. We used several tools, including a reduced-order simulation package, a simplified linkage model, and physical prototypes, to explore the bending stability of corrugated tubes. The global multi-stable bending of the tube comes from the snap-through (or partial inversion) of the frustum unit, which is dependent on the geometric parameters. Moreover, when the frustum unit is folded from flat sheets, the design space is expanded by local instabilities of the creases. The bending response can be anisotropic by modifying the tube cross-sections or by popping through the valley creases. This work provides an improved understanding of the mechanics of the corrugated tubes and gives insight into the design of such systems with desired axial and bending behaviors.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Data-Driven Inverse Characterization for In-Situ Microscopic Composite Properties

Author(s): *Zimu Su, *Vanderbilt University*; Caglar Oskay, *Vanderbilt University*;

In-situ properties of the constituents of composite materials differ from their pure bulk properties, and exhibit spatial variations typically due to the chemical interactions between the multiple constituents during the manufacturing process. Accurate in-situ characterization of the properties are therefore critical for high-fidelity predictive modeling of the composite behavior. In this work, we develop a general framework for inverse characterization of in-situ microscopic properties of fiber reinforcement composites. The inverse optimization problem is posed based on the statistical inference perspective, considering that the measurement data used in the identification is corrupted by noise. The optimal solution is achieved by minimizing the objective function which is expressed as the expectation of the discrepancies between the predictions and the measurements, where multiple experimental observations are leveraged and assumed to be random variables. The statistical consistency of proposed problem formulation is demonstrated and guarantees that the inverse modeling approach asymptotically provide the best possible prediction (i.e., risk consistency) and optimal solutions (i.e., estimation consistency) of the composite properties with increasing number of experimental observations. The performance of the proposed inverse modeling is shown in the context of characterization of elasticity and thermal-elasticity properties using two-dimensional numerical composite specimens. Enumeration algorithm is employed to solve the inverse problem with modest number of dimensions in the parameter space. The results of optimal solutions show asymptotic convergence in probability with the increasing number of experimental observations incorporated in the objective function. The investigations with respect to the influence of specimen size and fiber volume fraction show the positive effect of increasing the amount of experimental information. For inverse problems concerned with higher dimensional parameter spaces, sequential programming method (SQP) is employed to achieve the optimal solutions.

EMI 2022
Baltimore, MD, May 31 - June 3, 2022

Title: Modeling Multiblock Systems: Computational Analyses Backed by Experiments

Author(s): Jose Andrade, *California Institute of Technology*; Ares Rosakis, *California Institute of Technology*; Joel Conte, *University of California, San Diego*; Jose Restrepo, *University of California, San Diego*; Vahe Gabuchian, *California Institute of Technology*; John Harmon, *California Institute of Technology*; Andres Rodriguez, *University of California, San Diego*; Arpit Nema, *University of California, Berkeley*; Andrea Pedretti, *Energy Vault, Inc.*; *Ziran Zhou, *California Institute of Technology*; Luca Sironi, *The European Organization for Nuclear Research*; Marco Andreini, *The European Organization for Nuclear Research*; Filippo Dacarro, *EUCENTRE*; Davide Bolognini, *EUCENTRE*;

Recently, there have been a lot of applications in multiblock structures. At CERN, concrete blocks are stacked to make walls in order to shield radiation from particle colliders. At Energy Vault, multiblock tower structures are designed for renewable energy storage. In this talk, we present our work in seismic performance assessment of those multiblock structures using Level Set Discrete Element Method. By comparing the simulation result with the experimental result, we show that the proposed method is effective, accurate and computationally efficient in seismic assessment of such structures.

Andrade, J., Rosakis, A., Conte, J., Restrepo, J., Gabuchian, V., Harmon, J., Rodriguez, A., Nema, A., & Pedretti, A.. (2021). Seismic Performance Assessment of Multiblock Tower Structures as Gravity Energy Storage Systems. EngrXiv.

