EMI 2024 IC

ASCE Engineering Mechanics Institute 2024 International Conference

September 11-13, 2024

Vienna, Austria

Program & Book of Abstracts

Editors: Christian HELLMICH, Bernhard PICHLER, Stefan SCHEINER

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PLENARY LECTURES

Session | Date | Time | Room | Page Program | Page Abstract

PL1 | Wed, Sept 11 | 09:00-09:45 | EI7 | 7 | 36
Franz-Josef ULM (Massachusetts Institute of Technology, USA)
Mechanics and electrochemistry for bulk energy storage in concrete materials & structures

PL2 | Wed, Sept 11 | 13:30-14:15 | EI7 | 11 | 36
Agathe ROBISSON (TU Wien, Austria)
Development of microstructural heterogeneities in cementitious slurries and mortars at rest and under flow: a hypothesis for pumping blockage and material defects

PL3 | Thur, Sept 12 | 09:00-09:45 | EI7 | 17 | 36
Pol SPANOS (Rice University, USA)
Linearization approaches for stochastic dynamic analysis of systems endowed with non-integer order differential elements

PL4 | Thur, Sept 12 | 13:30-14:15 | EI7 | 21 | 36
Emanuela DEL GADO (Georgetown University, USA)
Memory of flow and residual stresses: from jammed soft solids to cement pastes

PL5 | Fri, Sept 13 | 13:30-14:15 | EI7 | 33 | 36
Alfredo SOLDATI (TU Wien, Austria)
Transfer fluxes, breakage, coalescence, and drop size distribution in turbulence

LIST OF MINI-SYMPOSIA & SESSIONS

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MS15: Fundamental and practical insights into characterizing, measuring, and mitigating shrinkage and creep in cementitious materials
Behrouz Shafei, Agathe Robisson & Dana Daneshvar

MS15 | Wed, Sept 11 | 10:15-12:15 | EI3 | 8 | 66-67

MS16: Mechanics of wood, wood-based products, biocomposites, and timber structures
Markus Lukacevic, Eric Landis, Sebastian Pech, Josef Füssl, Michael Schweigler, Carmen Sandhaas, Pedro Palma & Michael Dorn

MS16-1 | Wed, Sept 11 | 10:15-12:15 | EI7 | 9 | 67-68
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MS16-6 | Fri, Sept 13 | 09:00-11:00 | EI7 | 28 | 72-73

MS17: Up-scaling challenges in the modeling of civil engineering materials
Laurent Brochard

MS17-1 | Wed, Sept 11 | 14:30-15:50 | EI9 | 13 | 73-74
MS17-2 | Thu, Sept 12 | 14:30-15:50 | EI8 | 23 | 74-75

MS18: Computational methods for stochastic engineering mechanics
Ioannis P. Mitseas, Ioannis A. Kougioumtzoglou, Michael Beer & Jianbing Chen

MS18-1 | Wed, Sept 11 | 10:15-12:15 | EI2 | 9 | 75-76
MS18-2 | Wed, Sept 11 | 14:30-15:50 | EI2 | 13 | 76-77

MS19: Engineering mechanics in tunnelling
Günther Meschke, Xian Liu, Wei Song, Wouter De Corte, Jiao-Long Zhang

MS19-1 | Wed, Sept 11 | 14:30-15:50 | EI3 | 13 | 77
MS19-2 | Thu, Sept 12 | 16:20-18:00 | EI7 | 25 | 78

MS21: Computational methods for granular media
Shiwei Zhao, Ning Guo & Jidong Zhao

MS21-1 | Thu, Sept 12 | 14:30-15:50 | EI5 | 23 | 79
MS21-2 | Thu, Sept 12 | 16:20-18:00 | EI5 | 25 | 79-80

MS23: The mechanics, chemistry, and physics for cement and concrete decarbonization
Mohammad Javad Abdolhosseini Qomi, Kemal Celik, Konrad Krakowiak, Jiaqi Li, Hegoi Manzano, Guoqing Geng & Mohsen Ben Haha

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MS23-2 | Fri, Sept 13 | 11:30-12:30 | EI5 | 31 | 81-82

MS25: Non-local mechanics for unconventional modelling in bioengineering and advanced manufacturing
Emanuela Bologna & Massimiliano Zingales

MS25-1 | Fri, Sept 13 | 09:00-11:00 | EI3 | 29 | 82-83
MS25-2 | Fri, Sept 13 | 11:30-12:30 | EI3 | 31 | 83

MS27: Mechanical performance and durability of novel concretes and sustainable alternatives
Mija Hubler & Yunping Xi

MS27 | Thu, Sept 12 | 10:15-12:15 | EI8 | 19 | 84-85

MS28: Innovative experimental mechanics for fracture of heterogeneous materials
Eric Landis & Branko Šavija

MS28 | Fri, Sept 13 | 09:00-11:00 | EI8 | 29 | 85-86

MS29: Machine learning and artificial intelligence for constrained systems
Roger Ghanem, Clemens Heitzinger, Christian Soize & Minh Nhat Vu

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MS31: Collagen structure and mechanics
Philipp J. Thurner, Patrick Mesquida & Orestis G. Andriotis

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RS01: Various topics

RS01 | Wed, Sept 11 | 10:15-12:15 | EI5 | 9 | 89

Poster Session

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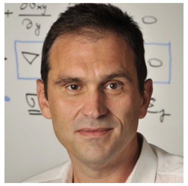
CONFERENCE AGENDA

Wednesday, September 11, 2024

Opening / Plenary Lecture Session

C. Hellmich | EI7

08:45-09:00	**Opening Session**
09:00-09:45	**Plenary Lecture 1** PL1 | 09:00-09:45 **Mechanics and electrochemistry for bulk energy storage in concrete materials & structures** Franz-Josef Ulm (Massachusetts Institute of Technology, USA)



Educated as civil engineer in Germany and France, with graduations at TU Munich (Germany) and at École Nationale des Ponts et Chaussées (France), and a doctorate from the latter institution, Franz-Josef Ulm spent his early scientific career at the Laboratoire des Ponts et Chaussées in Paris, France, receiving habilitation at École Normale Superieur de Cachan, France. Thereafter, he joined M.I.T., where he has been active as a professor ever since.
Throughout his career, he has belonged to the world leaders when it comes to opening engineering mechanics towards physics and chemistry, and as a result he has, over the years, largely transformed the understanding of the most important construction material, concrete. To that end, he has integrated essential aspects of physical chemistry, of experimental materials science and engineering, of computational statistical physics, and recently, of electricity, into the repertoire of application-oriented, yet fundamental engineering science.
His achievements have been prestigiously awarded in the academic realm, including memberships with the National Academy of Engineering of the United States of America, with the Austrian Academy of Sciences, and an Honorary Doctorate of TU Wien.

Abstract: Cement-based materials as insulators are unable to conduct electrical charge. However, when cement is mixed with a small amount of carbon black, the contrast between the hydrophobicity of carbon black and the hydrophilicity of cement leads to the build up of a volumetric wire throughout a load bearing porous matrix. When polarized, this volumetric wire is the backbone of the supercapacitor technology and permits storing energy in form of counterions along the carbon black surface. The stored energy scales with the volume of the material. In this talk, I will show different ways of approaching this energy storage capacity from an engineering mechanics point of view. First I will show that energy storage properties can be assessed by analogy by using the correspondence principle of viscoelasticity, when replacing stress by current and strain by voltage (potential difference). I will then dive deeper into the electrochemistry of the underlying process, which permits deriving the fundamental scaling relations for designing concrete structures not only for strength but for energy storage as well. This multifunctionality of electron-conductive cement-based materials and structures opens interesting perspectives for engineers to redesign our built environment for sustainability.

09:45-10:15	**Coffee Break**

10:15-12:15	MS05-1: Bone mechanobiology: experimental and computational assessment across the scales P. Pivonka, F. J. Martínez Reina — EI8	MS06-1: Structural vibration control C. Adam, A. Pirrotta — EI10	MS13-1: Computational geomechanics Y. Wang — EI9	MS15: Fundamental and practical insights into characterizing, measuring, and mitigating shrinkage and creep in cementitious materials A. Robisson, D. Daneshvar — EI3
	MS05-1:1 | 10:15-10:35 **Importance of drug order in sequential treatments against osteoporosis involving denosumab and romosozumab** F. J. Martínez Reina, R. Ruiz Lozano, J. L. Calvo Gallego, P. Pivonka	MS06-1:1 | 10:15-10:45 (Keynote Lecture) **Use of a hysteretic device in vibration mitigation** F. Vestroni, P. Casini	MS13-1:1 | 10:15-10:35 **Efficient approaches for simulating large deformation problems** J. P. Hambleton	MS15:1 | 10:15-10:35 **Creep and shrinkage of a limestone calcined clay cement paste determined in hourly performed three-minute creep tests** S. J. Schmid, O. Lahayne, L. Zelaya, B. Pichler
	MS05-1:2 | 10:35-10:55 **Bone micro-mechanobiology of implant-femur interaction: a multi method approach combing CT and SASTT imaging with analytical mechanics** L. Pircher, T. A. Grünewald, H. Lichtenegger, M. Liebi, A. Weinberg, C. Hellmich		MS13-1:2 | 10:35-10:55 **Particle finite element method for large deformation simulation of geotechnical hazards under fluid-solid interaction** W. Sun, W. Zhang, W.-H. Yuan	MS15:2 | 10:35-10:55 **Basic creep properties of the hydration products in mature slag-based CEM II concretes** M. Sorgner, R. Díaz Flores, T. Pilgerstorfer, B. Moritz, B. Pichler, C. Hellmich
	MS05-1:3 | 10:55-11:15 **Deep-learning based framework for automated mechanobiological analysis of bone response using micro-CT imaging data of mouse tibiae** P. Pivonka, A. Lagzouli, N. Muhl-Castoldi, V. Sansalone, D. M. Cooper, A. Othmani	MS06-1:2 | 10:45-11:15 (Keynote Lecture) **A theoretical and experimental study on the optimal design of Sliding Tuned Liquid Column Dampers for structural vibration control** C. Masnata, C. Adam, A. Pirrotta	MS13-1:3 | 10:55-11:15 **Implicit SNS-PFEM with dual mortar method for thermo-hydro-mechanical large deformation problems** X.-H. Wu, Q. Zhang, W.-Q. Feng, Z.-Y. Yin, H.-C. Fang	MS15:3 | 10:55-11:15 **Early-age elastic and creep properties of graphene oxide cement paste determined by three-minute-long creep tests** M. Shahid, S. J. Schmid, O. Lahayne, A. Robisson, B. Pichler
	MS05-1:4 | 11:15-11:35 **Digital volume correlation resolves load-induced high articular strain foci in osteoarthritis-prone joints** A. Sharma, L. Evans, A. Parmenter, J. Brunet, K. Madi, K. Staines, P. Lee, A. Pitsillides	MS06-1:3 | 11:15-11:35 **Implementation of tuned mass damper control concept for integrated seismic and energetic retrofit of existing buildings** M. Basili, M. De Angelis, F. Busato	MS13-1:4 | 11:15-11:35 **SPH implementation to large deformation of granular mass using an advanced hypoplastic constitutive model** C. Zhu, W. Wu, C. Peng, S. Wang	MS15:4 | 11:15-11:35 **Influence of cracking and viscoelasticity on nonlinear creep of concrete** R. Díaz Flores, C. Hellmich, B. Pichler
	MS05-1:5 | 11:35-11:55 **A multiscale bone cell population model based on a 2-state receptor model accounting for cellular responsiveness to PTH** C. Modiz, N. Muhl-Castoldi, S. Martelli, S. Scheiner, V. Sansalone, P. Pivonka	MS06-1:4 | 11:35-11:55 **A fundamental study on active vibration control of cross-laminated timber members** N. Hirschfeldt, T. Furtmüller, C. Adam	MS13-1:5 | 11:35-11:55 **Modelling multi-physical field coupling process of rock by discretized virtual internal bonds** Z. Zhang	MS15:5 | 11:35-11:55 **Long-term concrete strain measurements of large-scale experiments using vibrating wire strain gauges** W. Bachofner, J. Kollegger
		MS06-1:5 | 11:55-12:15 **Nanoscale modeling for structural vibration control** R. Barretta, R. Luciano, F. Marotti de Sciarra, M. S. Vaccaro	MS13-1:6 | 11:55-12:15 **Microfiber-reinforced bentonite clay for geological repositories of nuclear spent fuel: multiphysical laboratory tests and computational modeling** A. Azzam, M. Rahmani, Y.-R. Kim, J. Eun, S. Kim	MS15:6 | 11:55-12:15 **Characterization of time-dependent restrained shrinkage in thin ultra-high performance concrete overlays** D. Daneshvar, P. Preinstorfer, K. Deix, B. Shafei, A. Robisson
12:15-13:30	Lunch Break			

MS16-1: Mechanics of wood, wood-based products, biocomposites, and timber structures M. Lukacevic, M. Dorn — EI7	MS18-1: Computational methods for stochastic engineering mechanics I. P. Mitseas — EI2	RS01: Various topics H. A. Mang — EI5	10:15-12:15
MS16-1:1 | 10:15-10:35 **Variations in experimental investigations of clear wood: to what extend can multiscale micromechanical models explain them?** E. Binder, M. Schweigler, T. K. Bader	MS18-1:1 | 10:15-10:35 **An approximate analytical technique for transient response PDF of a linear oscillator under a non-Gaussian colored noise** T. Tsuchida, K. Kimura	RS01:1 | 10:15-10:35 **Analysis of the behavior of the structure under internal ANFO explosion** S. Ko, S. Choi, J. J. Kim, W. Kwon	
MS16-1:2 | 10:35-10:55 **Phase field method-based modeling of wood fracture** S. Pech, M. Lukacevic, J. Füssl	MS18-1:2 | 10:35-10:55 **Computing upper failure probabilities using optimization algorithms together with importance sampling** T. Fetz	RS01:2 | 10:35-10:55 **Bay Bridge** J. S Plachta	
MS16-1:3 | 10:55-11:15 **Characterizing a novel strand based engineered wood product for the use in construction** A. Ghazanfari, B. Kromoser	MS18-1:3 | 10:55-11:15 **Demonstration of continuous gamma process for site specific structural capacity quantification for aging infrastructure** T. Micic	RS01:3 | 10:55-11:15 **Numbers, structure and insight** K. W. Breitung	
MS16-1:4 | 11:15-11:35 **Analytical and experimental study on glulam trusses with birch plywood gusset plates** M. Debertolis, Y. Wang, T. Wang, R. Crocetti, M. Wålinder, L. Blomqvist, S. Rossi, A. Polastri, P. Rigo	MS18-1:4 | 11:15-11:35 **Seismic reliability analysis of structures by an active learning-based adaptive sparse Bayesian regression approach** A. Roy, S. Chakraborty, S. Adhikari		
MS16-1:5 | 11:35-11:55 **Analyzing the failure probability of glued laminated timber beams across varying sizes using the finite weakest-link theory** C. Vida, S. Pech, M. Lukacevic, J. Füssl	MS18-1:5 | 11:35-11:55 **Uncertainty quantification on seismic response of an RC bridge pier considering varying material properties** M. Kitahara, R. Kurihara		
MS16-1:6 | 11:55-12:15 **Preparation of samples for the production of Glued Solid Timber (GST) beams according to EN 14080** B. Jashari, R. Sejdiu, L. Idrizi, A. Bajraktari			

Lunch Break

12:15-13:30

Plenary Lecture Session

S. Scheiner | EI7

13:30-14:15	**Plenary Lecture 2**

Plenary Lecture 2

PL2 | 13:30-14:15

Development of microstructural heterogeneities in cementitious slurries and mortars at rest and under flow: a hypothesis for pumping blockage and material defects

Agathe Robisson (TU Wien, Austria)

Educated as a materials scientist and an engineer in France, with an undergraduate degree from Institut National des Sciences Appliquées of Lyon and a doctorate from École des Mines of Paris, Agathe Robisson has spent 15 years as an industrial researcher at Schlumberger, first at the Schlumberger Riboud Product Center in France, Schlumberger's central engineering center in Europe, and then at Schlumberger Doll Research in the US (a world renowned research center in the oilfield instrumentation sector), before joining Technische Universität Wien as Professor of Civil and Environmental Engineering in 2018. Robisson is an internationally recognized expert in the behavior of complex fluids, suspensions, the mechanics of soft materials such as elastomers, and cement, having co-authored numerous scientific publications and 17 patents issued in the US and simultaneously in Brazil, Canada, China, Mexico, Saudi Arabia, and numerous European countries. Robisson's most notable achievements include leading teams that developed a 0.25 inch diameter, accurate sapphire pressure sensor to operate at 15,000 psi (equivalent to 1,000 atm or 100 MPa) and about 150 centigrades, as well as a game changing hydraulic isolation packer in the oilfield industry. The latter exhibits the unique property of gaining strength as the material swells to fit the contours of an irregular confining space. She is currently bringing a fresh, industry-enriched perspective into academia.

Abstract: Cement pastes are negatively buoyant suspensions of non-Brownian particles (µm-size range), with attractive interactions due to highly charged hydration products (nm-size range). In mortar and concrete, sand (mm-size range) and aggregates (cm-size range) are added. These particles, depending on their size and density, may sediment under gravity, or migrate under flow, leading to the creation of heterogeneities, with zones less rich in cement particles, or zones more rich in sand and aggregates.

In this talk, we discuss the physical processes that lead to these heterogeneities by studying both model systems (oil and beads) and real systems (slurries, i.e. only cement particles, and mortars, i.e., with sand). By studying these systems under shear using a rheometer, under flow using a pumping system, or at rest using optical tools, we highlight the formation of heterogeneities. Result analysis is enabled by extensive rheological characterization and previous works on Newtonian based suspensions (Acrivos et al., Nott & Brady, Guazzelli et al.). While shear-induced migration of aggregates is held responsible for concrete pipe blockage, sedimentation of cement particles at rest may explain defects after cement hardening.

14:15-14:30	**Transition to Parallel Sessions**

Time				
14:30-15:50	**MS04-1: Continuum models for material failure: nonlocal, gradient-enhanced, micromorphic, and phase-field approaches** M. Neuner EI5	**MS05-2: Bone mechanobiology: experimental and computational assessment across the scales** F. J. Martínez Reina, P. Pivonka EI8	**MS06-2: Structural vibration control** C. Adam, A. Pirrotta EI10	**MS16-2: Mechanics of wood, wood-based products, biocomposites, and timber structures** S. Pech, M. Lukacevic EI7
	MS04-1:1 | 14:30-14:50 **An elasto-plastic finite-deformation micropolar material point method for strain localisation problems** T. J. O'Hare, P. A. Gourgiotis, W. M. Coombs, C. E. Augarde	MS05-2:1 | 14:30-14:50 **Efficient algorithmic formulation of trabecular bone remodelling using a two-scale model of trabecular bone** A. Papastavrou, P. Pivonka, P. Steinmann	MS06-2:1 | 14:30-14:50 **Vertical vibration control of a cross-laminated timber plate through fluid inerter** M. Chillemi, T. Furtmüller, C. Adam, A. Pirrotta	MS16-2:1 | 14:30-14:50 **Experimental investigations on horizontally restrained CFRP reinforced glued laminated timber beams** L. Esser, A. Frangi
	MS04-1:2 | 14:50-15:10 **Strain localization analysis of an infinitesimal micropolar elastoplastic constitutive model rooted in critical state soil mechanics** P. Hofer, M. Neuner, P. Gamnitzer, G. Hofstetter	MS05-2:2 | 14:50-15:10 **In silico-aided design of functionally graded porous scaffolds for bone tissue engineering** P. Posabella, M. Heljak, M. Costantini, W. Święszkowski	MS06-2:2 | 14:50-15:10 **Stochastic parameter identification of a fluid inerter-based control device** B. Goller, M. Chillemi, T. Furtmüller, C. Adam	MS16-2:2 | 14:50-15:10 **Layerwise model for the failure analysis of Cross Laminated Timber** G. Blondet, J. Bleyer, A. Lebée
	MS04-1:3 | 15:10:15:30 **A return-free plastic integration for mixed control problems and its applications in elastoplasticity of materials** L.-W. Liu, P.-H. Chen	MS05-2:3 | 15:10:15:30 **Osteogenic control of bone mechanobiology through BMP loaded interlocked scaffolds** K. Katti, S. Jaswandkar, K. Kundu, D. Katti	MS06-2:3 | 15:10:15:30 **Water-tank metabarriers for seismic surface waves attenuation** G. Failla, A. F. Russillo	MS16-2:3 | 15:10:15:30 **Long-term behavior of novel solid wood-concrete-composite floors with combined shear connectors** A. Müllner, A. Fadai
	MS04-1:4 | 15:30:15:50 **Finite element analysis of shear failure in sand using micropolar hypoplasticity** K. V. Basche, M. Schreter-Fleischhacker, G. Medicus, M. Neuner, G. Hofstetter	MS05-2:4 | 15:30:15:50 **The efficient numerical tool to simulate the phenomenon of trabecular bone remodeling for multiple load cases** M. Nowak, J. Polak	MS06-2:4 | 15:30:15:50 **Thermoacoustic Fano-based bistable energy converters: a novel paradigm of thermodynamic cycles for waste-energy recovery** S. Buonocore, A. Hubarevich, F. De Angelis	MS16-2:4 | 15:30:15:50 **Multi-scale multi-physics modelling of timber-concrete hybrid structures** L. Wan-Wendner

15:50-16:20 Coffee Break & Poster Session

PS01: Poster Presentations

Catering Area

PS01 |
Integrated evaluation of blast loads on reinforced concrete structures: a strength and ductility approachess
Y. Kim, S. Kim, J. Shin

PS02 |
Machine-learning based optimum retrofit scheme for reinforced concrete frame structures: a case study on 1980s school buildings
S. Kim, Y. Kim, J. Shin

PS03 |
Neural network-driven representation and computational particle mechanics via signed distance fields
Z. Lai, L. Huang

MS17-1: Up-scaling challenges in the modeling of civil engineering materials L. Brochard — EI9	MS18-2: Computational methods for stochastic engineering mechanics I. P. Mitseas — EI2	MS19-1: Engineering mechanics in tunnelling W. Song, G. Meschke — EI3	14:30-15:50
MS17-1:1 | 14:30-14:50 **Homogenization of weakly nonlinear phenomena in electroactive fluid saturated porous media with multiple time scales** E. Rohan, V. Lukeš, F. Moravcová, R. Cimrman	MS18-2:1 | 14:30-14:50 **Structural reliability of complex nonlinear systems exposed to evolutionary stochastic excitation** I. P. Mitseas, M. Beer	MS19-1:1 | 14:30-14:50 **Stability of unlined circular tunnel in layered rock masses** S. Sahu, J. P. Sahoo, G. Tiwari	
MS17-1:2 | 14:50-15:10 **Impact of various uncertainties on the modeling of sorption-induced deformations** J. Leng, P. Dangla, M. Vandamme	MS18-2:2 | 14:50-15:10 **Probabilistic model selection of the Ground Motion Prediction Models for Northern South America** B. Salazar, A. Ortiz, J. Marulanda	MS19-1:2 | 14:50-15:10 **Multiphase modeling of ground freezing-shotcrete interaction in tunneling construction** R. J. Williams M., G. Meschke	
MS17-1:3 | 15:10:15:30 **Study of crystallization pressure by molecular simulation** B. Mahmoud Hawchar, T. Honorio, M. Vandamme, F. Osselin, J.-M. Pereira, L. Brochard		MS19-1:3 | 15:10:15:30 **A deep learning-based method for detecting joints and evaluating segment deformation in shield tunnels** B. Zhang, W. Song, X. Liu	
MS17-1:4 | 15:30:15:50 **Towards a DFT approach to the mechanical properties of solids** A. Kahlal, V. Sermoud, G. Pijaudier-Cabot, D. Grégoire, C. Miqueu		MS19-1:4 | 15:30:15:50 **Will a concept of pre-structure be applicable to tunnels in squeezing ground?** Y. Yuan, B. Shi, Y. He, J.-L. Zhang	

Coffee Break & Poster Session

15:50-16:20

PS01: Poster Presentations

Catering Area

PS04 |
Shape-based vision system optimized for seismic damage detections of nonstructural components in buildings
I. Choi, B. K. Oh, H. W. Oh

PS05 |
Theoretical study on soil deformation induced by shield tunneling through soil-rock composite strata
Y. Qi, Z. Mu, J. Zhou, G. Wei

16:20-18:00	MS02: Structural dynamics and control for offshore wind turbines, including floating systems B. Fitzgerald EI2	MS04-2: Continuum models for material failure: nonlocal, gradient-enhanced, micromorphic, and phase-field approaches P. Gamnitzer EI5	MS06-3: Structural vibration control C. Adam, A. Pirrotta EI10	MS08-1: Instabilities at various scales: modelling, analysis and design N. Challamel, A. Wadee EI3
	MS02:1 | 16:20-16:40 **A machine learning approach for offshore wind turbine tower fatigue and fragility analysis** J. McAuliffe, S. Baisthakur, B. Fitzgerald	MS04-2:1 | 16:20-16:40 **Phase field simulation of hydrogen-assisted fatigue** C. Cui, E. Martínez-Pañeda	MS06-3:1 | 16:20-16:40 **Multifidelity reliability and sensitivity analysis** C. Proppe	MS08-1:1 | 16:20-16:50 (Keynote Lecture) **On the effects of the precritical nonlinearities on buckling of flexible systems** A. Luongo, M. Ferretti
	MS02:2 | 16:40-17:00 **A study on optimal sensor placement of multi-linked floating offshore structure for prediction accuracy improvement of structural response using distortion base mode method** K. Sim, K. Lee, M. Ki	MS04-2:2 | 16:40-17:00 **Robust and efficient implementation of generalized continuum models based on automatic differentiation with hyper-dual numbers** A. Dummer, M. Neuner, P. Gamnitzer, G. Hofstetter	MS06-3:2 | 16:40-17:00 **Active mass dampers for cross laminated timber floors - comparison between experimental and numerical investigations** T. Hillberger, T. Furtmüller, R. Maderebner	MS08-1:2 | 16:50-17:20 (Keynote Lecture) **Variational criteria for extreme values of the stiffness of proportionally loaded structures as solutions of an inverse problem** H. A. Mang
	MS02:3 | 17:00-17:20 **Advancing wind farm fatigue analysis: insights from high-fidelity modelling and machine learning** A. Alazhare, B. Fitzgerald	MS04-2:3 | 17:00-17:20 **Homogenized post-peak response of composites from phase-field fracture simulation at microscale** S. Sagar, S. R. Chowdhury	MS06-3:3 | 17:00-17:20 **Experimental investigation of track nonlinear energy sink with rotational mass using real-time hybrid simulation** C.-M. Chang, T.-L. Kao	
	MS02:4 | 17:20-17:40 **Blade pitch control of floating offshore wind turbines for mitigating corrosion fatigue deterioration and enhancing structural reliability** Y. Pu, J. Zhang, Y. Dong, B. Fitzgerald	MS04-2:4 | 17:20-17:40 **Comparison between block preconditioner and monolithic preconditioner for iterative solution of coupled multi-field problems from generalized continuum models** N. Alkmim, P. Gamnitzer, G. Hofstetter	MS06-3:4 | 17:20-17:40 **An investigation of the behavior of reinforced concrete coupling beams** D. Bhunia, R. P. West, J. K. Bhaskar	MS08-1:3 | 17:20-17:40 **The behaviour of thin composite plates with extension-bending coupling under harmonic compressive load** T. Kubiak, M. Bohlooly Fotovat
		MS04-2:5 | 17:40-18:00 **Microstructural characterization of fiber-reinforced cementitious composites using micro-CT measurements and evaluation of their mechanical behavior using simulations** J. Suh, T.-S. Han		MS08-1:4 | 17:40-18:00 **Large displacement analysis of angle-ply beam-type structures considering shear deformation effects** D. Banić, G. Turkalj, D. Lanc
18:30-21:00	**Welcome Cocktail** The Welcome Cocktail takes place at Cupola Hall in the Main Building of TU Wien - see area map at page 97. Music played by members of TUO, the orchestra of TU Wien.			

MS10: Advanced computational analyses for geotechnical and underground engineering B. Zhang, H. Wang — EI8	MS13-2: Computational geomechanics S. J. Semnani, Q. Zhang — EI9	MS16-3: Mechanics of wood, wood-based products, biocomposites, and timber structures S. Pech, E. Landis — EI7	16:20-18:00
MS10:1 | 16:20-16:40 **Multi-scale analyses on interfacial behavior between normal concrete (NC) and ultra-high performance concrete (UHPC)** B. Zhang, J. Yu, W. Chen, H. Liu	MS13-2:1 | 16:20-16:40 **Hybrid FEM and Peridynamic simulation of forerunning fracture in porous media** T. Ni, B. Schrefler	MS16-3:1 | 16:20-16:40 **Predicting the performance of glued-in rod joints** S. K. Alavi, H. R. Valipour, M. A. Bradford	
MS10:2 | 16:40-17:00 **A super-ellipsoid convex model based reliability analysis of rock tunnel with rock properties modelled via mixed uncertainty models based on available data** S. Maurya, G. Tiwari	MS13-2:2 | 16:40-17:00 **Numerical and analytical analysis of fracture closure modes and their importance in data interpretations** A. Dahi Taleghani, R. Wang	MS16-3:2 | 16:40-17:00 **Numerical assessment of brittle failures in dowel-type timber connections loaded parallel to the grain** C. Dapieve Aquino, M. Schweigler, L. Rodrigues, J. M. Branco, T. K. Bader	
MS10:3 | 17:00-17:20 **Thermal stresses in concrete beams as a result of multiscale constraints** H. Wang, Y. Yuan, H. Mang, Q. Ai, X. Huang, B. Pichler	MS13-2:3 | 17:00-17:20 **A pioneering framework for accurate reconstruction of arbitrary granular materials** R. Li, Z. Yin	MS16-3:3 | 17:00-17:20 **The effective timber thickness for brittle failure assessment of dowel-type connections** C. Dapieve Aquino, M. Schweigler, L. Rodrigues, J. M. Branco, T. K. Bader	
MS10:4 | 17:20-17:40 **3D numerical modelling of inter-seasonal heat harvesting of a geothermal road in the UK** J. Lyu, N. Makasis, L. Cui, B. Cao	MS13-2:4 | 17:20-17:40 **A novel clump-based breakage model in discrete element method for simulating crushable aggregates** C. Xu, Z.-Y. Yin, P. Wang	MS16-3:4 | 17:20-17:40 **Single-dowel steel-to-timber connections under cyclic and high strain rate loading** K. Sroka, A. S. Cao, P. Palma	
MS10:5 | 17:40-18:00 **Utilization of phase change materials in the support structure of geothermal tunnel: efficacy in geothermal hazard mitigating and heat energy storage** Q. Wang, H. Wang, J.-L. Zhang, E. Koenders, Y. Yuan		MS16-3:5 | 17:40-18:00 **Beam-on-foundation modelling of dowel-type timber connections under cyclic loading** A. Weese, M. Schweigler, C. Sandhaas, T. K. Bader	

Welcome Cocktail

18:30-21:00

The Welcome Cocktail takes place at Cupola Hall in the Main Building of TU Wien - see area map at page 97.
Music played by members of TUO, the orchestra of TU Wien.

Thursday, September 12, 2024

Plenary Lecture Session	
B. Pichler	EI7

09:00-09:45	**Plenary Lecture 3**

PL3 | 09:00-09:45

Linearization approaches for stochastic dynamic analysis of systems endowed with non-integer order differential elements

Pol Spanos (Rice University, USA)

Educated as mechanical and civil engineer in Greece and the US, with graduations at the National Technical University of Athens and at CalTech, and a doctorate from the latter institution, Pol Spanos joined first the University of Texas at Austin, and finally Rice University in Houston, where he has been active as a professor ever since.
He has been a pioneer in stochastic mechanics, with a very broad spectrum of applications, ranging all the way from structural engineering to biomedicine.
His achievements have been prestigiously awarded in the academic realm, including memberships with the National Academy of Engineering of the United States of America, of Russia, of India, with the American Academy of Arts and Sciences, and with the Chinese Academy of Sciences.

Abstract: Nonlinearity is ubiquitous. Further, nonlinear systems comprising elements with fractional order differentiation operators have received increasing attention in recent decades. Furthermore, systems exposed to stochastic excitations are quite common in engineering practice. The lecture will address issues relating to the determination of the response of stochastically excited nonlinear systems involving fractional order differentiation. In this regard, the technique of statistical linearization in various formats and versions will be discussed. This will be done in conjunction with an examination of the applicability of the related concepts of stochastic averaging, and harmonic balance In the process, the computational complexity and tediousness of determining the exact non-stationary stochastic response even of linear systems will be pointed out. Comments regarding cases involving combinations of stochastic and periodic excitations will be made. The analytical/semi-analytical results will be juxtaposed with data from pertinent Monte Carlo simulations. Some possible extensions or variations of the discussed approaches will also be outlined.

09:45-10:15	**Coffee Break**

10:15-12:15	**MS03-1: Coupled chemical, physical and mechanical processes in cementitious materials relevant to the short- and long-term behavior of R.C. and P.C. structures** R. Wan-Wendner EI10	**MS08-2: Instabilities at various scales: modelling, analysis and design** S. Yiatros, S. Karamanos EI3	**MS13-3: Computational geomechanics** Q. Zhang, C. Zhu EI9	**MS14-1: Vibration-based monitoring of structural systems** C. Stoura, S. Pakzad EI2
	MS03-1:1 | 10:15-10:35 **Application of DIC method to identify the relationship between crack width and deflection in reinforced concrete beams** D. Meiramov, Y. Seo, H. Ju	MS08-2:1 | 10:15-10:35 **Reversible energy absorption: harnessing sequential buckling in mechanical metamaterials** A. Wadee, A. Bekele, A. Phillips, A. Koellner	MS13-3:1 | 10:15-10:35 **Machine learning enabled landslide hazard assessment** S. J. Semnani	MS14-1:1 | 10:15-10:35 **Dynamic soil-structure interaction of railway bridges: simple lumped parameter models vs. detailed coupled Finite Element – Boundary Element approaches** P. König, C. Adam
	MS03-1:2 | 10:35-10:55 **Crack healing under sustained load in concrete: an experimental/numerical study** G. Di Luzio, L. Ferrara, A. Cibelli, R. Wan-Wendner	MS08-2:2 | 10:35-10:55 **On the capability of gradient elasticity models to predict instabilities in Fermi-Pasta-Ulam softening chains with short and long-range interactions** N. Challamel, C. Combescure, V. Picandet, M. Ferretti, A. Luongo	MS13-3:2 | 10:35-10:55 **Slide, hold, learn: dynamic friction meets neural networks** J. Garcia-Suarez	MS14-1:2 | 10:35-10:55 **Frequency-domain fatigue life evaluation of a steel bridge considering vibrational characteristics of traffic loads** M. Ishihara, Y. Yaohua, D. Su, M. Kitahara, T. Nagayama
	MS03-1:3 | 10:55-11:15 **Enhancing computational efficiency in lattice discrete particle modeling for analyzing concrete failure behavior** J. Wang, J. Vorel, W. Botte, R. Wan-Wendner	MS08-2:3 | 10:55-11:15 **Interfacial phenomena in the lateral-torsional instability of sandwich beams** A. Wurf, Y. Frostig, O. Rabinovitch	MS13-3:3 | 10:55-11:15 **Thermal creep of clayey soils: experiments and modelling** Z.-J. Chen, W.-Q. Feng, J.-H. Yin	MS14-1:3 | 10:55-11:15 **Impact of the modeling strategy on the dynamic response prediction of weakly coupled multi-span bridges subjected to high-speed trains** M. Mack, B. Goller, P. König, C. Adam
	MS03-1:4 | 11:15-11:35 **Evaporation in concrete early-age maturation: multiphasic model** S. Prskalo, M. H. Gfrerer, M. Schanz	MS08-2:4 | 11:15-11:35 **A multi-layered structural approach to stability of orthodontic brackets** B. Azarov, O. Rabinovitch	MS13-3:4 | 11:15-11:35 **Numerical analysis on negative skin friction considering creep under embankment loading** R. Liang, Z.-Y. Yin, J.-H. Yin	MS14-1:4 | 11:15-11:35 **Residual performance estimation of a seismic-isolated bridge based on ABC model updating using seismic response data** T. Kitahara, M. Kitahara, Y. Kajita
	MS03-1:5 | 11:35-11:55 **Mesoscopic simulation of corrosion-induced cracking of reinforced concrete** Y. Li, X. Ruan, H. A. Mang, B. Pichler	MS08-2:5 | 11:35-11:55 **Buckling load of an asymmetrically supported 3D column** P. Kočman, S. Schnabl	MS13-3:5 | 11:35-11:55 **Nonlinear ground response analysis of liquefiable fines-dominated deposits** D. Mistry, S. Mandal, G. R. Dodagoudar	MS14-1:5 | 11:35-11:55 **Modal identification of a railway bridge via drive-by acceleration data from a diagnostic vehicle** C. Stoura, V. Dertimanis, C. Kossmann, E. Chatzi
	MS03-1:6 | 11:55-12:15 **Novel meso-scale reactive-transport model for carbonation of OPC** M. Tang, Q. Phung, S. Seetharam, E. Coppens, J. Shao, R. Wan-Wendner	MS08-2:6| 11:55-12:15 **Test and design of fabricated steel I-profiles under compression** G. Langone, U. Ali, M. Shamlooei, X. Ruan, B. Rossi		MS14-1:6 | 11:55-12:15 **New methods for data-based determination of damping factors with application on railway bridges** A. Stollwitzer, L. Bettinelli, S. Loidl, J. Fink
12:15-13:30	**Lunch Break**			

MS16-4: Mechanics of wood, wood-based products, biocomposites, and timber structures M. Schweigler, M. Lukacevic — EI7	MS27: Mechanical performance and durability of novel concretes and sustainable alternatives M. Hubler — EI8	MS29: Machine learning and artificial intelligence for constrained systems R. Ghanem — EI5	10:15-12:15
MS16-4:1 | 10:15-10:35 **Advanced structural modeling of cross-laminated timber buildings: from elemental analysis to comprehensive structural assessment** <u>M. Wallner-Novak</u>, A. Fadai	MS27:1 | 10:15-10:35 **Characterization of functionalized binder systems by means of dynamic-mechanical analysis** <u>L. Göbel</u>, T. Schulz, M. Ganß	MS29:1 | 10:15-10:35 **Automatic differentiation and neural networks for parameter identification of hysteresis models** <u>M. Kaltenbacher</u>, E. Eniz Museljic, K. Roppert	
MS16-4:2 | 10:35-10:55 **A parametric framework to assess the limit states of tall timber buildings - preliminary results** <u>A. Clerc</u>, A. Frangi	MS27:2 | 10:35-10:55 **Novel design of cementitious composites with the use of limestone quarry waste and silica fume** <u>A. Kyriakidis</u>, H. Jaber, A. Georgiou, R. Panagiotou, I. Ioannou, A. Michopoulos	MS29:2 | 10:35-10:55 **Data-driven variational method for discrepancy modeling: application to nonlinear elasticity and viscoelasticity** <u>A. Masud</u>, S. Goraya	
MS16-4:3 | 10:55-11:15 **Learnings from monitoring of realized and under-construction timber buildings** <u>M. Dorn</u>, C. Larsson, C. Amaddeo, O. Abdeljaber	MS27:3 | 10:55-11:15 **Recyclable bio-synthesis hydrogel-based xoncrete (Bio-HBC): investigation of strength in successive material generations** <u>S. C. Lam</u>, N. Liu, W. Huang, Q. Yi, J. Qiu, F. Sun	MS29:3 | 10:55-11:15 **Influence of hemodynamics and temporal change in intracranial aneurysm shape on machine learning-based rupture prediction** <u>Y. Watase</u>, S. Fujimura, G. Kudo, H. Kanebayashi, T. Ishibasi, H. Ohwada, M. Yamamoto, Y. Murayama	
MS16-4:4 | 11:15-11:35 **Mechanical behaviour of timber chock structures for underground mine support** <u>M. Dehghanipoodeh</u>, J. Hashemi, H. Valipour, H. Masoumi	MS27:4 | 11:15-11:35 **Structural response of eco-UHPC with recycled steel fibers** <u>M. A. Moustafa</u>, A. Romero	MS29:4 | 11:15-11:35 **Learning mass-spring-damper dynamics via an incomplete equation of motion, Koopman operator and topology** <u>Z. Chen</u>, H. Sun, W. Xiong, N. Wang	
MS16-4:5 | 11:35-11:55 **Influence of drying shrinkage on dynamic properties of cross-laminated timber** <u>T. Furtmüller</u>, M. Kendlbacher	MS27:5 | 11:35-11:55 **Rehabilitation of deteriorated RC beams by applying external post-tension stresses: developing machine learning prediction models of ultimate limit state** <u>A. Badnjki</u>, T. Öztürk	MS29:5 | 11:35-11:55 **Physics Extraction Pods (PEP) find statistical closure** <u>R. Ghanem</u>	
		MS29:6 | 11:55-12:15 **Statistical surrogate models on small datasets for aeroacoustic computational modeling in liners of turbofan engines** A. Sinha, <u>C. Desceliers</u>, C. Soize, G. Cunha	
Lunch Break			12:15-13:30

Plenary Lecture Session

S. Scheiner EI7

13:30-14:15	**Plenary Lecture 4**

Plenary Lecture 4

PL4 | 13:30-14:15

Memory of flow and residual stresses: from jammed soft solids to cement pastes

Emanuela Del Gado (Georgetown University, USA)

Emanuela Del Gado is a physics Professor and the Director of the Institute for Soft Matter Synthesis and Metrology at Georgetown University. She was a Marie Curie Fellow and the Swiss National Science Foundation Assistant Professor at ETH Zurich, and has held visiting positions at M.I.T., ESPCI Paris, ENS Lyon, and University Paris-Saclay. She was elected Fellow of the Royal Society of Chemistry in 2018, she is a Fellow of the American Physical Society (2020) and a Fellow of the Society of Rheology (2023). Her research is aimed at the spatiotemporal characterization of microscopic dynamical processes and the unraveling of microstructural underpinnings in the rheology of soft materials, with a focus on colloidal gels, cement and clay gels, and other soft solids.

Abstract: Soft jammed materials can resist deformation or accommodate steady flow depending on imposed stresses and deformation rates. Designing these properties is central to a range of construction technologies and materials such as cement paste. Cessation of flow generally results in a complex stress relaxation process and finite residual stresses, and controlling these effects is especially important in additive manufacturing. In particular, even in relatively simple pastes and jammed particle suspensions, the rate of stress relaxation, as well as the magnitude of the residual stress have been shown to systematically depend on the preceding flow conditions. New insight into the mechanisms for stress relaxation, gained via microscopic simulations, highlights that flow in a broad range of yield stress fluids can be seen as a training process during which the material stores information of the flowing state through the development of domains of correlated particle displacements and the reorganization of particle packings optimized to sustain the flow. Flow cessation becomes then a way to retrieve this encoded memory. Combining simulations and experiments allows us to disentangle the role of elasticity and plasticity not only in steady flow, but also in the pre-yielding regime leading to ductile or brittle yielding and in the recovering of rigidity and mechanical stability after flow cessation.