Rosakis, A., Andrade, J., Gabuchian, V., Harmon, J., Conte, J., & Restrepo, J. et al. (2021). Implications of Buckingham's Pi Theorem to the Study of Similitude in Discrete Structures: Introduction of the RFN, μN , and SN Dimensionless Numbers and the Concept of Structural Speed. *Journal Of Applied Mechanics*, 88(9). doi: 10.1115/1.4051338

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: Corrosion Cracking Behavior of Reinforced Concrete Under Freeze-Thaw Cycles

Author(s): Xiguang Liu, *Xi'an University of Architecture & Technology*; *Ziwei Yan, *Xi'an University of Architecture & Technology*; Ditao Niu, *Xi'an University of Architecture & Technology*;

Reinforced concrete structures in cold regions suffered frost damage, CO₂ and Cl⁻ in service environment also caused the corrosion of steel bars in concrete. Under the long-term effects of freeze-thaw cycles, the corrosion of steel bars will be aggravated, which can seriously jeopardize the safety of existing structures. In this paper, the corrosion cracking behavior of reinforced concrete under freeze-thaw cycles was studied by theoretical analysis and experiment. The freeze-thaw tests of the reinforced concrete specimen with the different cover and the diameter of the steel bar were conducted, and the accelerated corrosion test was carried out for reinforced concrete specimens after the freeze-thaw test. Using DIC (Digital Image Correlation) technology to monitor the surface strain of the cover in corrosion test, the strains of the concrete surface at the time of concrete cracking are analyzed, and the shape of the corrosion contour of the frost damaged concrete is studied. The frost damaged concrete is divided into damaged layer and undamaged layer, and the calculation method of splitting tensile strength of damaged layer and undamaged layer concrete is proposed. Based on the theoretical model of corrosion ratio of rebars and the strength calculation method of the damaged concrete layer, the corrosion cracking condition model considering the freeze-thaw cycles and the compressive strength of concrete is established.

EMI 2022

Baltimore, MD, May 31 - June 3, 2022

Title: A Fault Detection and Diagnosis Algorithm for Extraterrestrial Habitats and its Experimental Validation

Author(s): *Zixin Wang, *Purdue University*; Yuguang Fu, *Nanyang Technological University*; Adnan Shahriar, *The University of Texas at San Antonio*; Benjamin Wogen, *Purdue University*; Mohammad Jahanshahi, *Purdue University*; Amin Maghareh, *Purdue University*; Arturo Montoya, *The University of Texas at San Antonio*; Shirley Dyke, *Purdue University*;

In the context of sustainable and long-term space human habitats, the structural health monitoring (SHM) of habitats is crucial and challenging due to the harsh environments. Future extraterrestrial habitats will face new threats stemming from extreme temperature fluctuations, degradation, meteorite impacts, high-frequency teleseismic events, and intense particle radiation. Establishing a suitable SHM framework for space habitats requires extensive theoretical and experimental studies, including system identification, model updating, fault-detection, diagnosis, and prognosis techniques. In this study, a data-driven fault detection and diagnosis (FDD) algorithm is developed to perform impact and damage detection of a dome structure. The features of time history data are extracted and fed into a neural network to detect and localize meteorite impacts. Frequency response function (FRF), which describes the input-output relationship between a structural response and an external excitation, is utilized as the vibration features to train the neural networks for damage detection. The FDD algorithm will detect and localize impacts and damage probabilities of each segment. The proposed FDD strategy is experimentally validated using a scaled geodesic dome in Herrick Technology Laboratories at Purdue University. A computer vision approach is developed to obtain the orientation of accelerometers. Modal analysis is performed using the hammer testing data to obtain the natural frequencies and mode shapes of the geodesic dome, which provides the necessary information for model updating. The dataset for training the FDD algorithm is calculated by the updated finite element model, and the FDD algorithm is validated by detecting and localizing impacts and damages using the experimental data.