14:15-14:30 **Transition to Parallel Sessions**

14:30-15:50	**MS03-2: Coupled chemical, physical and mechanical processes in cementitious materials relevant to the short- and long-term behavior of R.C. and P.C. structures** G. Di Luzio EI10	**MS08-3: Instabilities at various scales: modelling, analysis and design** S. Karamanos, S. Yiatros EI3	**MS14-2: Vibration-based monitoring of structural systems** C. Stoura, S. Pakzad EI2	**MS16-5: Mechanics of wood, wood-based products, biocomposites, and timber structures** E. Landis, M. Schweigler EI7
	MS03-2:1 | 14:30-14:50 **Phase-field-based chemo-mechanical modelling of corrosion-induced cracking in reinforced concrete** E. Korec, M. Jirasek, H. S. Wong, E. Martinez-Paneda	MS08-3:1 | 14:30-14:50 **Stability and bifurcation in nonlinear mechanics** C. Stolz	MS14-2:1 | 14:30-14:50 **Exploring graph neural networks for bridges SHM** G. Marasco, S. Pakzad	MS16-5:1 | 14:30-14:50 **Finite-element-based prediciton of moisture uptake and dry-out in CLT caused by water infiltration through end-grain surfaces** F. Brandstätter, M. Autengruber, M. Lukacevic, J. Füssl
	MS03-2:2 | 14:50-15:10 **Modeling two-phase mechanical behavior in lattice discrete particle models** J. Wang, J. Vorel, W. Botte, R. Wan-Wendner	MS08-3:2 | 14:50-15:10 **Closed-form solutions for the elastic-plastic buckling design of external pressure vessels** V. D. Do, P. Le Grognec, P. Rohart	MS14-2:2 | 14:50-15:10 **A perturbation technique for natural frequency analysis of structures with cracks or other sources of additional compliance** Y. Vetyukov, R. Buchta	MS16-5:2 | 14:50-15:10 **Stress development during and after kiln-drying of self-shaped Norway spruce bilayer plates** M. Naghdinasab, G. Dill-Langer, P. Grönquist
	MS03-2:3 | 15:10:15:30 **Multiscale modeling of concrete under mechanical and environmental impacts for ultrasonic based early damage identification** G. Vu, J. Timothy, G. Meschke	MS08-3:3 | 15:10:15:30 **Propagating instabilities in collapsible tubes of nonlinear elastic materials** I. Karetsa, A. G. Stamou, I. Gavriilidis, S. A. Karamanos	MS14-2:3 | 15:10:15:30 **The challenges of surrogate modelling of modal properties** B. Kurent, N. Friedman, S. Vallely, B. Popovics, S. Schoenwald, B. Brank	MS16-5:3 | 15:10:15:30 **Towards a consistent description of creep in spruce** F. K. Wittel, A. Ferrara, J. M. Maas, J. Amando de Barros
	MS03-2:4 | 15:30:15:50 **Time dependent deformations in concrete: a multi-physics multiscale model and its validation with Test Results** B. Pal, A. Ramaswamy	MS08-3:4 | 15:30:15:50 **Shape grammar for optimisation of perforated plates subject to buckling** E. I. Naraidoo, B. Rossi, Z. You	MS14-2:4 | 15:30:15:50 **Wavelet analysis and information theory for enhanced structural health monitoring: insights and strategies for anomaly detection in civil structures** A. Silik, M. Noori, W. Altabey, N. Farhan	MS16-5:4 | 15:30:15:50 **Asymmetric cortex structures in recent and fossil plants: an inspiration for 3D reticulated actuators** T. Masselter, T. Speck
15:50-16:20	**Coffee Break**			

MS17-2: Up-scaling challenges in the modeling of civil engineering materials L. Brochard — EI8	MS21-1: Computational methods for granular media P. Zhang, N. Guo — EI5	MS31-1: Collagen structure and mechanics P. J. Thurner, P. Mesquida — EI9	14:30-15:50
MS17-2:1 | 14:30-14:50 **Multiscale analysis of PVC geomembrane mechanical response through DEM simulations** N. Akel, A. Wautier, G. Stoltz, N. Touze, F. Nicot	MS21-1:1 | 14:30-14:50 **A framework for data-driven multiscale modeling of thermomechanical behavior of dense granular materials** R. L. Rangel, J. M. Gimenez, A. Franci	MS31-1:1 | 14:30-14:50 **A visco-hypoelastic model to describe the rate-dependent tensile responses of individual collagen fibrils** Y.-R. Chiang, O. G. Andriotis, C. Hellmich, P. J. Thurner	
MS17-2:2 | 14:50-15:10 **Role of the mesoscale in the mechanics of clays** L. Brochard	MS21-1:2 | 14:50-15:10 **Constitutive modeling of granular soils based on the shear-transformation-zone theory** N. Guo, W. Li, Z. Yang	MS31-1:2 | 14:50-15:10 **Collagen fibrillar pre-strain, ordering and internal stress gradients modulating small-scale biomechanics of cartilage and skin** H. S. Gupta	
MS17-2:3 | 15:10:15:30 **Linear elasticity of transversely isotropic paper sheets: comprehensive validation of a multiscale continuum micromechanics model** P. M. Godinho, C. Hellmich	MS21-1:3 | 15:10:15:30 **A temporal graph neural network-based simulator for granular materials** S. Zhao, H. Chen, J. Zhao	MS31-1:3 | 15:10:15:30 **Heterogeneous structure and dynamics of water in a hydrated collagen microfibril** M. Vassaux	
	MS21-1:4 | 15:30:15:50 **Elastoplastic constitutive modeling of granular materials via thermodynamics-informed neural networks** M. Su, N. Guo	MS31-1:4 | 15:30:15:50 **Identification and characterization of the MHC immunoglobulin receptor binding site in fibrillar type I collagen** J. Orgel, R. S. Madhurapantula, O. Antipova	
Coffee Break			15:50-16:20

16:20-18:00	MS03-3: Coupled chemical, physical and mechanical processes in cementitious materials relevant to the short- and long-term behavior of R.C. and P.C. structures R. Wan-Wendner EI10	MS08-4: Instabilities at various scales: modelling, analysis and design A. Wadee, N. Challamel EI3	MS09-1: Hybrid and sub-structuring analyses, experimental tests and numerical modeling in civil engineering F. Gatuingt, S. Grange EI2	MS13-4: Computational geomechanics C. Zhu, S. J. Semnani EI8
	MS03-3:1 | 16:20-16:40 **Study on the change of structural performance of RC structures building subjected to drying** R. Kurihara, N. Chijiwa	MS08-4:1 | 16:20-16:40 **Path-following for structures undergoing buckling instabilities and material damage** A. Köllner	MS09-1:1 | 16:20-16:40 **Hybrid simulation to investigate inelastic higher-mode effects in RC structural walls** P. Paultre, M. Aftabiazar	MS13-4:1 | 16:20-16:40 **Kinematics of hydraulic plucking in fractured rock** M. H. Gardner
	MS03-3:2 | 16:40-17:00 **Temperature impact on the mechanical and physical properties of lining concrete in nuclear waste disposal** S. Abdo, T. Phung Quoc, R. Caspeele, S. Seetharam, R. Wan-Wendner	MS08-4:2 | 16:40-17:00 **Buckling-driven design of material extrusion manufactured stayed polymer lattices** Y. Ou, C. Völlmecke	MS09-1:2 | 16:40-17:00 **Numerical modeling and experimental validation of novel, bioinspired seismic isolators** F. Fraternali, V. Adinolfi, G. Germano, J. de Castro Motta, G. Benzoni, A. Amendola	MS13-4:2 | 16:40-17:00 **Numerical modeling of the oscillation roller-subsoil interaction system** I. Paulmichl, R. Bergman
	MS03-3:3 | 17:00-17:20 **The influence of weather patterns and global warming on chloride ingress in concrete structures** H. Hamidane, O. Dehwah, Y. Xi, A. Messabhia, A. Ababneh	MS08-4:3 | 17:00-17:20 **Instability in crack propagation of layered materials using the phase field approach** S. Mrunmayee Uday, A. Rajagopal	MS09-1:3 | 17:00-17:20 **Pseudo-dynamic testing with sub-structuring applied to progressive collapse** J. B. Charrié, D. Bertrand, C. Desprez, S. Grange	MS13-4:3 | 17:00-17:20 **Solving inverse problems in granular mechanics with differentiable simulators** K. Kumar, Y. Choi
	MS03-3:4 | 17:20-17:40 **Temperature profiles of concrete members placed in different geographical regions: a guideline for installation and design of bonded anchors** I. Boumakis, T. Pregartner	MS08-4:4 | 17:20-17:40 **Computational modelling of cold-formed steel beam for improved seismic performance using optimization** B. Kumar, A. N. R. Chowdhury, C. Kolay	MS09-1:4 | 17:20-17:40 **Next generation friction damper** M. Titirla	MS13-4:4 | 17:20-17:40 **Molecular interactions regulate engineering properties of swelling clays** D. R. Katti, K. S. Katti
	MS03-3:5 | 17:40-18:00 **Chemo-thermo-hygro-mechanical modelling of blended concretes at elevated temperatures** S. Peters, G. Meschke	MS08-4:5 | 17:40-18:00 **Local buckling of compressed outstand plates: an analytical approach** J. Becque		MS13-4:5 | 17:40-18:00 **A phase field model for frictional fracture phenomena in rock masses** S. Liu, Y. Wang

18:20-22:30

Conference Banquet

The conference banquet on invitation by the Mayor of the City of Vienna will take place at Heurigen-Restaurant Fuhrgassl-Huber. The banquet will start at 19:30. Participants registered for the banquet are requested to have their banquet voucher with them.

Bus transfer: Busses to the conference banquet will start leaving at 18:20 in front of the conference venue. Return busses will start at 22:00. The last bus will leave at 22:30.

MS19-2: Engineering mechanics in tunnelling G. Meschke, J.-L. Zhang — EI7	MS21-2: Computational methods for granular media R. Rangel, S Zhao — EI5	MS31-2: Collagen structure and mechanics P. Mesquida, P. J. Thurner — EI9	16:20-18:00
MS19-2:1 | 16:20-16:40 **Numerical modelling of steel fiber reinforced concrete tunnel lining segment subjected to flexure** <u>M. Bhadury</u>, K. Kirupakaran, R. Gettu	MS21-2:1 | 16:20-16:40 **Metaball discrete element lattice boltzmann method for fluid-particle interactions with non-convex shapes** <u>P. Zhang</u>, S. Galindo-Torres	MS31-2:1 | 16:20-16:40 **Investigating stretched collagen fibrils using polarization-resolved second harmonic generation microscopy** <u>M. Harvey</u>, R. Cisek, D. Tokarz, L. Kreplak	
MS19-2:2 | 16:40-17:00 **Research on seismic response of prefabricated open caisson constructed by VSM method** <u>Z. Tang</u>, X. Liu	MS21-2:2 | 16:40-17:00 **Comparison of three different multiphase LBM strategies for numerically obtaining the soil water retention curve of granular materials** <u>C. M. Toffoli</u>, R. Hosseini, J. Grabe	MS31-2:2 | 16:40-17:00 **Mechanical behavior of individual collagen fibrils in force-controlled mechanical tests** M. Nalbach, M. Fuchs, N. Motoi, M. Rufin, O. Andriotis, G. Schitter, <u>P. J. Thurner</u>	
MS19-2:3 | 17:00-17:20 **Hereditary mechanics-based stress prognosis in segmented tunnel linings** <u>A. Razgordanisharahi</u>, M. Sorgner, T. Pilgerstorfer, B. Moritz, C. Hellmich, B. Pichler	MS21-2:3 | 17:00-17:20 **Resolved CFD-DEM modeling of debris flows, avalanches, and floods with arbitrary-shaped boulders and driftwood impacting structures and forests** <u>Y. Kong</u>, Z. Lai, J. Yin, J. Zhao	MS31-2:3 | 17:00-17:20 **Towards a real-time imaging of the assembly and disassembly of collagen nanofibers** <u>C. Garcia-Sacristan</u>, V. G. Gisbert, K. Klein, A. Šarić, R. Garcia	
MS19-2:4 | 17:20-17:40 **Research on evolution law of mechanical behavior of non-circular shield tunnel linings with cross-section geometry transformation** X. Liu, <u>Z. Liu</u>, Y. Ye, B. T. Cao, G. Meschke	MS21-2:4 | 17:20-17:40 **Multiscale insights into the behaviour of laterally loaded pile** <u>A. Zhang</u>, C. Couture, F. Collin	MS31-2:4 | 17:20-17:40 **Linking the electrostatic and mechanical properties of collagen** <u>P. Mesquida</u>, I. Sikka, R. Dupont, E. Gachon, Z. Bai	
	MS21-2:5 | 17:40-18:00 **Modeling and application of hydraulic fracturing based on adaptive finite volume-phase field method** <u>X. Yang</u>, N. Guo		

Conference Banquet

18:20-22:30

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Friday, September 13, 2024

09:00-11:00	MS01-1: Discrete models for the simulation of infrastructure materials	MS07: Stochastic mechanical behaviors of quasi-brittle materials	MS11-1: Mechanics of multiphase-multiscale granular and particulate systems	MS16-6: Mechanics of wood, wood-based products, biocomposites, and timber structures
	J. Elias, G. Pijaudier-Cabot EI2	M.-Z. Lyu EI10	M. Hattab EI9	M. Dorn, J. Füssl EI7
	MS01-1:1 | 09:00-09:20 **Constructing an isotropic damage model from coarse graining of lattice modelling results for quasi-brittle materials** J. Khoury, G. Pijaudier-Cabot	MS07:1 | 09:00-09:20 **Bayesian inference of constitutive law parameters for crack localization using full-field displacement measurements** A. Jafari, K. Vlachas, E. Chatzi, J. F. Unger	MS11-1:1 | 09:00-09:20 **A granular view of modelling a pandemic using the Discrete Element Method** M. Miot, N. Deng, A. Wautier, F. Nicot, R. Wan	MS16-6:1 | 09:00-09:20 **Novel olive stone biochar particle network for piezoresistive strain sensing in natural fiber-reinforced composites** S. Schulte, F. Lübkemann-Warwas, S. Kroll, A. Siebert-Raths
	MS01-1:2 | 09:20-09:40 **A novel DEM-based coupled 3D thermo-hydro-mechanical mesoscopic model for very-low porosity materials** M. Krzaczek, J. Tejchman	MS07:2 | 09:20-09:40 **FE-analysis of long-term performance of an epoxy bonded anchor based on nanoindentation and CT-scan** F. Zhu, K. Bergmeister	MS11-1:2 | 09:20-09:40 **Density relaxation in tapped granular systems: recurrent neural network model** A. D. Rosato, V. Ratnaswamy, Y. Chung, D. J. Horntrop	MS16-6:2 | 09:20-09:40 **A nanoindentation study on diverse technical lignins for bio-composite applications** L. Zelaya-Lainez, M. Schwaighofer, M. Königsberger, M. Lukacevic, S. Serna-Loaiza, F. Zikeli, M. Harasek, A. Friedl, J. Füssl
	MS01-1:3 | 09:40-10:00 **Static/dynamic response of partially saturated concrete using an improved fully coupled DEM/CFD approach** M. Krzaczek, J. Tejchman	MS07:3 | 09:40-10:00 **IInvestigation of installation effects on the fracture behavior of adhesively bonded joints** S. TerMaath, K. Bezem, A. Handy, C. Crusenberry	MS11-1:3 | 09:40-10:00 **Simulations of poro-elastic sand structures subjected to air and water flows** J. Bomberault, Q. Rousseau, N. S. Nguyen, G. Sciarra	MS16-6:3 | 09:40-10:00 **A sustainable approach to lignin as a wood binder** J. Schindler, G. Unsinn, L. Scolari, L. Zelaya-Lainez, S. Serna-Loaiza, F. Zikeli, M. Harasek, A. Friedl, J. Füssl, M. Lukacevic
	MS01-1:4 | 10:00-10:20 **Simulation on creep and stress relaxation of calcium silicate hydrate in microscale by discrete element method** Z. Zhang, G. Geng	MS07:4 | 10:00-10:20 **Scaling the unscalable: bridging stochastic discrete mesoscale simulations with analytical modeling for the statistical strength of concrete** M. Vořechovský, V. Sadílek, M. Kučera	MS11-1:4 | 10:00-10:20 **Effect of the grains shape on the mechanical behavior of granular material** R. D. Ferraz Burgos, H. Souli, K. Bicalho, S. R. De Melo Ferreira, F. Salvatore, J. Rech	MS16-6:4 | 10:00-10:20 **The livMatS fiber pavillon in the Botanic Garden Freiburg: cactus wood as inspiration – flax fibers as building material** T. Speck
	MS01-1:5 | 10:20-10:40 **Comparison of Lattice Discrete Particle Modeling (LDPM) implementations: lessons learned and future work** G. Cusatis, E. Lale, K. Yu, M. Troemner, M. Pathirage, Y. Lyu, I. Koutromanos, J. Elias, M. Stredulova, T. Xue, M. Alnaggar	MS07:5 | 10:20-10:40 **Simulation of multivariate Gaussian random fields considering nonlinear probabilistic dependencies and multi-spatial variabilities** M.-Z. Lyu, Y.-Y. Liu, J.-B. Chen	MS11-1:5 | 10:20-10:40 **Hydromechanical modeling of internal erosion in granular soils** P.-Y. Hicher	MS16-6:5 | 10:20-10:40 **Characterizing viscoelasticity of plant fiber-reinforced biocomposites through micromechanics modeling** M. Königsberger, S. Scheiner, J. Füssl
			MS11-1:6 | 10:40-11:00 **Shear banding in granular assemblies as an optimal dissipative structure** F. Nicot, X. Wang, A. Wautier, R. Wan, F. Darve	MS16-6:6 | 10:40-11:00 **Simulating failure in plant fiber composites: Analyzing the interplay of fiber, matrix, and interface mechanics** V. Senk, M. Königsberger, M. Lukacevic, J. Füssl
11:00-11:30	Coffee Break			

MS23-1: The mechanics, chemistry, and physics for cement and concrete decarbonization K. Celik — EI5	MS25-1: Non-local mechanics for unconventional modelling in bioengineering and advanced manufacturing M. Zingales — EI3	MS28: Innovative experimental mechanics for fracture of heterogeneous materials E. Landis — EI8	09:00-11:00
MS23-1:1 | 09:00-09:20 **Green's function-based estimation of heat release in modified calorimetric tests** H. Höld, B. Pichler, H. Rechberger, P. Aschenbrenner, C. Hellmich	MS25-1:1 | 09:00-09:20 **A mechanobiologic model of cellular signal trasduction based on non-local stability of the primary cilium** E. Bologna	MS28:1 | 09:00-09:20 **Experimental study on joint closure and slip behavior of rock like specimens with non-penetrating long joints under uniaxial compression based on surface displacement monitoring** H. Yin, S. Wang, J.-J. Song	
MS23-1:2 | 09:20-09:40 **Impact of seawater on the hydration and carbonation of reactive magnesium oxide cement** X. Wang, P. Krishnan, K. Celik	MS25-1:2 | 09:20-09:40 **Finite element analysis of buckyball-shaped microscaffolds for tissue engineering** A. Kumar, V. Kumbolder, L. Pircher, J. Fernandez Perez, R. V. Balasubramanian, A. Ovsianikov, S. Scheiner, C. Hellmich	MS28:2 | 09:20-09:40 **On the use of additional sensors during mechanical tests** S. Schmid, P. Pugacheva, C. Grosse	
MS23-1:3 | 09:40-10:00 **Influence of the production protocol and additives on the chemo-mechanical properties of M-S-H pastes** C. Dewitte, E. Bernard, M. Neji, P. Lura	MS25-1:3 | 09:40-10:00 **Comparative study of the bioresoption rate of PLLA/PGA scaffolds stored in different environments simulating biological intra-tissue fluid** A. Nikodem, A. Krala	MS28:3 | 09:40-10:00 **Rate effects on energy dissipation mechanisms in high-performance concrete** A. Carlson, E. Landis	
MS23-1:4 | 10:00-10:20 **Investigating carbonation and hydration of reactive magnesia cement using advanced transmission electron microscopy** N. Elmesalami, M. J. A. Qomi, K. Celik	MS25-1:4 | 10:00-10:20 **Non-local model of delamination of hereditary aortic lamina** G. Prezioso, M. Zingales	MS28:4 | 10:00-10:20 **Timelapse X-ray micro-CT imaging: adaptation to damage localisation in fresh cement mortar** P. Miarka, D. Kytýř, P. Koudelka, V. Bílek, Z. Tomičevič	
	MS25-1:5 | 10:20-10:40 **Numerical research on the effect of nebulizer frequency in maxillary sinus airflow under post-surgical conditions created by virtual surgery** H. Luo, M. Miwa, S. Fujimura, H. Kanebayashi, Y. Watase, K. Hoshino, M. Nakamura, F. Matumoto, M. Yamamoto	MS28:5 | 10:20-10:40 **Quantitative evaluation of fatigue damage in cement mortar: an in-situ approach using XCT** C. Kuang, N. Bin Jamal M, A. Michel	
		MS28:6 | 10:40-11:00 **Visualizing corrosion development in cracked reinforced concrete using X-ray tomography** S. Robuschi, M. R. Geiker, K. Lundgren	
Coffee Break			11:00-11:30

11:30-12:30	**MS01-2: Discrete models for the simulation of infrastructure materials** G. Pijaudier-Cabot, J. Elias — EI2	**MS09-2: Hybrid and sub-structuring analyses, experimental tests and numerical modeling in civil engineering** M. Titirla, S. Grange — EI10	**MS11-2: Mechanics of multiphase-multiscale granular and particulate systems** F. Nicot — EI9
	MS01-2:1 | 11:30-11:50 **In-plane fracturing process in dry-joint masonry walls using physics engines** A. Wang, D. Malomo	MS09-2:1 | 11:30-11:50 **Impact of threaded parallel couplers on the cyclic performance of reinforced concrete columns** M. Nasser, A. Ben-dahou, L. Michel, E. Ferrier, A. Gabor, R. Gardes, R. Boisson, C. Poissonnet, J.-M. Dolo	MS11-2:1 | 11:30-11:50 **Identification of pore network of clays using FIB-SEM imaging** F. Bennai, Y. Ding, J. Guyon, M. Hattab
	MS01-2:2 | 11:50-12:10 **Modeling fracture in wood at the mesoscale** H. Yin, S.-A. Brown, M. Troemner, G. Cusatis	MS09-2:2 | 11:50-12:10 **Analysis of the structural performance of the thermal bridge in building** N. H. Cuong, T.-V. Han, K. Lee	MS11-2:2 | 11:50-12:10 **Stress transmission in granular materials versus epidemic spreading in human societies** N. Deng, M. Miot, A. Wautier, F. Nicot, R. Wan
	MS01-2:3 | 12:10-12:30 **Macroscopic stress, couple stress and flux tensors for continuous and discrete heterogeneous media** J. Elias, G. Cusatis	MS09-2:3 | 12:10-12:30 **Predicting seismic performance of AFRP retrofitted RC column by applying machine learning-based fast running models** Q. B. To, J. Shin, K. Lee	MS11-2:3 | 12:10-12:30 **Swelling behavior of clayey geomaterials: insights from multiscale modeling** H. Mhamdi Alaoui, C. Zhao, W. Niu, P.-Y. Hicher
12:30-13:30	**Lunch Break**		

MS12: Computational wind engineering applications and validations R. Selvam, Z. Zhang — EI7	MS23-2: The mechanics, chemistry, and physics for cement and concrete decarbonization K. Celik — EI5	MS25-2: Non-local mechanics for unconventional modelling in bioengineering and advanced manufacturing E. Bologna — EI3	11:30-12:30
MS12:1 | 11:30-11:50 **A study of moveable wave overtopponing barrier on shore** <u>D. Won</u>, J. Seo, S. Song	MS23-2:1 | 11:30-11:50 **Engineered living building material (LBM) formed by binder jetting under Martian temperature and air pressure** N. Liu, S. C. Lam, W. Huang, Q. Yi, <u>J. Qiu</u>, F. Sun	MS25-2:1 | 11:30-11:50 **Computation of COVID-19 fatality rates based on an aging, hereditary mechanics-inspired modelling strategy** <u>N. Gjini</u>, C. Hellmich, S. Scheiner	
MS12:2 | 11:50-12:10 **Arecibo telescope response investigation in Hurricane Maria** <u>Z. Zhang</u>, X. Chu, R. Abbasi, P. Ghisbain, L. Cao, J. Abruzzo	MS23-2:2 | 11:50-12:10 **Investigation of the factors affecting the performance of brucite as a construction material recovered from desalination reject brine** <u>I. Singh</u>, R. Hay, P. Krishnan, K. Celik	MS25-2:2 | 11:50-12:10 **On modeling of human abdominal wall based on in vivo experiments** <u>I. Lubowiecka</u>, M. Troka, K. Szepietowska	
MS12:3 | 12:10:12:30 **Different tornado chamber effect on vortex formation using CFD** <u>R. Selvam</u>	MS23-2:3 | 12:10:12:30 **Utilization of desert sand with belite calcium sulfoaluminate cement** <u>P. Krishnan</u>, X. Wang, E. P. Bescher, K. Celik	MS25-2:3 | 12:10:12:30 **Dissipation and free energies of fractional-order quasi-linear hereditariness of biological tissues** G. Prezioso, <u>M. Zingales</u>	
Lunch Break			12:30-13:30

Plenary Lecture / Closing Session

C. Hellmich | EI7

13:30-14:15	**Plenary Lecture 5** PL5 | 14:45-15:30 **Transfer fluxes, breakage, coalescence, and drop size distribution in turbulence** Alfredo Soldati (TU Wien, Austria)  *Educated as a nuclear physicist in Italy, with graduation and doctorate from the University of Pisa, Alfredo Soldati has held several assistant and associate professorships in Italy, before – in parallel to his appointment with the University of Udine, he finally joined TU Wien, where he has been active as a professor ever since.* *He is a globally recognized expert in turbulent multiphase flow, with many environmental and industrial applications, including river flood forecasting and host-to-host airborne transmission of COVID-19.* *His achievements have been prestigiously awarded in the academic realm, including the rank of Fellow bestowed from the American Physical Society and from the European Society of Mechanics (EUROMECH).* Abstract: Existence of drops and bubbles in turbulence is granted by their interfaces, a tiny transition layer, a macroscopic perception of molecular properties. Interfaces play a pivotal role across a spectrum of environmental and industrial processes, since it is across interfaces that momentum, heat and mass transfer fluxes occur. A quintessential example is the daily exchange of CO2 at the ocean-atmosphere interface, a phenomenon intricately linked to the size distribution of bubbles and drops and the transfer coefficient across the interface. In this talk, we will give an historical perspective of the problem and we will briefly review the modelling and computational methodologies suitable to track interfaces. We will focus on the phase-field approach and we will present flow instances and phenomena in which surface tension, density and viscosity are varied. Emphasis will be placed on unraveling the intricate interplay between interfaces and turbulence, also covering the role of surfactants in modulating topological changes of drops (breakage and coalescence). Furthermore, we will examine the dynamics of heat and species transfer between dispersed and continuous phases, elucidating the role of fluid transfer properties in governing these processes.
14:15-14:30	**Closing Session**

ABSTRACTS

Plenary Lectures

PL1 | Mechanics and electrochemistry for bulk energy storage in concrete materials & structures

F.-J. Ulm

Massachusetts Institute of Technology, United States of America

Cement-based materials as insulators are unable to conduct electrical charge. However, when cement is mixed with a small amount of carbon black, the contrast between the hydrophobicity of carbon black and the hydrophilicity of cement leads to the build up of a volumetric wire throughout a load bearing porous matrix. When polarized, this volumetric wire is the backbone of the supercapacitor technology and permits storing energy in form of counterions along the carbon black surface. The stored energy scales with the volume of the material. In this talk, I will show different ways of approaching this energy storage capacity from an engineering mechanics point of view. First I will show that energy storage properties can be assessed by analogy by using the correspondence principle of viscoelasticity, when replacing stress by current and strain by voltage (potential difference). I will then dive deeper into the electrochemistry of the underlying process, which permits deriving the fundamental scaling relations for designing concrete structures not only for strength but for energy storage as well. This multifunctionality of electron-conductive cement-based materials and structures opens interesting perspectives for engineers to redesign our built environment for sustainability.

PL2 | Development of microstructural heterogeneities in cementitious slurries and mortars at rest and under flow: a hypothesis for pumping blockage and material defects

A. Robisson

TU Wien, Austria

Cement pastes are negatively buoyant suspensions of non-Brownian particles (µm-size range), with attractive interactions due to highly charged hydration products (nm-size range). In mortar and concrete, sand (mm-size range) and aggregates (cm-size range) are added. These particles, depending on their size and density, may sediment under gravity, or migrate under flow, leading to the creation of heterogeneities, with zones less rich in cement particles, or zones more rich in sand and aggregates.

In this talk, we discuss the physical processes that lead to these heterogeneities by studying both model systems (oil and beads) and real systems (slurries, i.e. only cement particles, and mortars, i.e., with sand). By studying these systems under shear using a rheometer, under flow using a pumping system, or at rest using optical tools, we highlight the formation of heterogeneities. Result analysis is enabled by extensive rheological characterization and previous works on Newtonian based suspensions (Acrivos et al., Nott & Brady, Guazzelli et al.). While shear-induced migration of aggregates is held responsible for concrete pipe blockage, sedimentation of cement particles at rest may explain defects after cement hardening.

PL3 | Linearization approaches for stochastic dynamic analysis of systems endowed with non-integer order differential elements

P. Spanos

Rice University, United States of America

Nonlinearity is ubiquitous. Further, nonlinear systems comprising elements with fractional order differentiation operators have received increasing attention in recent decades. Furthermore, systems exposed to stochastic excitations are quite common in engineering practice. The lecture will address issues relating to the determination of the response of stochastically excited nonlinear systems involving fractional order differentiation. In this regard, the technique of statistical linearization in various formats and versions will be discussed. This will be done in conjunction with an examination of the applicability of the related concepts of stochastic averaging, and harmonic balance In the process, the computational complexity and tediousness of determining the exact non-stationary stochastic response even of linear systems will be pointed out. Comments regarding cases involving combinations of stochastic and periodic excitations will be made. The analytical/ semi-analytical results will be juxtaposed with data from pertinent Monte Carlo simulations. Some possible extensions or variations of the discussed approaches will also be outlined.

PL4 | Memory of flow and residual stresses: from jammed soft solids to cement pastes

E. Del Gado

Georgetown University, United States of America

Soft jammed materials can resist deformation or accommodate steady flow depending on imposed stresses and deformation rates. Designing these properties is central to a range of construction technologies and materials such as cement paste. Cessation of flow generally results in a complex stress relaxation process and finite residual stresses, and controlling these effects is especially important in additive manufacturing, In particular, even in relatively simple pastes and jammed particle suspensions, the rate of stress relaxation, as well as the magnitude of the residual stress have been shown to systematically depend on the preceding flow conditions. New insight into the mechanisms for stress relaxation, gained via microscopic simulations, highlights that flow in a broad range of yield stress fluids can be seen as a training process during which the material stores information of the flowing state through the development of domains of correlated particle displacements and the reorganization of particle packings optimized to sustain the flow. Flow cessation becomes then a way to retrieve this encoded memory. Combining simulations and experiments allows us to disentangle the role of elasticity and plasticity not only in steady flow, but also in the pre-yielding regime leading to ductile or brittle yielding and in the recovering of rigidity and mechanical stability after flow cessation.

PL5 | Transfer fluxes, breakage, coalescence, and drop size distribution in turbulence

A. Soldati

TU Wien, Austria

Existence of drops and bubbles in turbulence is granted by their interfaces, a tiny transition layer, a macroscopic perception of molecular properties. Interfaces play a pivotal role across a spectrum of environmental and industrial processes, since it is across interfaces that momentum, heat and mass transfer fluxes occur. A quintessential example is the daily exchange of $CO2$ at the ocean-atmosphere interface, a phenomenon intricately linked to the size distribution of bubbles and drops and the transfer coefficient across the interface. In this talk, we will give an historical perspective of the problem and we will briefly review the modelling and computational methodologies suitable to track interfaces. We will focus on the phase-field approach and we will present flow instances and phenomena in which surface tension, density and viscosity are varied. Emphasis will be placed on unraveling the intricate interplay between interfaces and turbulence, also covering the role of surfactants in modulating topological changes of drops (breakage and coalescence). Furthermore, we will examine the dynamics of heat and species transfer between dispersed and continuous phases, elucidating the role of fluid transfer properties in governing these processes.

MS01: Discrete models for the simulation of infrastructure materials

MS01-1:1 | Constructing an isotropic damage model from coarse graining of lattice modelling results for quasi-brittle materials

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Lattice modelling of quasi-brittle materials such as concrete is a discrete, mesoscale, description of the material in which constitutive relations are prescribed at a lower scale compared to the scale at which continuum-based constitutive relations are written usually. The meso-structure of the material is represented explicitly. Complex nonlinear responses at the macroscale are obtained, while keeping the constitutive model at the mesoscale simple and less phenomenological compared to macroscale ones. Prediction capabilities and accuracy of the description of the mechanical response at the global level are, in many cases, better than those obtained with continuum-based models.
The superior capability of lattice approaches has a price: extensive computational cost in structural analyses. In this lecture, we implement a coarse graining approach based on averaging the equations of conservation to obtain coarse-grained, continuum-based, stress versus strain responses from the Lattice Discrete Particle Model (LDPM). Because stresses and strains are coarse-grained independently, their relationship yields a database of macroscopic continuum responses that can be compared to some existing constitutive models. This database is used to reconstruct an equivalent isotropic scalar nonlocal damage model. We obtain from the analysis a set of data points that represent the relationship between the variable that is assumed to control damage (strain-based quantity) and the damage variable itself (degradation of stiffness). Calculations show that the best set is obtained for an internal length that is about three times the maximum aggregate size, and that the internal length is independent from the coarse graining length.
Still, the resulting isotropic damage model is an approximation as the coarse-grained mechanical response is much more complex. Simulations of structural size effect provide estimates of such an approximation, along with maps of differences between the stress and strain distribution nearby the crack.

MS01-1:2 | A novel DEM-based coupled 3D thermo-hydro-mechanical mesoscopic model for very-low porosity materials

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Most of the physical phenomena in engineering problems occur under non-isothermal conditions. Moreover, even if the physical system is initially in a state of thermodynamic equilibrium, the physical phenomena or chemical reactions that occur may lead to local temperature changes and consequently to heat transfer. Therefore, understanding heat transfer in particulate systems is of great importance to many engineering applications such as environmental science, chemical and food processing, powder metallurgy, energy management, geomechanics and geological engineering. The need to consider the effect of heat transfer becomes critical in analyses of many multi-field problems in porous and fractured materials.
A novel DEM-based pore-scale 3D thermo-hydro-mechanical model of two-phase fluid flow and heat transfer in fluid and solids is based on a direct numerical simulation approach. The model's original concept is based on the notion that in a physical system, two domains coexist: the 3D discrete (solid) domain and the 3D continuous (fluid) domain. Both domains are discretized into a coarse mesh of tetrahedra.
The coupled thermal-hydraulic-mechanical (THM) model was validated by comparing the numerical results with the analytical solution of the classic 1D heat transfer problem. Numerical calculations were carried out for bonded granular specimens with a 3D DEM fully coupled with 3D CFD (based on a fluid flow network) and 3D heat transfer that linked discrete mechanics with fluid mechanics and heat transfer at the meso-scale. The heat transfer was related to both the fluid (diffusion and advection) and bonded particles (conduction). Bonded particle assemblies with two different grain distributions were considered. Perfect accordance was obtained between numerical and analytical outcomes. In addition, the effects of advection on the cooling of a bonded particle assembly were numerically shown (Figure 1). Finally, the authors' previously developed DEM-based 2D THM model was compared with a novel 3D pore-scale THM model.

MS01-1:3 | Static/dynamic response of partially saturated concrete using an improved fully coupled DEM/CFD approach

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The impact of free water on the static and dynamic compressive and tensile characteristics of concrete in two-dimensional (2D) mesoscale conditions was examined. An improved pore-scale hydro-mechanical model based on a fully coupled DEM/CFD approach was used to simulate the behavior of totally and partially fluid-saturated concrete. The idea behind the approach was a network of channels in a continuous area between discrete elements to create a fluid movement. A two-phase laminar fluid flow (water and air) was proposed in wet concrete that had a low porosity of 5%. Geometry and volumes of pores/cracks were considered to correctly track the liquid/gas content. A series of static and dynamic numerical simulations were run on bonded granular specimens of a simplified spherical mesostructure mimicking concrete in both dry and wet conditions. It was discovered that the saturation level had a major impact on how concrete behaved mechanically. As fluid saturation rose, so did the dynamic compressive and tensile strength. However, the static compressive and tensile strength diminished. In the dynamic range, the concrete mesostructure prevented fluid migration as a result of the rapid loading brought on by the high strain rate, and there were relatively few changes in pore fluid pressures and velocities. As a result, the pore fluid pressures slowed the rate of fracture, which led to increased strength. In the static range, the concrete mesostructure allowed for fluid migration as a result of the slow deformation, and there were changes in pore fluid pressures and velocities. As a result, the pore fluid pressures accelerated the rate of fracture, which led to declined strength. The numerical DEM-CFD results were in agreement with the corresponding laboratory test outcomes from the literature.

MS01-1:4 | Simulation on creep and stress relaxation of calcium silicate hydrate in microscale by discrete element method

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Cement and concrete, acknowledged as the most globally utilized materials, possess mechanical characteristics intricately linked to their long-term durability. Despite centuries of use, a complete understanding of these materials remains elusive. Calcium silicate hydrate (C-S-H), a fundamental component of cement, serves as the primary binding agent, crucial in determining concrete strength. The hierarchical structure of C-S-H encompasses various strength-related attributes across multiple levels. Numerous studies extensively delve into the molecular-scale mechanical properties, yielding significant insights. Additionally, comprehending the material's microscale mechanical properties is essential for its engineering functionality. At the microscale, it can be envisioned as a granular substance with a cohesive-frictional solid phase, reminiscent of porous media. Significant time-dependent phenomena including creep and stress relaxation, occur in concrete subjected to constant loading, particularly within C-S-H in cement paste, and play a crucial role in the long-term volume change of the material. Despite decades of research, accurately simulating such a complex phenomenon at the microscale remains challenging. For instance, molecular dynamics simulations typically deal with relatively small systems due to computational limitations. C-S-H exhibits complex nanostructures, requiring a larger scale to fully capture its mechanical behaviour. This complexity poses challenges in accurately representing its microstructure in finite element simulations. n this study, a novel discrete element method based on solid mechanics was employed to model creep and stress relaxation in C-S-H and explore microstructure development during these processes. Our simulations exhibit good agreement with nanoindentation creep tests, with detailed analysis conducted on the influencing factors affecting bulk mechanical responses. It was discovered that deviatoric stress, friction coefficient, and adhesion between surfaces significantly influence particle sliding, partially determining creep behaviours. These findings offer valuable insights into understanding the mechanism of creep in terms of microstructure change and can aid in nanoengineering C-S-H gels to minimize creep for enhancing concrete properties.

MS01-1:5 | Comparison of Lattice Discrete Particle Modeling (LDPM) implementations: lessons learned and future work

G. Cusatis[1], E. Lale[1], K. Yu[1], M. Troemner[2], M. Pathirage[3], Y. Lyu[4], I. Koutromanos[5], J. Elias[6], M. Stredulova[6], T. Xue[7], M. Alnaggar[8]

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The Lattice Discrete Particle Model (LDPM) is a discrete mesoscale model of concrete that can accurately describe the macroscopic behavior of concrete during elastic, fracturing, softening, and hardening regimes. LDPM has been calibrated and validated extensively through the analysis of a large variety of experimental tests. LDPM can reproduce with great accuracy the response of concrete under uniaxial and multiaxial stress states in both compression and tension and under both quasi-static and dynamic loading conditions.
The LDPM formulation is obtained by modeling the interaction among coarse meso-scale aggregate pieces as the interaction among polyhedral cells (each containing one aggregate particle) whose external surfaces are defined by sets of triangular facets. At each facet strain and stress vectors are used to formulate the constitutive law describing physical mechanisms such as tensile fracture, cohesion, friction, etc.
The presentation will give an overview of recent implementations of LDPM in various computational platforms. LDPM was implemented in the following software packages: Abaqus/Explicit via user subroutine; Project Chrono, a physics-based modeling and simulation infrastructure based on a platform-independent open-source design; Cast3m a multi-physics software developed by CEA; Open Academic Solver, an open-source software developed at Brno University; JAX-LDPM, an open-source GPU-based software in active development by researchers from the Hong Kong University of Science and Technology; and FE-MultiPhys, developed at Virginia Tech. The different implementations will be compared by simulating typical failure tests for concrete, including, but not limited to, unconfined compression test, three-point bending test, and splitting tensile strength test.
Finally the presentation will provide a vision for future LDPM developments that will likely be implemented in these software packages.

MS01-2:1 | In-plane fracturing process in dry-joint masonry walls using physics engines

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Dry joint unreinforced masonry (URM) structures are particularly vulnerable to earthquakes, despite being widespread in many seismically prone areas. While Discrete Element Methods (DEM) are typically used for simulating the seismic fracturing of dry joint URM, such refined computational solutions often require prohibitive analysis times. A still marginally explored, yet promising, alternative to DEM for the structural analysis of dry joint URM is the use of physics engines, which feature an unmatched computational speed when simulating separation, re-contact, and collisions between rigid body elements. However, these methods, presently used in primarily digital animation and robotic industries and therefore seek visually plausible rather than rigorous outcomes, tend to sacrifice accuracy when evaluating equations of motion to reduce the computational burden. This study explores the capabilities of PyBullet, a Python-based module operating the well-known, open-source Bullet Physics engine, in replicating the experimental in-plane (IP) fracturing behavior of dry joint URM walls under varying axial compression rates. Preliminary results indicate that PyBullet models can accurately predict the diagonal shear failures observed during IP testing and that the implicit Coulomb friction cone model utilized is suitable for simulating joint slip under shear-compression. Despite satisfactorily capturing the maximum displacement capacities and lateral strength for all the wall specimens, the adopted stick-slip interface model yields excessive IP stiffness in the linear elastic range, and improvements to this model are currently in progress. Quantitative comparisons with previous traditional DEM results show that response predictions obtained using PyBullet have analogous accuracy, but require significantly less time to complete, making them a promising alternative for full-scale URM seismic simulations.

MS01-2:2 | Modeling fracture in wood at the mesoscale

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The heterogeneous and biological nature of wood has historically led to difficulties in modeling fracture behavior. Finite element models often fail to relate the inherent material properties to model parameters, and the resulting complexity of parameter identification makes such models unsuited to infrastructure applications. Moreover, high-strain rate effects are not easily captured and generally require significant experimental data. To address both concerns, a connector-beam lattice model was developed. This 3D lattice model uses a novel method to represent the cellular structure of wood at the mesoscale via Voronoi tessellation and Lloyd relaxation. The resulting model geometry can capture the unique fracture behavior of wood arising from the orthotropic biostructure of wood cells and their annual growth ring patterns. Following this, a generalized Timoshenko beam formulation was derived which better captures the effects of curved beam deformations. The formulation was implemented via isogeometric analysis with zero-length beam connector elements capturing both in-plane and longitudinal fracture patterns of wood fibers. Model parameters can be largely identified via existing species data. This CBL model is shown to capture the orthotropic elastic behavior, the effects of growth ring orientation on fracture patterns, size effect the transverse plane, and strain-rate effects.

MS01-2:3 | Macroscopic stress, couple stress and flux tensors for continuous and discrete heterogeneous media

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This contribution offers a comprehensive derivation of equations for the macroscopic stress tensor, couple stress tensor, and flux vector in both continuous and discrete heterogeneous systems, where displacements and rotations are treated independently. In the first step, the macroscopic quantities are obtained for a heterogeneous Cosserat continuum. In the second step, these continuum equations are discretized, allowing to identify macroscopic quantities within discrete heterogeneous systems. Finally, the expressions for discrete systems are re-derived without the use of continuous formulation. The resulting formulas are presented in two variations, accounting for either internal or external forces, couples, and fluxes. The differences between these formulations are discussed.
The derivation relies on the principle of virtual work equivalence and sheds light on the essential role of the couple stress tensor concerning balance equations and permissible virtual deformation modes. Specifically, a crucial assumption regarding the selection of virtual kinematic modes was previously overlooked. We demonstrate that these modes can be arbitrarily chosen, resulting in different formulations of macroscale statics. One particular choice yields the formulation previously derived, but without acknowledging the hidden assumption. Particularly noteworthy is also the emergence of an additional term in the formula for the couple stress tensor, elucidating its dependence on location of the macroscopic point. To validate the resulting equations, comparisons are made with established analytical solutions and outcomes from other numerical models, considering both steady-state and transient conditions.

MS02: Structural dynamics and control for offshore wind turbines, including floating systems

MS02:1 | A machine learning approach for offshore wind turbine tower fatigue and fragility analysis

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The objective of this research is to showcase the capacity of Artificial Neural Networks (ANNs) in modeling intricate non-linear systems, particularly focusing on offshore wind turbine towers. Instead of employing traditional Blade Element Momentum (BEM) theory, the authors utilize ANN to predict aerodynamic forces acting on wind turbine towers, leading to a significant reduction in computational time for wind turbine response analysis.
In addition to aerodynamic force prediction, this study incorporates ANNs into fatigue analysis methodologies for offshore wind turbine towers. By leveraging machine learning approaches, the computational burden associated with fatigue analysis, which typically entails numerous time history simulations, is substantially reduced compared to traditional methods. This enables more efficient and cost-effective assessments of wind turbine structural integrity over their operational lifespan.
Furthermore, a fragility analysis is conducted on the IEA-15MW offshore wind turbine, with a specific focus on evaluating the serviceability limit state associated with foundation tilt. The analysis underscores the criticality of considering Soil-Structure Interaction (SSI) effects in offshore wind turbine design, particularly in regions prone to significant environmental loading.
The findings of this research highlight the potential of ANN-based approaches to revolutionize computational methodologies in wind energy engineering. By integrating machine learning techniques into fatigue analysis, significant computational efficiencies are achieved, facilitating more expedient and accurate assessments of wind turbine structural reliability.
In conclusion, this study contributes to advancing the understanding of ANN applications in wind energy engineering, emphasizing their role in improving computational efficiency and accuracy in fatigue analysis. Additionally, the research underscores the importance of considering SSI effects in offshore wind turbine design to enhance structural integrity and performance.

MS02:2 | A study on optimal sensor placement of multi-linked floating offshore structure for prediction accuracy improvement of structural response using distortion base mode method

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Recently, a study on digital twin has been actively conducted to evaluate the structural intensity of ships and offshore structures. Previously, conservative structural safety was secured through design with a high safety factor and periodic inspections, but recently, using digital twin technology, it is possible to evaluate the structural intensity in real time. By synchronizing measured sensor data in real time with a digital twin model and performing simulation, evaluation of structural intensity such as structural response distribution, structural defect detection, actual fatigue life according to the sea state is performed, and further, accident prevention, maintenance plan can be established. Structural intensity evaluation through precise computational numerical analysis requires a lot of computational cost to use as a digital twin model that require faster simulation speeds. Therefore, a digital twin model is built by applying various techniques such as order reduction method and deep learning that can secure low computational costs. In this study, optimization of measured sensor placement was performed to improve prediction accuracy of reduction order model about ships and offshore structure. The target structure was a multi-linked floating offshore structure, and the bending stress was predicted by order reduction model based on distortion base mode. A structural response database was established through fluid-structure coupled analysis, and distortion base modes were selected using mode orthogonality and autocorrelation coefficients. Although it costs a lot of computational time to evaluate performance of all possible sensor placement combinations, the optimization technique saved about 8 times the time cost, and the root mean square error related in prediction accuracy with resulted in a sensor placement was reduced by about 84.0% compared to numerical analysis results. In addition, it was confirmed that the measured sensor data in the model test had a 28.6% improved prediction performance compared to the previously set sensor placement.

MS02:3| Advancing wind farm fatigue analysis: insights from high-fidelity modelling and machine learning

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In this study, we present the results of a fatigue analysis conducted on a wind farm using NREL's state-of-the-art FAST.farm model, which have been developed to accurately simulate complex wind farm geometries and incorporate turbulence effects at the wind farm level. Leveraging these advanced models, we assessed the structural integrity and longevity of the wind farm under varying environmental conditions.
Through rigorous analysis, we investigated the fatigue accumulation patterns across turbines within the wind farm, considering the dynamic interaction of turbulent atmospheric conditions and wake effects. Our findings shed light on the critical factors influencing fatigue damage distribution and highlight the importance of comprehensive fatigue analysis for ensuring the reliability and durability of wind energy infrastructure.
Looking ahead, our future work will focus on leveraging these fast.farm models to generate synthetic datasets for training machine learning models, particularly Artificial Neural Networks (ANNs). By mapping external conditions to turbine loads, these ANN models will offer valuable insights into load prediction at the wind farm level.
While direct validation of load predictions remains a challenge due to data limitations, our approach will involve cross-checking power output predictions against Supervisory Control and Data Acquisition (SCADA) records. This verification process will provide an indirect validation method for assessing the accuracy and reliability of the ANN model's load predictions.
This ongoing research represents a significant advancement in the field of wind energy engineering, with a focus on enhancing predictive modeling capabilities for offshore wind farms. By integrating high-fidelity modeling techniques and machine learning methodologies, we aim to optimize operational efficiency and support informed decision-making in the renewable energy sector.

MS02:4 | Blade pitch control of floating offshore wind turbines for mitigating corrosion fatigue deterioration and enhancing structural reliability

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Owing to structural flexibility, floating offshore wind turbines (FOWTs) are prone to exhibit strong dynamic responses under severe wind-wave conditions, which can result in the accumulation of fatigue damage over time. As integrated with the high corrosivity of the offshore environment, FOWT deterioration accelerates and structural reliability further declines. The pitch control strategy for load reduction while remaining rated power generation at the above-rated wind speeds is considered a significant active control approach to mitigate fatigue damage and improve structural reliability. However, the current loading-reducing pitch controller focuses on lowering peak response or fatigue damage equivalent load (DEL) based on the linear fatigue damage accumulation theory, ignoring the corrosion influence and lacking a thorough reliability analysis. In this article, a comprehensive analysis framework combining pitch control strategy and C-F assessment is proposed to investigate the impact of pitch controller on the bolts' C-F performance, and further evaluate the component-level structural reliability. Based on the DTU 10-MW reference turbine and the C-F deterioration model, a fatigue-reduction-oriented pitch controller, the low authority linear-quadratic-integral controller (LQI) controller, is compared against the baseline controller (BC) used by the high-fidelity offshore wind turbine simulator OpenFAST on the corrosion-fatigue (C-F) behaviour of the bolts in ring-flange range connection of the FOWT tower and component-level reliability under various wind-wave conditions. The results show that the LQI controller offers improved performance in relegating stress ranges in bolts while optimizing power production, further improving the C-F situation and structural reliability. This highlights the importance of control strategy in FOWT structures and its effects on condition-based maintenance.

MS03: Coupled chemical, physical and mechanical processes in cementitious materials relevant to the short- and long-term behavior of R.C. and P.C. structures

MS03-1:1 | Application of DIC method to identify the relationship between crack width and deflection in reinforced concrete beams

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The serviceability of reinforced concrete beams is evaluated by the criteria of crack width and deflection according to the design codes. However, depending on the environment in which the reinforced concrete beam is located, it may not be possible to directly measure the crack width or deflection. Also, the calculation methods provided by the ACI 318 building code require the current load level to calculate crack width and deflection even though the load cannot be accurately determined. This study aimed to correlate the crack width and deflec-tion of reinforced concrete beams and provide a method to calculate them with crack width or deflection measured in the field. For this purpose, an experimental study was conducted for reinforced concrete beams with key variables such as tensile reinforcement ratio and cover thickness. During the experiment, the digital image correlation (DIC) method was utilized to measure deflection and crack width. The results were compared with those measured using LVDT and a digital crack measuring device. For the deflection, the results by DIC and linear variable differential transformer (LVDT) were quite close to each other, but the sum of the crack widths measured by the device in the range of measurement was relatively smaller than that measured by DIC. It suggests that some minor cracks were not detected by the naked eye when the device was used. The DIC measurement was just applied to the maximum moment zone due to the limitation of mea-surement range, and the deflection in the shear span was additionally evaluated considering the shear deformation. As a result, the relati-onship between crack width and deflection in reinforced concrete beams was identified by combining the DIC measurement data in the maximum moment zone and the data in the shear span.

MS03-1:2 | Crack healing under sustained load in concrete: an experimental/numerical study

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The construction of sustainable and resilient structures and infrastructures that ensure people's safety while minimizing maintenance costs is a crucial goal. One way to achieve this is through the healing of micro-cracks and defects. In real structures that are subjected to service loading, time-dependent behavior is of utmost importance, especially in the presence of cracks. Such cracks can lead to nonlinear creep behavior, which might ultimately cause structural failure. Hence, the new challenge is to investigate and quantify the effect of crack-healing on nonlinear creep behavior.
This study has two objectives. Firstly, it aims to experimentally investigate the effect of healing on specimens that are continuously subjected to sustained load under controlled environmental conditions. The amount of load is determined based on the expected service load, which is calculated as a fraction of the pre-cracking load. Secondly, the study aims to develop a comprehensive numerical framework to interpret and simulate the results observed in the experiments. For this purpose, an experimental investigation was conducted at Politecnico di Milano with reference to an Ultra-High-Performance Concrete developed in the framework of the H2020 ReSHEALience project for exposure to extremely aggressive environments. The numerical framework is based on the recent developments of the multiphysics lattice particle model (M-LDPM). 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 [4-5].

MS03-1:3 | Enhancing computational efficiency in lattice discrete particle modeling for analyzing concrete failure behavior

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Reliable and computationally efficient models are crucial for various applications, yet simulating granular material mechanics often poses challenges due to high computational cost. This paper addresses the need for trade-offs between accuracy and calculation time in computational models, focusing on concrete simulated at the coarse aggregate level using the lattice discrete particle model (LDPM). A novel discretization approach is proposed, which reduces the number of tessellation facets. Two options are investigated. In the first case, the number of facets is reduced from 12 to 6 per tetrahedron connecting 4 adjacent particles. In the second case all facets shared by a link between two particles are merged into a single facet. The study examines the computational cost and accuracy of predicting concrete fracture behavior via the novel discretization approaches for a number of different loading situations. Results indicate that both models significantly reduce computational cost while maintaining accurate predictions of structural mechanical response compared to the original LDPM and experimental data. The analyses validates the efficiency and promise of these approaches in advancing LDPM utilization for concrete mechanics simulations.

MS03-1:4 | Evaporation in concrete early-age maturation: multiphasic model

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The study presents a numerical model aimed at exploring the intricate behavior of concrete during its early stages of maturation, with a particular focus on thermo-mechanical and hygral phenomena. Drawing inspiration from Gawin's work [1], the model conceptualizes concrete as a multiphase material, comprising a solid phase (cement, gravel, etc.) and fluid and gas phases filling the pores with water and dry air, respectively. Distinguishing itself from previous models, this model based on the Framework of Theory of Porous Media integrates the processes of hydration-dehydration and evaporation-condensation, providing a comprehensive understanding of concrete behavior. To validate the model's efficacy, experimental investigations are conducted to examine the evaporation kinetics in fresh concrete and its impact on concrete's properties. Employing a multi-field finite-element solver, numerical simulations are performed to assess the model's predictive accuracy in capturing concrete behavior during its early hydration period. Through refinement and expansion upon Gawin's foundational model, including the incorporation of additional phenomena such as evaporation-condensation dynamics, the study enhances the predictive capabilities crucial for concrete mechanics research. Furthermore, the research focuses to deepen insights into the evaporation mechanisms within porous materials, pivotal for concrete's response to internal and environmental stimuli. Leveraging the Dynamic Vapor Sorption method facilitates a accurate investigation into the complex interplay between hydration, evaporation, and external influences, thereby broadening our understanding of concrete structure maturation.
[1] Gawin, D., Pesavento, F., Schrefler, B., Hygro-thermo-chemo-mechanical modelling of concrete at early ages and beyond. Part I: Hydration and hygro-thermal phenomena. International Journal for numerical methods in engineering, Wiley, 2006.

MS03-1:5 | Mesoscopic simulation of corrosion-induced cracking of reinforced concrete

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Corrosion-induced cracking is one of the most common deterioration problems of reinforced concrete structures. The embedded rebars corrode under the combined influence of moisture, oxygen, and an electrical field. The oxidation of iron leads to rust non-uniformly distributed around the single rebar, as considered in this work. Since the rust occupies a larger volume than the iron, corrosion results in pressure acting on the concrete surrounding the rebar. When the tensile stresses of concrete reach the tensile strength, the concrete starts cracking. Concrete is a composite material consisting of aggregates, (i) surrounded by interfacial transition zones and (ii) embedded in a mortar matrix. The transport of ions, the electrical conductivity, and crack propagation are influenced by the mesoscopic heterogeneity of concrete. Therefore, an accurate representation of the mesostructure is necessary for the simulation of corrosion-induced cracking. In the present contribution, a Finite Element model for corrosion-induced cracking of reinforced concrete is described. It accounts for

the interplay of the mesostructure of concrete and relevant multiphysical mechanisms. The model is used to simulate an accelerated corrosion test [DOI: 10.1007/BF02472805]. The non-uniform penetration of the corrosion front into the rebar and its associated non-uniform expansion are quantified based on the local current densities. The model is validated by comparing the simulated crack mouth opening displacements with corresponding measurements, performed at the surface of the tested specimen.

MS03-1:6 | Novel meso-scale reactive-transport model for carbonation of OPC

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Carbonation tests of hardened cementitious materials are time-consuming, even in accelerated conditions, presenting significant challenges for the design of experiments. It is widely acknowledged that utilizing a low CO2 concentration (<3%) is critical to accurately replicate natural carbonation conditions. Hence, a model is called for that is able to estimate the carbonation front during accelerated carbonation tests for a given concrete composition. Amongst abundant models in the literature addressing the carbonation process of hardened cementitious materials, kinetic models are promising as they can capture key features of the carbonation process as well as being computationally efficient. In this paper, we firstly provide a critical study of existing kinetic models discussing their theoretical foundations, input parameters, and primary applications. Then, we introduce an implementation in COMSOL of a reactive-transport model for OPC-based materials. Following this methodology, we advance to establish a novel 3-D meso-scale model based on lattice flow elements dual to the Lattice Discrete Particle Model (LDPM) for the mechanical analysis. This model uniquely employs conduit elements to represent CO2 diffusion pathways. Two CO2 concentrations (1%, 3%) are applied in both implementations with constant temperature field (20 °C) and relative humidity field (65%) to simulate accelerated carbonation tests in the environmental chamber. It is shown that the meso-scale model can predict well the average carbonation depth in comparison with continuum case while retaining the heterogeneity of concrete and, thus, spatial variability in carbonation front. Advantages and disadvantages of both implementations are discussed, providing insights into their applicability in simulating real-world carbonation processes that can help researchers in their design of experiments.

MS03-2:1 | Phase-field-based chemo-mechanical modelling of corrosion-induced cracking in reinforced concrete

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A new model for corrosion-induced cracking in reinforced concrete is presented [1,2]. Corrosion of steel in concrete is responsible for 70-90 % of prematurely deteriorated reinforced concrete structures and can even cause structural failure as infamously documented by recent collapses of aerated concrete panels in British schools. The state-of-the-art knowledge of the underlying processes has been incorporated into three interconnected submodels: (i) a reactive transport model for: (i.A) the transport of water and aggressive corrosion-activating species (such as chlorides or carbon dioxide) to the steel surface and (i.B) the transport iron ions released from the steel surface in the concrete pore space where they precipitate into rust, (ii) model for the corrosion-induced pressure resulting from the concurrent constrained accumulation of compressible rust in: (ii.A) the dense rust layer in the steel volume vacated by corrosion and (ii.B) in concrete pore space (evaluated with a newly proposed precipitation eigenstrain), and (iii) a phase-field fracture model calibrated to accurately describe the quasi-brittle fracture of concrete. The proposed model was implemented in COMSOL Multiphysics software and solved numerically with the finite element method. Both uniform and non-uniform corrosion case studies were investigated and validated with experimental data. Importantly, the model allows to simulate the impact of the magnitude of the current density on the propagation rate of cracks, which has been puzzling researchers for over 25 years. In addition, for the first time, time-to-cracking for highly porous aerated concrete was investigated.

[1] E. Korec, M. Jirasek, H.S. Wong, E. Martinez-Paneda, Phase-field chemo-mechanical modelling of corrosion-induced cracking in reinforced concrete subjected to non-uniform chloride-induced corrosion, Theoretical and Applied Fracture Mechanics. (2023) 104233.

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MS03-2:2 | Modeling two-phase mechanical behavior in lattice discrete particle models

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Concrete is a composite material comprising aggregates and a cement matrix at the mesoscale level. The mesoscale structure of concrete materials can significantly influence the macroscopic mechanical behavior, including failure modes and zones. While the Lattice Discrete Particle Model (LDPM) is a state-of-the-art approach for simulating concrete at the coarse aggregate level, it does not completely capture the heterogeneity between aggregates and the matrix. The LDPM model divides a basic four-particle tetrahedron into four subdomains, with each subdomain encompassing portions of both aggregates and the matrix. However, the original LDPM model simplifies this subdomain as a concrete material with uniform mechanical behavior. Due to this simplification of the actual heterogeneity, the original LDPM does not accurately predict the amount of experimentally observed scatter and spatial variability. To address this critical limitation, this paper introduces a heterogeneous LDPM, termed the two-phase LDPM. The two-phase LDPM considers the subdomain encompassing both aggregates and the matrix, thereby achieving greater realism. The introduced two-phase LDPM is assessed under a variety of stress and loading conditions including tension, compression, and shear by comparing with results obtained from the original LDPM model and experimental data from the literature. The study demonstrates the reliability of the two-phase LDPM, enhancing the predictive accuracy of the original LDPM model and elevating its utility in engineering applications.

MS03-2:3 | Multiscale modeling of concrete under mechanical and environmental impacts for ultrasonic based early damage identification

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Detecting and mitigating early-stage damage in concrete structures is vital for minimizing maintenance costs and extending infrastructure lifespan. Weak material degradation, such as load-induced initiation and propagation of microcracks, is a precursor of localized damage (macrocracking) in concrete structures and can be detected by means of multiple-scattered late arriving ultrasonic signals, also called coda signals [1]. However, accurately quantifying concrete damage is challenging due to the high sensitivity of these signals and the need to distinguish between irreversible changes (e.g., microcracking) and reversible variations caused by environmental factors like temperature and humidity.

To this end, we systematically explore how mechanical and environmental factors influence concrete microstructure and coda variations, respectively through a novel approach combining multiscale computational modeling and wave propagation simulations.

Firstly, damage initiation and progression in realistic mesoscale concrete models [2] is simulated using a novel reduced-order multiscale method [3]. Our methodology integrates continuum micromechanics damage modeling at microscale with an integral form of the Lippmann-Schwinger equation solver at mesoscale. The model is further extended to describe microstructural changes at various temperature and moisture conditions. Subsequently, the concrete specimens subjected to specific level of damage are analyzed by wave propagation simulations [4]. The proposed framework has been validated thoroughly with the experiment. Influence of concrete mixes on concrete behavior and coda variations, and its implications on separating effect of damage from environmental fluctuations shall be discussed.

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MS03-2:4 | Time dependent deformations in concrete: a multi-physics multiscale model and its validation with Test Results

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Concrete is a highly heterogeneous material that ranges from nanometre to metre scale. To characterise the behaviour of concrete, it is essential to know all the physical and chemical processes that occurs within its constituents to model the physics associated with creep and shrinkage in concrete structures. In the first part of this study, a coupled chemo-hygro-thermo-mechanical model of concrete is developed. Uncertainty tools based on a probabilistic framework are used to model the possible variations in the input variables in the hygro-thermo-mechanical formulation. Uncertainties in the selected set of important variables are reduced using Bayesian inference and short-time measured responses. For validating efficiency of the uncertainty reduction technique adopting Bayesian inference and global response sensitivity, the predictions of creep and shrinkage in concrete are compared with a few experiments from the North-Western University (NU) data base. The uncertainty reduction technique is then used to predict the long-time prestress losses in post-tensioned concrete beams and slabs cast in the laboratory. A hierarchical homogenization technique is used to introduce into the model different scales and validate it with test data. Thereafter the model has been modified to include the effects of the aggregates in the concrete matrix through a mesoscale treatment of the aggregate in a cement mortar matrix and bringing to fore the effects of micro-structural phenomena through a homogenisation-based upscaling technique of cement hydration processes taking place at micro-scale. This makes the multi-physics meso-model length scale dependent. Validation of the present approach with a range of experimental results highlights the robustness of the model in terms of optimum and targeted design of a cementitious material.

MS03-3:1 | Study on the change of structural performance of RC structures building subjected to drying

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In recent years, monitoring of existing reinforced concrete (RC) structures, such as nuclear power plants (NPPs) and multi-story RC buildings, has revealed a decrease in natural frequencies over decades. Moisture loss in concrete emerges as a potential cause of stiffness reduction. Understanding the mechanism of drying effects on structural performance requires a multi-scale perspective, considering moisture loss and stiffness change at the material level, and drying shrinkage-induced cracking at the structural level. This study investigates how concrete structural performance is influenced by shrinkage due to moisture loss through hydration or dissipation, employing multiscale integrated finite element analysis. The thermo-hygral analysis for RC lifetime over decades is applied with monitoring data of existing multi-story buildings and nuclear power plants in service. The reduced natural frequency is numerically replicated, revealing cracking near junction planes between structural members of different dimensions and dispersed cracks close to the surfaces of thick members. To deepen understanding of the impact of drying shrinkage, a cyclic shear loading test on shear wall specimens subjected to drying in a previous study was also reproduced by the analysis. In addition, a parametric study, focusing on the member scale, mix proportion, and surface treatment of concrete was performed. Difference of the drying speed by member scale was highlighted. The dominance of autogenous shrinkage in the case of high-strength concrete was also confirmed. In such cases, protection against drying may be disadvantageous as it impedes moisture supply from ambient air. The mechanism of stiffness reduction due to shrinkage and the complex relationships among multiple factors are quantitatively elucidated.

MS03-3:2 | Temperature impact on the mechanical and physical properties of lining concrete in nuclear waste disposal

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In Belgium, disposal of high-level nuclear waste in a stable geological environment is considered as a suitable technological option. Such waste is planned to be disposed in disposal tunnels lined with concrete. The waste generates a significant amount of heat for an extended period, which may affect the stability of the disposal liners as well as influence the stresses around the adjacent connecting gallery concrete liners. The structure is designed for long-term use, spanning hundreds of years. Therefore, it is crucial to study the decay of concrete properties due to exposure to high temperatures. This research covers different aspects of concrete properties at various scales to provide a comprehensive understanding of time-dependent deformation behaviour at different temperatures. The temperatures considered are 23 °C, 65 °C, and 85 °C, while the relative humidity is 65%. The research covers hydration kinetics, pore structure, moisture diffusivity, mechanical properties with particular focus on time-dependent deformation at the mesoscale for different curing ages. The mechanical properties of interest comprise compressive strength, static and dynamic modulus of elasticity, flexural strength, fracture energy, creep, and shrinkage for various sample sizes. The research provides a comprehensive analysis and a several findings on the effect of curing on the same concrete mixture over a period of one year. It is generally observed that temperature and drying have a significant impact on the physical and mechanical properties of concrete, particularly for concrete that is cured for less than 28 days and then exposed to elevated temperatures, which is confirmed and quantified in this contribution.

MS03-3:3 | The influence of weather patterns and global warming on chloride ingress in concrete structures

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This work aims to investigate the influence of weather conditions and global warming on chloride transport in concrete structures. In regions prone to cold temperatures and frequent freeze-thaw cycles, this study considers the effect of the freeze-thaw induced damage on chloride transport. Utilizing a multiscale approach based on finite element solutions of chloride, moisture, and heat transfer equations, chloride ion profiles within concrete were predicted. The simulations incorporated real meteorological data from four diverse locations, selected for their distinct climatic characteristics: Mediterranean (Annaba, Algeria), Arid Subtropical (Abu Dhabi, UAE), Equatorial (Accra, Ghana), and Continental (Oslo, Sweden). The findings indicate that, among the climates examined and considering the impact of freeze-thaw induced damage, the continental climate of Oslo demonstrated the most favorable conditions for chloride penetration. Following closely behind, the equatorial climate of Accra ranked as the second most conducive environment for chloride ingress, exhibiting only a slight disadvantage compared to the continental climate of Oslo. Notably, relative humidity emerged as the predominant factor influencing chloride transport over temperature. Despite global warming potentially reducing the frequency of freeze-thaw cycles annually, its impact on chloride transport in cold regions was found to be negligible. Conversely, in the other locations, global warming was observed to accelerate chloride transport by approximately 5% – 7%. Furthermore, incorporating daily temperature variations led to higher chloride profiles compared to average daily temperatures. The former resulted in a 12.5% reduction in the time to corrosion initiation. Understanding the influence of weather conditions and climate change is crucial for implementing effective adaptation strategies to mitigate premature structural degradation.

MS03-3:4 | Temperature profiles of concrete members placed in different geographical regions: a guideline for installation and design of bonded anchors

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Post-installed bonded anchors are used to connect structural and non-structural members in a variety of applications in concrete structures. The performance of bonded anchors can be influenced by several different parameters. One of the most important parameters that directly affects the bond strength of the adhesive anchor in both the short and long term, as well as various processes that occur at the material level of the adhesive, e.g. creep, curing, post-curing, is the temperature conditions during installation and over the design service life of the fastener. For this reason, different adhesive systems have different temperature ranges defined by the manufacturer. These temperature ranges include the maximum short-term temperature, which defines the highest temperature the adhesive fasteners can withstand for a short period of time, and the maximum long-term temperature, which represents the upper limit of the temperature range in which the fasteners can maintain their structural integrity and performance without significant degradation. Therefore, the service life of adhesive anchors is designed by considering the various environmental conditions of the region in which the structure is located. Typically, this is done by evaluating only the air temperature data at 2 m.

However, this may not be appropriate in many cases since the concrete members may experience different temperatures influenced by the amount of solar radiation and wind speed. The present study proposes a method that calculates the temperature profiles of concrete members under different conditions where the adhesive anchors are to be installed, considering the heat flux due to i. solar radiation, ii. convection and iii. heat conduction. In this way, temperature maps are generated for different geographical regions based on their historical environmental measurements. Finally, the concrete temperatures are coupled with the mechanical properties of the adhesives and the concrete.

MS03-3:5 |Chemo-thermo-hygro-mechanical modelling of blended concretes at elevated temperatures

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Cement is one of the largest global carbon dioxide emission sources worldwide. Replacing ordinary Portland cement clinker with silica fume, fly ash or other supplements can reduce the enviromental impact up to 50%. However, this contemporary cements show higher explosive spalling risks under fire loading in experiments. Although, the origin of this behaviour is still unclear, the pore pressure development of concrete under fire loading was identified as important influence on the spalling behaviour. Due to the variety of blended concrete compositions, experimental investigations of the pore pressures are very costly. Computational models offer a possible remedy to capture the pore pressure development for a variety of blended concretes and can lead to important insights into the problem's specifics with its multiphysical nature.
Based on chemo-thermo-hygro-mechanical analyses, the drying front of blended concretes under fire loading is investigated, considering four primary state variables, i.e., gas pressure, capillary pressure, temperature, displacement and two internal variables, i.e., dehydration degree, chemo-mechanical damage. Within a microporomechanical framework the chemo-mechanical damage is calculated via Eshelby-type homogenisation techniques and the dehydration degree for the different blended concretes is predicted by Arrhenius equations for each cement constituent.
Blended concretes, namely CEM II/A-LL, CEM III/B, CEM II/B-V, CEM IV/A, with different water to cement ratios are analysed in the context of a sensitivity study comparing the different inital moisture states and dehydration behaviours regarding the pore pressure development. It was shown that high initial volume fractions of C-S-H and monosulfoalumiates and a high fineness of grinding increase the pore pressure development.

MS04: Continuum models for material failure: nonlocal, gradient-enhanced, micromorphic, and phase-field approaches

MS04-1:1 | An elasto-plastic finite-deformation micropolar material point method for strain localisation problems

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Reliably modelling the emergence of shear bands in geotechnical failure events has long posed problems to conventional numerical modelling techniques, for two key reasons. Firstly, as such events generally involve very large deformations and complex boundary dynamics, mesh-based techniques like the finite element method can suffer a loss of accuracy and even breakdown of the numerics as elements become increasingly distorted. The chosen numerical technique for this work, the material point method (MPM), avoids this issue by instead discretising the domain into Lagrangian particles which deform through a background mesh. The mesh is used to complete a standard finite element calculation but is reset to its initial position after each load step, minimising any inaccuracy arising from mesh distortion. Secondly, the localisation of strain into shear bands introduces a discontinuity into an otherwise smooth displacement field; when using a classical continuum theory, this forces the governing system of equations to become ill-posed. This manifests as an unacceptable mesh-dependent solution, which does not converge towards a steady shear band thickness or failure load with refinement. To regularise this, the micropolar (Cosserat) continuum introduces a field of independent micro-rotations to the configuration space. The rotations and their spatial gradient (curvature) smoothen the solution field around the shear band with respect to a length scale taken to be indicative of the size of the microstructure. Simulations based on the micropolar continuum can therefore reliably predict shear bands with a finite thickness depending on the scale of the constituent microstructure, without resorting to artificial smoothing techniques. This presentation will outline an approach based on an extension of geometrically-exact micropolar theory into the paradigm of classical plasticity, incorporating frictional effects, and implemented within an implicit MPM. Application of the method to several quasi-static examples, including plane-strain tests and slope stability problems, will also be demonstrated.

MS04-1:2 | Strain localization analysis of an infinitesimal micropolar elastoplastic constitutive model rooted in critical state soil mechanics

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In terms of classical continuum constitutive models, the loss of ellipticity of the governing rate equilibrium equations entails localizing deformations and mesh sensitivity in finite element simulations. Extensions of such models rooted in the micromorphic continuum aim at remedying mesh sensitivity by introducing length scales to the constitutive formulation. The micropolar continuum, which goes back to the Cosserat brothers, constitutes a special case of the micromorphic continuum and is commonly employed for remedying mesh sensitivity accompanying shear band failure. Despite this fact, localizing deformations in the micropolar continuum remain a largely unexplored phenomenon. The aim of the present study is to thoroughly investigate the conditions for localizing deformations in the context of the micropolar continuum and to highlight their implications for structural simulations. To this end, we propose an infinitesimal elastoplastic micropolar constitutive model rooted in critical state soil mechanics and establish its localization characteristics. Investigations at the constitutive level highlight the stabilizing effect of the micropolar extension, which is increased both by the presence of couple stresses as well as by increasing the Cosserat shear modulus. Structural simulations exhibit good agreement with the results obtained at the constitutive level. Nevertheless, cases where shear band failure is not adequately regularized by means of the micropolar model are also identified. Moreover, the destabilizing effect of structural inhomogeneity is highlighted.

MS04-1:3 | A return-free plastic integration for mixed control problems and its applications in elastoplasticity of materials

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Mixed control problems represent the material problems for solving the part of stress and strain response if the counterparts of stress and strain are given/controlled. Most strain-controlled experiments belong to the mixed control problems such as the strain controlled uniaxial tests, the strain-controlled axial-torsional test, and strain-controlled biaxial tests. To deal with the mixed control problems, the plastic integration based on the pure stress representation or the pure strain representation are not workable hence additional treatment is needed in general. In this study, we explored the internal symmetry of an elastoplastic model for anisotropic materials under mixed control and developed its return-free integration for mixed control problems based on the theory of Lie algebra and Lie group. We conducted an error analysis of the return-free integration to demonstrate the its accuracy under different initial conditions. Using the accurate return-free integration, we investigated the contraction ratio and the r-value of differential materials.

MS04-1:4 | Finite element analysis of shear failure in sand using micropolar hypoplasticity

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In granular soils, shear loading often results in a failure that is distinctively characterised by the formation of shear bands in which the deformations localise. In order to predict the mechanical behaviour of geotechnical structures, it is essential to accurately capture this behaviour in numerical simulations.

The objective of this contribution is to critically assess the capability of a micropolar hypoplastic material model in predicting the shear failure of sand with finite element analysis. Specifically, the micropolar hypoplastic model introduced by Maier (2002) is evaluated, which enhances the well-established hypoplastic material model for sand developed by Wolffersdorff (1996). By employing both 2D and 3D finite element simulations, this study aims to predict the mechanical behaviour of sand specimens in standard laboratory tests, such as the biaxial and triaxial compression tests. It is shown that the micropolar hypoplastic model accurately represents the nonlinear, inelastic behaviour of sand, accounting for its density and pressure dependencies. A mesh sensitivity study confirms that the model is capable of predicting stress and deformation states during shear-dominated failure without encountering mesh sensitivity issues. This capability is superior compared to classical hypoplastic models that neglect the inherent granular microstructure. Additionally, the influence of the micropolar material parameters --the mean grain diameter and the grain roughness-- on material behaviour as well as shear band characteristics is studied. Finally, the numerical results of this study are compared with experimental laboratory test data to confirm the validity of the model.

MS04-2:1 | Phase field simulation of hydrogen-assisted fatigue

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We present a new phase field paradigm to predict hydrogen-assisted fatigue. The model combines a phase field description of fracture and fatigue, stress-assisted hydrogen diffusion, and a toughness degradation formulation with cyclic and hydrogen contributions. The predictive capacity of the proposed phase field formulation is verified via CT experiments over all the scenarios considered, spanning multiple load ratios, hydrogen gas pressures and loading frequencies. Results exhibit excellent agreements without any calibration with hydrogen-assisted fatigue data, taking as input only mechanical and hydrogen transport material properties, the material's fatigue characteristics (from a single test in air), and the sensitivity of fracture toughness to hydrogen content. Then, the model is used to examine the suitable test loading frequencies to obtain conservative Paris curve data, giving new insight into the frequency-dependent fatigue crack growth rate in the hydrogen-containing environment. Finally, we extend the formulation to simulate the fatigue failure of real large-scale hydrogen pressure vessels, showcasing the potential of the Virtual Testing paradigm in infrastructure exposed to hydrogen environments and cyclic loading.

MS04-2:2 | Robust and efficient implementation of generalized continuum models based on automatic differentiation with hyper-dual numbers

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Generalized continuum models for representing nonlinear material behavior including material failure in the finite strain regime are commonly formulated based on scalar elastic and dissipation potential functions. The evolution of stresses and internal variables, i.e., the material state, is governed by partial derivatives of the potential functions with respect to deformation and stress measures. Furthermore, for application of such models in implicit numerical analyses, the tangent operators, consistent with the numerical integration algorithm, are required. The present contribution introduces a semi-analytical split approach for the robust and efficient implementation of generalized continuum models in software for implicit numerical analysis, e.g. Finite Element codes. For this novel semi-analytical approach, automatic differentiation with hyper-dual numbers is utilized for computing partial derivatives of constitutive equations, i.e., scalar potential functions, which are then combined with hand-coded analytical derivatives for operations which are independent of the employed material model, e.g., push/pull operations. In a first step, this approach is introduced on a simple finite strain J2-plasticity model for a better understanding of the underlying concepts. Subsequently, a comprehensive 2D and 3D finite element study employing a finite strain gradient-enhanced micropolar damage-plasticity model is presented. Thereby, we demonstrate the superior properties of the novel semi-analytical split approach compared to numerical differentiation methods with regards to accuracy and robustness. Furthermore, the additional computational cost for automatic differentiation using the proposed split approach becomes negligible for large problems.

MS04-2:3 | Homogenized post-peak response of composites from phase-field fracture simulation at microscale

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Cohesive fracture develops at the macro level of some composites through micro-cracks coalescence and their interaction with micro-heterogeneity. A macroscopic damage model for such a material requires the prescription of an accurate homogenized constitutive behaviour, including elastic, strength and toughness characteristics. Numerical homogenization offers a way to predict these properties utilizing the microscale response. However, it involves two critical challenges: the ill-posedness of the microscale boundary value problem described through local constitutive models and the lack of separation of length scales, which invalidates the conventional scale transition rules. Circumventing these challenges, we propose a numerical scheme based on phase-field fracture (PFF) modelling and failure zone (FZ) homogenization to predict the macroscale constitutive response. The upscaling rule proposed ensures convergence of homogenized post-peak responses to unique functions with increasing size of microscopic volume element (MVE), justifying its representativeness. In earlier works, the actively damaging regions defined the evolving FZ in a Cauchy or micro-morphic continuum. However, in the PFF modelling, rapid strain localization leads to excessive shrinking of the active area within the damaged band. The homogenized jump predicted based on the strain of this active zone turns out to be erroneous. Hence, we implement a modified approach wherein the FZ remains unchanged throughout the loading and is marked based on the phase field at the stage of complete fracture. The zone of the non-zero phase field representing the through crack in the MVE is the modified FZ. One may interpret this FZ as a diffused interface between two adjacent parts of the MVE. We estimate the localization width and macroscopic direction of cracking from the identified FZ and gradient of PF contours. The average strain within FZ is used to compute the homogenized displacement jump across the diffused interface. Numerical experiments demonstrate the accurate prediction of homogenized traction versus separation.

MS04-2:4 | Comparison between block preconditioner and monolithic preconditioner for iterative solution of coupled multi-field problems from generalized continuum models

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In this work, we compare two approaches for preconditioning the iterative solution of a coupled multi-field problem derived from a generalized continuum model. The model is aimed at simulating failure in quasi-brittle materials such as concrete and rocks and it couples microrotation and nonlocal damage fields with the displacement field. Solving large and sparse linear systems can be a challenge, especially when dealing with complex systems like multi-field problems. The success of iterative methods depends on the spectral properties of the system matrix, so careful construction of the preconditioner is crucial. A usual approach for the multi-field case involves using a block preconditioner based on factorization, which requires problem-specific approximations of the Schur complement and sub-block inverses.

A popular choice for these inverse approximations is the Algebraic Multigrid Method (AMG), which has proven effective in many cases. Another strategy is to use AMG on the entire system as a monolithic preconditioner, which treats the block structure inside the preconditioner during hierarchy construction. Our investigations intend to demonstrate, for the proposed problem, the usefulness of treating the whole block system inside the AMG hierarchy and hence preserve the coupling aspects of the problem.

MS04-2:5 | Microstructural characterization of fiber-reinforced cementitious composites using micro-CT measurements and evaluation of their mechanical behavior using simulations

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The mechanical properties of fiber-reinforced cementitious composites FRCC are strongly influenced not only by the matrix and fiber characteristics but also by the fiber-matrix interfaces. In this study, the correlation between microstructural characteristics and mechanical properties of FRCC, i.e., polyvinyl alcohol (PVA) fibers embedded in cement paste matrix, was analyzed through a synergistic approach of combining experiment and simulation.

The microstructural characteristics of FRCC including the fiber-matrix interface were investigated using 3D X-ray micro-CT images. The 3D FRCC microstructures were segmented into 5 phases (pores, fibers, outer products, inner products, and unhydrated phases). PVA fibers have the similar density compared with the cement paste matrix so that the grayscale values from micro-CT images are not distinct. Therefore, segmentation methods for FRCC including an artificial intelligence based approach were proposed in this study.
Using the microstructures obtained from the micro-CT, mechanical responses under direct tension were evaluated by phase-field fracture model simulations. The input modeling parameters for the multiple phases of the cement paste matrix were determined from the nanoindentation test results. Input parameters between fiber and matrix interfaces were parameterized based on the grayscale values of micro-CT images to investigate their effect on the mechanical behaviors of FRCC. The simulation confirmed that the analysis framework provides insights into the effect of microstructural features of FRCC on its mechanical behavior.

MS05: Bone mechanobiology: experimental and computational assessment across the scales

MS05-1:1 | Importance of drug order in sequential treatments against osteoporosis involving denosumab and romosozumab

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Drug treatments against osteoporosis are commonly divided into anti-catabolic and anabolic. The former act to reduce bone turnover and achieve the increase in bone mass mainly from mineralisation of the existing bone matrix. The latter increase bone mass by enhancing osteoblastic activity resulting in new bone formation. The duration of treatments is often limited to a few years due to reported side effects, but discontinuation of treatment might pose significant risk for fracture in some drugs such as denosumab. Switching to a different drug is the most commonly adopted strategy; however, it is not clear what is the best combination of a dual-drug therapy, the lapse between treatments and other parameters defining the combination that needs to be studied.
Clinical trials are long and costly and may have ethical implications that can be avoided with in-silico trials. In this work we have simulated two drug treatments: denosumab (anti-catabolic) and romosozumab (with a dual effect anabolic and anti-catabolic). We evaluated BMD gain and fracture risk by incorporating a damage model into the bone remodelling algorithm.
Our results showed that greater BMD gain is achieved by starting with romosozumab. The reason for this is that anti-catabolic treatment decreases bone turnover rate and the population of osteoblast precursors. The main action of romosozumab is to increase the proliferation of these precursors, so that their population should be as high as possible for a better efficacy of the drug. Therefore, prior administration of an anti-catabolic drug may be counterproductive to the effectiveness of romosozumab.
An optimum treatment should minimise fracture risk at the lowest possible dose to prevent adverse effects of drugs. For this reason, we propose here an optimisation procedure to obtain an optimum sequential treatment (romosozumab + denosumab) using a patient-specific model of bone remodelling including a pharmacokinetics-pharmacodynamics model of both drugs.

MS05-1:2 | Bone micro-mechanobiology of implant-femur interaction: a multi method approach combing CT and SASTT imaging with analytical mechanics

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While mechanobiology has been mainly studied in terms of vascular porosity changes and trabecular orientations, we here present a combined experimental-computational approach to explore the interplay of mechanical forces and biological structures at the scale below, i.e. at the textural orientations of the extracellular bone matrix (ECM).
As a model system, we consider developing murine femoral bone adjacent to a resorbing cylindrical magnesium implant of 1.6 mm diameter, one month after surgery. Hereby the implant is approximately located in the middle of the femur and orthogonal to the axis of the femoral shaft.
The system is documented in terms of micro Computed Tomography (μ-CT) scans, Small-Angle X-ray Scattering Tensor Tomography (SAXS-TT) and a back-scattered electron micrograph (BSE). These datasets are mutually registered, yielding a real-scale digital-twin data space which spans over multiple length scales. Hereby a general review on the creation of such a digital twin is given with methods for the identification of landmark features like the implant axis, the femoral bone axis, and cross-sectional parameters of an interpenetrating cylindrical model. In the latter, the implant is represented by the geometrical object “solid circular cylinder” and the femoral cortical bone by a “cylindrical annulus” fitted to associated voxels in the μ-CT scans.
The musculoskeletal loading acting onto the femur during physiological locomotion, is reconstructed from a pertinent inverse-dynamic model [Wehner 2010], and mapped to this geometrical model with the means of an extension to classical Bernoulli-Euler beam theory. This extension takes into account that the cross-sections vary along the femur shaft axis and thereby activate shear flows usually not considered in beam theory.
Principal and maximum shear stress directions obtained by the aforementioned modeling approach are compared to the SAXS-TT textural orientations of the ECM. This enlarges our understanding of mechanical stimulation in bone mechanobiology.
[Wehner 2010] DOI: 10.1016/j.jbiomech.2010.05.028

MS05-1:3 | Deep-learning based framework for automated mechanobiological analysis of bone response using micro-CT imaging data of mouse tibiae

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Study of preclinical animal models of osteoporosis (OP) are typically conducted using micro computed tomography (microCT) at selected bones sites and have provided invaluable insights into bone physiology and pathology. Among these, the mouse tibia loading model has contributed to the current understanding of the link between bone structure and function.
One challenge of using these models is the generation and processing of large amounts of data including image- segmentation, registration and analysis together with performing in-silico mechanical assessment using finite element analysis (FEA) to identify highly loaded bone regions. The final step in this analysis pipeline is performing statistical analyses to determine which OP intervention strategies are most effective. Manual execution of these tasks is time consuming and costly, but also makes reproducibility of results difficult due to user-specific parameters.
In this contribution, we develop a deep-learning based approach for automating the above tasks [1]. We demonstrate the performance of this approach based on the data of Sugiyama et al. 2008 [2], i.e. mice treated with different doses of parathyroid hormone (PTH) and mechanical loading (ML). We analyse tibia response both in trabecular and cortical regions both for whole bone quantities (bone area, marrow area, BV/TV) and local quantities (cortical thickness) together with automated in-silico mechanical analysis indicating bone regions experiencing highest strains.
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MS05-1:4 | Digital volume correlation resolves load-induced high articular strain foci in osteoarthritis-prone joints

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Osteoarthritis (OA) is an age-related degenerative joint disease with known mechanical aetiology1,2. The distinction between the mechanical loads essential in preserving healthy joint ageing, versus those that drive OA onset and progression remains, however, ill-defined. Here, we perform hierarchical characterisation of full-field biomechanical strains across whole tibial epiphyses in a murine OA model and normal intact joints, under physiological load.

Whole hindlimbs from OA-prone STR/Ort and healthy parental CBA mice (N=3) at ages before OA onset (10-weeks) and advanced OA (40-weeks) were subjected to in-situ physiological loading. A series of high-resolution synchrotron computed tomography images (1.45 μm/voxel) of each joint were acquired after stepwise displacement-controlled loading (European Synchrotron Radiation Facility, Grenoble, BM05-beamline). Following tomographic reconstruction, 3D strain magnitudes and patterns were quantified by digital volume correlation (DVC) across all anatomical zones (Avizo 3D, XDVC).
3D displacements and strain fields were quantified across entire tibial epiphyses with nanoscale displacement accuracy of <90nm (0.06voxels) and strain precision of <350μstrain (0.035%). We found load-induced compressive and tensile strains were effectively transferred between articular-to-metaphyseal regions in all joints. In STR/Ort joints, however, additional regionalised foci of high magnitude compression and tension were observed across articular zones, which were completely absent in all CBA joints. Global average strain quantification revealed higher tension (P=0.0001) and compression (P=0.0089) in STR/Ort versus CBA at 10-weeks. At 40-weeks, tensile but not compressive strains were higher in STR/Ort (P=0.0107). Our data indicate that altered microarchitecture in OA-prone joints is linked to detrimental strain concentration at articular regions. In healthy joints however, load-induced strains are efficiently transferred to remote epiphyseal regions. We speculate that strain patterns arising at pre-OA stages, predetermine the pathological architectural changes that arise with advancing OA. Quantification of localised, region-specific strains and correlation with shifting joint microarchitecture will aid in deciphering these pathological mechanisms.

MS05-1:5 | A multiscale bone cell population model based on a 2-state receptor model accounting for cellular responsiveness to PTH

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Bone remodeling, controlled by the interaction of osteoblasts, osteoclasts, and osteocytes within basic multicellular units (BMUs), is a dynamic process crucial for mineral homeostasis and bone maintenance. Cell communication within BMUs is regulated by the RANK-RANKL-OPG signalling pathway controlling activation and survival of osteoclasts and, due to coupling, bone formation and resorption (1). Additionally, factors such as TGF-β and parathyroid hormone (PTH), have been identified to affect bone remodelling (2).
Many mathematical models have been developed either at the whole systems scale (3) or at the bone tissue scale (4) to better understand the bone remodeling process. A major assumption in these models is that hormonal concentrations (or ligand concentrations in general) are constant and bone cell responses can be described by a simple 1-state receptor ligand model which delivers Hill type control functions. Here, we develop a multiscale bone remodeling model, where dynamic PTH glandular secretion is accounted for together with formulation of a 2-state receptor model (5, 6). The formulation of a cellular responsiveness function from the 2-state receptor model is linked to the bone cell activities in bone remodeling. Using this formulation, we investigate cases of bone diseases related to the parathyroid gland including hypoparathyroidism and hyperparathyroidism.

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MS05-2:1 | Efficient algorithmic formulation of trabecular bone remodelling using a two-scale model of trabecular bone

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In this presentation, we introduce a novel two-scale computational approach tailored to model cancellous bone remodelling. This approach offers a novel perspective on computational biomechanics by efficiently integrating meso- and macro-scale considerations. At the macro-scale, conventional principles governing one-scale continuum bone remodelling are upheld, focusing on established kinematics and kinetics. However, we depart from traditional methods by refraining from phenomenologically postulating constitutive behavior at this level. Instead, we derive it from the meso-scale.
At the meso-scale, our approach leverages computational efficiency by idealizing trabecular architecture as a truss network, dynamically adapting trabecular cross-sectional areas in response to mechanical loading. The synergy between meso- and macro-scale dynamics is achieved through sophisticated up- and down-scaling techniques.
Computational experiments demonstrate the effectiveness and computational efficiency of our proposed two-scale approach. Notably, it seamlessly captures anisotropic properties stemming from the irregular trabecular architecture at the meso-scale. Moreover, it provides a unique opportunity to directly explore various trabecular structures, acting as a virtual “magnifying glass” for detailed analysis.
The presentation will discuss the potential for further advancements, including the exploration of more complex trabecular architectures and the integration of micro-scale bone cellular activities. Through this study, we aim to inspire advancements in biomechanical research and enhance our understanding of cancellous bone remodelling processes for clinical applications.

MS05-2:2 | In silico-aided design of functionally graded porous scaffolds for bone tissue engineering

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Recent advancements in 3D printing (3DP) technologies, particularly light-based ones, have augmented the production of functionally graded porous structures (FGPSs) tailored for tissue engineering (TE) applications. However, selecting optimal architectures for specific tissue scaffolds involves time-consuming trial-and-error processes. Therefore, there is an urgent need to integrate in silico-aided procedures with 3DP methods to streamline and optimise this workflow.
This study focuses on exploiting such procedures by developing an in silico tool for the design, mechanical validation, and optimisation of light-based 3D-printed porous structures designed for bone TE scaffolds. The architectures were designed with full interconnectivity, varied pore sizes, layer pore size gradients, and porosities. Employing low-force stereolithography 3DP for its superior resolution and cost-effectiveness, quasi-static uniaxial compression tests were conducted for mechanical property assessment in low-speed analyses. Finite element models were then employed to validate mechanical and fluid flow properties, while morphological analysis aided in identifying printing accuracy and limitations. Finally, an artificial neural network (ANN) was trained to determine the correlation between the scaffolds' architecture and their mechanical properties.
Firstly, it was possible to control the printability of structures, understanding printing limitations arising from material properties (e.g., the viscosity of the liquid resin and its stiffness) and design methodology. Secondly, the developed finite element (FE) model enabled the correlation of scaffolds' architecture with their mechanical properties, predicting the elastic region of the stress-strain curve. Finally, the trained ANN facilitated the creation of functionally graded TE scaffolds with desired stiffness by selecting optimal structural properties such as pore size and pore size gradient.
The obtained data are a starting point for establishing an automated workflow to generate ad-hoc FGPS based on specifications for mechanical properties. Further works will include using the ANN to predict structural non-linear properties under large deformations (e.g., absorbed energy).

MS05-2:3 | Osteogenic control of bone mechanobiology through BMP loaded interlocked scaffolds

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Worldwide, an estimated 4M bone grafts are performed each year. While many products are available that are used for bone regeneration for small defects or non load-bearing defect filling, non-union grafts and grafts for treatment of bone metastasis of prostate cancer are the most challenging. Severe skeletal failures result in prostate cancer bone metastasis patients and these are often the reason for the morbidity of prostate cancer bone metastasis. We report the use of a novel interlocked Bone morphogenic protein 2 and 7 (BMP2 and BMP7), coated scaffold block-assembly for applications for non-union defects. Increased surface area allowed by the interlocking interfaces enhance bioactivity while maintaining appropriate mechanical integrity.

Extracellular matrix (ECM) formation is enhances in the interlocked assembly. A longer-term study up to 63 days with BMP coated scaffolds indicates a 120% increase in the elastic modulus obtained using nanomechanical evaluation. Interestingly a significant increase in the bone-related protein and osteogenesis-related Wnt-factors was observed in BMP coated scaffolds. It is to be noted that the BMP release rate in the media is about 17-days while the influence on ECM formation lasts much longer, indicating the critical role of BMPs on initial stage osteogenesis. Additional studies report effective use of BMPs in influencing fundamental osteogenic pathways while adverse effects on metastasized cancer. The novel interlocked BMP loaded scaffolds present a unique approach for tuning osteogenesis and thus impacting mechanical behavior of bone.

MS05-2:4 | The efficient numerical tool to simulate the phenomenon of trabecular bone remodeling for multiple load cases

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The observation proposed by Julius Wolff - called Wolff's law - can be described as a structural adaptation of the bone to the external forces. Thus the trabecular bone remodeling process numerical simulation has to include a very important aspect of the external load, namely the variable loads has to be taken into account. For the simulation purposes it means that the numerical tool must be able to simulate multiple load cases and the geometric form of the bone must correspond to these loads. The presented trabecular bone remodeling numerical tool enables multiple load case simulation taking into account the postulates regarding the evolution of the trabecular bone. The trabecular bone remodeling regulatory model applied to an actual three-dimensional trabecular structure requires the preparation of an appropriate numerical approach. Since the local change on the structural surface leads to global minimization of the strain energy for the whole structure, the fulfillment of both postulates requires energy distribution analysis on the structural surface. Thus, the most important role in such an approach must be played by a very efficient finite element mesh generator for structural computations as well as an efficient computational environment. In both cases, it becomes necessary to use parallel processing. So, on one hand it will be possible to repeat virtually the observations recorded on the micro-CT scans, and on the other hand, to better adjust the continuous models of the trabecular bone remodeling phenomenon. The developed software promises to simulate significant fragments of trabecular bone tissue, and as equipment develops, also structures covering the entire bone. Mesh generator performance is no longer a limiting factor nor is computing power. Technically the numerical system is .Net C# project designed with Inversion of Control paradigm design pattern that provides pluggable and extensible platform.

MS06: Structural vibration control

MS06-1:1 | Use of a hysteretic device in vibration mitigation (Keynote Lecture)

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Nonlinearities produce notable modifications of the dynamic response of mechanical systems. Nonlinearity is usually experienced as a source of unease, not to mention undesirable effects. However, recent advances make it possible to recognize that nonlinearity can also play a critical role and can even give advantageous effects [1].

Nonlinear coupling is an important phenomenon. In the case of strong nonlinearities, which characterize most of proposed nonlinear absorbers, the involvement of modes not directly excited is greater and novel phenomena occur. Here, focus is on the occurrence of novel periodic motions, that is the nonlinear system exhibits a number of resonances greater than the number of degrees-of-freedom, favouring the spreading of energy among the modes.

A standard technique to lower structural vibration of increasingly lean structures is to use elements capable of dissipating energy. The proposal to add a hysteretic element makes it possible to combine the twofold aim of increasing the structure dissipation and of introducing a strong nonlinearity. Hysteresis characterizes the mechanical behaviour of various materials and elements. With respect to viscoelastic tuned mass damper (TMD), introduced by the pioneering work by Den Hartog [2], the restoring force of a hysteretic vibration absorber combines the elastic and dissipation characteristics without the need of a damper. The modification of resonance frequencies, due to the notable dependence of stiffness and damping properties on the oscillation amplitude, easily leads to condition of internal resonance, with an increase of nonlinear modal coupling [3].

The hysteretic device, referred to is based on the restoring force of cables in flexure and it is described by the Bouc-Wen model, whose parameters are identified by experimental results. First, the case of internal resonance 1:1 which resembles the Den Hartog proposal is dealt with. In a definite excitation range, its effectiveness is similar to that of viscoelastic TMD, but in this case no typical phenomena of nonlinear dynamics are activated. Then, is the case of internal resonance conditions n:1, with $nn > 1$ which promotes a rich variety of nonlinear phenomena. In particular, the occurrence of a novel mode around the first resonance through a bifurcation mechanism involves the second mode in the response, with a beneficial effect on the vibration amplitude of the directly excited first mode.

The analysis performed demonstrated the efficiency of adding a hysteretic element to a structure, suitably tuned, for the passive control of structural vibrations.

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MS06-1:2 | A theoretical and experimental study on the optimal design of Sliding Tuned Liquid Column Dampers for structural vibration control (Keynote Lecture)

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This study proposes a passive structural vibration control strategy based on the use of a sliding variant of the well-known Tuned Liquid Column Damper device (referred to as STLCD) and examines both theoretical and experimental perspectives. The STLCD configuration consists of a U-tube container filled with liquid that can slide along a linear guide rail and is connected to the structure by a spring-dashpot system. This setup, unlike conventional fixed TLCDs, offers the flexibility of tuning for short-period systems since the spring can be used for tuning and the dashpot for added damping. However, similar to TLCDs, the STLCD also shows slightly nonlinear behavior, hence, an equivalent linear mechanical model is employed to streamline the analyses necessary for the optimal design of the device. In particular, the selection process of the optimal design parameters of the STLCD is discussed, assuming a Gaussian white noise process as base excitation, with the aim of minimizing the total acceleration variance of the structural system. To validate the introduced mathematical formulation, experimental tests are conducted at the Laboratory of Experimental Dynamics at the University of Palermo, Italy, examining both time and frequency domains. Finally, the control performance of a scaled model of an STLCD-controlled structure is evaluated against its uncontrolled counterpart and commonly used devices such as the TLCD and the Tuned Mass Damper (TMD), under harmonic excitations, providing a comparative analysis.

MS06-1:3 | Implementation of tuned mass damper control concept for integrated seismic and energetic retrofit of existing buildings

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Structural rehabilitation of existing building heritage often built without modern seismic design considerations is a critical issue in seismic prone regions of the European community, where the 40% of them is affected by moderate earthquake activity. At the same time, energy rehabilitation to enhance existing buildings energy efficiency is a key issue, since the 75% is considered energy inefficient due to aging. While seismic and energy rehabilitation have been always considered two separate problems, in recent years the scientific community is making efforts to explore integrated seismic and energy retrofitting techniques, combining into a single assessment, aiming at simultaneous benefits also pointing to a more sustainable design [1].

The study explores new possible schemes where the structural control strategy based on the tuned mass damper concept is effectively combined with suitable energy retrofitting strategies in a single intervention. In fact, while tuned mass damper ant its variations, is considered effective for mitigating the seismic risk, it is not explored in conjunction with interventions to improve buildings energy efficiency. The integrated interventions proposed are implemented on the building roof, which can be disconnected and isolated from the substructure, or rebuilt and isolated from the substructure, adding improved energy performances. Various structural solutions are investigated based on different control approaches: non-conventional TMD, large mass TMD [2], TMD with inerter [3]. The framework where the methodology for the implementation of the integrated intervention, comprising its optimal design and the structural and energy assessment, is described. Numerical simulations on a typical example of the Italian building stock are presented where the different integrated strategies are compared and a procedure to select the best integrated intervention is highlighted.

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MS06-1:4 | A fundamental study on active vibration control of cross-laminated timber members

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Cross-laminated timber (CLT) is a structural member composed of layers of wood glued together perpendicular. When compared to common concrete or steel structures, CLT structures are considered lightweight, which makes them more prone to vibrations that can cause discomfort to people inside buildings made of CLT. It is therefore desirable to reduce the vulnerability of CLT components to vibration by implementing smart measures, such as passive or active control mechanisms, without changing the design of the CLT structure. This paper presents a study on the feasibility of active vibration control of CLT panels based on laboratory tests and mathematical modelling. In the laboratory tests, external excitation is applied by electrodynamic shakers. The resulting CLT-shakers assembly is an electromechanical system, i.e., a system composed of a mechanical and an electromagnetic subsystem, which interact through coupling elements. First, system identification is performed to obtain the parameters composing the CLT-shakers system, which are both mechanical (such as mass, damping and stiffness elements) and electromagnetic (such as inductance and resistance) in origin, where a mathematical model of the whole electromechanical system is compared with experimental data of the multi-input multi-output system excited by both shakers with independent white noise inputs. Active vibration control depends on an external power supply and requires a set of actuators and sensors. In this study, active vibration control of the CLT panel is performed by using one of the shakers for excitation and the other one for control. A setup where the target point of vibration mitigation and actuator are not positioned in the same location in the CLT panel is used, known as non-collocated control. This non-collocated configuration poses additional challenges in the control process and will be examined in more detail. Both Velocity Feedback and Optimal Control are conducted, presenting two different approaches to non-collocated vibration control.

MS06-1:5 | Nanoscale modeling for structural vibration control

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Smart ultrasmall devices offer fascinating opportunities for structural control since they enable extremely accurate and efficient real-time monitoring of parameters such as strain, stress, vibration and temperature [1-2]. Due to their reduced size, small-scale sensors allow for placement in hard-to-reach areas of structures while nanoactuators can conveniently operate according to the sensor feedback. Nanoscale energy harvesters can convert structural vibrations into electrical energy, supporting self-powered structural monitoring without external power sources. Additionally, NEMS-enabled structures can be integrated into Internet of Things networks for remote monitoring. To properly model these nanodevices, accurate assessment of size effects is needed. The work investigates dynamics of nano-systems, exploiting non-conventional approaches of nonlocal continuum mechanics [3-4]. Modelling of size effects is achieved adopting an integral approach based on a stress-driven convolution [5]. The relevant problem is reverted into an equivalent differential formulation. Fundamental natural frequencies are numerically assessed for selected case studies of current nanomechanical interest, providing benchmark results for modelling and design of small-scale devices.

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MS06-2:1 | Vertical vibration control of a cross-laminated timber plate through fluid inerter

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The more recently introduced inerter fictitiously increases the mass of the system to which it is connected, creating a mass amplification effect. This property makes it particularly attractive for use in mass-dependent devices employed in structural vibration control, i.e., the prevention and mitigation of vibrations. Conceptually, the inerter can be viewed as a two-terminal device, where its internal force is directly proportional to the relative acceleration between the two terminals. The constant of proportionality, called inertance, is the apparent mass generated, which can be notably large. In practical applications, it is effectively utilized in combination with springs and dashpot dampers, giving rise to Tuned Inerter Dampers as an alternative to traditional Tuned Mass Dampers (TMDs). Among the various prototypes of inerters, fluid inerters stand out as simpler to design and develop, with less pronounced parasitic effects compared to their mechanical counterparts. However, their inherent nature makes them susceptible to nonlinearities, such as fluid viscous shear friction, pressure drops, and other tribological effects. To mitigate these undesirable nonlinearities, a proposed solution is to connect the fluid inerter to the structure through a spring-dashpot damper element, referred to as flexible connection. To evaluate the practical feasibility of this type of connection, a novel experimental test is presented, focusing on a fluid inerter used for vibration control in a cross-laminated timber panel subjected to vertical vibrations. In addition, the control performance of the fluid inerter is compared with that of a conventional TMD, providing insight into its efficiency in controlling multi-modal structures. Finally, optimization procedures are employed to identify the connection parameters of both the TMD and the inerter, aiming to improve their performance in effectively controlling the structure.

MS06-2:2 | Stochastic parameter identification of a fluid inerter-based control device

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In the last decades, the topic of structural control has gained increasing attention in structural design due to the fact that structures are becoming increasingly slender and therefore more prone to vibrations. In the context of passive control, fluid inerter-based control systems represent a novel development with great potential. Their main advantage is that the apparent mass (called inertance) which is able to reduce the displacement and/or acceleration of the structure, is orders of magnitudes higher than its physical mass.

In order to fully explore and optimize the performance of the fluid inerter-based control device, a numerical model that accurately represents the structural behavior is required. In civil engineering applications, the frequency range of interest is usually low, meaning that any non-linear effects that may occur play a major role and cannot be neglected in the numerical model. The selection of model type is intrinsically related to the determination of its associated parameters such that the model predicts the measured performance. Despite the high accuracy of the established numerical model, there may still be a gap between the model and the measurement due to the presence of uncertainties in the parameters. The identification of model parameters in a stochastic setting provides a means to understand and reduce the discrepancies between model and real behavior.

In the present study, the so-called subset simulation method, which has originally been developed for reliability analysis, is used for the stochastic identification of model parameters. It is shown that in this framework, issues such as non-uniqueness of the solution can be addressed and information about the spread of parameter values can be gained to obtain a more realistic model, which represents the real structural behavior more accurately.

MS06-2:3 | Water-tank metabarriers for seismic surface waves attenuation

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This work proposes periodic water-tank metabarriers for attenuation of seismic surface waves. The dispersion properties of the infinite metabarrier are investigated by means of the Bloch-Floquet theory for different dimensions and cross-section geometries of the unit tank. The surface wave modes are identified by introducing the sound cone and making use of a pertinent energy parameter. Next, dynamic analyses of a finite metabarrier are carried out in frequency and time domains, validating the proposed concept.

MS06-2:4 | Thermoacoustic Fano-based bistable energy converters: a novel paradigm of thermodynamic cycles for waste-energy recovery

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In this work, we propose a radically new approach for thermo-acoustic energy conversion based on the concept of Fano-based bistable systems. The proposed device, in its simplest version consists of a bilayer polymeric cylinder with harder core and softer and thinner shell. The heat source enforced at the core-shell interface induces thermo-mechanical stress fields. The stress field causes the occurrence of wrinkling patterns in the shell and the release of acoustic energy by a snap-through-buckling mechanism. We show that, when the shell is acoustically resonant at a specific frequency, the synergetic interplay of snap-through and Fano-resonances is capable of producing high amplitude and long-lasting pressure oscillations. In other words, under specifics conditions, the synergetic interaction between wrinkling instabilities and Fano resonance is able to extract mechanical energy from the heat source. The efficiency of the system in converting heat-into-work under resonant conditions is at least 6 times higher than that out of resonance. Notably, for a temperature difference of 1 K between the heat source and the surrounding water, the system may reach a conversion efficiency above 70 % of the theoretical Carnot efficiency. The so-generated mechanical oscillations can be converted in electrical energy for instance by using sound-to-energy converting systems such as conventional loudspeakers. The characteristics of the heat source have been selected to be representative of low-grade thermal sources (e.g. waste-heat, intermittent sources) abundantly available in natural, and industrial contexts. Importantly, the systems may be adapted to many different geometries spanning from the proposed core-shell cylinders in which the heat source can be either inside the tube (for instance an exhaust gas/liquid outlet) or outside the tube, to plates (like a solar panel system). This novel concept may lay the foundation of a new class of devices able to recover waste energy from a large variety of cases.

MS06-3:1 | Multifidelity reliability and sensitivity analysis

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Due to the advancing possibilities of modeling, computing technology and data acquisition, today a variety of simulation models and data is available that is nearly unmanageable. This diversity in turn opens new possibilities for the development of computational methods in which information from different sources and of different quality is merged to further increase the efficiency of computational procedures. This is particularly important for reliability estimation and sensitivity analysis, which not only require many model evaluations, but also a careful consideration of the mutual influences between model parameters and model refinement on the one hand and the quality of the estimation on the other.

Several multilevel and multifidelity information fusion methods are presented and compared for the computation of the failure probability in the context of reliability assessment. Furthermore, the potential of machine learning to provide surrogate models and to guide the information update procedure is investigated.

MS06-3:2 | Active mass dampers for cross laminated timber floors - comparison between experimental and numerical investigations

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The particular challenge for civil engineers in the structural design of timber floors to reach the requirements for serviceability is well known and normally decisive for the dimensioning. Extensive modeling of timber slabs in combination with active vibration elements has shown that, compared to simple passive vibration dampers, a significant improvement in vibration behavior is possible also with a considerable reduction in mass. The interpretation of these results suggests to intensify the research in the field of active vibration control of slabs in residential buildings. The active damping systems are intended to positively affect slender slab structures and their vibrational characteristics. The current work includes the vibrational behavior of cross laminated timber floors and how these characteristics can be affected. The dynamic parameters are determined for a single-span cross laminated timber slab, which can be used for the following investigations with active control. Comparative values of different control systems are already available. The current control systems use the acceleration values of the continuous vibration measurement for the counteraction and levels of intensity. Random and dynamic motions caused by people moving on the slab systems increase the difficulty to solve this task using common control techniques. Both acceleration feedback as well as velocity feedback are tested and a significant reduction in vibration acceleration of the timber slabs can be reached. Important for the validation of the results are the analytical investigations and the software-supported verification of the measurement data according to the vibration excitation including active damping. Implementation of active control in the FE-simulations and comparisons between experimental and numerical investigations are currently in progress. This enables the comparison of results from different types of excitation and particularly the very important person-induced excitation. The aim is the possibility to use the FE-simulations and analyze entire slab systems with active vibration control.

MS06-3:3 | Experimental investigation of track nonlinear energy sink with rotational mass using real-time hybrid simulation

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Mass dampers are a widely accepted control technique for seismically-excited tall buildings. When these mass dampers are optimally tuned to the primary natural frequencies of buildings, the structural responses (i.e., floor displacements and accelerations) can be effectively mitigated. However, the tuned mass dampers may introduce a large displacement when buildings are subjected to intensive earthquake loadings. To address this shortcoming, some researchers suggested adding nonlinear restoring forces to mass dampers, such as forming a track nonlinear energy sink. Still, a sufficiently large mass in this nonlinear mass damper is a critical issue. Therefore, this research develops a track nonlinear energy sink with a mass moment of inertia. The proposed mass damper not only has the feature of nonlinear restoring forces but also increases effective mass by rotational components. This study first derives the equation of motion for a building with the proposed mass damper. A design method based on the frequency-domain input-output relationship is established. To further verify the damper performance, a prototype track nonlinear energy sink with a mass moment of inertia is fabricated and experimentally evaluated by real-time hybrid simulation. The experimental results exhibit that the proposed mass damper outperforms the conventional track nonlinear energy sink. Moreover, only adequately effective mass, i.e., sufficient momentum to maintain static friction, is feasible to generate control performance against input ground motion.

MS06-3:4 | An investigation of the behavior of reinforced concrete coupling beams

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The use of coupled shear walls has been one of the potential options as an earthquake-resistant system in reinforced concrete high-rise buildings in recent times. When the coupled shear walls are subjected to earthquake motion, energy dissipates in the coupling beams depending on the design at the base of the shear walls. This paper aims to simplify the behaviour of coupling beams with feasible boundary conditions using analytical, numerical, and experimental analyses. Considering Galano and Vignoli's (2000) scaled model as a reference point, analytical equations have been developed and validated with numerical analysis using ATENA 2D 2006 software to study the behavior of coupling beams. Nonlinear static pushover analyses have been considered as one of the methods used in this software. A series of specimens were cast to evaluate the actual response of a prototype model, with an Lw1 and Lbr equal to 200 mm, Lw equal to 500 mm and a thickness of 100 mm. Based on the analytical results, the prototype model can be considered an appropriate scale model to conduct numerical and experimental investigation of the behavior of the reinforced concrete coupling beam. Numerical analyses based on feasible boundary conditions render good approximations to experimental deflections and thus give confidence in the use of this technique in the design office.

MS07: Stochastic mechanical behaviors of quasi-brittle materials

MS07:1 | Bayesian inference of constitutive law parameters for crack localization using full-field displacement measurements

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Physics-based models of mechanical structures are widely adopted for assessing and predicting the behaviour of structures. In the context of structural mechanics, the constitutive law that describes the stress-strain relation forms an important modelling component, which suffers from a considerable amount of uncertainties. These uncertainties primarily arise due to the inherent simplifications and assumptions placed in favor of facilitating the modeling process. Bayesian techniques have been proven to be effective for tackling uncertainties associated with the identification of material model parameters and quantifying the confidence level that can be associated with the placed modeling assumptions.
We present a Bayesian framework for the identification of constitutive parameters of quasi-brittle materials suffering strain localization effects, via the use of full-field displacement measurements. The proposed framework explores the idea of force-based Finite Element Model Updating (FEMU-F), which relies on measured full-field displacements and aggregated forces. In particular, the scheme takes advantage of FEMU-F, in contrast to the conventional FEMU, where the information from full-field displacements is directly incorporated into the model. We also address the uncertainties involved in the measured displacements, by treating them as additional unknown variables to be identified, alongside the constitutive parameters. These unknown variables collectively form the inputs to a well-defined objective function, which forms the basis for the Bayesian inference problem. To efficiently solve this Bayesian problem, we employ a variational Bayesian scheme that relies on approximate posteriors represented as multivariate normal distributions. We demonstrate the proposed framework for the parameter identification of a nonlinear path-dependent gradient damage constitutive law, which exhibits strain localization and softening behaviour. The first example illustrates the effectiveness of the inference procedure, highlighting the advantage of FEMU-F in incorporating information about cracks. The second example demonstrates a sub-domain analysis suitable for inferring models with limited domain knowledge; e.g. with uncertain Dirichlet boundary conditions.

MS07:2 | FE-analysis of long-term performance of an epoxy bonded anchor based on nanoindentation and CT-scan

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Epoxy-based adhesive mortars are applied as bonding materials for the heavy duty fastener in buildings and constructions worldwide. The long-term behavior of the adhesive mortars is a significant influencing factor on the sustained load and lifetime of bonded anchors. An adhesive mortar is a heterogeneous material consisting of resin and fillers. For the analysis of the long-term performance of the bonded anchor, it is fundamental to understand the long-term behavior of the bonding material on the microscale. This contribution presents a novel prediction approach for the long-term load capacity of the epoxy-based bonded anchor by using nanoindentation and FE-simulation. The long-term mechanical properties of the adhesive mortar were measured by using the precise nanoindentation technology on the micro level. Based on the experimental nanoindentation results, the numerical long-term time-independent material parameters were characterized in a concrete model by means of stochastic FE-simulation. For analysis of the imperfection effect of a real bonded anchor, the nanoindentation was employed on the micro level to investigate the error load transfer on the interface between mortar and concrete drillhole without drill-hole cleaning. On the macro level, the macroscale defects of an installed bonded anchor were found by using the computer tomography. It is demonstrated that the FE-model based on the nanoindentation results can correctly predict the long-term performances of a bonded anchorage system.

MS07:3 | Investigation of installation effects on the fracture behavior of adhesively bonded joints

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Joining dissimilar materials to create layered structure enables lightweight, customized designs for complex shapes and specific design requirements that optimize the performance of each material in the structure. An enabling technology for joining dissimilar materials without increasing weight and which overcomes many of the limitations of traditional joining methods is adhesive joining. Adhesive joining uses a polymeric material (adhesive) to bond the two dissimilar materials (adherends) such that the adhesive provides strength and stiffness to the structure. The bondline behavior between the two materials is a critical component in structural reliability and the installation process directly impacts the macroscale performance of an adhesive joint.
It is well established that the surface preparation of the adherends and the application of the adhesive lead to microstructural features and defects in adhesively bonded joints and that this resulting microstructure dictates macroscale mechanical behavior. While the microstructure significantly influences the in-situ macroscale performance, probabilistic characterization of the feature and defect distributions for varying installation conditions and the correlation to macroscale properties are lacking. Peridynamics offers a computational solution to rapidly generate stochastic models from probabilistic distributions of microstructural features and subsequently simulate progressive damage under loading.
A methodology has been developed to generate probabilistic distributions of features (including the surface roughness profile) and defects such as voids from images and to formulate peridynamics models from these distributions. Peridynamics analysis is then performed to simulate progressive damage due to the microstructural defects to statistically correlate microstructure to macroscale behavior. This method will be presented along with validated demonstrations based on physical test data for composite to metal joining.

MS07:4 | Scaling the unscalable: bridging stochastic discrete mesoscale simulations with analytical modeling for the statistical strength of concrete

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Mesoscale discrete models, particularly those resolving large mineral grains via tessellation, excel in depicting realistic crack patterns and nonlinear responses of concrete-like materials under mechanical stress. These models excel in portraying progressive damage, inelastic deformations, and energy dissipation, standing out as close approximations for the response of laboratory-sized structures However, adapting these models for real-sized infrastructure is computationally challenging: the sheer number of grains in larger volumes hinders processing on standard computers. Techniques like grain coarsening and selective modeling have been employed to address this.
This presentation showcases an efficient implementation of a damage-based mesoscale discrete model, validated against concrete dog-bone specimen tests. The model accurately matches the response characteristics of specimens, maintaining 2D shape similarity and constant thickness. However, it falls short in fully capturing the experimentally observed strength dependence on structural size, attributed to the model's inability to fully account for statistical size effects due to random material property fluctuations. By modeling material parameters as autocorrelated random fields, we achieve a closer fit to experimental data, though predictions for sizes beyond 2 meters remain unfeasible due to the 2D plane stress simplification and the complex nature of stress redistribution processes.
We propose an analytical model to compute exceedance probabilities over spatially varying thresholds, extending our previous work on extremes of averaged random fields. This model, through the analytical

derivation of effective strength as a sliding average of a random field, allows for predictions of strength in larger structures with correct asymptotic behavior, bridging the gap to classical Weibull statistics. Our findings suggest this approach not only matches the mesoscale simulation results but also provides a viable pathway for predicting larger structure strength, underscoring the potential of mesoscale modeling in overcoming computational and theoretical challenges in the field of concrete mechanics.

MS07:5 | Simulation of multivariate Gaussian random fields considering nonlinear probabilistic dependencies and multi-spatial variabilities

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The inherent variability and imperfections in materials lead to randomness in engineering structures, greatly affecting structural stochastic response analysis and safety assessment. Therefore, it is essential to establish the rational modeling and precise simulation of random sources. The uncertainty in random sources is characterized by three aspects: the randomness of individual variables, the probabilistic dependence among multiple variables, and the spatial correlation of random variables. There are already some models that can effectively describe individual aspects. However, quantifying uncertainty in all these three aspects simultaneously remains a significant challenge. A novel method is proposed for simulating multivariate random fields, which can satisfy each spatial autocorrelation and arbitrary copula dependency given in the modeling condition. The analytical expression for the function regarding the spatial autocorrelation coefficient of variables is derived firstly. The numerical implementation procedures for simulating multivariate fields are introduced. The efficacy of the proposed method is validated with engineering application examples. The results demonstrate the ability of the proposed method in simultaneously capturing spatial parameter variability and probabilistic dependencies. This method furnishes refined stochastic input data for advanced structural stochastic response analysis and safety evaluations. The approach can be extended to simulate non-Gaussian random fields.

MS08: Instabilities at various scales: modelling, analysis and design

MS08-1:1 | On the effects of the precritical nonlinearities on buckling of flexible systems (Keynote Lecture)

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This talk concerns the analysis of the effects of high flexibility on buckling and post-buckling of beams and beam-like systems. Preliminary, the Feodosiev system [1], consisting of a planar inverted pendulum, axially soft, is analysed in the nonlinear field. It is shown that, when the axial stiffness of the rod is lowered, the bifurcated paths detach from the non-trivial fundamental path, thus explaining the disappearance of buckling [2,3].

Successively, the lateral buckling of a highly flexible fixed-free beam, subjected to bending in a principal inertia plane, is investigated [4]. A 1D exact polar continuum model, internally constrained, is used. The nonlinear, nontrivial path is determined, in which the beam undergoes large in-plane displacements. Then, the model is linearized in the out-of-plane and twist displacements, to capture the critical points at which flexural-torsional buckling manifests. Notably, the relevant linear boundary value problem is ingeniously tackled through an analytical-numerical approach, strategically exploiting linearity. The study unveils the crucial role of precritical deformations, showcasing their propensity to augment critical loads compared to classic theory assumptions, thereby positively influencing the buckling process. These findings resonate with the existing literature concerning axially soft compressed beams, albeit via a distinct eigenvalue divergence mechanism.

The implications of the results extend beyond mere validation, suggesting further explorations concerning loading condition interactions, nonlinear analysis, imperfection sensitivity, constitutive law modelling, and innovative buckling suppression mechanisms. To this end, a paradigmatic reverse pendulum, embedded in a 3D space and grounded with a Cardanic joint, could be used from preliminary investigations.

This research paves the way for a deeper understanding of bifurcations from non-trivial path in the presence of large precritical deformations, offering a rich landscape for future works.

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MS08-1:2 | Variational criteria for extreme values of the stiffness of proportionally loaded structures as solutions of an inverse problem (Keynote Lecture)

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Stiffness is a key term of structural mechanics. The same applies to the adjectives stiffening and softening in the context of structures subjected to proportional loading. In the course of the loading process, originally stiffening (softening) structures may become softening (stiffening) structures. This occurs at the unknown load level at which the stiffness of the structure concerned attains a maximum (minimum) value. Extreme values of the stiffness of proportionally loaded structures are points of inflection of their mechanical behavior. Therefore, it is astonishing that analytical criteria for stiffness maxima and minima of such structures do not exist. In recent publications it has been claimed that points of inflection of eigenvalue functions of a special linear eigenvalue problem in the framework of the Finite Element Method (FEM) mark extreme values of the stiffness of proportionally loaded structures. The task of this lecture is to present the scientific foundation of this assertion in the form of criteria for stiffness maxima and minima based on variational calculus. This amounts to the solution of an inverse problem, with the mentioned numerical results as the observed effect and the sought variational criteria as the unknown cause. In general, analytical solutions for extreme values of the stiffness of proportionally loaded structures are inaccessible. Nevertheless, knowledge of their scientific basis is not only a fundamental scientific value in its own right, but also enhances the understanding of the intricacies of FE analysis for numerical determination of the load level of stiffness maxima and minima.

MS08-1:3 | The behaviour of thin composite plates with extension-bending coupling under harmonic compressive load

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The investigations were made on thin plates made of laminate with a layer arrangement where extension-bending mechanical coupling exists. The plates under analysis were subjected to in-plane compressive harmonic load. The equations of motions describing the plate's deflection in time were derived analytically considering classical plate theory employing the Galerkin method. The damping was also included. To check the correctness of obtained results using the proposed analytical-numerical the finite element method was employed. The numerical model was prepared, and the obtained from both methods results were compared. Different parameters describing harmonic load, i.e., the mean value and amplitude, were assumed. In all analyzed cases, the mean value of harmonic load had the compressive character and was in the range from 0 to critical static buckling load. The amplitudes were assumed in such a way that the maximal load could be even higher than the buckling static load or/and the minimal load value could have the tension character. The plate's behavior was analyzed based on phase portraits and Poincare maps, assessing if they have periodic or chaotic behavior. The obtained results show different behavior of such a plate depending on the amplitude and mean value of harmonic excitation load. It could mean that such structures with proper dimensions could be used in microelectromechanical systems (MEMS) as sensors that generate energy and give different signals depending on excitation load parameters.

MS08-1:4 | Large displacement analysis of angle-ply beam-type structures considering shear deformation effects

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University of Rijeka, Croatia

This work introduces a shear deformable beam model designed for the nonlinear stability analysis of laminated beam-type structures. Each wall of the cross-section is symmetric and balanced angle-ply laminate. The incremental equilibrium equations for a straight thin-walled beam element are derived within the framework of updated Lagrangian formulation and the nonlinear displacement field of cross-sections, which accounts for the restrained warping and the large rotations effects. Throughout the analysis, Hooke's law is assumed to be valid. The shear deformable beam theory incorporated in this model addresses the flexural-torsional response of a composite beam. It also considers the coupling between bending and non-uniform torsion, particularly when dealing with non-symmetric cross-sections. Cross-section properties are calculated based on the reference modulus, allowing for the modelling of various angle-ply laminates. The accuracy and reliability of the proposed numerical model were validated through verification on benchmark examples. The results obtained affirm that the model is free from shear locking issues, indicating its effectiveness in capturing the behaviour of laminated beam-type structures under different types of loads and support conditions.

MS08-2:1 | Reversible energy absorption: harnessing sequential buckling in mechanical metamaterials

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The advent of additive manufacturing allows the design of increasingly intricate mechanical metamaterial lattices for enhanced engineering performance. In structural systems that absorb energy and shield a more valuable structure, mechanical properties with a quasi-zero stiffness (QZS) immediately after exhibiting a high initial stiffness, can ensure that a desired amount of energy may be absorbed within a limited displacement. This limits the stress transfer to the valuable structure while the absorption system has a considerably reduced structural volume compared to conventional systems. Presently, a mechanical model, comprising rigid-links and springs, is formulated that generates a system of nonlinear algebraic equations with the aim of simulating the elastic deformation of a series of deforming cells of the lattice structure. Under loading, the structure switches deliberately between conventional material behaviour (with a positive Poisson's ratio) to that exhibiting auxetic behaviour (with a negative Poisson's ratio) through a sequence of snap-through instabilities within individual lattice cells. The equations are solved using numerical continuation techniques and the resulting sequence of instabilities may be controlled to maintain the load in the QZS zone while the necessary energy quantity is absorbed and elasticity is maintained. This is a departure from the usual paradigm where such structures tend to be sacrificial and introduces the feasibility of such structural elements being redeployable and reusable that were previously single-use, which could be advantageous in quite diverse applications within different branches of engineering.

MS08-2:2 | On the capability of gradient elasticity models to predict instabilities in Fermi-Pasta-Ulam softening chains with short and long-range interactions

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This paper is devoted to the static bifurcation of a nonlinear elastic chain with softening and both direct and indirect interactions. This system is also known as a generalized softening FPU system (Fermi-Pasta-Ulam nonlinear lattice) with p=2 nonlinear interactions (nonlinear direct and second-neighbouring interactions). The static response of this n-degree-of-freedom nonlinear system under pure tension loading is theoretically and numerically investigated. The mathematical problem is equivalent to a nonlinear fourth-order difference eigenvalue problem. The bifurcation parameters are calculated from the exact resolution of the fourth-order linearized difference eigenvalue problem. It is shown that the bifurcation diagram of the generalized softening FPU system depends on the stiffness ratio of both the linear and the nonlinear parts of the nonlinear lattice, which accounts for both short range and long range interactions. This system possesses both a saddle node bifurcation (limit point) and some unstable bifurcation branches for the parameters of interest. We show that for some range of structural parameters, the bifurcations in (n-1) unstable bifurcation branches prevail before the limit point. In the complementary domain of the structural parameters, the bifurcations in (n-1) unstable bifurcation branches prevail after the limit point, which means that the system becomes unstable first, at the limit point. At the border between both domains in the space of structural parameters, the bifurcation in (n-1) unstable bifurcation branches coincide with the limit point, with an addition unstable fundamental branch. This case is the hill-top bifurcation, already analysed by Challamel et al. (2023) in the case p=1 interaction. The paper also discusses the capability of continuous gradient elastic systems to capture the bifurcation parameters of the discrete system.

Challamel N., Ferretti M. and Luongo A., Multi-degenerate hill-top bifurcation of Fermi-Pasta-Ulam softening chains: exact and asymptotic solutions, Int. J. Non-linear Mech., 156, 104509, 1-11, 2023.

MS08-2:3 | Interfacial phenomena in the lateral-torsional instability of sandwich beams

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Lateral-torsional instability characterizes beams subjected to bending about the major axis that unstably shifts into a combination of bi-axial bending and twist. Opposed to the buckling and wrinkling of sandwich structures, which were extensively investigated in the past three decades, the lateral-torsional instability of sandwich beams and the resulting evolution of interfacial phenomena typical to such layered configuration were not. In that context, the lateral instability of such sandwich beams and the interfacial mechanisms it involves define open questions that are addressed here.

The study explores the evolution of interfacial phenomena under lateral-torsional instability of soft-core sandwich beams. Due to the layered structure of the sandwich beam and the significant differences in thickness and elastic moduli of the layers, the transfer of tractions across the core's interfaces is essential to this unique structural form. The lateral-torsional instability, which drives the sandwich beam into a completely new, un-designed, and off-optimal regime, immediately impacts all aspects of the response, including the interfacial response. The sudden instability is expected to be involved with significant amplification of the interfacial shear and out-of-plane normal tractions, potential degradation of the bond, or even delamination and failure of the composite beam. The quantification of such mechanisms is at the focus of the current investigation.

The investigation of this aspect of lateral-torsional instability adopts an analytical methodology and combines geometrically nonlinear analysis with a high-order torsional sandwich beam theory. The latter integrates the rich stress and deformation fields in the compliant core into the analysis. Numerical results obtained by the analytical model look at the interfacial tractions before, at, and after the point of instability and into their effect on the composite structure. The presentation will look into these effects, aiming to assess the impact of lateral instability on the performance of soft-core sandwich beams.

MS08-2:4 | A multi-layered structural approach to stability of orthodontic brackets

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This research investigates the stability of orthodontic bracket structures and the integrated bracket-adhesive-tooth structural system. In particular, the investigation focuses on the stability structural debonding failure of such orthodontic brackets. In that context, it applies structural concepts of geometrical nonlinearity and interfacial instabilities to investigate a fundamental problem in orthodontic therapeutic treatment.

Orthodontic braces are a common treatment addressing both medical and aesthetic needs. The orthodontic system consists of brackets that are bonded to the teeth with a layer of adhesive and a wire that connects them. Like any layered structure, the Tooth-Adhesive-Bracket (TAB) system is exposed to instability in the form of delamination, detachment, or separation failure. Such failure impairs the effectiveness of the therapeutic process and requires the attention of both the patient and the physician. The available body of knowledge found in the literature with regard to debonding failure is mostly based on experiments and models that focus on the stability strength of the system. Models that address the structural stability of the system and the potentially unstable evolution of the failure are missing. This research relies on an analytical approach and formulates a 2D nonlinear structural model that describes and tracks the stability of the debonding failure in orthodontic brackets. The model combines a high-order theory for the representation of the compliant layer of adhesive and cohesive interfaces that introduce the spontaneous evolution of interfacial failure. Quantitative results obtained through numerical solution of the nonlinear governing equations demonstrate the capabilities of the model and highlight the unstable nature of the failure mechanism. The study establishes an analytical foundation for the quantitative analysis of the instability, gains insight into the nature of the detachment failure, and mechanistically explains the driving forces in the failure mechanism.

MS08-2:5 | Buckling load of an asymmetrically supported 3D column

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This contribution presents a novel exact solution for the buckling load of an asymmetrically supported 3D column. The equations that form the basis for our exact solution are taken from the pioneering work of J. C. Simo (1985). In the first part, we present the axioms and basic equations of the 3D beam model, which are then linearized around the primary equilibrium configuration. In the second part, we explain the solution procedure and finally present an illustrative example. In the illustrative example, we focus on a straight column with a constant cross-sectional area. We show how different boundary conditions and their spatial orientation with respect to the cross-sectional plane affect the buckling load of such a column. This means that we can determine the buckling load of a column which is not supported symmetrically in the directions of its principal axes. The presented solution is useful when we want to evaluate the bearing capacity of a column that cannot be designed based on the minimum buckling load due to technical, spatial or other constraints.

MS08-2:6 | Test and design of fabricated steel I-profiles under compression

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Fabricated I-profiles – especially those that fall outside the range of more common catalogued sections – can exhibit behavior that is poorly accounted for by existing design methods. This observation is particularly common in hybrid profiles, where the web and flange are made of different grades or types of steel. To fill some of the gaps in existing experimental literature, compression tests were conducted on twenty stub columns. The tests include hybrid and homogeneous sections with stainless-steel and carbon steel covering a wide range of values for sectional slenderness. Strength predictions from the effective width method, direct strength method (DSM), and continuous strength method (CSM) are then compared. As found in past investigations, the general form of the DSM provides overly conservative estimations of the compressive strength when the cross-section exhibits substantial post web local buckling reserve leading to yielding in the flanges, with little flange deformation. In this case, a modified form of the direct strength method was recently proposed to expand the applicability of the technique to a greater subset of fabricated I-profiles. With these tests added to the available experimental evidence, the recently proposed modifications to design methods are evaluated. This theoretical and experimental work advances understanding of which design methods are most appropriate to employ for fabricated and hybrid sections under pure compression.

MS08-3:1 | Stability and bifurcation in nonlinear mechanics

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The analysis of stability and bifurcation is studied in nonlinear mechanics with dissipative mechanisms: plasticity, damage or fracture. The description of the behaviour is based on definittion of a set of internal variables. This framework allows a unified description of the material behaviour via two potentials: the free energy (for reversible part) and the potential of dissipation to describe the irreversibility. In the case of standard generalized materials the internal evolution is governed by variational inequalities which depend on the mechanism of dissipation. These inequalities are obtained under energetic considerations in an unified description based upon energy and driving forces associated to internal parameters evolution. Criteria for existence and uniqueness of the system evolution are then deduced. Examples are presented for plasticity, fracture, delamination and damaged materials, on specific geometry and external loading parameters.

MS08-3:2 | Closed-form solutions for the elastic-plastic buckling design of external pressure vessels

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The buckling phenomenon represents one of the main failure modes observed in pressure equipments, due to the thinness of the shell structures involved and the compressive stresses stemming from standard loads such as external pressure. Some methodologies exist for the buckling design of pressure vessels, assembled in codes such as the ASME Boiler and Pressure Vessel Code (BPVC) or the French CODAP. These rules are either analytical but limited to a certain range of validity, or in the form of recommendations for performing finite element analyses.

In view of this, the objective of the present study is to provide a purely analytical methodology for the elastoplastic buckling analysis of a complete equipment under external pressure, made up of a cylindrical shell and semi-ellipsoidal ends, allowing thus for a reliable and efficient design. First, original closed-form solutions are obtained for the two separate parts. Corrections are made so as to take account of the connection between the assembled components. Then, different buckling scenarii can be envisaged. The buckling response of the pressure equipment may initially involve either the cylindrical shell or the ends, depending on the respective critical pressures. In both cases, buckling may be elastic, plastic or occur intermediately at the threshold pressure, within the so-called continuum of bifurcation points. An analytical tool is finally built, which enables to determine the buckling type but also the critical pressure expected in practice, after comparing all the possible scenarii. This predictive tool makes it possible to obtain very efficiently mappings of the buckling types and critical pressures by varying any geometric and/or material parameters, for optimization purposes. It is first validated by comparison with numerical finite element computations carried out on complete equipments, and then confronted to the results obtained with the use of the French CODAP recommendations.

MS08-3:3 | Propagating instabilities in collapsible tubes of nonlinear elastic materials

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The proper functionality of a human body relies on several continuous physical processes, many of which are carried out through biological ducts/tubes. For instance, veins, arteries and airways are natural conduit systems where blood and air are conveyed towards them respectively into the human body. Previous studies have shown that those tubular components are prone to collapse under critical conditions of internal and external pressure, resulting in malfunctioning of main physical processes. This coupled problem of flow through collapsible biological tubes has been studied for several decades through extensive numerical and experimental work. In the present study, the actual coupled fluid-structure problem is simplified by examining the response of elastic tubes prone to collapse under uniform external pressure, emphasizing on nonlinear material behavior. The problem is approached numerically using Abaqus/Standard for analyzing tube models with values of D/t ratio ranging from 12 to 30 and considering different nonlinear elastic material properties. Material behavior is described using (a) a power-law constitutive model that follows deformation theory of plasticity and (b) hyperelastic models. The main purpose of the paper is to examine whether a small deviations from linear elastic behavior is able to cause a localized collapse pattern and trigger buckle propagation. Elastic tubes with biological material properties are used. Results from three dimensional (3D) and two-dimensional (2D) models are obtained and compared. The numerical results show that localized collapse and propagation is possible to occur in tubes made of nonlinear elastic material.

MS08-3:4 | Shape grammar for optimisation of perforated plates subject to buckling

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Steel plates are employed in many structural forms such as the webs and flanges of beams and columns, rack sections and bridge girders. These plated structures are often perforated for ease of manufacture (e.g. cope holes), service (e.g. passage of pipes) or for aesthetic purposes (e.g. cladding). The addition of perforations can also be structurally beneficial: reducing structural mass without greatly compromising the elastic buckling capacity. Depending on the orientation, size, and location of a regular array of perforations, the elastic buckling capacity may even increase.

In this paper, an algorithm is used to determine what arrangement of perforations is more likely to benefit the elastic buckling capacity of a given slender plate. This geometry is assessed computationally, and a shape grammar approach is used to optimise the structural weight to elastic buckling capacity ratio.

MS08-4:1 | Path-following for structures undergoing buckling instabilities and material damage

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For structures, designed to withstand loading beyond their critical buckling load, the consideration of material damage that may occur within the post-critical response is necessary. Characteristic examples are composite and advanced structures, where either pre-existing damages or post-critical deformation represent the source of material damaging processes initiated within the post-critical response. Despite some work on path-following for nonlinear elastic systems being available within the research community, an extension to include material damage remains missing. The current work aims at closing this gap by developing a path-following solution algorithm that is capable of studying conventional elastic instability phenomena, such as tracing post-critical and critical subset paths for distinct and compound bifurcation phenomena, as well as determining and tracing damage initiation points and tracing post-critical paths associated with material damaging. The path-following solution algorithm is developed to facilitate semi-analytical model descriptions, with the governing functional, equilibrium equations and all damage growth conditions being determined symbolically. Characteristic elastic instability phenomena and interactions between structural instability with material damaging will be presented.

MS08-4:2 | Buckling-driven design of material extrusion manufactured stayed polymer lattices

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Lattice structures are increasingly favoured for their excellent strength-to-weight ratios, but they face the challenge of elastic buckling failure at low density. A novel type of lightweight and high-performance, collinear polymer lattice with the concept of stayed slender columns will be presented, which is fabricated through material extrusion additive manufacturing [1]. The buckling and post-buckling behaviour of perfect and imperfect stayed cells (UCs) and two-dimensional lattices are investigated analytically and experimentally.
The analytical study is performed reminiscent of [2] with a three degree of freedom system based on the general theory of elastic stability [3]. The Rayleigh-Ritz method is utilized to describe the deformation of the structure. The equilibrium states are calculated in a Python-based module “Pyfurc” [4]. Several deformation modes were analytically simulated to analyse their buckling behaviour. Parametric studies of perfect and imperfect systems are performed.
Uniaxial compression tests are conducted on the corresponding UCs and lattices to observe the buckling behaviour using digital image correlation.
The experimental and simulation results demonstrate that the ultimate loads of the UCs and lattices with stays are significantly increased compared to those without stays and that the load carrying capacity can be tuned with buckling-driven imperfections.

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MS08-4:3 | Instability in crack propagation of layered materials using the phase field approach

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The crack propagation in layered materials is seen to grow in different ways. The kinking of the crack at the start of propagation or the deviation of the crack from its path are some cases identified as unstable crack propagation. The crack path stability primarily depends on the stress state near the crack tip. Based on the nature of stress, the crack path deviation is seen in the layered materials. The stress parallel to the crack surface, identified as T-stress, is responsible for different crack path trajectories (Cotterell, 1966). The effect of the nature of T-stress and the stress intensity factor on the crack path in layered materials is studied and shown in the literature. The crack path in the layered material can also travel in a wavy trajectory within the layer based on the competition between these two factors (Fleck, 1991). The crack path trajectory can also travel from one interface to another through a layer of adhesive. Symmetry plays an important role in the instability of crack propagation.
The study aims to portray the point of instability in the crack path in layered materials using the phase field approach. The effect of stress near the crack tip can be captured with the help of stress-based failure criteria (Miehe, 2015). This criterion will give a condition satisfying which the crack propagation will be seen.

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MS08-4:4 | Computational modelling of cold-formed steel beam for improved seismic performance using optimization

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The utilization of cold-formed steel (CFS) beams in moment-resisting frames (MRFs) has recently gained significant attention among researchers. It offers advantages such as lighter weight, cost-effectiveness, and faster construction. However, the CFS section is slender, making the members susceptible to buckling. Nevertheless, due to the low bending stiffness of the CFS sheet, it can be bent into any desired cross-section. Consequently, this capability allows for optimizing CFS cross-sections to improve structural performance. This study aims to improve the seismic performance of CFS flexural members by developing a methodology to obtain improved structural performance with enhanced non-linear post-peak behaviour. A detailed finite element (FE) model was developed using ABAQUS, considering material and geometric non-linearity. This model was subsequently validated with results available in the literature. A multi-objective genetic algorithm is linked to FE analysis to optimize the CFS cross-section to maximize moment capacity and ductility. Four cross-section prototypes were optimized, and the results were compared based on the Pareto front. Furthermore, based on simulation results, limit states of failure that cause the degradation of the stiffness and strength of the beam are identified. Additionally, seismic performance criteria such as energy dissipation and the effect of cyclic loading have been investigated.

MS08-4:5 | Local buckling of compressed outstand plates: an analytical approach

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Unlike current design approaches to local buckling of plates, which are based on empirical equations (e.g. the Winter equation or the Direct Strength equations), this research presents a novel analytical approach, focusing on outstand steel plates. The derivation of the method is rooted in the Föppl-von Karman equations, which are further simplified by making a number of basic mechanical assumptions about the post-buckling stress field reminiscent of the Vlasov assumptions. An approximate solution to the emerging differential equation is obtained, which assumes a polynomial displacement profile in the transverse direction of the plate. This solution agrees eminently well with the results of finite element simulations, both for the case of a geometrically perfect plate and a plate containing an initial imperfection. By combining the obtained post-buckling stress profile with a failure criterion based on von Karman’s effective width concept, a closed-form strength equation for compressed outstand plates is derived, which is seen to be a sole function of the plate slenderness and a dimensionless imperfection factor. This equation agrees closely with the available experimental data.

MS09: Hybrid and sub-structuring analyses, experimental tests and numerical modeling in civil engineering

MS09-1:1 | Hybrid simulation to investigate inelastic higher-mode effects in RC structural walls

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Reinforced concrete (RC) structural walls are used as seismic force-resisting systems in most modern high-rise buildings. It has been demonstrated that shear force amplification occurs in yielding RC walls during a strong earthquake due to higher vibration mode effects. Several numerical studies have been performed to predict the amplification factor. The complexity of seismic responses of RC walls in plastic hinge zones has led some to doubt predicted shear force amplification results when using nonlinear numerical analysis. The substructure hybrid test method provides the opportunity to experimentally evaluate the seismic response of an entire RC wall structure under actual earthquake forces. Hybrid tests were conducted on 8-story ductile regular RC walls using advanced controlling methods to investigate the phenomenon. The studied structure was divided into experimental and numerical subassemblies. The experimental test specimen corresponded to the first story of a model RC wall as a key region of interest, while the remaining wall was modeled numerically. A series of tests based on short-duration earthquake ground motions typical of eastern Canada seismic hazard regions resulted in higher than code-specified shear amplification factors. Considering the possibility of a large-magnitude, long-duration earthquake generated by the Cascadia Subduction Zone (CSZ) in western Canada, two numerical modeling methods were used for an inelastic time history analysis of a 10-story RC wall located in Vancouver subjected to ground motions selected from a subduction ground motion database based on the conditional spectrum (CS) method. It was found that a large-magnitude long-duration earthquake could cause several amplified shear cycles, raising concerns about the risk of brittle shear failure. Considering these results, a second hybrid test was performed using a newly build testing system and new test controls. Results of the tests confirm that multiple high shear demand, larger than code recommended values, occurred during the earthquake excitation.

MS09-1:2 | Numerical modeling and experimental validation of novel, bioinspired seismic isolators

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During the process of movement, it has been observed that animals strive to achieve a state of resonance between the forces generated by contracting muscles and their inherent vibration frequencies. This frequency tuning mechanism enables the animal to minimize energy consumption [1]. In the context of leg and arm bones, when flexed by muscles, they function akin to pendulums, while tendons serve as nonlinear springs and shock absorbers. This study demonstrates the possibility of designing seismic metaisolators by tessellating unit cells with diverse architectures, resembling human bones and incorporating stretchable cables that imitate muscle tendons. Interestingly, these metaisolators invert their function: instead of aiming for resonance with earthquake frequencies, they leverage tendons to adjust the nonlinear stiffness of the system [1]-[3]. Moreover, the metaisolators can be constructed using environmentally sustainable components, eliminating the need for heavy industry. They can be partially or entirely created using commonplace 3D printers and materials that are biobased and/or recycled. The metallic components can be produced using standard lathe machines available from online suppliers of metal parts or generated through a desktop metal 3D printer.

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MS09-1:3 | Pseudo-dynamic testing with sub-structuring applied to progressive collapse

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This paper presents the analysis of RC frame subjected to progressive collapse within the framework of pseudo-dynamic testing. Since the WTC events, the latter topic is of growing importance in order to better understand the effect of damage propagation (local or global bearing loss).
On the one hand, due to their cost and complexity (size, instrumentation, dynamic loading application, etc.), experimental bearing loss tests on full-sized buildings are often limited in terms of storeys and reproducibility. On the other hand, numerical models accounting for geometrical and material non-linearity can be tricky to calibrate to closely match the real response of the considered structure.
Pseudo dynamic approach is appealing because it allows considering dynamic effects coming from inertial forces induced by the mobilized mass during the bearing loss. The pseudo-dynamic technics involves quasi-static tests which simplify the experimental setup and limit hydraulic power needed to impose the loading. One step further, sub-structuring permit to split the entire framed structure into an experimental part, which is in this case the critical structural element, and the rest of the structure is modeled through the finite element method. Experimental and numerical parts are coupled through the method proposed by [1].
In order to demonstrated the ability of the pseudo dynamic approach with sub-structuring to reproduce progressive collapse mechanism ([2]), a classical bearing loss scenario is considered. Full scale RC beams (4 and 6 meters long) are subjected to a central column removal. Pushover and pseudo dynamic tests are performed to compare the static and dynamic response. In this work, the leading idea is to benefit from the advantages of the pseudo dynamic technic combined with sub-structuring approach, to better characterize the whole structure repsonse accounting for dynamic effects.

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MS09-1:4 | Next generation friction damper

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Passive energy dissipation systems, such as friction dampers (FDs), viscous dampers (VDs), and tuned-mass dampers (TMD) have been proposed to reduce the dynamic response of structures under seismic excitations. The efficacy of such devices towards the anti-earthquake design of structures seeks to minimize the extent of damage upon them, using absorbing a considerable amount of the seismic energy input due to their hysteretic behavior. In this field, a lot of researchers proposed friction dampers with huge dimensions and as well as expensive material [Pall et al. 1980; Grigorial et al 1993]. Mrad et al. [2021] in a comparison of 3 energy dissipation systems (TMD, VDs, and FDs) show that FDs can improve the performance of all structures under seismic action. Still, they are more suitable for low-rise buildings, as in high-rise buildings the number of them makes the total cost expensive. Titirla et al [2017] have proposed an innovative energy dissipation system, mentioning CAR1, which consists of very simple material and it is far from the heavy industry for this device to be able to be used in both developing and undeveloped countries. This device has a lot of advantages compared to other common friction dampers. Still, the main disadvantage is that to achieve high load capacity is necessary to have a big diameter of the devices or a big number of dampers which means that the total cost needs to increase [Titirla et al 2018]. This study aims to reply to the previously unanswered questions by i) finding an equilibrium between the cost and the advantages of this type of friction damper, by proposing and investigating various configurations, ii) examining the effectiveness of recycled metals and smart materials, as part of the main elements of the device, iii) investigating how structural systems respond to realistic dynamic or seismic loading.

MS09-2:1 | Impact of threaded parallel couplers on the cyclic performance of reinforced concrete columns

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This study examines the impact of compact mechanical threaded couplers on the cyclic performance of reinforced concrete columns, with a focus on foundation-to-column connections under axial and cyclic loading conditions. A series of experimental analyses were conducted on six square-section column configurations, subjected to both monotonic and cyclic loading tests. These configurations varied in splice types, ranging from non-spliced reinforcement bars, overlap splices, to threaded mechanical splices, with some couplers strategically positioned at various heights to assess the influence on structural behavior.The experimental methodology adopted controlled displacement tests to simulate real-world loading conditions, concentrating on key structural parameters such as lateral load-bearing capacity, ductility, absorbed energy, and stiffness. Furthermore, the study incorporated advanced digital image correlation techniques to monitor crack propagation, offering precise evaluations of local behaviors and crack distribution patterns. Additionally, the integration of fiber optic sensors along longitudinal rebars presents a novel approach to enhance real-time monitoring of structural integrity, providing precious insights into stress distribution and early detection of potential failures.Preliminary findings suggest that the use of compact mechanical threaded parallel couplers does not compromise structural performance when compared to traditional continuous rebar configurations. In fact, alternating the placement of mechanical couplers along the column height has been identified as a potentially efficient and reliable method for bar splicing, aiming to mitigate bar slipping. Notably, critical parameters including failure load, overall stiffness, and crack distribution closely matched within the uncertainty range of the tests, aligning with existing regulatory standards for crack management.This research significantly advances the understanding of RC behavior in foundational structures, advocating for the adoption of threaded parallel couplers as an effective reinforcement method under diverse loading conditions. The findings highlight the potential for these innovative connection techniques to improve construction efficiency and structural resilience, marking a significant contribution to the field of civil engineering.

MS09-2:2 | Analysis of the structural performance of the thermal bridge in building

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This study focuses on reducing energy consumption in buildings by developing a thermal bridge breaker to minimize heat loss between walls and parapets, improving energy efficiency. The effectiveness of the proposed solution is evaluated whether the reinforcing bar connection could accurately represent the performance of the structure before loading through experimental testing, and computational simulations using the LS-DYNA program. The study also suggests crucial input parameters and constitutive models for concrete and steel within the LS-DYNA program. Finally, this research aims to provide valuable insights into designing energy-efficient building structures that can withstand various loads.

MS09-2:3 | Predicting seismic performance of AFRP retrofitted RC column by applying machine learning-based fast running models

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Fiber reinforced polymer (FRP) materials consistently show excellent performance in strengthening and repairing reinforced concrete structures under different types of loads. This work introduces the creation of finite element (FE) models for retrofitted RC column with AFRP-retrofitted using the dynamic analysis software LS-DYNA. The damage evaluation of seismic performance is examined by considering criteria such as drift and energy-based damage limitations. To significantly reduce computational time without sacrificing accuracy, fast-running machine learning models such as recurrent neural network (RNN) and adaptive neuro-fuzzy inference system (ANFIS) were used to predict the seismic damage performance of RC column structures. The optimal FRM was selected after assessing many criteria including R-square values, mean absolute error (MAE), and root mean square error (RMSE).

MS10: Advanced computational analyses for geotechnical and underground engineering

MS10:1 | Multi-scale analyses on interfacial behavior between normal concrete (NC) and ultra-high performance concrete (UHPC)

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As a kind of cement-based composite material with ultra-high strength, ductility, and durability, ultra-high performance concrete (UHPC) is a promising repair material to strengthen existing concrete infrastructures like bridges and tunnels. To achieve reliable and effective reinforcement, the interfacial performance and failure mechanism between UHPC and normal concrete (NC) becomes a critical issue. A series of experimental work was conducted to test the UHPC-NC interfacial behavior under various stress states and the interfacial morphology was measured by 3d scanning to obtain the roughness parameters, providing a basis for further numerical investigations. Then, a numerical framework on multi-scales was established to analyze the mechanical behavior of the NC-UHPC interface, considering effects of the meso-structure of UHPC and the treated interface roughness. NC was regarded as a homogeneous matrix whose failure was described by the elastic-plastic damage model in form of coupled gradient-enhanced damage evolution. UHPC is characterized by the second-order mean-field homogenization (MFH) method to consider its components on meso-scale. The interface is represented by the cohesive zone model (CZM), whose load transfer capability was described by the effective traction-separation law (TSL). Resultantly, mechanical behavior and deboning failure mechanism of the UHPC-NC interface was revealed, and the influence of the roughed interface morphology and the meso-structure of UHPC was evaluated. The loading resistance of a UHPC-NC composite element would benefit from the increased interfacial bonding strength. The interface roughness, the substrate concrete strength have positive effects on the mechanical properties of the interface.

MS10:2 | A super-ellipsoid convex model based reliability analysis of rock tunnel with rock properties modelled via mixed uncertainty models based on available data

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Uncertainties in rock properties are primarily divided into aleatory uncertainties, caused by inherent randomness, and epistemic uncertain-ties, resulting from limited or subjective data. This study introduces an integrated reliability method that employs both probabilistic and non-probabilistic models to characterize input uncertainties, based on their available information. Statistical parameters and best-fit pdfs are used to model inputs with sufficient data whereas a super-ellipsoid convex model with minimised volume is used to model inputs with limited data. The super-ellipsoid model is transformed into a unit hyper-sphere. The non-probabilistic reliability index (is defined as the minimum distance from the origin to the failure surface. A double loop algorithm, combining Monte-Carlo simulations and convex-model based reliability measure, is developed to estimate the probabilistic distribution of in the presence of mixed inputs. The methodology is illustrated using a rock tunnel as a case study. Unlike conventional reliability methods, this approach can address mixed uncertainties based on the exact information available. Further, the method estimates the uncertainty in reliability measure i.e., statistical measure and pdf of by truly propagating the impreciseness of mixed inputs, instead of its fixed value based on assumed probability distributions. The current ap-proach can be viewed as more advanced than traditional methods because it accurately accounts for input uncertainties due to limited in-formation, without incorporating subjective data. This provides users with a more informed understanding of tunnel stability.

MS10:3 | Thermal stresses in concrete beams as a result of multiscale constraints

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Temperature changes and the resulting thermal stresses may be a threat to the long-term durability of concrete structures. Thermal stresses in concrete structures can be stimulated by constrained thermal eigenstrains on different scales of observation. Taking concrete beams, as an example, three different scales are defined, namely, the microstructural scale of the concrete material, the cross-sectional scale, and the macrostructural scale of the beams.
In order to quantify the multiscale thermal stresses, the scale transition (i) from cement paste, sand, and aggregates to the material scale of concrete, (ii) from the material scale of concrete to the cross-sectional scale of the beam considered, and (iii) from the cross-sectional scale to the macrostructural scale of the beam was established. Microstructural stresses in concrete constituents of a thermally-loaded concrete beams were quantified. Furthermore, the influence of different heating speeds, different concrete constitutions, different internal relative humidities, and different geometric dimensions of the beams were discussed in the framework of sensitivity analyses. This helps in understand of the multiscale nature of thermal stresses in concrete structures.

MS10:4 | 3D numerical modelling of inter-seasonal heat harvesting of a geothermal road in the UK

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This study presents a 3D numerical investigation into a road integrated with a shallow geothermal energy system (SGES) in East England. An SGES uses the upper few metres of the ground as a heat source and sink to provide heating/cooling and energy storage efficiently by circulating fluid through the ground heat exchanger. This study focuses on the inter- seasonal heat harvesting processes inside the road system and its impact on the performance of the pavement. A time-dependent numerical model was developed using COMSOL Multiphysics to simulate these processes, accounting for heat transfer between the pavement, adjacent soil, and the fluid within the embedded pipes. The model also incorporated phase change materials (PCMs) in the soil to enhance thermal conductivity and energy storage potential. The SGES modelling used realistic UK climate data and soil temperature profiles to define the boundary conditions. This study evaluated the impact of various design parameters on the SGES, such as pipe diameter, burial depth of the pipes, fluid flow rate, and soil thermal conductivity, particularly with the inclusion of PCMs. The goal is to ascertain the influence of these variables on energy storage efficiency during the summer. Furthermore, the stored energy can be harnessed to warm the pavement in winter, thereby enhancing climate resilience and reducing weather-related road maintenance costs.

MS10:5 | Utilization of phase change materials in the support structure of geothermal tunnel: efficacy in geothermal hazard mitigating and heat energy storage

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The high temperature in geothermal tunnels not only brings challenges to the construction but also a reflection of the large amount of heat energy stored in these tunnels. This study applies the phase change materials (PCMs) to geothermal tunnels combined with the ground source heat pump (GSHP). The system is expected to mitigate the challenges resulted from geothermal hazard, such as high environmental temperature and additive thermal stresses in the support structure, and show advantage in heat energy storage. A finite element model is established to investigate the performances of system, and the validation of model is conducted by comparing with in-situ experimental results. Furthermore, the performances of system are evaluated by parametric analysis, including the operation mode, phase transition temperature, and latent heat. The simulation results reveal that the combination of PCMs and GSHP can adjust the environmental temperature and decrease the thermal stresses in the construction period of tunnels compared with common support structures. This can bring more thermal comforts to workers in geothermal tunnels. Meanwhile, the system increases the efficiency and sustainability in heat energy storage in the operation period. The longer time for the rest of GSHP and larger latent heat increases the efficiency in energy extraction.

MS11: Mechanics of multiphase-multiscale granular and particulate systems

MS11-1:1 | A granular view of modelling a pandemic using the Discrete Element Method

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The virus spread from person-to-person contact in a pandemic is similar to the particulate dynamics associated with granular materials. Thus, a fundamental and deterministic modelling approach that combines granular mechanics with epidemiology, immunology and sociology is developed.
A population of individuals is seen as an assembly of point masses upon which we apply equations of motion constrained by socio-economic agenda. As the distance between individuals is a key factor of virus transmission, the contact law between individuals allows for a 'social' repulsive force which prevents people from being too close. Once contact is established, a transfer of viral load occurs, the degree of which is governed by protective measures. The evolution of viral load within an infected individual is antagonized by the immune response according to demographics, among others. This is mathematically described by a set of prey-predator ordinary differential equations.
Numerical simulations of a large, heterogenous population reveal episodes of structured waves of infected regions in space that are suggestive of transient localized deformation patterns in sand and clay. Other phenomena analogous to granular material behaviour are also discussed.

MS11-1:2 | Density relaxation in tapped granular systems: recurrent neural network model

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We report on simulations of microstructure development in assemblies of monodisperse spheres in a tapped container modeled through discrete element simulations. 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 taps from which evolution curves of the solids fractions were obtained. Drastically different progressions of the individual realizations were observed that featured sporadic 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. Visualizations further revealed the formation of crystalline regions separated by dislocations facilitating bulk sliding motion in the system through periodic boundaries. Simulations conducted at a higher tap acceleration promoted a larger frequency of jumps in density over the taps, resulting in more of the realizations attaining an apparent final saturation density.
A recurrent neural network model developed with a 60% training set was used to forecast the ensemble-averaged density in the limit of large numbers of taps. The model appeared to be able to capture jumps exhibited in the simulations beyond the training set. Our findings suggest that it may be possible to analyze the evolution of granular microstructure by applying deep learning methods. The inclusion of physics-informed quantities into the learning feature space may provide an enhanced ability to understand the process towards the development of predictive surrogate models.

MS11-1:3 | Simulations of poro-elastic sand structures subjected to air and water flows

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Climate changes induces (among others) rising sea level, intensification of the rainfall events and more frequent drought periods. These changes in the environment will have an impact on coasts morphodynamics. Coastal dunes, which are typical natural structures, will be more often subjected to higher hydro-mechanical loadings, in comparison with the last decades situation. In particular, we expect to observe more frequent imbibition/drainage cycles, which may lead to the increase in their erosion kinetics. As a matter of fact, from a microscopic perspective, the mechanical strength of geomaterials is strongly affected by that of the capillary bridges between the grains. From a macroscopic perspective, this typical feature is usually understood as a dependancy of the mechanical strength on the suction (or equivalently saturation degree). In order to capture this specific behaviour through macroscopic numerical modelling, it remains mandatory to address first the hydrodynamics of the partially saturated soils. Having in mind this problematic, we propose to simulate the response of a sandy structure to environmental loads and evolving water table height, solving a partially saturated poro-elastic model by FEM. We propose here to have a particular look at the air phase, now considered as an active phase, say characterized by a non-constant pressure. If this hypothesis seems physically realistic, and constitutes a crucial point of our approach, it brings down several numerical challenges to be able to tackle the coexistence of saturated and partially saturated zones, or capturing the nucleation of drainage or imbibition fronts at the external boundaries. In order to address these two problems, we propose (i) a revision of the variational formulation of the problem to incorporate a moving saturation front, and (ii) a dedicated algorithm to capture the shift in the boundary conditions nature when the soils undergoes a full saturation.

MS11-1:4 | Effect of the grains shape on the mechanical behavior of granular material

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The mechnical behavior of granular materials is depending on many parameters like the grain size distribution, the grains shape etc. The aim of this paper is to study the influence of each parameter independently. In order to reach this objective, samples are preapred with grains with controlled shapes and sizes. At first the influence of shape is studied, the samples contain only one size of grains. After that, mixtures are preapred, in this paper, only mixtures made with the same shapes will be presented.
Tests are carried out on samples made only with spherical and pyramidal grains. The size of the grains are fixed to 1 mm and 10 mm. After that, mixtures are made with these shapes and sizes in order to start to understand how the shape and the size of the grains influences the mechanical behaviour of the granular materials. In all cases, the samples are compacted to a relative density of 50%.
The triaxial tests showed that in the case of spherical grains, the maximum deviator stress is not depending on the radial a stress, indeed, it is constant whatever, the value of the applied radial stress. For the pyramidal grains, the results show an increase of the maximum deviator stress when the value of the radial stress increases. This behavior is due to the friction forces between the angular grains.
The study of the behavior of mixtures containing different sizes of spherical grains, a slight evolution of the mechanical behavoir is observed only when the amount of fine grains filled the spaces between the coarser grains. However, this evolution is not very important. The evolution of the mechanical properties of mixtures made with pyramidal grains with different sizes is more important than that with spherical grains.

MS11-1:5 | Hydromechanical modeling of internal erosion in granular soils

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Geo-structures are subject to hydraulic flows varying in time and space. Water passing through these porous media can cause the detachment and transport of certain particles from the soil constituting the structures and their foundations. This problem is generally referred to as “internal erosion”. The term suffusion, a type of internal erosion, refers to the detachment and transport of finer particles through a coarser porous soil matrix due to hydraulic flow. The temporal evolution of suffusion can modify the hydraulic and mechanical properties of soils and can lead to significant changes in the behavior of structures which can eventually cause their failure. Based on the theory of porous media, a new numerical model was formulated to take into account both erosion and filtration during suffusion. In order to carry out analyzes at the scale of a structure, an elastoplastic model for granular soils was coupled to the suffusion model. The hydromechanical model was implemented in the Abaqus finite element code and used to evaluate the impact of internal erosion on the stability of structures. The evolution of suffusion within a dike was analyzed, as well as the effects of the location of a leak cavity. The results showed that two damage mechanisms are possible: a sliding of the downstream part of the dike and a sinkhole developing in the upper part of the dike. The phenomenon of internal erosion can also affect the stability of natural slopes. On an example studied in the laboratory, we show that the mechanism of instability of the material constituting the slope depends on the percentage of fines and that its reduction by suffusion can lead to the rupture of the slope during imbibition of water by addition from the surface or rise of the water table.

MS11-1:6 | Shear banding in granular assemblies as an optimal dissipative structure

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Granular materials are now known to be an illustration of complex materials as they display emergent macroscopic properties when loaded. An initially homogenous response can bifurcate into a heterogeneous one with the appearance of a rich variety of structured kinematical patterns. The shear banding that ensues illustrates a symmetry-breaking transition with multiple choices of macroscopic behaviours, a common feature of dynamical complex systems. Even though the phenomenon has been studied for decades, this regime transition remains mostly mysterious in geomaterials, with no convincing arguments that could link it to the underlying microscopic mechanisms. This contribution revisits this issue by invoking fundamental extremal entropy production principles to seek any connection with the second-order work theory in the mechanics of failure. Our findings are verified through discrete element simulations that highlight the fundamental role played by the elastic energy stored within a granular material before a bifurcation occurs, which also corresponds to a minimization of the entropy production. The analysis suggests a new interpretation of the intriguing shear banding phenomenon as a bifurcation with the emergence of optimal dissipative structures germane to nonequilibrium thermodynamics of open systems.

MS11-2:1 | Identification of pore network of clays using FIB-SEM imaging

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This paper proposes new an original technique aiming to go further towards the 3D characterization in clay microstructure. To achieve this, an approach using FIB-SEM imaging coupled with image processing techniques has been developed allowing to generate a three-dimensional microstructure from digital 3D reconstruction. (Ding et al., 2023). The tests using FIB-SEM technique were carried out on remolded saturated clay samples submitted to one-dimensional compression. Particular emphasis was placed on how to rebuild, with sufficient accuracy, the pore network of an observed micro-volume. Then, pores properties were investigated in terms of pore size distribution, morphology, and spatial orientations. Finally, Pore size distribution deduced from FIB-SEM was then superimposed to mercury intrusion porosimetry results allowing more discussions around the FIB-SEM technique efficiency.
Ding, Y ., Bennai, F., Jrad, M., Guyon, J., Hattab, M. 2023. Three-dimensional pore network of kaolin using FIB-SEM imaging. Particulate Science and Technology. https://doi.org/10.1080/02726351.2023.2292271

MS11-2:2 | Stress transmission in granular materials versus epidemic spreading in human societies

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Both granular materials and human societies are dynamic and nonlinear that can be regarded as illustrations of complex systems. An important feature in granular materials under external loading is force transmission through particle contacts, whereas in populations during epidemic varying quantities of circulating pathogens are transmitted during social interactions [1, 2]. An assembly of granular materials consisting of interacting particles shows emergent properties on the macroscopic scale under external loading. The mechanism behind emergent properties can be illustrated by network-related statistics. For example, the emergence of asymptotic states such as the critical state agrees with the evolution of the number of grain loops as mesostructures [3] that ensue in this stress-strain regime. Similarly, the population network is a key to understanding the spread and evolution of epidemics and the use of network-driven strategies has been regarded as an important pathway for structuring responses, i.e. discrete outbreaks into clusters versus generalized, diffuse ones [1, 4]. In this research, we interpret the upscaling processes of the two complex systems within a thermodynamic framework [5] as both address the laws of macroscopic quantities versus microscopic entities through the ontology of activity or change of state. We explore how stress transmission in granular materials and pandemic spreading in human society can be described with a similar conceptual framework, as they both consist in information transmission based on a network composed of individual components and their interactions that upscale to a larger population and scale. The comparison gives us new insights into the two systems.

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MS11-2:3 | Swelling behavior of clayey geomaterials: insights from multiscale modeling

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Most soils and rocks contain varying fractions of clay minerals within their solid matrix. These geomaterials can exhibit a significant swelling potential toward chemo-thermo-hydromechanical loadings. To ascertain their swelling behavior across various scales, several multiscale modeling techniques have been developed, with molecular dynamics, micromechanics-based approaches and double-porosity models being the most common. Molecular dynamics simulation is a computational technique that applies Newton's second law of motion to depict the movement of particles within a granular system. Micromechanics-based approaches upscale the poro-elasticity law from the clay layer level to the sample scale through homogenization. Dual-porosity models are generally based on elasto-plasticity, incorporating different hydro-mechanical laws at two distinct scales. Although their significant contribution to the understanding of clay swelling behaviour, these techniques have been insufficiently reviewed, compared and discussed mutually in the literature. This paper aims to provide a cross-look at these multiscale approaches by presenting the theoretical background of existing formulations, highlighting breakthrough results, discussing major differences, current challenges and proposing future perspectives.

MS12: Computational wind engineering applications and validations

MS12:1 | A study of moveable wave overtopponing barrier on shores

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Waterfront facilities are increasing on coastal area for tourism and residential purposes. Low-pressure storms such as typhoons cause overtopping and damage to facilities. To prevent this, fixed and movable overtopping prevention walls are being installed in Korea. However, fixed overtopping prevention walls are not preferred because they impede the view of the coast. In this study, a multifunctional movable barrier was studied. It is usually used as a tourist pier and is erected when overtopping waves are forecast. To analyze its applicability, hydraulic experiments, structural analysis and experiments, and detailed design were performed. In the hydraulic experiment, the amount of wave overtopping and the wave pressure acting on the barrier were analyzed. And in structural analysis and experiments, performance tests of major members were performed. Finally, a full-scale barrier with a height of 2m was manufactured, and a winch was used to operate it.

MS12:2 | Arecibo telescope response investigation in Hurricane Maria

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Thornton Tomasetti, United States of America

The Arecibo Telescope in Puerto Rico collapsed on December 1, 2020. After the incident, Thornton Tomasetti Inc. (TT) was engaged by the Florida Space Institute to conduct a forensic investigation of the root cause of the collapse. An essential focus of the investigation was the impact of wind loads, and particularly of Hurricane Maria in 2017, the strongest hurricane that the telescope had experienced in its service life. Computation fluid dynamic (CFD) analysis is computationally expensive for complex structures or winds with long durations. Conducting this type of analysis may be feasible by involving high-performance computing systems. However, given the scope of the investigation, as well as the limited time and budget, performing such a sophisticated CFD analysis of the telescope subjected to the full hurricane time history was infeasible. TT adopted a cost-effective method to simulate the wind loads on the telescope during Hurricane Maria, and apply those forces to a structural analysis model. A CFD model of the telescope was used to generate wind forces at a constant wind speed, and was validated by previous wind tunnel tests on a physical model of the telescope. The validation shows that the CFD analysis can adequately depict the wind tunnel test results, and that the wind forces can be scaled based on wind speeds. The wind forces from CFD analysis were then scaled to time-varying forces based on the on-site measured wind speeds during Hurricane Maria. The time-varying forces were subsequently applied to a finite element (FE) model of the telescope to evaluate its dynamic response during Hurricane Maria. This presentation provides description of each analysis step, validation of the wind force scaling method, and the telescope's response to Hurricane Maria. The results show that the forces in the cables supporting the telescope increased 14% during Hurricane Maria.

MS12:3 | Different tornado chamber effect on vortex formation using CFD

R. Selvam

University of Arkansas, United States of America

Several tornado chambers are designed and built all around the world to understand the tornado loading on structures. Each tornado chamber structure is different and behaves differently. Verma and Selvam (2022) classified them into three major categories. To understand further the vortex forming mechanism in different chambers, computational fluid dynamics (CFD) is used. In this study different types of chambers like side opening and top opening are considered for analysis. In addition, different sizes like small aspect ratio of the chamber are also considered. Here aspect ratio is the ratio of height of the inlet (ho) to the radius of the chamber (ro).

When the aspect ratio is much smaller, extensive computer time is needed if it is a time dependent flow. For this steady state solver was also proposed. The steady state solver is based on SIMPLE method and the unsteady solver is based on fractional step method. The performance of these CFD methods will be reported. The computed vortex parameters for different chambers will be presented. Vortex parameters for aspect ratio varying from 0.03 to 1 will be reported. From the analysis, the difference in vortex formation mechanism for different chambers will be illustrated using visualization. The research findings help to understand the vortex formation mechanism and efficient design the tornado chambers in the future.

MS13: Computational geomechanics

MS13-1:1 | Efficient approaches for simulating large deformation problems

J. P. Hambleton

University of Cambridge, United Kingdom

Problems involving large deformation invite onerous computational approaches, but adequate accuracy can potentially be obtained using models built from relatively simple principles. Model efficiency is highly desirable for numerous reasons, ranging from unlocking possibilities for virtual prototyping to enabling faster than real-time (FTRT) simulation for control and path planning. This presentation discusses pathways for constructing efficient models based on approximating the shape of the boundary and/or the rule(s) for updating the boundary. The first method, referred to as the 'sequential kinematic method,' rests on notions from flow theory of plasticity. Key advantages of this approach are the clarity and rigor of the underlying principles, but the method is limited in its applicability, particularly with respect to restrictions on material type. The presentation describes a second class of techniques, referred to as 'data-driven methods,' that are more general but resort to machine learning, thus obscuring the formulation and requiring that sufficient data is available for model training. Examples covered in the presentation include indentation, granular column collapse, and orthogonal cutting. These methods and examples lend insight into the physical nature of the problems and highlight possible future modeling techniques with high potential for efficiency.

MS13-1:2 | Particle finite element method for large deformation simulation of geotechnical hazards under fluid-solid interaction

W. Sun, W. Zhang, W.-H. Yuan

South China Agricultural University, China

Particle-based methods have effectively simulated large deformation issues involving geotechnical hazards such as landslides, debris flows, and earth dam breaches, and have garnered widespread attention in the field of computational mechanics in recent years. Currently, commonly used particle-based methods for geotechnical large deformation simulation include Smoothed Particle Hydrodynamics (SPH), Material Point Method (MPM), and Particle Finite Element Method (PFEM). Among them, PFEM, inheriting the solid theoretical foundation of the finite element method, is increasingly receiving attention in the field of computational mechanics. In response to the shortcomings of PFEM, such as the need for continuous mapping of field variables between Gaussian points, we introduce a node integration technique based on strain smoothing into PFEM and propose an improved particle finite element method—the Smoothed Particle Finite Element Method (SPFEM). The complete computational theory framework for SPFEM is derived. This method is further extended to dynamic, coupled, and contact analysis, ultimately enabling three-dimensional GPU parallel numerical computation of large deformations in geotechnical hazards under fluid-solid interaction.

MS13-1:3 | Implicit SNS-PFEM with dual mortar method for thermo-hydro-mechanical large deformation problems

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This talk introduces a novel stable node-based smoothed particle finite element method (SNS-PFEM) integrated with the dual mortar contact method, designed to address fully coupled thermo-hydro-mechanical (THM) structure-soil interaction geotechnical problems, particularly those involving large deformation. The proposed SNS-PFEM framework offers three key advancements: (1) it proposes a smoothed thermal strain, enabling elastoplastic thermo-mechanical analysis in NS-FEM and SNS-FEM; (2) it presents the SNS-PFEM framework as a viable model for fully coupled THM large deformation problems; and (3) it implements the dual mortar contact method within the THM SNS-PFEM framework to effectively model structure-soil contact. The validity of this method is demonstrated through four benchmark tests, including the thermo-mechanical (TM) coupled sliding beam, the hydro-thermal (HT) coupled moving liquid, the THM coupled thermal consolidation, and the THM coupled half space heating. Additionally, the proposed THM SNS-PFEM framework is applied to investigate the interaction behavior between submarine pipelines and seabed soil during penetration and buckling, with a specific focus on thermal effects. The results reveal the competition mechanism between thermal expansion and friction degradation, and how these factors influence soil resistance, providing a promising contribution to the understanding and modeling of complex geotechnical problems.

MS13-1:4 | SPH implementation to large deformation of granular mass using an advanced hypoplastic constitutive model

C. Zhu[1], W. Wu[2], C. Peng[3], S. Wang[4]

[1]Zhejiang University, China; [2]Universität für Bodenkultur Wien (BOKU), Austria; [3]ESS Engineering Software Steyr GmbH, Austria; [4]Wuhan University, China

In this work, an advanced hypoplastic model incorporating the critical state is integrated into smoothed particle hydrodynamics (SPH) for the numerical investigation of geotechnical large deformation problems. Besides, a return mapping strategy is proposed to regulate the stress state to avoid calculation failure. To this end, a closed-form solution to predicting the failure surface implicitly incorporated in the hypoplastic model is derived. The proposed SPH method is examined with element tests such as the oedometer test, simple shear and biaxial compression test, from which good performance of this SPH model is observed. Finally, the SPH model is applied to numerically reproduce the sand column collapse and rigid footing problem to investigate the effect of the initial void ratio on soils' behavior.

MS13-1:5 | Modelling multi-physical field coupling process of rock by discretized virtual internal bonds

Z. Zhang

Shanghai Jiao Tong University, China

The multi-physical field coupling simulation of rock is a very important issue in geomechanics and petroleum engineering. The complicated coupling process among different physical fields is very difficult to simulate in the framework of conventional continuum mechanics because it involves the fracturing problem. To explore new approach to this problem, the discretized virtual internal bonds(DVIB) is extended to modelling the multi-physical field coupling process of rock. DVIB was originally proposed to simulate the dynamic fracture of solid. It considers a solid to consist of discrete bond cells. Each cell has a finite number of bonds. Each bond is characterized by a bond potential in mechanics, which intrinsically contains the fracture mechanism. In the present multi-field coupling analysis of rock, each bond simultaneously functions as the mechanical linkage, the thermal conductivity, the fluid flow and the acid reactant transport channel. By this method, the hydraulic, mechanical, thermal and chemical field are unified together on an individual bond. The coupling process is allowed to occur in a bond. The coupled governing equations of a bond are derived. By this approach, the complicated 3D multi-field coupling process is reduced to a 1D bond problem, which significantly simplifies the analysis of the coupling problem and improves the efficiency of numerical simulation. The perspective of this method should be inspiring in the simulation of reservoir stimulation.

MS13-1:6 | Microfiber-reinforced bentonite clay for geological repositories of nuclear spent fuel: multiphysical laboratory tests and computational modeling

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Disposing of the waste deep underground in the geological repository is the most preferred long-term solution for nuclear waste disposal. The canister containing the high-level waste can be buried deep underground and encapsulated by engineered barrier material (EBM), which separates it from the natural rock. Bentonite clay is the most preferred EBM due to its advantageous properties, such as low cost, great long-term stability, high thermal resistance, and low permeability. However, bentonite is subjected to a complex multiphysics environment as the canister generates heat, causing bentonite to desiccate, while moisture infiltrating from the host rock causes bentonite to swell. A better-performing EBM that is less permeable and more resistant to desiccation cracking and chemical degradation is imperative. As a promising solution to the significant societal challenge, an inorganic microfiber-reinforced EBM (i.e., IMEBM) is proposed. This study investigates the effects of inorganic microfibers embedded in bentonite to develop such IMEBMs by conducting laboratory tests and integrating the tests with computational multiphysics modeling. Experimentally, two tests were developed and conducted: (1) a restrained ring shrinkage test was designed and conducted to observe the desiccation-induced deformation and cracking behavior captured by a digital image correlation (DIC) system, and (2) a 3-D soil tube test incorporating moisture (mass) transport and heat transfer, which is to identify multiphysical material characteristics of IMEBMs. Each laboratory test was computationally simulated based on a multiphysical finite element (FE) method to identify material properties that are a function of moisture and temperature. The resulting test data (DIC images of deformation, 3-D X-ray CT images of soil microstructures, measurements of temperatures and moisture over time, etc.) and multiphysical model parameters demonstrate the effects of microfibers on crack-associated desiccation behavior of bentonite subjected to complex multiphysical conditions of the engineered barrier system for geological repositories.

MS13-2:1 | Hybrid FEM and Peridynamic simulation of forerunning fracture in porous media

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The process of dynamic fracture propagation within saturated porous solids is known to exhibit variability, often deviating from smooth and continuous behavior. Experimental evidence and field observations have consistently documented instances of stepwise fracture tip advancement and pressure oscillation within such media. This phenomenon arises from the complex interplay between mechanical waves and pore pressure waves, leading to a transition in fracture advancement behavior from smooth to stepwise, and ultimately to forerunning patterns. In this study, we employ a hybrid Finite Element Method (FEM) and Peridynamic (PD) model to delve into the fracture advancement process within porous media under diverse loading conditions. The Peridynamics model accurately captures the deformation of the solid skeleton and tracks crack propagation, while the FEM equations describe fluid mechanics within the porous medium. The coupling between hydrodynamics and mechanics adheres to Biot theory, and a staggered scheme is utilized to solve the coupled system. A one-dimensional dynamic consolidation problem is first addressed for validation of the presented approach. The dispersion behavior of the PD-FEM model is also analyzed. Subsequently, a cantilever beam model is simulated under various loading conditions, considering both dry and saturated porous media. The numerical simulations elucidate that forerunning fracture phenomena are prevalent in both dry and saturated porous media. This occurrence can be attributed to the influence of incident stress waves within the material domain ahead of the crack, or the intricate interaction between incident stress waves, reflected stress waves, and pore pressure waves. The phenomena presented in this study open up interesting suggestions for further research, particularly in the context of potential experimental investigations.

MS13-2:2 | Numerical and analytical analysis of fracture closure modes and their importance in data interpretations

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MiniFrac tests, Diagnostic Fracture Injection Tests (DFIT), and their revisions like DFIT flowback tests are commonly used in the field to determine in-situ stress and other rock properties such as permeability. However, there have been ongoing debates over the interpretation methods for DFIT, primarily driven by the simplifying assumption of uniform fracture closure. Despite significant research on fracture propagation, there have been limited advancements in understanding fracture closure mechanisms. Fractures may close uniformly from tip to mouth or may start receding from the tip or closing at the mouth (near the wellbore). Depending on the rock permeability, fracture conductivity, and other factors, each of these closure modes can occur, and the resulting pressure signature would be significantly different. This lack of understanding has led to confusion in the interpretation of DFIT data. To address this challenge, this study proposes first a detailed analytical solution and second a fast method to describe or predict fracture closure modes. Inspired by field data and previous literature, a scaling analysis is conducted to define dimensionless numbers that can determine different fracture closure modes under various flowback rates. Fully coupled 2D and 3D geomechanics and fluid flow models are built to validate the proposed analytical and scaling analysis. The model, similar to the real test, consists of two stages: injection and flowback. The impact of fracture roughness on fracture conductivity changes during closure is also incorporated into the model to achieve results comparable with field data. This work aims to provide a better understanding of fracture closure mechanisms and offer a practical approach to interpret DFIT data more reliably, leading to improved characterization of in-situ stresses and rock properties.

MS13-2:3 | A pioneering framework for accurate reconstruction of arbitrary granular materials

R. Li, Z. Yin

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Reconstructing the microstructure of granular materials is an essential approach to understanding and elucidating granular mechanics. However, a persistent challenge has been the accurate reconstruction of arbitrary granular materials from three-dimensional (3D) X-ray micro-computed tomography (μCT) images. This study first proposes an innovative framework to bridge the reconstruction of granular materials and vision foundation models. An automatic multi-mode generator is tailored to extract two-dimensional (2D) low-quality mask maps denoting granular grains from raw μCT images, utilising vision foundation models. These 2D low-quality mask maps are subsequently transformed into high-quality ones, well-preserving interior textures and boundaries, by one three-step strategy. The stacked 2D mask maps are fed into an optimal-transport-based algorithm to achieve one accurate 3D mask map. All procedures are applied to μCT images from three orthogonal orientations of granular materials, yielding three 3D mask maps. Finally, the complete 3D mask map is acquired by combining three orthogonal mask maps. Our method is tested on four granular materials of varying sizes and shapes (including porous) and compared with the benchmark watershed segmentation. The results indicate that our method is state-of-the-art and significantly outperforms the benchmark in all metrics. Over-segmentation can be repaired automatically with our method. The performance of a foundation model in extracting 2D mask maps is not necessarily proportional to training data scaling. The proposed generic framework is robust enough to reconstruct arbitrary granular materials in different scenarios, even with high porosity or extremely irregular morphology.

MS13-2:4 | A novel clump-based breakage model in discrete element method for simulating crushable aggregates

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Particle breakage significantly influences the mechanical properties of granular materials at both macro and micro scales, while particle shape also plays a crucial role in various simulations. In current discrete element method (DEM) approaches, clumps, which are composed of multiple overlapping spheres, have been widely adopted as an efficient technique to represent real particle shapes. However, due to the inherent nature of clumps, which do not consider internal interactions between sub-particles, they cannot be directly employed to simulate particle breakage. To address this limitation and bridge the gap between particle shape representation and breakage simulation, this study proposes a novel clump-based method for simulating particle breakage in DEM. The proposed method introduces a breakage criterion based on the statistical stress analysis of clump particles. The location of breakage initiation and propagation is determined by evaluating the stress level of the sub-spheres constituting the clump. By leveraging extensive single-particle crushing studies and summarizing the observed patterns, a breakage mode criterion that integrates three-dimensional Voronoi tessellation is proposed. The sub-spheres within the clump are utilized to capture the actual stress concentration characteristics of the particle, enabling the definition of breakage modes. The accuracy and robustness of the proposed method are validated through a comprehensive series of single-particle and multi-particle experiments, demonstrating its ability to reproduce realistic breakage patterns and force-displacement responses. Compared to existing DEM breakage methods, the proposed model better considers the local stress concentration characteristics of particles and captures the influence of multiple contact forces on continuous crushing, while the clump-based breakage algorithm efficiently balances computational efficiency. This innovative approach provides a solid foundation for future research on breakage simulations considering particle morphology, offering a powerful tool for accurately modeling particle breakage in granular materials.

MS13-3:1 | Machine learning enabled landslide hazard assessment

S. J. Semnani

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Landslides are devastating natural disasters that occur frequently around the world, resulting in significant economic losses and casualties. Statistics show that the most frequent and widespread damaging type of landslides are triggered by precipitation. Machine learning techniques have been applied to predict landslides based on past events. However, there are a number of challenges associate with these techniques, including appropriate selection and design of machine learning algorithms, input features, and training datasets. In this work, we present an enhanced machine learning modeling strategy for landslide hazard assessment. Average landslide susceptibility map of California is generated based on the developed model, and is shown to align well with the historical observations.

MS13-3:2 | Slide, hold, learn: dynamic friction meets neural networks

J. Garcia-Suarez

EPFL, Switzerland

Recurrent Neural Networks (RNNs) have been shown able to learn and predict complex mechanical behavior of geomaterials. In this talk, I will show that RNNs also possess the capacity to learn rate-and-state friction laws from synthetic data, another relevant phenomenon in the geotechnical setting.

The data employed for training the network is generated through the application of traditional rate-and-state friction equations coupled with the aging law for state evolution. A novel aspect of our approach is the formulation of a loss function that explicitly accounts for initial conditions, the direct effect, and the evolution of state variables during training. It is found that the RNN, with its GRU architecture, effectively learns to predict changes in the friction coefficient resulting from velocity jumps, thereby showcasing the potential of machine learning models in understanding and simulating the physics of frictional processes.

MS13-3:3 | Thermal creep of clayey soils: experiments and modelling

Z.-J. Chen[1], W.-Q. Feng[2], J.-H. Yin[1]

[1]The Hong Kong Polytechnic University, Hong Kong S.A.R. (China); [2]Southern University of Science and Technology, China

Geo-energy engineering and energy geotechnics will induce temperature changes in the soil grounds. It has been widely observed in laboratory and field investigations that the mechanical behaviour of clays is sensitive to temperature variations. For clayey soils, plastic deformation and time-dependent behaviour are especially concerning. In this study, a series of temperature-controlled laboratory tests, including oedometer tests, constant-rate-of-strain consolidation tests, and triaxial tests on both normally consolidated and over-consolidated clays. The results demonstrated that temperature changes have significant effects on the creep behaviour of clays. The viscoplastic strain rates are accelerated upon heating, which causes additional settlements in drained conditions, and excess pore pressure generation or effective stress relaxation in undrained conditions. Based on experimental observations, a new viscoplastic model of clayey soils is developed to account for the thermal effects. A virgin heating line is introduced into the existing equivalent-time model framework, providing a state-based theory for depicting the viscoplastic strain rates of clayey soils. The new model is further enhanced with a series of advanced features, including the plasticity anisotropy, structuration of sensitive clays, as well as the sub-loading behaviour of over-consolidated clays. The thermal parameters of the model can be easily calibrated through a heating-cooling test in oedometer conditions. The model is validated using laboratory test data with complicated temperature and loading conditions. Finally, the constitutive model is implemented in a finite element programme to conduct thermo-hydro-mechanical analysis on the long-term behaviour of energy foundations in clayey soil ground.

MS13-3:4 | Numerical analysis on negative skin friction considering creep under embankment loading

R. Liang, Z.-Y. Yin, J.-H. Yin

The Hong Kong Polytechnic University, Hong Kong S.A.R. (China)

When a pile is embedded in a newly or recently reclaimed site, negative skin friction (NSF) is mobilized due to larger soil settlement compared to pile settlement. The generation of NSF imposes an additional axial force on the pile, which has a detrimental rather than beneficial effect. However, the impact of soil creep on the long-term development of NSF remains poorly understood. This study employs numerical analysis to investigate this effect. Initially, an elasto-viscoplastic model with an enhanced time integration algorithm is proposed and successfully implemented into the finite element package ABAQUS. Subsequently, a two-dimensional axisymmetric pile-soil interaction model is established and calibrated using a known field case. Parametric studies are then conducted to examine the varying degrees of creep effect on the evolution of NSF and the neutral plane (NP, which represents the position where soil settlement coincides with pile settlement), during both primary and secondary consolidation periods. The findings indicate that a higher creep coefficient of the soil leads to an increase in NSF and a descending trend of the NP. The delayed development of NSF due to creep is attributed to an increase in excess pore pressure during the early stages of consolidation. Moreover, the position of the NP undergoes significant variation at the onset of consolidation when considering creep effects. Finally, an exponential prediction model is proposed to account for the time dependence of the NP location.

MS13-3:5 | Nonlinear ground response analysis of liquefiable fines-dominated deposits

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Indian Institute of Technology Madras, India

Saturated loose alluvial deposits exhibit phenomena like soil liquefaction and alteration of ground motion during strong seismic event which cause damage to structures built on them. Though the saturated soils contain a significant amount of fines and still they are susceptible to liquefaction and hence their behaviour must be assessed through site-specific nonlinear ground response analysis (GRA). This study considers the response analysis of Bengal Geosynclinal basin filled with riverine sediments and are the part of the region around the city of Kolkata, India. The subsurface profile of these deposits has been characterized by drilling boreholes and consists of layers of very dense sand and silty layers having higher thickness above the hard surface. These layers have been overlain by the silty sand with loose to medium density and silty layers right up to the ground surface. The effective stress based nonlinear GRA is carried out for the selected basin sediment deposits using DEEPSOIL v7.0 to account for the shear strength degradation and to estimate the pore pressure generation. Critical-state-based constitutive models viz. PM4Sand and PM4Silt are also employed within the framework of fully-coupled finite element analysis to characterise the liquefaction response of the deposit. These models have been calibrated using a single-element modelling of the Cyclic Direct Simple Shear (CDSS) test. In the analyses, spectrum compatible time histories are used and responses in the form of variation of shear strain and pore pressure within the deposit with time is obtained. Though the deposit has appreciable amount of fines, the soil experienced liquefaction and thereafter the softening behaviour is noticed. This information is very useful in damage assessment of structures built on the liquefiable deposits having higher fines content. For future constructions in the Geosynclinal basin region, this information has to be used accordingly in the damage assessment.

MS13-4:1 | Kinematics of hydraulic plucking in fractured rock

M. H. Gardner

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Scour by hydraulic plucking is a fundamental process in landscape evolution in which large, competent rock blocks are eroded from a fractured rock mass by flowing water. This process also affects engineered structures interacting with water, such as dams and bridges, and often leads to operational and safety concerns because erosion of large volumes of material can compromise structure foundations and serviceability. To assess potential scour at a site, present methods either are empirically derived, assume a specific failure mode, or significantly simplify the geometry of potentially eroding rock particles. This limits the broader applicability of these methods and their ability to offer actionable insight into scour risk. Therefore, the discrete-element method coupled with the lattice Boltzmann method was applied to assess hydraulic plucking of fractured rock. In this approach, the three-dimensional shape of rock particles was considered explicitly, including how each particle interacts dynamically with fluid. Additionally, the highly turbulent flow conditions at which plucking often occurs were modeled using large-eddy simulation. Comparison of numerical results with scaled flume experiments show that this modeling methodology is able to capture the correct kinematic failure mode in rock block removal without restricting the potential failure mechanism, and naturally captures the governing response. This capability makes this scour assessment technique broadly applicable since site-specific characteristics can be input directly into scour risk assessments to understand the influence of local features on the plucking process.

MS13-4:2 | Numerical modeling of the oscillation roller-subsoil interaction system

I. Paulmichl, R. Bergman

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This contribution presents an improved two-dimensional numerical model of the dynamic roller-granular subsoil interaction system that facilitates the numerical prediction of both the achieved soil compaction (“improvement depth”) and the dynamic drum response in terms of acceleration (“measurement depth”) of a specific oscillation roller. In this plane-strain model, the intergranular strain enhanced hypoplastic constitutive model captures the nonlinear inelastic behavior of the soil below the drum. The numerical simulations are performed with the Finite Element software suite ABAQUS/Standard by implementing the hypoplastic soil model using an in-house Fortran code (UMAT). Thus, the linear elastic layer applied to the soil surface (“protective foil”) proposed by the author in the original model is no longer required to ensure the numerical stability of the model. In order to study both the soil compaction and the drum response, the soil layer to be compacted is modeled with linearly increasing thickness resting on a fully compacted subsoil and a loose subsoil, respectively. The effect of a roller pass at standard excitation frequency on an initially loose soil is investigated for selected roller speeds in terms of the reduction of the void ratio. The influence of the predicted soil compaction on the drum response is simultaneously analyzed in the time and frequency domain in terms of the drum center acceleration. In addition, an experimentally found Continuous Compaction Control (CCC) parameter for dynamic rollers with an oscillatory drum is evaluated. It is shown that the developed model qualitatively predicts the fundamental response characteristics of the interacting oscillation-subsoil system observed in field tests. Moreover, the numerical model is capable of predicting the depth of influence of the selected oscillation roller.

MS13-4:3 | Solving inverse problems in granular mechanics with differentiable simulators

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Solving optimization and inverse problems are critical for engineering design and analysis. Despite the computational power, calculating derivatives, i.e., evaluating the forward simulation multiple times with small perturbations, is computationally very expensive and is prone to numerical instability. Traditional forward simulations cannot be used in machine learning models for optimization, as they cannot compute gradients with respect to the input parameters (reverse mode). We propose a novel Differentiable Programming simulator that combines automatic reverse differentiation with a second-order gradient-based optimization algorithm, such as L-BFGS, to develop a fully-differentiable Material Point Method (MPM) simulator. Using the differentiable simulator, we can identify the input material properties by iteratively updating the input parameters by minimizing a loss function. Typically the loss function is the norm of the difference to the target observation. We then minimize this gradient (loss corresponding to the input parameters) using a second-order optimization algorithm. The differentiable MPM is a novel tool to provide gradients through a simulator, which can be coupled with existing machine learning algorithms to generate real-time decisions and optimization in robotics.

We exploit physics-embedded differentiable graph network simulators (GNS) to accelerate particulate and fluid simulations and solve challenging forward and inverse problems. GNS represents the domain as graphs with particles as nodes and learned interactions as edges. GNS allows learning localized physics compared to global dynamics, improving generalization. GNS achieves over 500x speedup for granular flow prediction compared to parallel CPU simulations. The differentiable GNS enables solving inverse problems through automatic differentiation, identifying material parameters that result in target runout distances. Granular column collapse experiments demonstrate friction angle inversion based on final runout profiles. Additionally, we also derive material parameters and loads from videos by constructing 3D point clouds using Neural Radiance Fields. We then iteratively minimize diffGNS to derive material properties and loading conditions.

MS13-4:4 | Molecular interactions regulate engineering properties of swelling clays

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Swelling clays are found all over the world. In the presence of water, these clays swell and exert swelling pressure when constrained. These clays cause enormous damage to the infrastructure of the order of 20 billion dollars annually in the United States. These clays are also used as barrier materials in environmental engineering, drilling muds in petroleum extractions, and drug delivery carriers in the pharmaceutical industry. The predominant clay minerals in swelling clays are typically the Smectite group of clay minerals, with montmorillonite clay being the most common. We have developed a multiscale approach that includes molecular dynamics (MD), steered molecular dynamics, and discrete element modeling tightly integrated with experiments at various length scales to elucidate the fundamental mechanisms that influence macroscale properties of swelling clays that include swelling, swelling pressure, permeability, compressibility, shear strength, etc. The molecular models of Na-montmorillonite clay developed in our studies mimic SWy-2 from the Clay Minerals Society and correspond to the clay used in the experiments. The MD simulations of the hierarchical elements of clay, including the dual-stacked clay sheets, the clay tactoids, and clay aggregates, are used to evaluate the mechanical response of the clay with various levels of hydration, and the relationships between binding interaction energies, interlayer swelling, and exfoliation. Long MD simulations evaluate fluid flow into the interlayer and identify the associated mechanisms. Discrete element modeling simulations describe the role of particle breakdown on swelling and swelling pressure. Molecular dynamics simulations of clay with fluids with a wide range of dielectric constants and experiments further illustrate the crucial role of molecular interactions between clay and fluids on the macroscale properties. Our results indicate that the molecular interactions alter the clay microstructure, the molecular interactions between the clay and fluids, which in turn influence the macroscale properties of swelling clays.

MS13-4:5 | A phase field model for frictional fracture phenomena in rock masses

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The sharp crack topology can be regularized into the diffusive crack topology, resulting in an outstanding challenge in computational contact mechanics. But in the realistic scenario, contact with normal and tangential forces are ubiquitous in geological discontinuous structure. Hence, it (is) meaningful to pixelized interfaces in (the) voxel-based models for modeling compressive failure process of (a) rock mass. In this study, we propose a phase-field model for frictional fracture phenomena in rock masses. Our model has two novel features: (i) a level-set function characterized by the phase-field variable for interface; (ii) a Drucker–Prager type plastic criteria for stick and slip state. It is worth noting that the interfacial indicator function proposed in this study will be updated with the phase-field evolution to reflect topology changes due to crack propagation. We assume a linear elastic (no-tension) response for the relationship of the diffused interface in the normal direction. In the case of tangential contact, the stick and slip distinction is done by a slip condition, which is analogous to the yield condition in plasticity theory. In addition, an alternative splitting strategy of energy takes an analogous expression with Helmholtz free energy in continuum breakage mechanics is proposed. It continuously interpolates the damaged bulk and residual interface systems so that enables us to model the contact behaviors in the regularized interface region. We also provide a robust numerical solution strategy to treat the spatiotemporal evolution of frictional damage and sliding. Our model is validated by five benchmark problems, and the numerical simulations are compared with some published data. We proceed to apply this model to study the complex failure mechanism of crack initiation and propagation in CCBD specimens with various boundary conditions, where the effects of confining pressure and friction are discussed.

MS14: Vibration-based monitoring of structural systems

MS14-1:1 | Dynamic soil-structure interaction of railway bridges: simple lumped parameter models vs. detailed coupled Finite Element – Boundary Element approaches

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In railway bridge dynamics, the accurate prediction of deck accelerations is essential to ensure ballast stability, track quality, and the overall structural integrity of the bridge. Adequate modelling of the track, bridge, and subsoil is often a difficult challenge due to the conflicting requirements of accuracy and efficiency of the chosen modeling approach. Therefore, the modeling approaches found in the literature often focus either on efficiency by making simplifying assumptions about the foundation, the subsoil, the track and the bridge, or on accuracy by modeling of the geometry and material of the structural components and the subsoil in detail. The objective of this contribution is to assess the reliability of an efficient modelling strategy that includes the track, bridge, and foundation on the subsoil in the form of a simple two-dimensional lumped parameter model in comparison to a sophisticated, fully three-dimensional transient coupled finite element – boundary element approach. The fundamental modal properties of both models and their respective subsystems are evaluated and used to optimize the simplified approach. Special emphasis is placed on the accurate consideration of the dissipative effect of propagating waves in the infinite domain of the soil. Final conclusions regarding the applicability as well as the limitations of the simplified approach are drawn from the comparison of the acceleration response predictions due to the passage of a train for both models.

MS14-1:2 | Frequency-domain fatigue life evaluation of a steel bridge considering vibrational characteristics of traffic loads

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Fatigue damage can be evaluated in both the time and frequency domains. While time-domain methods are more accurate than frequency-domain methods, they are also more computationally expensive, particularly for long input signals. Frequency-domain methods, on the other hand, are more computationally efficient, but require stationary and Gaussian input signals. To apply the frequency-domain method to estimate fatigue in steel bridges, this assumption must be satisfied. However, the input vibrations derived from vehicle loads do not meet this requirement. As a result, the fatigue life of the main girders obtained from the frequency method was only about a thousandth of that from the time-domain method. This research aimed to reduce the discrepancy in estimated fatigue life between the time and frequency methods.

Although the previous study used 166 cases for the stress definition, modal transformation and reduction technique contributed to use 20 cases, which made the stress definition more accurate. Furthermore, the grouping and compression of input vibrations significantly contributed to minimizing the discrepancies. The grouping was based on the vehicle weights, while the compression strategy involved shortening the intervals between two vehicles to the longer passing time of the two, but only if the original intervals were longer than the passing times. As a result of these methodological improvements, the error margin in the fatigue life estimation was reduced to 10%.

In addition, this research demonstrates that the frequency-domain method significantly shortens calculation time. Remarkably, the method allows for the fatigue estimation of a 10-day input signal to be completed for about 8.6 hours, which is nearly the same as for a 3.5-hour input. It is important to highlight that this calculation efficiency is notably greater than expected in the time domain, where the estimated calculation time is around 4,100 hours.

MS14-1:3 | Impact of the modeling strategy on the dynamic response prediction of weakly coupled multi-span bridges subjected to high-speed trains

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A high-speed train passing a bridge structure at a critical speed can induce large bridge vibrations. In particular, the acceleration of the bridge deck is a critical design parameter because exceeding the normative limit can cause ballast instability resulting in track misalignments. Therefore, it is of utmost importance to realistically predict the acceleration response of the bridge in the design process based on a sufficiently accurate yet computationally efficient mechanical model. In engineering practice and research, a variety of modeling strategies exist with varying degrees of sophistication. For the structure, these can range from simply supported Euler-Bernoulli beam models that capture the bridge to two beams representing the structure and the track separately that are coupled by vertical and horizontal spring-damper elements, to sophisticated 3D finite element models that capture the components of the bridge and the track (and possibly the subsoil) in detail. The train modeling strategy ranges from single loads to detailed train models with multiple DOFs. Many bridges are single-span structures, but especially high-speed railway bridges span large valleys and thus consist of several single-span structures of the same length, weakly coupled by the superstructure of ballast and rail. The objective of this study is to evaluate the effect of different modelling strategies on the numerical prediction of the dynamic response of such weakly coupled ballasted bridge structures. In particular, different beam models with and without soil-structure-track interaction as well as with and without consideration of the weak coupling between the adjacent bridge structures are considered. The results of deterministic (semi-probabilistic) analyses and probabilistic failure assessments are performed and compared for the different models.

MS14-1:4 | Residual performance estimation of a seismic-isolated bridge based on ABC model updating using seismic response data

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With an increasing number of bridges being decades old since their construction, it is crucial to assess the residual seismic performance of existing bridges, taking into account changes in structural parameters due to ageing, to ensure the resilience and robustness of road networks. To this end, we investigate the approximate Bayesian computation (ABC) model updating using seismic response data, in which a well-known sequential Monte Carlo sampler, called transitional Markov chain Monte Carlo (TMCMC) is employed to gradually minimize the Euclidian distance between the simulated acceleration response time histories and the corresponding observed acceleration time histories. The target system is a seismically isolated bridge pier with deterioration of both the rubber bearing and the reinforced concrete pier. Firstly, the effects of different input ground motions and different noise-to-signal ratios on the ABC model updating results are investigated. Furthermore, the nonlinear dynamic analysis is performed using the updated bridge pier model against different input ground motions to demonstrate the effectiveness of the ABC model updating for estimating the residual seismic performance considering the ageing deterioration.

MS14-1:5 | Modal identification of a railway bridge via drive-by acceleration data from a diagnostic vehicle

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Bridges play a pivotal role in railway transportation infrastructure. However, they are susceptible to the effects of time and wear. Concurrently, the ever-increasing demand for mobility requires higher travel speeds and imposes heavier loads, further challenging their integrity and safety, thus necessitating diligent monitoring to ensure railway network safety. Traditional Structural Health Monitoring (SHM) techniques, employing fixed sensors on bridges, offer reliable data collection but are limited in their ability to comprehensively inspect numerous bridges within a network. An approach utilizing mobile vibration-based monitoring, employing sensors on passing trains, presents a promising alternative. By operating such trains at regular intervals, continuous data collection becomes feasible, providing crucial insights into bridge deterioration over prolonged observation periods. To this end, this work proposes a model-based methodology to extract modal parameters of bridges based on acceleration data collected by traversing trains, focusing on a truss bridge located on the Loetschberg axis of the Swiss Federal Railways (SBB) network. The Loetschberg axis serves as a key north-south route through the Alps, holding significance for Switzerland and Europe as a whole. Leveraging acceleration data collected from the diagnostic vehicle (gDfZ) of SBB and the available multibody vehicle model of the diagnostic vehicle, the proposed approach utilizes a model-based Kalman filtering approach for state and input estimation coupled with a subspace identification method to determine bridge frequencies. The aim is to monitor changes in the bridge's modal frequencies in time, enabling assessment of its remaining lifespan and prompt repairs in case of damage. By ensuring the safety and reliability of this critical railway infrastructure, we aspire to contribute to the seamless operation of rail transportation within Switzerland and across Europe.

MS14-1:6 | New methods for data-based determination of damping factors with application on railway bridges

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A realistic and economical dynamic assessment of railway bridges requires, first and foremost, input parameters that correspond to reality. In this context, the applied damping properties of the structure have a decisive influence on the results in the prediction of resonance effects and further in the assessment of the compatibility between rolling stock and railway bridges. Concerning the damping factors used in dynamic calculations, the standard prescribes damping factors depending on the type of structure and the span. However, these factors can be regarded as very conservative values which do not represent reality. As a result, in-situ measurements on the structure are often necessary to classify a bridge categorized as critical in prior dynamic calculations as non-critical. Regarding in-situ tests, a measurement-based determination of the damping factor is inevitably

accompanied by a scattering of the generated results due to the measurement method used and also as a result of the individual scope of action of the person evaluating the test and this person's interpretation of the measurement data.
With this background, this contribution presents new methods and analysis tools for determining the damping factor, intending to reduce the scatter of the results and limiting the scope of action of the person evaluating the test. Methods and analysis tools are discussed for methods in the time and frequency domain. Based on in-situ tests on 15 existing railway bridges, the data-based procedure for determining the damping factor is explained, and the methods are compared in the time and frequency domain. It is shown that a clearly defined evaluation algorithm can significantly reduce the scattering of results. Furthermore, it is shown that the excitation method substantially influences the determined damping factors.

MS14-2:1 | Exploring graph neural networks for bridges SHM

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Ensuring bridges' structural integrity is crucial for safety and resource optimization. Accelerometers offer a wealth of structural data easily collected to capture the structural dynamic response, essential for tasks like damage detection and life-cycle assessment. However, developing efficient, accurate, and reliable data processing methods remains a challenge.
Over time, a plethora of data-driven and physics-based methods have been devised to improve feature extraction accuracy. Among the hybrid methods, graph neural networks (GNNs) have recently been emerging as a standout choice. Originating from fields like biology and traffic prediction, GNNs show promise by integrating physical information into data-driven approaches, leveraging the strengths of each method. Consequently, GNNs exhibit exceptional performance in predicting critical structural insights.
This research proposes a GNN architecture for converting acceleration signals into strains, overcoming limitations associated with direct strain signal acquisition for life cycle assessment aim. Through a numerical case study, we demonstrate the efficacy of GNNs in Structural Health Monitoring, showcasing their significant potential in improving bridge assessment strategies.

MS14-2:2 | A perturbation technique for natural frequency analysis of structures with cracks or other sources of additional compliance

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Small changes in an elastic structure, such as additional compliance due to local damage (cracks) or variation of inertial properties, influence the spectrum of natural frequencies. The energy approach allows to estimate the small frequency shifts when the vibration modes of the unperturbed (original) structure are available, which greatly simplifies the solution of problems of structural optimization and damage identification. The asymptotic proof of the relations of the energy approach is easy in case of simple changes in mass distribution or stiffness. The situation becomes more sophisticated when the perturbed structure possesses richer kinematics than the original, i.e. when the perturbed vibration modes become incompatible with the constraints of the original structure. Thus, it is common to model cracks in beams or plates by local hinges with rotational springs, which essentially introduces new degrees of freedom. Another example is the correction of the vibration frequency due to shear flexibility compared to a Bernoulli-Euler beam or Kirchhoff plate model. Elastic supports also fall into this category. The present contribution provides a novel mathematical proof of the energy approach using methods of structural and analytical mechanics. By performing the analysis at the abstract level of a discretized model, we capture the full variety of linearly elastic structures ranging from 3D continua to rods, plates, and shells. Using this technique, we show for the first time that the simple relations of the energy approach lose their validity in the situation of multiple (repeating) natural frequencies and must be replaced by a specially constructed eigenvalue problem of reduced dimensionality. The theoretical analysis is illustrated by simple "toy models", which demonstrate the asymptotic accuracy of the linearized relations for frequency increments. Furthermore, we investigate the practically relevant problem of the vibrations of a square plate with added line mass or a crack of arbitrary shape, modeled as a rotational spring.

MS14-2:3 | The challenges of surrogate modelling of modal properties

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Structural identification and structural health monitoring often require the development of surrogate models. This is mainly for their reduced computation time, but also for other reasons, such as the possibility of offline computation without the need to access the licensed software. The basis for fitting a surrogate model is the evaluation points, which are sampled over the domain of the selected parameters and evaluated by the parametrised finite element model. When the quantities of interest are the modal properties, additional challenges linked to the mode classification arise. These challenges will be presented and discussed using a timber structure example.
There are several possible criteria for classifying the computed modes into fitting groups. One might use the order of the natural frequencies as a criterion, however, that would lead to incorrect classification in the presence of mode crossing. On the other hand, if the mode shape correlation to a reference evaluation point is chosen, the phenomenon of mode veering would lead to discontinuous jumps between the modes. While more advanced mode tracking procedures that follow the evolution of the natural frequencies and mode shapes alongside continuously varying the modelling parameters may appear to offer a superior alternative, they are prone to fail around the coalescing point. Additionally, spatial aliasing that occurs due to improper discretisation may add to the complexity of the problem at hand.
A case study of a timber structure showcases the challenges of mode crossing, mode veering, and spatial aliasing. We present the techniques for improving the success of mode classification and the overall accuracy of the surrogate model. Finally, we update the model using modal data obtained by shaker testing of the structure.
Financial support of EU Horizon Europe for the BUILDCHAIN project (grant agreement 101092052) is gratefully acknowledged.

MS14-2:4 | Wavelet analysis and information theory for enhanced structural health monitoring: insights and strategies for anomaly detection in civil structures

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Structural health monitoring (SHM) plays a vital role in the timely detection of anomalies in civil structures, ensuring their safety and durability. Wavelet analysis has emerged as a powerful technique for comprehensive structural analysis, integrating time and frequency domains seamlessly. This study introduces mutual information-based information theory techniques into wavelet analysis, aiming to enhance anomaly detection in SHM. By applying wavelet scalograms to structural dynamic acceleration responses, the study identifies informative time-frequency regions and tracks changes in wavelet coefficients induced by damage events. Through thorough analysis, it reveals the efficacy of wavelet analysis in promptly detecting transient damage events and monitoring long-term structural health changes. Notably, the incorporation of mutual information-based techniques enriches the analysis by providing deeper insights into structural dynamics and enhancing anomaly detection strategies. Mutual information serves as a valuable feature of damage, enabling a more nuanced understanding of structural behavior and bolstering proactive maintenance strategies. This integrated approach underscores the pivotal role of wavelet analysis and information theory in ensuring structural integrity and facilitating informed decision-making for sustainable infrastructure management.

MS15: Fundamental and practical insights into characterizing, measuring, and mitigating shrinkage and creep in cementitious materials

MS15:1 | Creep and shrinkage of a limestone calcined clay cement paste determined in hourly performed three-minute creep tests

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Limestone calcined clay cements (LC3) are a promising alternative to traditionally used ordinary Portland cement (OPC). So far, little research has been performed on the early-age creep properties of LC3. This motivates a multi-technique experimental study of three bind-ers: an OPC, a binary blend called limestone Portland cement (LPC) containing, by mass, 70% OPC and 30% limestone, as well as an LC3 containing, by mass, 70% OPC, 15% limestone, and 15% calcined clay. Quasi-isothermal differential calorimetry is used to study the reac-tion kinetics. Macroscopic mechanical tests comprise uniaxial compressive strength tests, ultrasonic pulse velocity measurements, and hourly performed three-minute creep tests, to characterize the material strength, the elastic stiffness, and creep properties from 1 to 7 days after cement paste production. 870 creep tests are evaluated individually to identify the evolution of the elastic modulus, the creep modulus, and the creep exponent. The existing test evaluation protocols [https://doi.org/f8hgjp, https://doi.org/czmn] are extended to explicitly account for shrinkage strains. LC3 was found to be less creep active than LPC, slightly more creep active than OPC from 1 to 3 days after paste production, and less creep active than OPC from a material age of about 3 days. Macroscopic creep and shrinkage of OPC, LPC, and LC3 are qualitatively related to the microstructural phase evolution of the binders, which is studied with CemGEMS.

MS15:2 | Basic creep properties of the hydration products in mature slag-based CEM II concretes

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The demand for accurate characterization of slag-based CEM II concretes is becoming increasingly important, as the construction sector shifts towards eco-efficient materials. In the present contribution, the basic creep behavior of mature slag-based CEM II concrete as used for Tubbing production at Koralm tunnel in Austria, is identified from classical macroscopic creep tests, and traced back to mixture-invariant characteristics of the hydration products, by means of an adaption of a well-validated multiscale micromechanics model for CEM I concrete. The model is based on an extension of Powers' hydration model towards consideration of slag, and on an isochoric creep function for the CEM II hydration products. The creep function considers (i) short-to-long-term creep through a piecewisely-defined function comprising a power law for the short-term portion and a logarithmic law for the long-term portion, (ii) temperature dependence of hydrate properties, and (iii) the influence of the internal relative humidity. Downscaling of mechanical properties from the concrete level to the scale of the hydration products evidences a shear creep compliance of CEM II hydration products, which exceeds, by a factor of two, the one known for ordinary Portland cements, CEM I. For the purpose of model validation, the identified shear creep compliance of CEM II hydration products is used for predicting the creep of another slag-based CEM II concrete with a different composition. It is concluded, that slag-based CEM II concretes are especially suitable for applications, where a faster stress relaxation under displacement-controlled conditions is beneficial, e.g. precast segmental tunnel linings.

MS15:3 | Early-age elastic and creep properties of graphene oxide cement paste determined by three-minute-long creep tests

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Graphene oxide has gained substantial attention as a carbon-based nanomaterial in cement-based composites. The present study is focused on the effect of graphene oxide on the early-age creep properties of three cement pastes. The first paste, serving as a reference, is produced by mixing distilled water with an ordinary Portland cement which is free of tricalcium aluminate, at an initial water-to-cement mass ratio amounting to 0.42. The second paste is produced by adding a polycarboxylate superplasticizer to the recipe of the first paste. The dosage of the superplasticizer amounts to 0.09% by weight of cement. The third paste is produced by adding graphene oxide to the recipe of the second paste. The dosage of the graphene oxide amounts to 0.09% by weight of cement. Uniaxial compressive strength tests and ultrasound pulse transmission experiments, evaluated by means of the theory of elastic wave propagation through isotropic media, are performed at material ages of 1, 1.5, 2, and 3 days. Hourly three-minute creep testing is carried out from 1 to 3 days after material production. The execution of the non-aging linear creep experiments and their evaluation within the framework of the linear theory of viscoelasticity follows the developments of Irfan-ul-Hassan et al. [https://doi.org/f8hgjp]. The obtained results show that both the dynamic ultrasonic tests and the quasi-static creep tests deliver virtually the same moduli of elasticity, while neither the superplasticizer nor the combination of superplasticizer and graphene oxide have a significantly influence on to the early-age evolution of the uniaxial compressive strength, the elastic stiffness, and the creep properties.

MS15:4 | Influence of cracking and viscoelasticity on nonlinear creep of concrete

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Concrete exhibits linear creep behavior under uniaxial compression for stresses smaller than some 40% of its strength. Above this level, nonlinear creep occurs. Herein, an analytical model is formulated, explicitly separating the contributions to nonlinear creep from (i) viscoelastic phenomena, and (ii) cracking-induced damage. A re-analysis of a multilevel creep test on a mature concrete [http://doi.org/c795rc] is performed. During the test, the creation of microcracks was monitored by means of the acoustic emission technique. The obtained experimental data are used as input to formulate the analytical model as follows. A validated multiscale model for strength upscaling is used to quantify the hydration degree of the concrete based on its reported strength. This is then used in combination with the reported mix design to predict the linear creep properties of the concrete using another multiscale model valid for nonaging basic creep of cementitious materials under water-saturated conditions. A creep reduction factor is introduced to account for a relative humidity smaller than 100%. The affinity concept [http://doi.org/dzsxwf] is used to estimate nonlinear viscoelastic properties of concrete. Innovatively, damage of concrete is explicitly accounted for through a newly introduced damage factor describing the relation between microcracking to the corresponding decrease in concrete stiffness. Cracking events happening both during quasi-static loading and during sustained loading are shown to have an important influence on the behavior of the specimens. The developed model is able to reproduce also other non-linear creep experiments very accurately up to stress levels beyond the limit of applicability of the affinity concept. This confirms that nonlinear viscoelastic phenomena govern the creep behavior at medium stress levels, while cracking-induced damage dominates the behavior at high stress levels.

MS15:5 | Long-term concrete strain measurements of large-scale experiments using vibrating wire strain gauges

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Creep and shrinkage are an essential part of the material properties of concrete. To describe the time-dependent behaviour of concrete structures with mathematical models, a huge number of experimental tests is needed to calibrate and improve these models concerning creep and shrinkage of concrete.

Most of the creep and shrinkage tests which are available in the literature were conducted on small sized specimens which are tested under constant environmental conditions. The major goal of a research project conducted by the TU Wien since 2017, is to perform creep and shrinkage tests on large-scale concrete specimens under real environmental conditions. Therefore, large-scale prismatic concrete specimens with cross-sectional areas of up to 1m² were produced and exposed to real environmental conditions. To observe the stress induced creep strains, half of the large-scale specimens were loaded with a post tensioning system. The other half of the large-scale specimens were load-free to measure the load independent eigenstrains (consisting of the shrinkage strains, thermal strains and strains due to cracking). The continuous measurement of the concrete strains is ensured by means of vibrating wire strain gauges.

After more than six years of measuring, the vibrating wire strain gauges showed that they are capable for long-term concrete strain measurements. In the presentation, the usage of vibrating wire strain gauges and the creep and shrinkage measurements of the whole measurement period are presented. Finally, the influence of different environmental conditions (due to different production dates) is discussed.

MS15:6 | Characterization of time-dependent restrained shrinkage in thin ultra-high performance concrete overlays

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Thin ultra-high performance concrete (UHPC) overlays offer a protective layer to extend the service life of transportation infrastructures such as bridge decks. The restrained shrinkage in bonded concrete systems can, however, cause stresses that eventually lead to overlay cracking and/or interface debonding. While a transition from normal concrete (NC) to UHPC overlays has helped address several performance issues in bonded concrete composites, questions regarding the impacts of the overlay geometric features (e.g., thickness and slope) and mixture composition (e.g., fiber inclusion and use of recycled cementitious materials) on the development of restrained shrinkage stresses and potential failures remain. These standing questions motivated the current study, in which a set of experimental tests was designed to characterize the overlay shrinkage and determine the composite possible failure modes. The experimental test campaign systematically covered the effects of overlay geometry and mixture characteristics. A set of UHPC-NC specimens were cast with overall dimensions of 180×75×15 cm3 and slopes up to 5%. Integrated distributed fiber optic sensors (DFOS) were employed to monitor the strains inside the bonded UHPC overlays for a period of six months. The collected data provided firsthand information on the magnitude and spatial distribution of restrained shrinkage as well as potential crack formation in the UHPC-NC composites over time. By addressing the potential early-age shrinkage issues, this study outcome is expected to optimize the use of thin UHPC overlays, especially to protect NC substrates.

MS16: Mechanics of wood, wood-based products, biocomposites, and timber structures

MS16-1:1 | Variations in experimental investigations of clear wood: to what extend can multiscale micromechanical models explain them?

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Hardwood in European mixed forests will increase in response to climate shifts and thus investigating their properties gains prominence in research. Wood, whether softwood or hardwood, is hierarchically organized and the macroscopic, anisotropic mechanical properties are governed by the microstructure. The presented application of multiscale models aims to explore the influence of microstructural character-istics for an explanation of observed macroscopic variations in experimental testing of stiffness and strength perpendicular to the grain and rolling shear. A validated multiscale micromechanical model for the stiffness of softwood was presented by Bader et al. (2011) and further extended to hardwood by de Borst and Bader (2014). In the latter study, the model was validated for beech and nine other hardwood species. In this work, the mechanical properties of the softwood species spruce as a reference and the hardwood species beech and birch, are inves-tigated. The experiments were conducted on prismatic clear wood specimens (50 mm width, 20 mm thickness (grain direction), and 60 mm height), enabling clear wood material-level testing. However, due to thickness and annual ring distribution of the raw material, the inclination of the annual rings of early- and latewood, defining the radial and tangential direction (RT-plane) of the idealized orthotropic mate-rial, varies in the test series. The influence of this RT-plane rotation and the variation in microstructural parameters, like microfibril angle, lumen, vessel, and ray cell properties, on the global stiffness, are modelled based on multiscale models for the three investigated species. The micromechanical models are applied to obtain values of the nine independent components of the stiffness tensor with corresponding realistic modelling variations. These tensors are then rotated within the RT-plane to investigate the influence on the global clear wood be-havior. The modelled global stiffness values are subsequently compared with the experimental results.

MS16-1:2| Phase field method-based modeling of wood fracture

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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. In this work, the focus is laid on a cohesive phase field method [1]. With this method, especially geometric compatibility issues that limit the use of, e.g., 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 [2,3] contains a stress-based split 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. The developed algorithm was validated on various problems. 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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[2] S. Pech, M. Lukacevic, and J. Füssl, „A hybrid multi-phase field model to describe cohesive failure in orthotropic materials, assessed by modeling failure mechanisms in wood“, Eng. Frac. Mech., Bd. 271, S. 108591, Aug. 2022, doi: 10.1016/j.engfracmech.2022.108591.

[3] S. Pech, M. Lukacevic, and J. Füssl, „Validation of a hybrid multi-phase field model for fracture of wood“, Eng. Frac. Mech., Bd. 275, S. 108819, Nov. 2022, doi: 10.1016/j.engfracmech.2022.108819

MS16-1:3 | Characterizing a novel strand based engineered wood product for the use in construction

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The growing demand for resource-efficient construction materials seeks additional engineered wood products (EWPs), focusing especially on higher utilization of the raw materials. One possibility is to use strand-based EWPs. For a broader use, a detailed characterization, as basis for a safe dimensioning is needed. This study, therefore, aims to characterize a novel EWP, in both single and three-layered configurations, highlighting its potential for construction applications. A range of standardized mechanical tests, including tension, compression, shear, and bending was carried out on both single and three-layer configurations, to identify the material's strength and the most critical elastic constants, i.e. Poisson's ratios, elastic moduli, and shear moduli. These properties were assessed across the material's three principal directions, essential for accurate material modeling and dimensioning. These experimental efforts were paralleled by a first attempt at a 3D finite element model (FEM) in Abaqus to simulate the material behavior when it is subjected to out of plane bending load. In conclusion, this research not only represents a significant effort towards the accurate representation of material in mechanical properties but also a robust framework for computational models, offering promising avenues for material optimization and exploring complex loading scenarios in structural design. Future work will focus on expanding and improving the modeling framework and conducting plastic analysis and failure criterion, further aligning numerical simulations with real-world material performance.

MS16-1:4 | Analytical and experimental study on glulam trusses with birch plywood gusset plates

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Previous investigations demonstrated the potential of birch plywood as a valid substitute for steel plates in connections of timber structures. However, in those studies, the tests on birch plywood were limited to a simple stress state (e.g. uniaxial tension), instead of being in a complex stress state with combined multidirectional tension and compression forces, which is typical for a truss node. Furthermore, the size of the tested specimen is relatively small compared to the real case.

In this study, 6 full-scale trusses with a span of approximately 6.5 meters were tested. Each truss consisted of glulam elements with birch plywood plates at the nodes, connected by either MUF-based glue or smooth dowels with a diameter of 8 mm. The thickness of the birch plywood plates varied between 9, 12 and 21 mm. As designed, failure should occur in the node of the truss, which was subjected to compression from the vertical post and tension from the two rafters. Plywood failure occurred in all the dowel trusses and the glued truss with 9 mm plywood, while glue line failure occurred for the glued trusses with 12 and 21 mm plywood. The doweled truss with 21 mm plywood plates will be tested at the end of April 2024. Certain disparity was observed when comparing predicted and actual failure modes. For example, plywood failure was predicted for the glued truss with 12 mm plywood, however, glue line failure was observed.
Furthermore, analytical estimations showed a slight overestimation of the experimental capacity. This is currently attributed to the fact that the nodes were assumed as hinges in the calculations, despite the fact that they are able to transmit bending moment. Lastly, the thickness of the plywood plates depicted an influence on the load-carrying capacity of the trusses but no significant influence on the stiffness.

MS16-1:5 | Analyzing the failure probability of glued laminated timber beams across varying sizes using the finite weakest-link theory

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Wood is an excellent building material, as evidenced by its remarkable strength-to-weight ratio. Designing for high reliability with an extremely low failure probability, requires a deep understanding of material properties characterized by probability distribution functions (PDFs). However, directly determining these PDFs through experiments or simulations for such low probabilities is challenging due to their dependency on geometric size and loading conditions.
The finite weakest-link theory [1] provides a practical solution for quasi-brittle materials like wood, employing a combined Weibull and Gaussian distribution. Initially, the Weibull distribution describes only the far-left tail for sufficiently small structures, while as the size increases, the distribution transitions from Gaussian to Weibull dominance. The scaling of the PDF is based on the size of a representative volume element (RVE) and the elastic stress state. Identifying the distribution parameters is challenging, requiring sufficiently large sample sizes of various structural sizes, including large-scale ones.
We estimated all the distribution parameters, allowing us to scale the PDF of bending strength for glued laminated timber beams. This was made possible by a comprehensive simulation campaign [2], where beam sections were simulated under constant bending moments, considering discrete cracks and plastic deformations. Additionally, we utilized experimental data and adhered to standards. With this framework, we obtained bending strength PDFs specific to the beam size and loading configuration. As a result, we were able to quantify the size effect and determine size-dependent failure probabilities.

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[2] C. Vida, M. Lukacevic, G. Hochreiner, J. Füssl, “Size effect on bending strength of glued laminated timber predicted by a numerical simulation concept including discrete cracking”, Mater. Des., 225 (2023) 111550, doi: 10.1016/j.matdes.2022.111550.

MS16-1:6 | Preparation of samples for the production of Glued Solid Timber (GST) beams according to EN 14080

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Timber is one of the materials that continues to be very important in the field of modern constructions. There are many researches carried out in the field of production and use of Glulam beams (GLT) and Glued solid timber (GST) and many of them are not based on the relevant standard of Eurocode 5.
The research aims to present the experimental and analytical analysis, beginning from the procedure of selection of raw material according to EN 14080, determination of moisture content of test pieces, defining dimensions of the samples (cutting slices), measuring, scaling samples and its drying. Determination of density of test pieces according to ISO 13061-4:2014 and production with all phases.
The test slice was cut of full cross section referred to standard EN 13183-1 and minimum 20mm dimension in the direction of the grain, at a point by at 300mm from either end of the test piece.
Each test slice was marked and measured in longitudinal, radial and tangential directions (8 measurements were done per each piece with Nonius Caliper) and each piece has been scaled (accurate equip. to 0,01 g) and dried in an oven dry state. Equipment for drying ensured free internal circulation of air and capable of maintaining a temperature of (103 ± 2) °C. The density of wood is determined based on the ISO 13061-4:2014 standard.
After drying the samples and determining the moisture content and determining the density of the samples experimentally, the Spruce wood (Picea Abies PCAB) was found to be of class T30 (C50) according to EN14080, material of sufficient quality for use in the production of beams. The production of Glued Solid Timber beams in this study for this experimental purpose, turned out to be a promising and well-executed for the use in constructions.

MS16-2:1 | Experimental investigations on horizontally restrained CFRP reinforced glued laminated timber beams

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The number of tall timber buildings being constructed in recent years is on the rise. This makes the topic of robustness increasingly relevant. With the use of carbon fibre reinforced polymers (CFRP), timber elements can be reinforced to improve strength properties and make failure modes more ductile. An investigation has taken place on the ability of CFRP reinforced softwood glued laminated timber to form catenary action in full-scale specimens. A novel setup has been used to perform a series of full-scale experiments. In order for catenary action to be activated, horizontal restraints are required. The setup comprises hinges to allow free rotation however no horizontal displacements. These idealised boundary conditions are a starting point to gain a better insight of the combined flexural and tensile actions occurring inside the beams during loading. In order to allow for the comparison with and validation of existing analytical models, the tensile force in each specimen is monitored using strain gauges, whilst deflections, rotations and strains are measured using a combination of LVDTs and optical measurement systems.

MS16-2:2 | Layerwise model for the failure analysis of Cross Laminated Timber

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Cross laminated timber (CLT) is a wood-based product increasingly utilized in construction. It comprises multiple layers of boards arranged orthogonally to each other, providing the resulting panel with bearing capabilities in both bending and in-plane directions. Nevertheless, the computation of load-bearing properties for CLT remains challenging, as highlighted by recent studies. One of the primary challenges is establishing a comprehensive link between structural CLT properties and the base materials and layup parameters. Due to the inherent variability of wood and the orthotropic arrangement of CLT, extensive testing is necessary to determine mean and characteristic values.
To tackle this issue, this contribution proposes an efficient computational model. Initially, a layerwise plate model is developed to reduce computation costs compared to a full three-dimensional model, while maintaining precision in stress field calculations, particularly at layer interfaces. The resultant 2D multilayer plate model is implemented in the FEniCSx open-source finite-element package. Subsequently, damage models are devised to simulate crack initiation and propagation within or between layers, capturing the interaction between these diverse damage mechanisms. Anisotropic phase-field models are notably employed to regularize intra-ply damage localization. Following initial validation of individual damage mechanisms, the model will be calibrated and its predictions tested against available experimental data from various failure tests.

MS16-2:3 | Long-term behavior of novel solid wood-concrete-composite floors with combined shear connectors

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A novel multi-layered solid wood-concrete-composite floor system with combined shear connectors based on a structural design of the traditional "Dippelbaumdecke" (dowel beam floor) is introduced and investigated by means of its long-term static load-bearing and deflection behaviour on varying assessable scales.
The presented publication aggregates the results of the related experimental and analytical long-term investigations and gives an insight into the consequential time-dependent load-bearing behaviour of the assessed structural system under short-term loads, as well as into the arisen deflection behaviour of the structural component and its related creep mechanisms under permanent long-term loads.
As mentioned initially, the paper primarily focusses on the long-term static load-bearing and deflection behavior of the assessed novel structural system. These studies cover experimental and analytical investigations on varying assessable scales, as the properties of the examined composite floor system can ideally be described based on a combination of large-scale and mid-scale level explorations (overall structural floor system level resp. shear connector level).
In more detail, the investigations thereby are executed in form of flexural tests for the large-scaled explorations as well as in form of double symmetric push-out tests for the mid-scaled explorations. Furthermore, as the investigated structural system contains combined shear connectors, all experimental and analytical investigations are conceptualized and conducted for each stand-alone typology as well as for the combined typology.
Based on this chosen setup of structural investigations it becomes possible not only to describe the assessed structural system and its time-dependent properties on varying length scales, but also to characterize the explicit interactions between the used stand-alone shear connector typologies. In conclusion, decisive general parameters, as well as resulting explicit temporal effects within the composite system can be gained experimentally and can be pursued analytically. Furthermore pertinent statements regarding the ongoing standardization process of timber-concrete-composite structures can be derived thereof.

MS16-2:4 | Multi-scale multi-physics modelling of timber-concrete hybrid structures

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As a replacement of concrete and steel, timber is increasingly being recognized and used in the construction industry in the past decade thanks to the emergence and spread of Engineered Wood Products (EWPs). There are two scales of adopting hybrid structures: on the system level by adopting different materials for each building component, e.g. timber columns combined with concrete floor and steel beams, and at the building component level by combining different construction materials in one building element, e.g. CLT-concrete composite floor slabs. Building components formed by timber-concrete are often referred to as Timber-Concrete Composite (TCC) components. The connection/bonding mechanisms for TCC typically include dowel type fasteners, notches, notches combined with steel fasteners, and adhesives. To promote timber-based hybrid structures with sustainability goals, advanced computational tools to predict long-term behavior are required. The analysis and prediction tool also needs to be adapted for the specific use cases on the structural scale while keeping a fundamental multi-physics framework for scientific soundness.
The author proposes a multi-scale multi-physics modelling framework for timber-concrete hybrid structures. The proposed modelling framework starts from the micro-macrostructure of wood looking into moisture transport and diffusion, then upscales to timber element scale linking to time-dependent mechanical behavior, lastly incorporates the connections between timber-concrete and the mechanical responses on the structural scale. The formulation for timber and composite elements builds on the previously developed multi-scale multi-physics aging framework for concrete by the author and coworkers, which was implemented in the specialized modeling software MARS. As the hygroscopic and mechano-sorptive behavior of timber display similarities to that of concrete, it provides high feasibility to adapt the aging framework to fit the mechanical responses and long-term behavior of timber and TCC.

MS16-3:1 | Predicting the performance of glued-in rod joints

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Timber joints featuring glued-in rods (GiR), comprising a combination of a rod, adhesive (glue), and timber, play a crucial role in the mass timber construction industry. The reliable and efficient design of GiR joints is essential for the success of large-scale timber-based structural systems. However, the intricate mechanical complexities inherent in the load-displacement behavior of timber and adhesive joints pose significant challenges in accurately analyzing and designing GiR connections.
This contribution aims to employ the theory of elasticity to establish an analytical procedure for evaluating the stiffness and loading capacity of GiR joints under various loading configurations. The proposed analytical model allows for treating the adherents as isotropic, orthotropic, or multilayer composite materials.
The accuracy of the proposed analytical model is assessed by comparing it with laboratory test data and Volkersen's model, providing valuable insights for the efficient design of timber connections involving GiR.

MS16-3:2 | Numerical assessment of brittle failures in dowel-type timber connections loaded parallel to the grain

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The design of robust timber buildings requires reliable methods for assessing possible failures of connections that can have serious consequences. This contribution proposes a three-step modelling approach to predict: (i) the ductile load-displacement behaviour of individual fasteners, (ii) the stress distribution in the timber matrix, and (iii) the brittle failure of the timber in laterally loaded connections with steel fasteners and slotted-in steel plates. The local nonlinear behaviour of single dowel-type fasteners was determined utilising a beam-on-foundation approach, which subsequently was used to define nonlinear springs located at the fastener's shear plane in a multiple fastener connection model to obtain the stress distribution in the timber matrix. The timber member and the steel plate were modelled using 3D shell elements with linear-elastic orthotropic and isotropic material properties, respectively. The interaction between rigid cylinders, representing the fasteners, and the 3D shell elements, representing the timber and steel members, was characterized by defining hard contact in the normal direction and friction in the tangential direction. A Python-scripted post-processing module, based on linear elastic fracture mechanics, evaluated potential brittle failure through the mean stress approach. The stress distribution was obtained for each load increment during numerical analysis and used to calculate the mean stress length for various potential failure paths along the grain direction. The failure criteria were assessed for each pre-defined path and load increment to identify the critical path and estimate the connection's load-carrying capacity. The numerical model accurately fitted previous experimental tests regarding load-carrying capacity and connection slip, providing realistic load distribution in multiple fastener connections and accurate predictions of crack initiation, while taking advantage of high computational efficiency.

MS16-3:3 | The effective timber thickness for brittle failure assessment of dowel-type connections

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Due to high localised shear and perpendicular to the grain tensile stress concentration, timber in dowel-type connections may fail before the ductile connection capacity is reached. Experimental studies have found that even if timber connections are designed to avoid brittle failure in accordance with international standards, they still may exhibit brittle failures. In response, the scientific community has endeavoured to develop more accurate and reliable design models to predict the brittle load-carrying capacity, and suitable for engineering applications in a straightforward way. For connections with stock fasteners, embedment stresses are practically uniform across the thickness of the timber member, allowing to activate the entire timber member for the connection load transfer. However, in connections with slender fasteners prone to bending, and therefore, promoting ductility, the embedment stresses can vary significantly across the member thickness. Thus, it is essential to assess the length which effectively contributes to the connection's load-carrying capacity. This length can be defined by the so-called "effective thickness" of the timber member. Various models are available in the literature for estimating the effective thickness of timber based on the bending deformation of the fasteners. These models primarily differ in the theoretical definition of the effective thickness and do not consider the non-linear connection behaviour. In this context, the main objective of this contribution is to establish a mechanical understanding of the effective thickness of timber used in the design of dowel-type connections. This is achieved by drawing insights from a numerical non-linear beam-on-foundation model, and comparison of results with analytical formulations presented in international standards and the literature. In addition to the model validation, a parametric study is presented considering timber-to-steel connections with single, double, and multiple shear planes. Various parameters such as plate thicknesses, fastener slenderness ratios, and material properties are varied for a comprehensive comparison with other models.

MS16-3:4 | Single-dowel steel-to-timber connections under cyclic and high strain rate loading

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The recent trend towards taller timber buildings gives robustness requirements a more prominent role. These buildings must be able to resist initial damage from accidental events (e.g., the loss of a column) without disproportionate consequences. In recent years, several examples of partial or full building collapse have occurred due to, e.g., renovation works or explosions. The collapse of a structural member often results in dynamic loading that imposes high strain rates and vibrations. Dowelled steel-to-timber connections are commonly used in practice, but the influence of cyclic and high strain rate loading on their structural behaviour is not yet well understood.

Steel-to-timber connections with a slotted-in steel plate and a single laterally-loaded dowel were tested under high strain rate monotonic loading and quasi-static cyclic loading. The experiments were performed on LVL Kerto-S connected by S235 dowels with a diameter of 10 mm, and comprised four different load-to-grain angles between 0° and 90°. Five different strain rates were investigated between 0.05 mm/s (quasi-static) and 150 mm/s.

First analyses of the experimental data for high strain rates (150 mm/s) and load-to-grain angles of 0° revealed a minor increase in mean maximum force by 4% and a significant decrease in ductility by 46%, compared to the quasi-static reference case. For load-to-grain angles of 90°, the increase in mean maximum force was 11% with negligible changes in ductility. In both cases, the failure mode remained ductile with three hinges forming in the dowels, even though less pronounced for high strain rates. For 0° load-to-grain angle, splitting within the timber side members was observed after extensive deformation of the dowels.

In the cyclic tests, failure occurred through rupture of the dowel after reaching the cycles with four to eight times the yield displacement. The hysteresis loops showed pinching as well as strength and stiffness degradation.

MS16-3:5 | Beam-on-foundation modelling of dowel-type timber connections under cyclic loading

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Beam-on-Foundation (BOF) models were mainly applied to represent the mechanical behaviour of timber connections with laterally loaded dowel-type fasteners under monotonic loading. Modelling of such connections under cyclic loading, applying BOF-models, is however less investigated. The aim of this study is to contribute to a better prediction of the global hysteretic behaviour, the load distribution along the fastener, and potential fatigue failure in the steel fastener of timber-to-steel connections with a single dowel-type fastener under large cyclic loads.

This was achieved through the extension of an existing monotonic BOF-model and its conversion into a quasi-static simulation using Abaqus Explicit R2022x. In the BOF-model, the fastener is represented by linear Timoshenko beam elements with a linear-elastic nonlinear-plastic material behaviour. Spring elements, defined by uniaxial connector elements in Abaqus, represent the embedment behaviour of steel and timber. For steel, a linear-elastic and for timber, a nonlinear-elastic-plastic embedment behaviour, using the Richard-Abbott function, was implemented. A parameterised unloading behaviour was added to the connector definition using an inverted Richard-Abbott function. For both, loading and unloading behaviour, the function depends on the properties of the timber material and the load-to-grain angle. To account for a different unloading behaviour at different displacement levels, an additional dependency on the displacement at the start of the unloading phase was incorporated. Cyclic embedment tests of dowels in spruce were conducted to generate input properties for the connector elements of the BOF-model.

For validation of the connection model, quasi-static cyclic tests were carried out on timber-to-steel connections with one dowel. Good overall agreement was found between simulation results and the experiments with respect to the global hysteresis shape and dissipated energy. Strength and stiffness properties were especially well predicted for the initial loading phase, while the unloading stiffnesses showed larger deviations.

MS16-4:1 | Advanced structural modeling of cross-laminated timber buildings: from elemental analysis to comprehensive structural assessment

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Cross-Laminated Timber (CLT) has significantly increased the potential for the use of wood in sustainable multi-story mass timber buildings. This paper explores the structural modeling of bracing systems in mid-rise CLT buildings under both static and dynamic loading conditions. The study aims to enhance the understanding and application of engineering models, ranging from simplistic hand-calculation methods to complex three-dimensional finite element models. For realistic modeling, the structural behavior at various levels, including connections, CLT elements and their interfaces, floor plans, and the overall structural system, must be described and discussed comprehensively.

Stress-strain properties of commonly used connections are described for both linear and non-linear analyses based on design codes and scientific literature. The horizontal displacement behavior of CLT shear walls is influenced by the element build-up, the connection stiffness, and the level of vertical load. At floor plan level, the distribution of reaction forces due to horizontal loads may be determined on a 2D-stiffness approach.

For dynamic analysis, the building can be modelled as a single three-dimensional Timoshenko beam element, a space frame model, or a finite element shell structure. The beam model, utilizing cross-section values from 2D-Stiffness calculations supports simplified engineering models. 3D structural models incorporate additional factors, such as the in-plane stiffness of the bracing ceilings, edge interconnections of walls across corners, and ceiling bending rigidity.

The study compares various analysis models, emphasizing the potential of push-over analysis in accordance with Eurocode 8 - Design of structures for earthquake resistance. The investigation also explores the potential of vertical prestressing with crenellated interlocking of wall elements. The paper concludes with a practical use case demonstrating the application of these modeling techniques at different complexity levels, highlighting critical findings and proposing directions for future research to develop robust, reliable, and efficient design tools for CLT buildings.

The research project Sys.Wood is supported by the Austrian Research Promotion Agency (FFG): FFG Project number: FO999896268.

MS16-4:2 | A parametric framework to assess the limit states of tall timber buildings - preliminary results

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A concrete core usually provides the lateral stiffness of tall timber buildings. To further decrease their carbon footprint and construction time, lateral stiffening systems comprising only timber would be highly beneficial. Given the flexibility of timber, wind-induced serviceability displacements and accelerations are often the governing design criteria. However, the ultimate limit state should not be neglected and may sometimes be governing. In this paper, we present a parametric framework to assess and compare the serviceability and ultimate limit state of tall timber buildings with lateral stiffening systems comprising timber members. The framework assesses both gravity and lateral wind loading. Based on the building geometry, material properties, vertical loads and wind characteristics, it determines the relevant load combinations and the corresponding utilizations. The framework serves as an important tool to determine the relevance of various parameters on the limit states, and can optimize the structural systems and material use of tall timber buildings.

MS16-4:3 | Learnings from monitoring of realized and under-construction timber buildings

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The number of timber buildings is increasing worldwide and many different typologies, use cases, and structural systems are found. The timber-construction industry has yet to reach the same level of standardization as the conventional construction industry. There is simply less experience since timber as a high performing, mass

product is on the market for not more than 25 years.
In this research work, multiple buildings have been analyzed and the performance of the realized as well as the designed building has been compared. Realized buildings were evaluated through monitoring of the dynamic behavior, the test campaigns consisted of (a series of) one-time measurements during construction phase or in the completed building, respectively. This was made possible using a self-developed data acquisition system which allowed quick deployment without disturbing the residents or the construction process. In parallel, design models were created using commercial software. For the models, realistic parameters regarding material, foundation, the effect of non-structural walls, and connection properties were deployed.
The comparison between the models and the measured values often shows significant differences: while the mode shapes are basically identical, the eigenfrequencies regularly deviate significantly between model and reality. Interestingly, deviations in both directions are found. Parametric studies highlight the significance of different properties, the sensitivity of the properties often become evident. Using this method of comparison and the parametric study, the “most important” parameters can be identified. It is proposed that those parameters should be focused on in the design when selecting the “most appropriate” values.

MS16-4:4 | Mechanical behaviour of timber chock structures for underground mine support

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Timber chock is one of the most important standing support systems widely employed in underground mining operations. This type of standing support system offers numerous benefits, including cost-effectiveness, rapid installation, and minimal service requirements. The structures of timber chocks are made by stacking several timber end-notch components, providing a full contact area between layers and an interlocking structure, which is constructed from Australian hardwood timbers, particularly the Gum family. The timber chock can stabilize mining areas where the roof is uncontrollably deforming, resisting converging loads from both the roof and floor to maintain underground stability and productivity at a high level. Thus, investigating timber chock is crucial for improving mine safety during operations. However, there are instances where overestimating the load-bearing capacity of the supports leads to collapse. This paper presents an investigation into the mechanical characterization of timber chocks. To this end, several experiments were conducted to determine the mechanical properties of timber chock structures. First, several small and clear sample tests, such as compression perpendicular to the grain and static bending tests, were conducted based on British standards. Additionally, visual grading of hardwood timber components was conducted to determine the structural grading of timber components. Then, as timber chocks have a full-contact structural configuration, compression tests were conducted on two-row timber chock structures to examine their behaviour at the contact level. Lastly, the effect of aspect ratio was studied to obtain the stiffness, load-carrying capacity, and dominant failure modes of the timber chocks under compression. The findings contribute to a deeper understanding of the mechanical behaviour of timber chocks subject to critical underground loading scenarios.

MS16-4:5 | Influence of drying shrinkage on dynamic properties of cross-laminated timber

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In this contribution, experimental modal analyses for a cross-laminated timber (CLT) plate are presented. The plate with dimension 1.2x1 m, consisting of three layers, is supported freely and excited by an electrodynamical shaker while the vibration response is recorded by a Laser-Doppler vibrometer in a frequency range from 50 to 750 Hz. Two series of experiments are discussed where the average moisture content differs by 2.6% as a consequence of drying due to in-door storage of the plate. Although the mass of the plate is reduced by drying, natural frequencies of the plate are reduced due to shrinkage. This is particularly the case for torsion-dominated modes (the first natural frequency is reduced from 95 to 91 Hz, for instance). This leads to the conclusion that the opening of joints in between the narrow faces of the timber boards is mainly responsible for this loss of torsional stiffness.
In accompanying finite element simulations employing a higher-order plate theory, effective elastic material properties (Young’s and shear moduli, respectively) are obtained by model updating for both sets of experimental data. Assuming homogeneous behavior throughout the plate, it is concluded that both the Young’s modulus in fiber direction and the in-plane shear modulus is reduced by approximately 10% due to shrinkage. These results are confirmed by more detailed 3D finite element simulations considering frictional contact between the narrow faces.
Hence, this contributions demonstrates the relatively grave effect of a low amount of drying shrinkage on the elastic and dynamic properties of CLT plates which complicates the assessment of the dynamic properties of these structures in practice.

MS16-5:1 | Finite-element-based prediciton of moisture uptake and dry-out in CLT caused by water infiltration through end-grain surfaces

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Timber constructions and engineered wood products, such as cross-laminated timber (CLT), demonstrate significant moisture-dependent mechanical behavior. Moisture infiltration through end-grain surfaces is particularly problematic when dry-out is prohibited, impairing CLT. However, few studies examine moisture infiltration followed by moisture dry-out and current models struggle to simulate these conditions properly. Using the model of Autengruber et al. [1], including free water transport, allows for a realistic simulation of these conditions [2]. This was validated by replicating the experiments of Kalbe et al. [3]. They examined the moisture content development of several CLT plates, where end-grain surfaces were exposed to water for one week, followed by two weeks of drying in various climate conditions. The simulations were refined by calibrating the mass transfer coefficients of water vapor and free water, where in a sensitivity analysis it was shown that the most significant impact on moisture changes emerges from the latter one. Additionally, the influence of glue lines in CLT panels on moisture transport was examined, revealing minor effects on surface layers but increasing influence towards the middle layer.

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MS16-5:2 | Stress development during and after kiln-drying of self-shaped Norway spruce bilayer plates

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In the past years, a new method for the production of curved cross-laminated timber (CLT) has been developed, so-called “self-shaping”. In contrast to the current state of the art using cold bending of lamellae, the inherent hygroscopic properties of wood, i.e. swelling and shrinkage due to moisture content changes, are harnessed through a bilayer setup of lamellae. Hereby, the adhesive bonding of two cross-wise arranged lamellae is used to block the deformation compatibility at the interface, leading to high curvatures of the bilayer setup. Typically, a drying process is used for the shaping, as lamellae need to be dried down to service moisture content conditions regardless. During the drying process of structural bilayer components, residual stresses are induced by shaping. These developing residual stresses and strains can be heavily impacted by moisture and temperature gradients. As a result, controlling these two factors is of great importance in order to reliably compute residual stresses. State-of-the-art computational models are fairly able to predict the deformation of timber structures and their curvature during a self-shaping process. However, up to date, no investigations considering industrial kiln-drying conditions with respect to accelerated moisture gradient conditions have been conducted. In this study, 3D moisture and temperature gradients resulting from an adapted kiln-drying process are computed using the Finite Element Method. Residual stresses and strains are computed using a rheological model for wood, considering time and moisture-dependent effects such as stress relaxation through visco-elastic and mechano-sorptive creep. Quantitative residual stresses, such as longitudinal, transverse, and rolling-shear stresses in both lamellae of self-shaped wood bilayers are assessed and shown. These values are of relevant importance for consideration in the structural engineering design of curved CLT structures assembled from wood bilayers.

MS16-5:3 | Towards a consistent description of creep in spruce

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An improved description of the rheological behavior of wood is key for ventures into novel applications of wood with an improved degree of material activation. These efforts are not only impaired by the strongly disordered, hierarchical microstructure. Also, non-negligible effects of moisture on pretty much every constitutive relation, further complicate the accessibility by numerical simulations. It is almost superfluous to mention that variations between species, trunks, and even between positions inside the trunks, as well as imperfections, pose further challenges. As creep strains can exceed the elastic deformations by a factor of 2 or more, depending on the climatic conditions and stress states, it becomes evident, that the rheonomous reaction of wood on mechanical and hygric load requires particular attention.

On two novel applications, weaknesses of the model and today's underlying wood physical foundation are identified – like orthotropic mechanosorptive and viscoelastic creep. We determine creep experimentally on different scales like the macro scale, the tissue scale, as well as the tracheid scale at different moisture and loading states. Parameters of moisture-dependent creep models, based on Prony series, are identified independently for the different anatomic orientations, including all 6 shear directions. In the second step, different data reduction strategies are evaluated on the experimental data of different scales to provide a comprehensive and experimentally founded basis for rheological numerical models with increased generality.

MS16-5:4 | Asymmetric cortex structures in recent and fossil plants: an inspiration for 3D reticulated actuators

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Plant movements are often the result of a combination of elastic deformation and stiffening tissues. This makes them excellent sources of inspiration for hingeless biomimetic actuators. In the framework of a biomimetic biology push process, we present the transfer of functional motion principles of hollow tubular geometries surrounded by a reticular structure. Our plant models are the recent genera Ochroma pyramidale (balsa) and Carica papaya (papaya), as well as the fossil "seed fern" Lyginopteris oldhamia, which possess a network of macroscopic fibre structures enveloping the entire stem. Asymmetries in these fibre networks, caused specifically by asymmetric growth of the secondary wood, allow the inclined stems of O. pyramidale and C. papaya to straighten. Comparable structural rearrangements occur in the cortex of L. oldhamia. This similarity in (adaptable) anatomical structures leads to the conclusion that the cortex of L. oldhamia was also able to readjust the orientation of the stem and branches in response to mechanical stress.

In general, fibre angles play a crucial role in stress-strain relationships in a tubular reticular structure. When braided tubes are subjected to internal pressure, they become shorter and thicker if the fibre angle is greater than 54.7 degrees. However, if the fibre angle is less than 54.7 degrees, they become longer and thinner. We have used simple functional demonstrators to show how insights into functional principles from living nature can be translated into plant-inspired actuators with linear or asymmetric deformation.

MS16-6:1 | Novel olive stone biochar particle network for piezoresistive strain sensing in natural fiber-reinforced composites

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Natural fiber reinforced composites (NFRCs) suffer from water absorption and low temperature stability resulting in fiber degradation and subsequent material failure. Built—in piezoresistive sensors are investigated to monitor deformation/strain of the component. As a low-cost material from renewable resources biochar particles derived from olive stones were applied on flax plies and yarn bundles that served as model systems. Carbon black samples as prominent petrochemical variants were used as a reference. Biochar and carbon black covered fiber systems were laminated in epoxy resin followed by tensile tests. The electrical resistance was recorded simultaneously during testing. Biochar with a broad size distribution from nano to high micrometer range (D < 200 µm) was superior in sensor performance compared to carbon black and biochar with a smaller particle size range D < 20 µm. Gauge factors (GF) of NFRC samples with integrated biochar particles reached 30-80 while carbon black could not exceed a GF of 8. Sustainable biochar derived from olive stones exhibits therefore great potential as an alternative in carbon particle piezoresistive sensors to connect the mechanical state of a structural component with its electrical resistance.

MS16-6:2 | A nanoindentation study on diverse technical lignins for bio-composite applications

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Lignin stands as a pivotal constituent of wood, ranking as the second most prevalent organic material across the globe. The escalating demand for sustainable and renewable resources propels the exploration of innovative applications for technical lignins, such as their integration as a matrix in bio-composites. Nevertheless, the pursuit of modeling these bio-composites hinges on the precise identification of lignin's mechanical properties, a facet that remains relatively elusive at present. Complicating matters further, technical lignins sourced from lignocellulosic materials exhibit notable disparities in their chemical composition, size, cross-linking, and functional groups. These variations arise from discrepancies in the raw materials used and the isolation methods employed, including the pulping process and subsequent isolation and purification techniques. Hence, it becomes imperative to address these disparities when evaluating and understanding the mechanical characteristics of lignin. To tackle this challenge, our study delves into the examination of five distinct hot-pressed lignins, each derived through diverse extraction processes from varying feedstocks. The assessment employs microscopy-aided grid nanoindentation, aiming to unravel the nuanced mechanical properties of these lignins. Through such meticulous investigation, we endeavor to contribute valuable insights that will aid in comprehending the intricate interplay between lignin's structural variations and its mechanical behavior. The derived mechanical properties exhibit a robust correlation with the porosity observed in the lignin specimens. This correlation finds an apt description through the Mori-Tanaka homogenization scheme within the framework of continuum micromechanics. Employing this micromechanics fit, we conducted a reverse calculation to determine the stiffness of "solid" lignin devoid of any pore influence, revealing Young's modulus of 7.12 GPa. The noteworthy alignment between the micromechanics model and the experimentally measured indentation modulus validates that the indentation modulus of solid lignin remains consistent across all five variants. Remarkably, this consistency holds true irrespective of the extraction process or the specific feedstock employed.

MS16-6:3 | A sustainable approach to lignin as a wood binder

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The exploration of natural adhesives for wood-based products offers a sustainable solution to the environmental and health issues posed by synthetic adhesives. Among natural substances, lignin, a primary element of plant cell walls, stands out for its adhesive capabilities. We investigate the adhesive qualities of lignins sourced from a variety of plants and manufacturing methods, testing them in multiple forms, such as powder, liquid supernatant, and as a solvent for impregnating delignified wood veneers. The performance of lignin against urea-formaldehyde adhesive, with a particular focus on how pressing temperature and time influenced their adhesive strengths. Initial tests were carried out using a system inspired by the Automated Bonding Evaluation System (ABES) to measure the bond strength of urea-formaldehyde under various conditions, establishing a baseline for assessing lignin adhesives.

We evaluated lignin's adhesive potential by examining the effects of pressing duration, wood veneer treatment, and solvent choice on the adhesive properties of lignin. Lignins derived from Kraft and soda pulping processes showed encouraging adhesive characteristics under certain conditions. We highlight the significant impact of the lignin's botanical source, processing method, and pressing parameters on its effectiveness as an adhesive. We identified key challenges such as humidity control and the fine-tuning of pressing conditions that influence adhesive performance. Although lignin-based adhesives have not achieved the efficacy of synthetic alternatives, our findings emphasize lignin's potential as a sustainable adhesive, noting that specific pressing conditions and wood veneer treatments can enhance its adhesive quality.

MS16-6:4 | The livMatS fiber pavillon in the Botanic Garden Freiburg: cactus wood as inspiration – flax fibers as building material

T. Speck

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The livMatS fiber Pavillon is an example of a bioinspired sustainable construction. It originates from the successful collaboration of an interdisciplinary team of architects and engineers from the Cluster of Excellence IntCDC, University of Stuttgart and biologists/biomimeticists and material scientists from Cluster of Excellence livMatS, University of Freiburg.
The inspiration for the pavilion came from columnar cacti such as the saguaro cactus (Carnegia gigantea), and the prickly pear cactus (Opuntia sp.), which are characterized by their special wood structure. The up to 20 m tall saguaro cactus has – like many other columnar cacti – a cylindrical wooden body that is hollow on the inside and thus particularly light. The individual wooden elements grow together to form a net-like structure, which gives the wooden body additional mechanical stability. By analyzing the (micro-)arrangement of the reticulated wood with µCT and MRI, and abstracting these net structures, the structural and mechanical properties of biological wood structures could be transferred to the pavilion's lightweight load-bearing elements.
The supporting structure of the livMatS pavilion consists of 15 flax fiber elements designed by digital planning and prefabricated exclusively from continuous spun natural fibers in a robot-assisted coreless fiber winding process, replacing the intergrowth that causes the netlike structures in the biological models. With a total area of 46 m2, the entire fiber structure weighs only about 1.5 t and is designed to withstand the full snow and wind loads of the applicable building codes.
The pavilion, made (nearly) entirely of recyclable materials, points the way to a new greener architecture of the 21st century. Contributing to the resource-efficient architectural approach are the load-bearing elements made of renewable raw materials (flax, sisal) and the transparent ceiling elements made of polycarbonate. The ceiling elements can be shredded and remelted at the end of their useful life.

MS16-6:5 | Characterizing viscoelasticity of plant fiber-reinforced biocomposites through micromechanics modeling

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Plant fiber-based biocomposites are a sustainable alternative to traditional materials in several industries, including the construction sector. The excellent mechanical performance of the cellulosic fibers results in a reinforced composite that can be used for structural elements, such as beams, plates, or shells. To ensure the serviceability of biocomposite structures, the characterization of the (time-dependent) viscoelastic material behavior is essential. In this contribution, we aim to tackle the characterization by multiscale micromechanics modeling.
Both the polymer and the plant fiber are viscoelastic materials. Plant fibers deform over time due to the viscous nature of lignin (and hemicellulose) as well as through sliding phenomena occurring in the interfaces between cellulosic fibrils. The microscopic mechanisms and the viscoelastic properties of lignin and of the polymer matrix are then incorporated into a multiscale model to upscale them to the composite scale. Thereby, the correspondence principle of viscoelasticity is exploited to perform the homogenization using classical continuum micromechanics homogenization theory, albeit in the Laplace Carson space.
Comparison of model results with creep test data from single-fiber creep tests and creep tests on wood allows for back-calculation of the missing interfacial viscoelastic parameters. Then, the model is used to predict the creep behavior of several different biocomposites, varying in terms of plant source, polymer material, production method, and fiber orientation distribution. Model predictions are successfully compared to results from experimental testing campaigns. Sensitivity studies demonstrate that typically, the polymer creep dominates the composite creep, particularly at high temperatures. At high moisture contents of the plant fibers, however, the amplified creep of the fibers leads to a pronounced increase in the composite creep.

MS16-6:6 | Simulating failure in plant fiber composites: Analyzing the interplay of fiber, matrix, and interface mechanics

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This study presents an advanced numerical model for plant fiber-reinforced composites, addressing a significant gap in predictive modeling for these environmentally friendly materials. Our model describes the complex interactions between cellulosic fibers and matrix in biocomposites, accounting for all major failure mechanisms: matrix softening, fiber breakage, and fiber-matrix debonding.
Employing nonlinear plasticity, XFEM, and cohesive zone models, we simulate failure in a unit cell with two fibers and periodic boundary conditions [1]. This approach enables a precise prediction of nonlinear macroscopic behavior in biocomposites. Validated against experimental data, the model accurately predicts tensile and compressive properties of both short- and long-fiber composites.
The unit cell method also enables further sensitivity analyses, providing valuable insights into effects such as the softening related to decreased interfacial shear strength and the strengthening impact of longer fibers. This research paves the way for future studies on lignin-based biocomposites [2] and aims to establish a comprehensive link between analytical [3] and numerical modeling approaches for a robust mechanical prediction model for complex biocomposite materials.
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MS17: Up-scaling challenges in the modeling of civil engineering materials

MS17-1:1 | Homogenization of weakly nonlinear phenomena in electroactive fluid saturated porous media with multiple time scales

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The conference paper is devoted to the fluid-structure interaction (FSI) in periodic porous structures with electroactive elements (EAE), such as the piezoelectric, or flexoelectric segments controlable by external circuits. Such smart porous materials can serve for fluid pumping, or conversely to energy harvesting, in both cases the electro-mechanic energy conversion is due to the peristaltic deformation. To explore functionality of such metamaterial structures, multiscale computational tools using the homogenization of the FSI problem. Cell problems (at the microlevel) provide characteristic responses of the microstructures with respect to macroscopic strains, fluid pressure and electric potentials. The homogenized model is derived under the small deformation and linear constitutive law assumptions at the heterogeneity level, however, in the deformed configuration; this is necessary to respect the nonlinearity in the FSI and to capture ``the fluid pumping'' property. At the microlevel, a strong heterogeneity in the material parameters is introduced in terms the scale parameter of the asymptotic analysis. To respect dynamic effects of the flow in bulged pores, where the nonlinear advection term of the acceleration is non-negligible, two time scales are considered and an appropriate time scaling of the fast-slow dynamics is introduced in a proportion to the spatial scaling. In addition, propagating acoustic waves (actuated by the EAE) lead to the acoustic streaming effect also characterized by two temporal scales. The nonlinearity associated with deforming configuration is respected by deformation-dependent homogenized coefficients. To reduce the computational efficiency, the sensitivity analysis of the homogenized coefficients with respect to deformation induced by the macroscopic quantities is employed. This enables to avoid the two-scale tight coupling of the macro- and microproblems otherwise needed in nonlinear problems using the "FE²" method. The paper summarizes our recent theoretical results and their potential applications in the research of multi-functional materials with potential use in civil engineering.

MS17-1:2 | Impact of various uncertainties on the modeling of sorption-induced deformations

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A clear understanding of the physical mechanisms leading to sorption-induced deformations in porous materials is essential to model the mechanical response of various materials, such as coalbed and shale formation during natural gas production and CO2 sequestration or wood during drying. To describe the drying shrinkage of partially saturated porous materials with a wide pore size distribution, we improve a poromechanical model proposed by El Tabbal et al. (2020), based on the thermodynamic theory and which takes into consideration the capillary forces, Bangham effect, and Shuttleworth effect. One improvement lies in how we estimate strain variation during cavitation. We validate the model by applying it to experiments conducted by various authors with various pairs of adsorbate and adsorbent, during which both sorbed amounts and strains were measured. In general, this macroscopic model can predict the shape of strain isotherms during physisorption without any fitting parameters. We then discuss the impact of several uncertainties on the predicted deformations, namely the uncertainty on the cavitation pressure, the experimentally defined "dry" state, and the calculation of BET-specific surface area. We show that the impact of those various uncertainties on the predicted shape of the strain isotherm is negligible.

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MS17-1:3 | Study of crystallization pressure by molecular simulation

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The process of salt crystallization within porous media is widely recognized as a substantial contributor to the deterioration of construction materials, geomaterials, and built heritage. When salts crystallize, they can exert mechanical pressure on pore surfaces, leading to material damage. However, despite its importance, the crystallization within porous networks remains poorly understood. We propose an investigation combining molecular simulations and theoretical development to quantify and clarify the origin of the crystallization pressure at the finest scale. This study should allow the identification of the parameters controlling the phenomenon and thus pave the way to mitigate or prevent salt damage.

At thermodynamic equilibrium, crystallization pressure results from the change in the solubility of a crystal as it is compressed. Direct molecular dynamics simulations to compute the solubility of salts are challenging because the time scale of dissolution and precipitation, microseconds or more, is at the limit or beyond computing capabilities. For this reason, we use a thermodynamic integration approach to overcome this issue. With this approach, we can quantify the effect of stress on NaCl solubility, and more specifically the effect of stress anisotropy which has been disregarded so far. We use these results to revisit the existing theory describing crystallization pressure and extend it to account for stress anisotropy.

Moreover, we conduct molecular simulations to determine the critical pressure threshold at which the wetting film, separating the crystal from the surface of the pore and responsible for the crystal growth, will disappear. This approach offers valuable insights into the stability and resilience of this film under varying pressure and temperature conditions.

MS17-1:4 | Towards a DFT approach to the mechanical properties of solids

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This research endeavours to initiate a robust foundation for investigating various mechanical properties linked to the complex interaction between the solid and fluid phases within nanoporous materials with potential application in Civil Engineering.

In this study, we investigate the elastic properties of solids using the classical density functional theory (cDFT). While typically used for understanding the properties of inhomogeneous fluids, cDFT has only been used in a few studies for solid phases [1, 2]. In this contribution, we start by computing the phase diagram of a Lennard-Jones gas-liquid-FCC system to gain insights into its equilibrium behaviour. Then, we depart from the liquid-FCC system and compute a stable reference crystal solid state where the crystal is in equilibrium with external forces at a given temperature. Using this reference state, we subject the stable structure to small deformations while keeping the number of atoms constant. By minimizing the free energy of the deformed structure, we can derive the stress and deduce the elastic properties.

We compare our approach with data on real FCC materials, such as Nickel (Ni) and Iron (Fe), to assess the reliability of cDFT as an upscaling technique based on the atomistic description of a material, and providing continuum-based expressions. The ultimate goal of this study is to propose an upscaling-based poromechanical framework that integrates cDFT descriptions of both fluids and solids.

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Aknowledgments: This work was partially financed by the Investissement d'Avenir French programme (ANR-16-IDEX-0002) under the framework of the E2S UPPA hub Newpores.

MS17-2:1 | Multiscale analysis of PVC geomembrane mechanical response through DEM simulations

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Geomembranes are materials used as impermeable barriers to guarantee structure waterproofing and the conservation of water. The annual growth of the global geomembrane is anticipated to continue with an increased drought crisis due to climate change.

Even if they are not primarily designed to provide mechanical resistance, geomembranes face challenges from mechanical actions that could potentially degrade their impermeability properties, and so compromise their waterproofing functionality. For example, unprotected geomembrane in contact with a granular layer for drainage may experience tensile forces, that raise the risk of puncturing failure. Furthermore, if improper operating techniques are used during installation, the geomembrane may be susceptible to unexpected mechanical actions, that could result in a premature failure. To the best of our knowledge, no research has been done to interpret the microscopic origin of geomembrane failure.

In this study, a micromechanical model of PVC geomembrane is adopted to explore the elementary mechanisms underlying macroscopic behavior. The model relies on the Discrete Element Method (DEM) to depict PVC geomembrane microstructure at the nanoscale, as a semi-crystalline assembly of polymers embedded in a matrix of plasticizers.

By employing this original multiscale approach, we seek to demonstrate a connection between macroscopic deformation and internal microscopic mechanisms. Through such a detailed analysis at the microstructural level, we show promising results to unravel the intricate elementary processes governing the mechanical response of PVC geomembrane up to failure.

MS17-2:2 | Role of the mesoscale in the mechanics of clays

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Clays are geo-materials containing extremely fine mineral grains with peculiar hydro-mechanical behavior, the most well-known being the drying shrinkage. Indeed, the nanometric mineral layers can adsorb water in the inter-layer, which induces large deformations. Although the crystalline swelling at the layer scale was identified long ago in the 1950's by XRD, much progress in its fundamental understanding has been made in the last 20 years thanks to the development of molecular simulations. Atomistic modeling offers an unprecedented nanoscale description of the mechanisms of swelling, with quantitative estimates of the mechanical behavior at the scale of a single mineral layer, in particular, the coupling with humidity and the thermo-mechanical response. Yet, the up-scaling from the mineral layer to the clay matrix remains a challenge, in particular, because the mesoscale (nm to µm) is hardly accessible to experimental observation, and the microstructure at this scale can only be inferred indirectly (e.g., from small angle scattering). As an alternative to experiments, granular 'mesoscale' simulations have emerged which aim at taking advantage of the fine understanding obtained at the molecular scale to propose 'coarse-grained' models at larger scales. In this work, we propose a mesoscale model for sodium Wyoming montmorillonite, designed to investigate specifically the anomalous thermo-hydro-mechanical couplings. The model addresses a few key features of the mesostructure: the degree of local anisotropy, the flexibility of the clay minerals, and the hydration states. Investigating the response to mechanical and osmotic loadings, the model exhibits a THM behavior quantitatively consistent with that usually observed experimentally for montmorillonite, although the systems considered are limited to about 100 nm. This suggests that the mesoscale is central in the emergence of the macroscopic mechanical properties of clays.

MS17-2:3 | Linear elasticity of transversely isotropic paper sheets: comprehensive validation of a multiscale continuum micromechanics model

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Every day, wood-pulp-based paper is a relevant engineering material that may exhibit considerable variability in its macroscopic, mechanical properties. To quantitatively decipher the origins of that variability, a multiscale, continuum-micromechanics-based model for the linear elasticity of transversely isotropic paper sheets is presented, which reflects an experiment-based description of the hierarchical, nanoscopic-to-macroscopic scale organization of such sheets and of their constituents. At a length scale of few nanometers, clusters of hemicellulose, lignin, as well as water and extractives deposits, presenting virtually spherical shapes, indiscriminately aggregate to form a polymer blend. Still at a nanometer length scale, collections of cellulose Iα, cellulose Iβ, and cellulose II crystals, exhibiting next to elliptical-cylindrical geometries, parallelly precipitate into a contiguous matrix of amorphous cellulose to constitute a cellulose fibril. Further up, at a length scale of few micrometers, bundles of cellulose fibrils, indicating nearly circular-cylindrical configurations, helically accumulate into an adjacent polymer blend matrix to build-up a pulp fiber. Finally, at a length scale of few hundreds of micrometers, constellations of wood pulp fibers, displaying close to elliptical-cylindrical contours; as well as of pores, appearing to spheroidally mirror the transverse shape of said fibers; planarly, arbitrarily combine to materialize as a transversely isotropic paper sheet. Model validation rests on carefully collected datasets, altogether containing over a thousand experimental values, standardly, independently determined across ample regions of space and time, as well as a very, very small number of theoretically predicted values. Based thereon, values for the elasticity of a mean, softwood-based, unbeaten, chemical pulp fiber and of corresponding cellulose fibrils as well as of paper sheets of varying porosity are theoretically (continuum micromechanically) predicted, which agree very well with respective, experimentally determined values. Our investigation enriches fundamental paper research, and at the same time provides a valuable basis for improved paper production, development, and use.

MS18: Computational methods for stochastic engineering mechanics

MS18-1:1 | An approximate analytical technique for transient response PDF of a linear oscillator under a non-Gaussian colored noise

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This study is dedicated to acquiring an approximate analytical solution of the transient response probability density function (PDF) of a single-degree-of-freedom linear oscillator under a non-Gaussian colored noise. The non-Gaussian colored noise is characterized by a first-order PDF and a specified power spectral density (PSD) with a bandwidth parameter and is represented by a one-dimensional Itô stochastic differential equation. The transient response PDFs of the oscillator are sought by applying an approximate analytical method for stationary response PDFs recently developed by the authors in a time-dependent manner. First, the equivalent non-Gaussian excitation method is applied to calculate the transient response moments up to the fourth order. Then, using these moments, the transient response PDFs are determined resorting to the Hermite moment model. The present analytical technique can treat any excitation PDF and bandwidth parameter value, as long as the combination of response skewness and kurtosis is within the applicable range of the Hermite moment model. In numerical examples, the transient response PDFs of the oscillator driven by highly non-Gaussian noises possessing symmetric and asymmetric PDFs are analyzed. Widely different bandwidth ratios between the excitation PSD and the system frequency response function are also taken into account, since the response PDF characteristics vary significantly with the bandwidth ratio. The accuracy of analytical results is illustrated through comparisons with the corresponding Monte Carlo simulation (MCS) results. Furthermore, the time-varying characteristics of the non-Gaussianity of the transient response PDF are investigated based on the obtained PDF solutions.

MS18-1:2 | Computing upper failure probabilities using optimization algorithms together with importance sampling

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The uncertainty about the values concerning properties of an engineering structure can be modelled by a family of probability density functions parametrized by t in a set T. The output of such a model is typically the upper failure probability, which is the solution of the global optimization problem max p(t): t in set T where p(t) is the failure probability for a fixed parameter value t.

We estimate p(t) using Monte Carlo simulation which means function evaluations (FE computations) for each of N sample points. This high computational effort has to be multiplied in addition by the number of function evaluations p(t) needed for solving the above optimization problem to find the t resulting in the upper failure probability. To reduce the number of parameter values t requiring new samples in the optimization algorithm we re-use the samples already generated for parameters t of previous optimization steps using importance sampling or reweighting [1]. Here, we take the importance sampling ratios into account which leads to importance sampling on sets of a partition of the space of the uncertain properties [2]. This method is combined with strategies to reduce the variance such as design point methods or particle dynamics. The efficiency of the new method is demonstrated for a moderate scale engineering problem.

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MS18-1:3 | Demonstration of continuous gamma process for site specific structural capacity quantification for aging infrastructure

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In its most general formulation, the safety for ageing infrastructure is represented as a function of the capacity and load effect. However, for ageing infrastructure, the imbedded complexity of time dependent capacity functions and variety of load components that can be present introduce a high level of uncertainty. In addition, due to the strategic importance of most of the civil infrastructure site specific deterioration, maintenance and repairs need to be accounted for. In order to provide an uninterrupted service systematic and practical models for evaluation of the likelihood of failure are needed.
Monitoring techniques that are emerging are increasing availability of site-specific data, however, with variable accuracy. For ageing infrastructure, the substantial issue of benchmarking performance cannot be resolved deterministically and probabilistic methodology that can integrate diverse data from various monitoring sources would be very valuable for owners. In this paper the continuous gamma process is implemented as an effective probabilistic model for infrastructure ageing process characterization.
Using the example of the capacity of a steel structure subject to corrosion, this paper will address application of continuous gamma process to include information from site-specific sources. Time dependent gamma process parameters are obtained from prior data, Micic (2019). The outcomes will be considered and evaluated against Straub et al. (2020) and corresponding traditional reliability analysis methods. It will be demonstrated that the stochastic gamma process offers consistent account of prior data and thorough prediction of future capacity thus, providing a useful planning tool.
Furthermore, assuming gradual ageing, it will be demonstrated that the methodology enables inclusion of emerging environmental data such as climate projections. Thus, it will be demonstrated that the stochastic gamma process representation for capacity is a consistent and a rigorous estimate for infrastructure safety prediction that enables inclusion of environmental, maintenance, repair and monitoring data.

MS18-1:4 | Seismic reliability analysis of structures by an active learning-based adaptive sparse Bayesian regression approach

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Seismic reliability analysis (SRA) of structure is a time-varying reliability analysis problem where one needs to integrate the effect of stochastic nature of earthquakes and uncertainty of various structural parameters. In this regard, the Monte Carlo simulation (MCS) technique is noted to be quite simple in concept and the most accurate for estimating the probability that the seismic demand of a structure exceeds its capacity for the target hazard level over the entire duration of the considered earthquakes. However, the approach needs to execute a large number of repetitive nonlinear dynamic response analyses of structures to obtain seismic responses. Metamodeling technique has emerged as a viable alternative technique to alleviate such computational burden while retaining the maximum possible accuracy. In SRA, the dual metamodeling approach is typically adopted to deal with stochastic nature of earthquakes. However, this approach assumes that seismic responses of different earthquakes follow a lognormal distribution. On the contrary, a direct metamodeling approach where separate metamodels are constructed for approximating responses of each earthquake avoids such prior assumptions. Though adaptive training near the limit state is important in the metamodeling-based reliability analysis, its implementation is quite challenging due to the record-to-record variation of earthquakes. In this context, an adaptive sparse Bayesian regression-based direct metamodeling approach is proposed for SRA. In the present study, an active learning-based algorithm is developed for adaptive training of metamodels to approximate different earthquakes' responses. In this regard, it can be noted that sparse Bayesian regression is computationally faster than Kriging due to the sparsity involved in sparse Bayesian learning. Thereby, the overall performance of the proposed approach is expected to be better than the existing adaptive Kriging approach in terms of both accuracy and computational cost. The effectiveness of the proposed approach is illustrated by numerical examples of SRA.

MS18-1:5 | Uncertainty quantification on seismic response of an RC bridge pier considering varying material properties

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In reliability-based seismic design, it is crucial to consider not only the uncertainty in the input ground motions, but also the uncertainty in the material properties of the system of interest. To investigate the uncertainty in the nonlinear seismic response of reinforced concrete (RC) piers, Takahashi et al. (2016) conducted a 3D shake table test at E-Defence in Japan. In this test, 16 medium-scale pier specimens were simultaneously excited against the JR Takatori station record of the 1995 Kobe earthquake to ensure the same dynamic inputs. The results showed that the nonlinear seismic responses, including the maximum displacement response and the residual displacement, can vary significantly due to the uncertainty in the material properties.
In this study, the RC pier specimen used in the above shake table test is modelled as a finite element (FE) model using the 3D nonlinear FE analysis software called COM3. The material properties, such as the compressive strength of the concrete and the yield strength of the rebar, are characterised as random variables based on the material test results. An adaptive probabilistic integration approach is then used to efficiently yet accurately quantify the uncertainty in the nonlinear seismic responses of the FE model. This approach is based on the Bayesian active learning methods, which have recently attracted much attention in the field of structural reliability. The results of the uncertainty propagation are compared with the results of the shake table tests.
It is also planned in our future work to investigate Bayesian model updating using the shake table test results to inversely quantify the uncertainty in the FE model parameters. A comparison of the model updating results and the material test results can provide an insight into the effects of modelling error and hysteresis nonlinearity on the uncertainty in the seismic responses.

MS18-2:1 | Structural reliability of complex nonlinear systems exposed to evolutionary stochastic excitation

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A novel stochastic dynamics methodology for performing reliability analysis concerning complex hysteretic structural systems initially at rest and subjected to fully nonstationary seismic excitation is proposed. The approach aligns consistently with contemporary aseismic codes provisions whereas the induced seismic excitation vector consists of stochastic processes characterized by evolving power spectra, matching, in a stochastic sense, with the code compliant elastic response acceleration spectra of specified modal damping ratio and scaled ground acceleration. By leveraging the potent nonlinear stochastic dynamics concepts of stochastic averaging and statistical linearization, the method allows for the efficient determination of the approximative time-varying response amplitude joint probability density function. The proposed methodology enables the efficient estimation of evolving survival probability surfaces for various intensity measures adhering to various damage-state rules. Notably, an incremental mechanization analogous to the one used in standard incremental dynamic analysis is proposed to ensure the necessary compatibility for applications in the fields of structural and earthquake engineering. Characteristic of the structural behavior is that, for higher barriers associated with severe damage-states under low levels of excitation intensity, the survival first-passage probability reaches a constant non-zero value. The method is accompanied by a low computational cost addressing complex nonlinear and hysteretic structural behaviors while complying with current aseismic code provisions. A numerical example for illustrating the reliability of the proposed methodology is presented. The accuracy of the proposed method is assessed in a Monte-Carlo based context conducting nonlinear response time-history analysis which involves a large ensemble of accelerograms compatible with Eurocode 8 response acceleration spectra.

MS18-2:2 | Probabilistic model selection of the Ground Motion Prediction Models for Northern South America

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Ground Motion Prediction Equations (GMPE) are an important input for the probabilistic estimation of Earthquake Hazards. These models predict intensity parameters (i.e., spectral acceleration or velocity) induced by an earthquake as a function of the magnitude and source-to-site distance. GMPEs are proposed for earthquake sources, and their parameters are determined through model updating after direct field earthquake records from seismic stations. There are many GMPEs proposed in the literature for the different tectonic environments found in places like Northern South America (Colombia, Ecuador, and Venezuela). Probabilistic seismic hazard estimation methodologies involve using the best GMPEs to reduce uncertainty when estimating the design of earthquakes. Therefore, selecting the best models in an uncertain environment is an important task commonly faced in this analysis. This work presents an application of Bayesian model updating and model selection for estimating the uncertainty and comparing GMPEs for Northern South America.

MS19: Engineering mechanics in tunnelling

MS19-1:1 | Stability of unlined circular tunnel in layered rock masses

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Layered rock masses are common geological formations due to which numerous engineering activities typically confront stratified rock masses. The analysis of tunnel stability issues typically assumes a single homogeneous rock mass. However, the majority of rock tunnel projects are excavated in stratified rock formations. This study introduces a two-dimensional (2D) plane strain model for predicting the stability of a rock tunnel subjected to surcharge along the horizontal surface in the presence of rock stratification. The stability of unlined circular tunnel in layered rock mass is examined using lower bound finite element limit analysis (LB-FELA) to obtain the numerical solutions in parametric form while adhering to the Hoek-Brown (HB) failure criterion. The effects of material constant, geological strength index, layer thickness to diameter ratio, relative thickness between upper and lower layer, and relative strength ratio between top and bottom layer are thoroughly studied through extensive parametric research. The results of the study indicate that the arrangement order of the weak and strong rock layers, the size of the tunnel's diameter, and the thickness of the rock layer all play a significant role in determining the stability of the tunnel. It is important to note that the stability of the tunnel is significantly influenced by alterations in the parameters of the lower layer of rock in which the excavation of tunnel is done, as opposed to modifications in the parameters of the upper layer. Moreover, the geological strength index is found to be the most sensitive parameter out of the group of input parameters considered. The results will provide the field practitioners with a rational approach for dealing with practical aspects of tunnel subjected to surcharge at the ground surface when the rock mass stratification is present.

MS19-1:2 | Multiphase modeling of ground freezing-shotcrete interaction in tunneling construction

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Artificial ground freezing is employed for temporary ground improvement in tunneling. Ground freezing is commonly used to stabilize the ground before the excavation of cross passages in tunneling. During the construction of the cross passages, the frozen ground is excavated, and the tunnel is supported immediately by shotcrete shells. In this contribution, we present a novel computational framework for the modeling of the interaction of frozen ground and shotcrete during cross-passage construction. The computational framework consists of a three-phase (soil, water, ice crystals) thermo-hygro-mechanical finite element model for the modeling of soil freezing based on [1] and a four-phase (soil, water, air, ice crystals) thermo-mechanical finite element model for partially saturated shotcrete that considers freezing. This framework considers the evolution of the stiffness, strength, and creep properties and the hysteresis effects during freezing-thawing of the ground in conjunction with the shotcrete hydration and creep properties dependent on the hydration degree based on [2]. Finally, we present a numerical case study of the construction of cross passages which is modeled in two stages: the first stage involves the modeling of an artificial ground freezing phase and the second stage involves the tunnel excavation, the shotcrete installation with its internal hydration heat generation and the evolution of the hydration dependent primary creep deformations.

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MS19-1:3 | A deep learning-based method for detecting joints and evaluating segment deformation in shield tunnels

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Shield tunnels, as a type of prefabricated assembly structures, have shown their susceptibility to excessive deformation over time due to earth pressure, posing a growing challenge to ensuring the safety and reliability of tunnel structures. Therefore, it is crucial to monitor the structural deformation of subway tunnels to assess their reliability and guide their maintenance. Advanced technologies, such as laser scanning for precise point clouds and close-range photogrammetry for high-definition imaging of internal tunnel surfaces, are currently being employed to obtain essential operation and maintenance data. However, the deformation status of a shield tunnel is complex in practice, including the rigid body displacement of joints and the deformation of concrete segments. Therefore, simple convergence deformation cannot fully represent a tunnel's service condition. While the circumferential joints can be identified from images via computer vision techniques, the identification accuracy of longitudinal joints within a single ring is low, making it difficult to accurately separate the point cloud of each segment. Additionally, there is a lack of methods for calculating the deformation of concrete segments using point clouds. To address this issue, this study proposes a deep learning-based method for detecting segment joints and calculating segment deformation by respectively leveraging imagery and point clouds. Incorporating model matching mechanism, a deep neural network based on the encoder-decoder architecture is constructed, with the hybrid information of images and point clouds as inputs, and the joint dislocation and segment deformation as outputs. Compared to traditional methods, the proposed method improves segmentation accuracy through enhanced feature extraction based on both intensity and depth information. Additionally, through accurate point cloud segmentation and model matching algorithms, the deformation of segment concrete can be obtained, which can be further applied in the maintenance of real-world shield tunnels.

MS19-1:4 | Will a concept of pre-structure be applicable to tunnels in squeezing ground?

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In order to describe the rheological behavior of squeezing rock surrounding tunnels, the CVISC viscoelastic plastic model is adopted. It consists of the Burgers model and the M-C plastic body in series. The radial displacement of the squeezing rock is divided into instantaneous elastic-plastic and viscoelastic displacement, because of the independence of the viscoelastic and elastic-plastic components of the CVISC model. On this basis, the analytical solutions for the plastic and viscoelastic radial displacements are derived, respectively. Then the obtained solutions are superimposed, resulting the complete close-form solutions for the displacements of the surrounding rock. They allow for analyzing the evolution of the radial displacements and stresses of the surrounding rock over time. With the help of numerical simulations based on FLAC3D and the theoretical solutions obtained from open literature, the reliability of the derived solutions is demonstrated. Parametric studies of the derived solutions with emphasize on long-term deformation of surrounding rock in squeezing ground are carried out. The results show that the three most critical parameters are internal friction angle, cohesion, and Young's modulus of rock. This inspires us to propose a concept of pre-structure which has much higher internal friction angle, cohesion, and Young's modulus than the rock. This concept means support structure is constructed prior to the excavation of tunnels. Followed numerical solutions provide evidence that such a concept is beneficial in terms of reducing the deformation of surrounding rock in squeezing rock.

MS19-2:1 | Numerical modelling of steel fiber reinforced concrete tunnel lining segment subjected to flexure

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The use of steel fiber reinforced concrete (SFRC) in tunnel lining construction through tunnel boring machine has gained popularity across the world for the past few decades due to its high toughness and improved durability performance compared to conventional reinforced cement concrete (RCC). In addition to the soil surcharge during the serviceable life, the precast tunnel segments experience bending stresses during the transient stage involving demoulding, stacking, and handling of the segments which could potentially lead to unforeseen critical cracks in the segment. The large-scale testing of precast segments is not always viable and can be very expensive. In this study, the SFRC tunnel segment is tested numerically under three-point bending using DiANA software. The uniaxial stress-crack opening law in tension is obtained through inverse analysis which is performed by comparing experimental and numerical results of the notched beam modelled in DiANA using a discrete crack approach. To simulate the fracture behaviour of SFRC tunnel segment under three-point bending, non-linear finite element analysis is performed using the smeared crack approach and the SFRC constitutive law obtained from the inverse analysis. Finally, the model is validated by comparing the results of numerical analysis with full-scale experiments performed on the tunnel segments.

MS19-2:2 | Research on seismic response of prefabricated open caisson constructed by VSM method

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In recent years, prefabricated open caissons constructed by VSM method have been widely utilized around the world, for the advantages of high construction precision and speed, low disturbance to the surrounding environment, and adaptability to various stratum. Compared with open caisson foundations, the stiffness of prefabricated open caisson is small; Compared with shield tunnels, the direction of prefabricated open caisson is vertical, and the external load for each ring is mainly uniform pressure. Therefore, the seismic response of prefabricated open caisson constructed by the VSM method requires further study. To address the above problems, this paper developed refined 3D finite element models to investigate the seismic response of precast open caissons. Continuum shells with rebar layers are utilized to simulate the shaft segment, equivalent nonlinear springs are used to simulate the joint bolts, and viscous-spring artificial boundaries are utilized to apply the earthquake waves. Seismic responses of three structural forms, including integral models without joints, models that only consider ring joints and models that consider ring and longitudinal joints, are analyzed and compared under different ground motion directions and stratum. Conclusions are obtained as follows: 1) Structural seismic response is mainly controlled by the horizontal ground motion, while the impact of vertical ground motion on the structure is low; 2) The structural lateral deformation type is related to the connection stiffness. When the connection stiffness rises, the structural lateral deformation will close to bending deformation. On the contrary, it is closer to the shear deformation; 3) Internal force and damage to the structure are mainly concentrated in joints. In addition, the internal force and deformation of ring bolts are significantly higher than that of longitudinal bolts. In other words, the stiffness of ring bolts takes control of the seismic response of prefabricated open caisson constructed by the VSM method.

MS19-2:3 | Hereditary mechanics-based stress prognosis in segmented tunnel linings

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A combined experimental-computational approach is used for predicting stresses in a segmented tunnel lining [1]. Vibrating wire sensors equipped with thermistors were used to measure strains and temperature inside (i) plain concrete specimens undergoing uniaxial creep tests over one year, exposed to the environmental conditions of the Koralm tunnel, and (ii) precast reinforced concrete tubbings consituting the lining of the Koralm tunnel. A Boltzmann-type thermo-viscoelastic model is used to translate measured strain histories into corresponding stress histories. The used creep function consist of a power law describing short-term creep and a logarithmic law describing long-term creep of concrete. The stress histories are inserted into a Drucker-Prager failure function in order to quantify degrees of utilization. The latter stabilizes some four months after installation of the analyzed segmental tunnel ring. Seasonal temperature fluctuations are found to have a rather insignificant effect on the stresses and the degrees of utilization. Extrapolating the measured strain histories up to 150 years allows for long-term predictions of stresses and degrees of utilization. It is found that stress levels are expected to remain at some 40% of the concrete's strength, throughout the service life of the tunnel.

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MS19-2:4 | Research on evolution law of mechanical behavior of non-circular shield tunnel linings with cross-section geometry transformation

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As effective solutions for subsurface projects in high-density urban underground spaces, non-circular shield tunnels have been successfully employed in numerous projects. However, given the various types of cross-sections available, engineers are always confronted with pivotal decisions regarding the selection of different types of cross-sections. Furthermore, there exists a notable research gap concerning differences of the structural behavior between tunnel linings with different cross-sections. With continuous cross-section geometry transformation, the evolution of structural behavior, ultimate bearing capacity, and distribution of weak parts of non-circular tunnels have not yet been thoroughly investigated, as well.

In this study, a parameterization method for cross-section geometry of different non-circular tunnels is proposed. This method establishes geometric connections between different non-circular tunnels, such as typical quasi-rectangular segment tunnels (QRST tunnels) and double-o-tube tunnels (DOT tunnels). A test-validated macro-level nonlinear structural model is then proposed to reveal the elastoplastic failure processes of different tunnel structures. Additionally, for the quantitative evaluation purpose, an energy-based robustness evaluation method considering the entire structural bearing process is proposed. Finally, the evolution process of structural mechanical behavior during the continuous transformation of geometric parameters of non-circular tunnel structures are revealed and analyzed. The results show that the influence of changes in cross-section geometric parameters on the mechanical behavior and failure mechanism of non-circular shield tunnel structures are effectively captured, thereby facilitating the selection of an appropriate non-circular tunnel regarding the specific engineering conditions.

MS21: Computational methods for granular media

MS21-1:1 | A framework for data-driven multiscale modeling of thermomechanical behavior of dense granular materials

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Continuum-discrete multiscale strategies for simulating granular materials aim to combine the computational efficiency of a continuous method at the macroscale with the accuracy of a discrete method at the micro level. However, oftentimes this approach still falls short in terms of efficiency as the discrete response needs to be solved continuously at several RVEs. Therefore, surrogate models based on machine learning have recently been employed to predict the discrete response. In this presentation, we introduce a data-driven continuum-discrete multiscale methodology for thermomechanical analysis of packed granular media. In particular, we employ the Finite Volume Method to solve the macroscale problem and the DEM to compute the microscale response in RVEs. Therefore, several RVE simulations are performed offline, whose discrete solutions are homogenized. A database of microscale solutions is then created to relate microstructure properties with the variables required in the continuous method at the macroscale. This database is used to train an Artificial Neural Network, which serves as a surrogate model for the continuous method to predict the homogenized microscale response without resorting to online DEM simulations. The focus of this presentation is on thermal effects, including heat conduction and thermal expansion. To simulate these phenomena, we built surrogate models that relate the effective thermal conductivity of granular materials with their local porosity and fabric, as well as the change in these last two properties with the deformation of the particles due to temperature change. In addition, we show the effects of bulk motions within granular media during thermal expansion, which is a phenomenon that cannot be captured by periodic RVEs. Therefore, we simulate this behavior at the macroscale, with a simplistic model based on the mass transport equation. The presented examples, even restricted to two-dimensional analyses, confirm the potential of the methodology as a rapid and accurate predictive tool.

MS21-1:2 | Constitutive modeling of granular soils based on the shear-transformation-zone theory

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The shear-transformation-zone (STZ) theory is a mesoscale-based approach that attributes the macroscopic plastic deformation of materials to the flipping, creation, and annihilation of mesoscopic structures known as STZs. The theory has been highly successful in capturing the viscoplastic shear behaviors of metallic glasses. In this study, the potential of the STZ theory in constitutive modeling of both fine-grained and coarse-grained granular soils is demonstrated, considering essential soil properties such as dilatancy, pressure sensitivity, and critical state. The study provides a fresh perspective for understanding the yielding mechanism and hardening of soils through the lens of mesostructural evolution.

MS21-1:3 | A temporal graph neural network-based simulator for granular materials

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Granular materials exhibit complex behaviors influenced by particle interactions, contact forces, and temporal dynamics. In this work, we propose a novel Temporal Graph Neural Network (TGN)-based simulator for accurately modeling granular material dynamics. Our approach represents granular systems as temporal graphs, capturing evolving particle interactions over time. The TGN architecture learns temporal dependencies and non-linear relationships among granular particles, enabling accurate simulation of phenomena like granular flows. Specifically, the discrete numerical simulations of column collapse by using hiearchical multiscale modeling are conducted as training and test data for the TGN-based simulatior. The hieararchical multiscale modeling approach couples the material point method (MPM) with the discrete element method (DEM), where the mechanical response of a representative volume element (RVE) simulated by DEM offers constitutive relations to MPM bypassing any continuum-based constitutive models. The TGN-based simulator learns the interactions among material points simulated in MPM at discrete time instants such that it is capable of simulating granular flows under given initial and boundary conditions. In conclusion, our work presents a versatile TGN-based simulator for granular materials, providing a powerful tool for efficiently simulating granular flows. It can be further integrated into digital twin systems for real time simulations.

Acknowledgments: This work was supported by Research Grants Council of Hong Kong (by GRF Project No. 16206322), and the Project of Hetao Shenzhen-Hong Kong Science and Technology Innovation Cooperation Zone (Grant No. HZQBKCZYB-2020083).

MS21-1:4 | Elastoplastic constitutive modeling of granular materials via thermodynamics-informed neural networks

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Data-driven methods offer a promising framework for constitutive modeling of materials. However, traditional data-driven models suffer from insufficient generalization capabilities and may produce predictions that contradict established physical laws due to scarce training data. To address these challenges, this study introduces a thermodynamics-informed neural network (TINN) for the elastoplastic constitutive modeling of granular materials. Based on thermodynamic elastoplastic theory, the TINN model integrates elastic free energy, stored plastic work, and dissipation. By incorporating a path-dependent recurrent neural network (RNN) and three sub-fully connected neural networks, the TINN model effectively captures the mechanical response and energy evolution of sheared granular materials. The total loss function of TINN combines data-driven and physics-informed components. The TINN's effectiveness and generalization capabilities are evaluated by testing it on diverse datasets, including both simulated and experimental data. The simulated virtual data are derived from existing elastoplastic models or discrete element method (DEM) simulations employing stress probing techniques. By modifying the loss function, TINN can be easily applied to the prediction of drained and undrained shear tests of sand. It accurately captures the mechanical response of sand and implicitly satisfies the thermodynamic laws. The results demonstrate that the TINN model excels in both generalization and robustness, outperforming pure data-driven methods in terms of performance and reliability.

MS21-2:1 | Metaball discrete element lattice boltzmann method for fluid-particle interactions with non-convex shapes

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Fluid-particle systems can involve particles with very complex shapes in many natural and engineering processes. To model these systems, the particles are often simplified as spheres for simplicity. However, particle shapes can significantly impact the overall mechanical behaviors at the macroscale. To address this challenge, we introduce a coupled scheme between the Metaball Discrete Element Method and the Lattice Boltzmann Method. The complex particle morphology is elegantly described by the Metaball function, and both the collision algorithm between non-convex particles and the coupling with fluid benefit from the use of Metaball functions. The proposed model has the potential to simulate many fluid-particle systems with realistic particle shapes.

MS21-2:2 | Comparison of three different multiphase LBM strategies for numerically obtaining the soil water retention curve of granular materials

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This research focuses on obtaining and comparing the soil water retention curve (SWRC) via numerical modelling using three different multiphase extensions of the lattice Boltzmann method (LBM). The SWRC is a fundamental behavioral characteristic of unsaturated soils, that describes the variation of suction given imposed changes in saturation degree or vice-versa. The LBM is a computational fluid dynamics method, suitable for handling the complex geometries inherent to flow through the pore space of soils. Given that most soils exist in an unsaturated state, it is important that the modelling is done for the combined flow of the air and water phases, and thus multiphase or multicomponent extensions have to be employed. In this research the multiphase Shan-Chen, multicomponent Shan-Chen, and He-Chen-Zhang (phase field) extensions are considered. An in-house code for each of the three methods is developed and used to simulate the SWRC for a packing of granular soils. The accuracy of the predictions made by each method is measured by comparing the results with the SWRC obtained by experimental means. The three methods are also compared in terms of required computational power and time. Finally, a list of pros and cons for each method is provided to assist future researchers in choosing a suitable modeling tool.

MS21-2:3 | Resolved CFD-DEM modeling of debris flows, avalanches, and floods with arbitrary-shaped boulders and driftwood impacting structures and forests

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Geophysical mass flows, such as debris flows, avalanches, and floods, are often observed by the presence of large boulders and driftwood, whose shapes significantly influence the behavior of flow transportation, jamming, impact, and deposition. However, quantitatively assessing how the shapes of these large-sized solids alter flow behavior remains an open question. This challenge arises from complexities involved in capturing the interactions between fluids, arbitrary-shaped boulders or wood, and structures. In this study, we employ a newly developed resolved computational fluid dynamics and discrete-element method (CFD-DEM) framework to simulate the interactions between arbitrary-shaped solids and viscous slurry or water. Specifically, the shapes of boulders, driftwood, and trees are obtained from reduced-scale samples using X-ray computed tomography (CT) techniques, and the CFD and DEM models employ the immersed boundary method (IBM) and signed distance field (SDF) method, respectively. As a result, the proposed CFD-DEM coupling framework offers a unified treatment of fluid-arbitrary-shaped solids-structure interactions in geophysical flows. Through flows carrying wood and boulders against a slit dam and forests, we test the modeling capability and explore the effects of different shapes on flow-structure interactions. The high-fidelity numerical predictions of flow-structure interactions demonstrate reasonable consistency with experimental and real-world observations. Therefore, this physics-based model holds significant potential for geophysical flow hazard assessment and broader applications in nature and engineering scenarios. Acknowledgments: This research was supported by the UGC-PolyU Start-up Fund (Grant No.: A0049544).

MS21-2:4 | Multiscale insights into the behaviour of laterally loaded pile

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Monopiles are commonly used as foundations for offshore wind turbines. The behaviour of the pile depends on the interactions between the pile and the surrounding soil mass. Evaluating and understanding the soil-pile interaction is crucial for the design of monopiles.

Numerical methods such as the finite element method (FEM) are often used for the design and analysis of the behaviour of laterally loaded pile. However, the behaviour depends on the capability of the adopted constitutive model, which poses challenges in accurately reproducing complicated behaviour such as the cyclic response and strain localization. Multiscale numerical approaches, as an alternative to classical phenomenological laws, provide a new perspective to investigate the soil-pile behaviour. In this method, FEM is used to define the boundary value problem, while the discrete element method (DEM) is employed to derive the constitutive relationship at each Gauss point of the FEM mesh. Consequently, the strengths of FEM and DEM are integrated in a concurrent model, which enables to capture the complicated soil behaviour in large-scale boundary value problems.

This study presents a multiscale analysis by coupling FEM and DEM to investigate the complex interactions between laterally loaded piles and dry sands. Insights from the macroscale, such as the p-y curve and displacement field, are provided and compared with the results derived from pure FEM simulations. Moreover, microscopic insights, including contact force chain and particle arrangement close to and far from the pile are presented to interpret and better understand the macroscopic behaviour.

MS21-2:5 | Modeling and application of hydraulic fracturing based on adaptive finite volume-phase field method

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In recent years, there has been increasing interest in predicting fluid and moisture-driven crack propagation in deforming porous media, particularly in the modeling of hydraulic fracturing, also known as "fracking." The phase-field fracture method has become the most popular approach for crack propagation simulations due to its ability to capture complex crack behaviors without the need for explicit tracking of crack surfaces and additional fracture criteria. Currently, almost all phase-field hydraulic fracturing simulations are built within a finite element framework. In this study, we model hydraulic fracturing using an adaptive finite-volume phase-field framework proposed previously. The porous medium is based on classical Biot's poroelastic theory, with fracture behavior controlled by the phase-field model. Crack propagation is driven by elastic energy, where the phase-field value serves as an interpolation function to transition fluid properties between intact and fully damaged regions. The framework is validated using a classic 2D specimen subjected to increasing internal pressure and compared with analytical solutions. Additionally, simulations are conducted for scenarios including single crack propagation, interaction between hydraulic fracturing and pre-existing natural fractures, and interactions among multiple hydraulic fractures. The resulting crack propagation patterns and pressure distributions under different conditions are analyzed and compared, demonstrating the feasibility of this framework.

MS23: The mechanics, chemistry, and physics for cement and concrete decarbonization

MS23-1:1 | Green's function-based estimation of heat release in modified calorimetric tests

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Cement hydration is an exothermal process where the reaction between cement and water leads to heat release per time and mass of hydrated cement. In the classical evaluation of a calorimetric test, the total heat leaving the tested hydrated sample is set equal to the heat generation rate of the hydrating sample. This overall heat release rate typically follows a trend characterized by a first peak, an induction period and a main peak. However, such an evaluation is based on the assumption of stationarity, i.e. the internal energy of the individual volume elements making up the hydrating sample is assumed to stay constant over the entire testing period.

The current contribution leaves the aforementioned assumption aside, by focusing on the instationary heat generation and conduction in a cylindrical sample, described by a convolution integral where Green's functions link heat release rates to temperatures. Hence, the calorimeter needs to be equipped by an additional temperature sensor. The new approach leads to an improved estimate for the heat release rate of cement, with the first peak being twice as large as that estimated by the traditional method, and occurring three times earlier.

Moreover, it is interesting to relate the two peaks in the hydration heat release trend to the two key phenomena governing hydration: dissolution of cement clinker and precipitation of hydration product out of a super-saturated solution (Nicoleau & Nonat 2016). Indeed, the first peak occurs once a temporally constant ion concentration, as measured by coupled plasma – optical emission spectrometry (ICP-OES) is reached. This shows that the first peak, identified here with unprecedented precision, is associated with a strongly exothermic dissolution process.

Nicoleau, L. & Nonat, A. 2016. A new view on the kinetics of tricalcium silicate hydration. Cement and Concrete Research 86, pp. 1–11.

MS23-1:2 | Impact of seawater on the hydration and carbonation of reactive magnesium oxide cement

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Reactive magnesium oxide cement (RMC) is emerging as a sustainable alternative to ordinary Portland cement (OPC) due to its lower production temperatures, ability to sequester carbon dioxide (CO2), and recyclability. Despite these advantages, RMC often exhibits low hydration rates, necessitating the addition of hydrating agents, like magnesium acetate or magnesium chloride. Seawater, abundant in magnesium ions, arises as a potential natural alternative to these agents. This study thoroughly investigates seawater's dual impact on both the hydration and carbonation processes of RMC. The results reveal that seawater not only expedites hydration kinetics but also significantly influences the carbonation of RMC, leading to notable enhancements in the mechanical performance of the RMC mortars. Seawater-based mortar samples exhibit a remarkable 60% increase in compressive strength, achieving 81.1 MPa and a 65% increase in flexural strength, reaching 5.3 MPa, after 28-day accelerated carbonation, surpassing RMC mortars mixed with 0.1M magnesium acetate solution. Utilizing X-ray diffraction (XRD), thermogravimetric analysis (TGA), and scanning electron microscopy (SEM) techniques, this study unveils a substantial increase in hydrated magnesium carbonates in the seawater samples. The promising results will have wide-ranging effects on concrete production for non-structural applications not only in water-scarce regions that rely on energy-intensive desalination processes, but also globally.

MS23-1:3 | Influence of the production protocol and additives on the chemo-mechanical properties of M-S-H pastes

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New objectives have been proposed to reduce greenhouse gas emissions and address the ecological impacts of human activities. CO2 emissions mainly come from burning and decarbonation of limestone in the production of building materials, particularly traditional cement. To lower the emissions, other binders, based on a different chemistry as for example MgO-based cement, are considered. When magnesium binders hydrate, they can result in the formation of different magnesium phases. One of these is magnesium silicate hydrate (M-S-H). Several studies have examined the chemical, and microstructural characteristics and the stability of M-S-H, but their mechanical properties have not been thoroughly investigated. This study investigates the microstructural and elastic properties of M-S-H pastes at the low scale (micrometres scale) after undergoing various production protocols. These protocols were developed to address the high water demand of reactive MgO and microsilica, using various w/b ratios, materials, and adjuvants. Carbonates and phosphates were used as an accelerator and/or superplasticizer in certain mixtures to analyse their effects on the mechanical properties. Chemical (XRD, TGA, SEM/EDS), microstructural (N2 Physisorption and water saturation), and mechanical characterizations (indentation) were conducted.

MS23-1:4 | Investigating carbonation and hydration of reactive magnesia cement using advanced transmission electron microscopy

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Reactive MgO cement (RMC) serves as a sustainable substitute for ordinary Portland cement (OPC), functioning as a low-carbon binder. RMC reacts with water and absorbs environmental CO2 to precipitate hydrated magnesium carbonates (HMCs). The strength of the ultimate RMC-based composite is influenced by the particular polymorphs of HMCs that precipitate, determined by the CO2 curing conditions and the composition of the RMC. This study investigates the polymorphism in HMCs by observing the hydration and carbonation reactions of RMC using both ex-situ and specialized in-situ gas cell techniques with Transmission Electron Microscopy (TEM). The first step of the experiments is the sample preparation for both ex-situ and in-situ experiments. For the ex-situ experiments, the sample is first imaged under the microscope, and information about the lattice parameters is obtained before exposure. The sample is then immersed in water for a certain duration to allow complete hydration. The hydrated sample is then imaged in the TEM to obtain information about the formed hydration products. The in-situ experiments are conducted by flowing gases into and out of the gas cell at the required concentration and temperature. Changes in the sample morphology and phases are then captured with videos and images taken using in-situ TEM. Diffraction patterns and lattice images collected from TEM also provide information about the different phases of HMCs formed during the experiments. These results help provide valuable information on the hydration and carbonation of magnesia, which will, in turn, aid in evaluating and enhancing the properties of RMCs.

MS23-2:1 | Engineered living building material (LBM) formed by binder jetting under Martian temperature and air pressure

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This study explores the development of a novel construction material, Hydrogel-based concrete (HBC), specifically designed for Martian environments. HBC is a composite material formed by mixing flowable hydrosol with inert aggregates, offering low energy consumption and minimal shipped ingredients. A variant of Bio-HBC, known as living building material (LBM), incorporates genetically modified yeast cells (Saccharomyces cerevisiae) to produce recombinant SpyTag/SpyCatcher pairs and collagens, which form bio-hydrogel with strong cohesive properties. The study uses the addition of a small portion of engineered yeast to the HBC yields bricks with higher mechanical properties when cured under harsh environments. The bio-HBC has great potential to be adopted with unique attributes such as self-repair, stimuli-responsiveness, and environmental adaptivity.

The study also investigates binder jetting, a low-energy-consuming additive manufacturing process, as a potential method for automatically constructing structures using Bio-HBC. We developed an environmental chamber capable of mimicking Martian conditions, including temperature and air pressure, to test the material's printing compatibility and mechanical performance under extreme environments. The experiments focused on understanding and characterizing binder-powder interaction, determining suitable printing process parameters, and controlling depressurization for successful binder jetting under Martian conditions. The findings demonstrate that Bio-HBC exhibits improved mechanical properties when cured under harsh environments compared to traditional HBC. Additionally, the use of genetically modified yeast cells promotes adhesion and prevents the formation of porous joint structures during freezing.

MS23-2:2 | Investigation of the factors affecting the performance of brucite as a construction material recovered from desalination reject brine

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Reactive magnesium oxide (MgO) cements (RMC) have emerged as one of the promising sustainable alternatives to ordinary Portland cement (OPC) owing to their lower production temperature (700-1000 °C) and reduced CO2 emissions [1]. Further, the permanent CO2 sequestration during the strength development of RMC significantly decreases the net CO2 emissions, making RMC a leading candidate for carbon-neutral/negative construction material. RMC is primarily obtained by calcining naturally occurring but geographically limited magnesite deposits. Therefore, as an alternative route, RMC is also synthesized by calcination of brucite (Mg(OH)2) recovered from concentrated brine resources (viz. desalination waste) or seawater using chemical processes. This alternative route for RMC production also addresses the challenges related to magnesite availability and management of the byproducts of the desalination process. It has been shown that the synthesized brucite could be directly carbonated for rapid strength gain and utilization as a construction material, also reducing the CO2 emissions due to the elimination of calcination requirement [1]. However, several challenges are associated with the utilization of brucite, such as high-water consumption, optimization of carbonation conditions, reduced porosity for maximized strength gain, effect of alkali agents on the performance of the synthesized brucite, etc. This study investigated the above-mentioned factors and their impact on the overall performance of brucite for construction applications. The results demonstrated that the different factors affected the type and content of the carbonation phases formed, which in turn, affected the overall compressive strength. The results also indicated that optimization of the synthesis conditions can enhance the compressive strength and CO2 absorption capacity of brucite.

[1] I. Singh, R. Hay, K. Celik, Recovery and direct carbonation of brucite from desalination reject brine for use as a construction material, Cem. Concr. Res. 152 (2022), 106673.

MS23-2:3 | Utilization of desert sand with belite calcium sulfoaluminate cement

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As urbanization and infrastructure development drive the demand for concrete, natural resources, especially river sand, face increasing pressure. On the other hand, desert sand is abundant but remains underutilized due to its narrow particle size distribution and high specific surface area, which require higher cement content to bind its grains. This study aims to harness desert sand in mortars by using it with belite calcium sulfoaluminate cement (BCSA). The slightly expansive nature of BCSA cement allows for minimal usage while effectively binding the sand particles. In this work, naturally available dune sand, vast deposits of which are available in the United Arab Emirates (UAE) and the broader Middle East and North Africa (MENA) region, were utilized with BCSA cement. The results show that the complete replacement of standard sand with desert sand is feasible when a small quantity of superplasticizer (1% by mass of binder) is used in the mixture. Since BCSA cement is known for its rapid setting ability, the effect of desert sand on the setting time of the mixtures and compressive strengths at different ages (from 1 hour to 28 days) was also investigated. The results indicate that the compressive strength of desert sand mortars (~50 MPa) is comparable to those made from standard sand at the age of 28 days. The results are promising from an environmental perspective since the production temperature of BCSA is lower compared to ordinary Portland cement (OPC) thus reducing the carbon footprint. Using desert sand also reduces reliance on river sand, thereby promoting sustainable construction practices.

MS25: Non-local mechanics for unconventional modelling in bioengineering and advanced manufacturing

MS25-1:1 | A mechanobiologic model of cellular signal trasduction based on non-local stability of the primary cilium

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The mechanotrasduction of intracellular stimuli represents a fascinating aspect of mechanobiology since many different pathways may activate the gene expression of different kind of cells. The main parameters and phenomena activating the mechanotrasduction have to be fully uncovered so that therapeutic stimulation to capture self-healing by some specific pathologies is still a fondamental challenge in the field of biomedical engineering.

In this study the author aims to show that possible source of mechanotrasduction is the flutter-induced instability of primary cilia on the anchoraging cytoskeleton. In particular, the cilium is modelled as an Euler-Bernoulli cantilever beam clamped at one side and free on the other side that is completely equivalent to a Leipholtz column, in which the follower load is distributed along the ciliary axoneme. By finding the critical load for which this system becomes unstable, it is possible to link it to the velocity with which the extracellular fluid is tangentially distributed along the cilium. The analysis is carried out introducing a generalized version of the Ruth-Hurwitz criterion that may be used in presence of hereditary materials as the cilium fibers.

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[2] Ingber D.E., 2003, Mechanobiology and diseases of mechanotransduction. Ann. Med. ;35:564–577. doi: 10.1080/07853890310016333.

[3] Bologna, E., Zingales, M. (2018). Stability analysis of beck's column over a fractional-order hereditary foundation. Proc. Of the R. Soc. Of London A: Math. Gen. 474(2218), 20180315

MS25-1:2 | Finite element analysis of buckyball-shaped microscaffolds for tissue engineering

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Scaffold-based tissue engineering is a fast-growing field. Thereby, scaffolded spheroids are extensively utilized as building blocks, for facilitating the regeneration of defective tissue, due to their enhanced self-bioassembly and tissue fusion. For successful clinical application, scaffolds should be biocompatible. To that end, scaffolds made of cross-linkable gelatins and PCL-based resin were considered here. In terms of the scaffold shape, we focus in this study on truncated icosahedron shape–often referred to as "buckyballs". Clearly, the geometric parameters of the scaffold influence the resulting mechanical stiffness and load-bearing capacity. The objective of this study was to study, numerically, the effect of the geometric parameters on the corresponding mechanical properties of buckyballs (i.e., the shape and the length of the struts making them up), while maintaining a porosity allowing for sufficient cell retention. The numerical studies were performed by means of the commercial Finite Element software Abaqus, relying on periodic homogenization based on appropriately chosen unit cells, in order to predict the stiffness tensor components of densely packed scaffolds. For the unit cells, linear Timoshenko beam elements (B31) were used, with linear elastic material behavior (considering varying Young's moduli). Furthermore, circular, rectangular, square, and elliptical cross sections were chosen, while the overall buckyball size amounted to 200 μm. Six effective strain states were applied by adjusting periodic boundary conditions on master nodes of the unit cell to determine the effective stiffness. The buckyball stiffness turned out to be linearly dependent on the Young's modulus of the material used to fabricate the scaffold. Interestingly, the rate of stiffness increase due to an increase in strut diameter is equal to the rate of stiffness decrease due to an increase in edge length. Hence, the ratio of cross-sectional size over the strut length turned out to be the key design parameter for buckyball optimization.

MS25-1:3 | Comparative study of the bioresoption rate of PLLA/PGA scaffolds stored in different environments simulating biological intra-tissue fluid

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The biocompatibility of medical devices replacing biological tissues is related to the substitution of tissue function, and similarity in a number of physical, mechanical or structural parameters. Modelling the optimal scaffold, from the point of view of matter flow, energy and mass, has been the aim of numerous scientific papers for many years. In all this, it is not only the moment of implantation that is important, but above all the nature of the changes during the operation of such a device. The implanted device does not have the ability to adjust its properties to changing internal conditions: load values, chemical and biological properties of the intradural fluid associated with inflammation, for example. It is therefore important to determine the rate of change of its degradation in different environments, so that both the implant and its degradation products are not toxic to the living organism. The aim of this research is to determine both the structural and physical changes of the 3D-printed scapulae in different solutions simulating a biological environment. The test material consists of the PLLA/PGA copolymer scapes stored in PBS solution, a liquid with a pH of 4.0 and 7.0. In order to determine the resorption rate, each of the scapes was subjected to measurements every 30 days, in which the weight and geometry of the scapes and the pH of the solution were determined. A differential analysis based on a comparative method of mictrotomographically reconstructed scans (SkyScan 1172, Bruker) was carried out to analyse the changes occurring at each stage of material degradation.

MS25-1:4 | Non-local model of delamination of hereditary aortic lamina

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Aortic dissection is a cardiovascular pathology that consists in the laceration of the innermost layer of the aortic wall (the tunica intima) with the consequent leakage of the blood into the other layers of the vessel, resulting in the creation of a "false lumen". Even if this condition is quite rare, it represents one of the most serious cardiovascular diseases.

This is the reason why a previous study established a new biomechanical model of interface to predict the aortic dissection [1]; in particular, the mode I debonding problem was analysed. The aortic wall was modelled

by using two Euler-Bernoulli beams clamped at one end, transversally loaded at the other one and joined together through a cohesive interface. The novelty of this approach consisted in the introduction of non-local terms [2], in the governing equation of the problem, to consider the forces transmitted by collagen fibres of non-adjacent elements.
However, even if the two beams were modelled as two elastic ones, it is proven that the aortic tissue displays a non-local time-dependent mechanical behaviour.Consequently, the aim of this study is to propose a new model to describe aortic dissection that considers the hereditary behaviour of the aortic wall, modelled by using two hereditary beams.Finally, some numerical simulations, with different values of non-local parameters, will be provided to demonstrate the goodness of the proposed model.
[1] Alotta, G., et al., "A non-local mode-i cohesive model for ascending thoracic aorta dissections (ATAD).", 2018 IEEE 4th International Forum on Research and Technology for Society and Industry (RTSI). IEEE, 2018. p. 1-6, (2018).
[2] Di Paola, M., et al., "Physically-based approach to the mechanics of strong non-local linear elasticity theory.", Journal of Elasticity 97: 103-130, (2009).

MS25-1:5 | Numerical research on the effect of nebulizer frequency in maxillary sinus airflow under post-surgical conditions created by virtual surgery

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Eosinophilic Sinusitis (ES) represents a unique subtype of paranasal sinusitis, characterized by nasal polyps near sinus openings due to chronic inflammation. The presence of nasal polyps complicates the treatment of sinusitis, often necessitating Endoscopic Sinus Surgery (ESS) as the condition progresses. However, residual inflammation in the sinus post-surgery can contribute to the recurrence of ES. Recently, vibrating nebulizers that deliver medication at specific frequencies have been introduced as a potential treatment for sinus inflammation, with particular anticipation for their application in case of ES. Nevertheless, the optimal vibration frequency to achieve maximal therapeutic benefit in nasal polyp cases remains unclear. This study utilized Computational Fluid Dynamics (CFD) to identify the most effective frequency of vibrating nebulizers for treating maxillary sinus inflammation in case of ES. Using medical imaging data from the target case, we simulated ESS of the nasal cavity and sinuses through virtual surgery. We analyzed airflow in the maxillary sinus, assuming drug diffusion based on post-surgical data. The inflow frequency of the nebulizer was adjusted at 0-125 Hz with 25 Hz increments to evaluate its impact on airflow within the maxillary sinus. Six control sections were defined: one at the natural ostium of maxillary sinus on each side, and two internal sections on each side. The frequency at which the largest Forward direction Volume Flow rate was observed in each inspection section was defined as the optimal frequency. The results revealed that 50Hz was the optimal frequency at the natural ostium, and a frequency range of 0-50Hz was optimal within the maxillary sinus under post-surgical conditions. Furthermore, changes in vibration frequency affected the direction of inflow and location of vortex, leading to varying optimal frequencies within the sinus. Therefore, utilizing CFD analysis to identify the optimal frequency for each specific inflammation site could improve therapeutic outcomes.

MS25-2:1 | Computation of COVID-19 fatality rates based on an aging, hereditary mechanics-inspired modelling strategy

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COVID-19 has clearly highlighted the need for reliable, mathematical modeling-based predictions in epidemiology. Standard models in the field do not account for the time delay between infections and corresponding fatalities, and often, also the fact that the underlying model parameters evolve over time is neglected. In order to tackle this challenge from an innovative perspective inspired by hereditary mechanics, we conceptualize it as a "mechanobiological problem", formulating a "aging infection-to-death-rate delay rule", through which the fatality trends are computed from infection histories. In contrast to the aforementioned standard models in the field, our model does account for delay effects within pandemic dynamics and incorporates exponentially decaying country-/territory-/US state-specific fatality fractions, which are governed by the initial fatality fraction and the characteristic time of fatality decay. When compared to the kinetics approach, as it is standardly implemented in the traditional SIR models, our novel approach allows for better fatality predictions from recorded infection numbers than the death kinetics model for remarkable 93 % of the 228 countries, territories and US states considered in this study. Moreover, it shows promising capabilities for short-term fatality predictions, as the derived parameters of our hereditary mechanics-based model are fairly stable over extended periods of time. Thus, by focusing here on the aging nature of pandemics and evolving parameters, the precision of epidemiological predictions is clearly improved based on the proposed model, emphasizing the benefits of integrating mechanobiological principles into epidemiological modelling. This way, it seems possible to better address the complex challenges posed by dynamic infectious diseases like COVID-19.

MS25-2:2 | On modeling of human abdominal wall based on in vivo experiments

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The paper addresses the issue of computational modeling of the human abdominal wall based on in vivo studies. The motivation for the research are abdominal defects, such as hernias, and the problem of their effective repair. Often the repair is done with the use of synthetic implants, that typically do not mimic the mechanical properties of the human tissue they replace. This causes a state of stress, which may lead to the implant detaching and thus to the recurrence of the hernia.
The complex, multi-layered structure of the abdominal wall causes differences in the mechanical behavior of its various regions, which are easy to observe e.g., through different ranges of strains under physiological loads. This causes difficulties in adjusting the appropriate properties of implants used as substitutes for healthy tissue in the area of the defect (hernia). The complexity makes the structure not easy to model.
In this article we discuss the problems of computational modeling of the human abdominal wall based on experimental data collected on the surface of the abdominal wall during changes in intra-abdominal pressure. We define numerical models by means of finite element method. We analyse the impact of changes in the mechanical properties of various abdominal regions on the forces in the connection between the implant and the tissue. We relate the results of numerical studies to experimental data based on digital image correlation. We use neural networks (self-organizing maps) in the analysis, which helps to determine regions with similar mechanical behavior under the influence of intra-abdominal pressure change.

MS25-2:3 | Dissipation and free energies of fractional-order quasi-linear hereditariness of biological tissues

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Material hereditariness has been a topic of great interest since 20th century. Indeed, several materials display a non-local time-dependent mechanical behaviour since they have memory of their past stress-strain history. This peculiarity led to the formulations of mathematical models, to characterise them, based on the use of fractional calculus; in such a way, it was possible to express the relations between stress and strain as non-local convolution integrals with power-law kernels to describe their time behaviour, in an appropriate way.
This non-locality in time was also considered from an energetic point of view. In fact, the work spent by these materials, during the loading phase, is recovered only in a partial way, during the unloading phase, and the remaining part is dissipated in the form of heat. This is the reason why, starting from the already established fractional-order models, a new formulation for the dissipation function, based on non-local convolution integrals, was proposed [1].
However, it was demonstrated that biological materials cannot be analysed by using the relations of linear hereditariness, since they display a non-linear behaviour even for low stress-strain levels. For this reason, in previous studies, the authors established new mechanical models to properly fit the non-linear fractional-order relations between stress and strain [2].
Consequently, the aim of this study is the extension of the dissipation to the framework of non-linear hereditariness involving fractional-order decaying functions.
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MS27: Mechanical performance and durability of novel concretes and sustainable alternatives

MS27:1 | Characterization of functionalized binder systems by means of dynamic-mechanical analysis

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Nowadays, mortar and concrete systems are not just simple building materials made of water, cement, and aggregate. The demands for building materials in terms of technical, ecological, and economic properties are constantly increasing, especially due to the growing im-portance of building maintenance and repair. Therefore, repair materials are continuously subject to innovation, with a particular focus on binder systems in research and development. The modification and variation of individual components allows for the adjustment of pro-cessing and usage properties adapted to the application. The synergistic use of mineral and organic binder components enables the achievement of diverse and optimal properties.
However, researching the mechanical and physical properties of such systems is typically very time-consuming. The numerous possibili-ties for variations in components and the dosage quantities result in a large number of potential formulations. The mechanical properties of these formulations are usually determined through quasi-static tests on relatively large test specimens at room temperature. If there is a need to have additional information on the temperature- or moisture-dependent behavior of the materials, it will result in a test matrix that requires a significant amount of time and material.
The objective is to develop a new technique for characterizing the mechanical properties of functionalized binder systems under varying environmental conditions. In the present contribution, a high-load dynamic-mechanical measuring system for solids will be presented to investigate the mechanical behavior of small test specimens using dynamic loading at defined temperatures or humidity levels. Examples of dynamic-mechanical analyses of selected binder systems composed of organic and mineral components are shown. The initial results indicate that the DMA investigation method can significantly contribute to the development and research of new and existing binder systems.

MS27:2 | Novel design of cementitious composites with the use of limestone quarry waste and silica fume

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The construction sector faces the challenges and obligations of handling and reducing the use of raw materials and increasing the reuse and recycling streams of waste disposal. The incorporation of industrial by-products in cementitious composites and the use of locally sourced materials contributes towards producing cementitious building materials with lower embodied energy, yet acceptable mechanical properties, thus promoting sustainability within the construction industry. This study investigates the utilization of limestone quarry waste and silica fume, as partial replacement to fine sand and cement, respectively, in cementitious composites. The limestone waste material used as filler in this study originated from a local quarry, while the silica fume was imported. Various cementitious mixtures were designed and produced in the laboratory, following a parametric design process, whereby alternative proportions of the industrial by-products were used. During the design of the mixtures, specific performance objectives were set. The physico-mechanical properties of the hardened composites were rigorously examined at different curing ages to assess the effect of the industrial by-products on the cementitious mixtures hereby produced. The results highlight the potential of the utilization of industrial by-products in cementitious composite materials. Mixtures with silica fume showed better enhancement in compressive strength between 7 and 28 days of curing, compared to mixtures without silica fume. The workability assessment of the mixtures in the fresh state confirmed the feasibility and practicality of the manufacturing process of the specific composites. These findings project a potential avenue for the utilization of limestone quarry waste and silica fume as sustainable alternatives in cementitious material production, thus offering pathways to reduce the environmental impact of these materials while maintaining or improving their physico-mechanical properties. The incorporation of the aforementioned substitute waste materials contributes to the promotion of ecologically conscious activities and meets the desires of the public for greener building materials.

MS27:3 | Recyclable bio-synthesis hydrogel-based xoncrete (Bio-HBC): investigation of strength in successive material generations

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The Mars colonization vision is progressing faster than anticipated, due to rapid advancements in space exploration technology, which pave the way for future Mars missions. Addressing challenges such as extreme low temperatures, lack of substantial atmosphere, and resource scarcity on Mars is essential for successfully establishing sustainable habitats and infrastructure.In this study, a bio-synthesis hydrogel-based concrete (Bio-HBC) containing a physically crosslinkable sand-hydrogel scaffold and genetically engineered yeast cells - S. cerevisiae capable of expressing proteins on the yeast's cell surface was recently developed. Here, Bio-HBC design factors, i.e., yeast/gelatin ratio, sol/sand ratio, curing regimes, and types of protein expressed, are evaluated.
Bio-HBCs were produced using various yeast-to-gelatin ratios, ranging from 0:5 to 5:0. To mimic the Martian environment, curing conditions that replicated extreme low temperatures (-48 °C) and low atmospheric pressure (8 Pa) were adopted. These Bio-HBCs were examined for mechanical properties, microstructural properties, and recovery of original properties in successive generations. The results indicate that the compressive strength and elastic modulus of Bio-HBCs initially increased with the yeast/gelatin ratio, peaked at a critical value, and subsequently decreased. Specifically, a 3:7 yeast/gelatin ratio achieved an average compressive strength of 11.9 MPa and an elastic modulus of 398.9 MPa. Notably, the findings reveal that abiotic HBCs have significant regeneration potential, as they maintained their properties through three successive material generations.

MS27:4 | Structural response of eco-UHPC with recycled steel fibers

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Ultra-high performance concrete (UHPC) has become increasingly popular for several applications, e.g. bridge structures joints, because of its superior mechanical performance. However, the large-scale implementation of UHPC for full structural members is yet to be fully realized because of the high cost associated with the material. Emerging UHPC uses local and sustainable materials that can be economically feasible and environmentally sustainable. This study explores the structural performance of eco-UHPC with recycled steel fibers (RSF) and manufactured steel fibers (MSF) for full precast bridge columns. Two sets of identical 1/3-scale bridge columns were fabricated at a precast plant, including four footing foundations with conventional concrete. The specimens were tested under combined axial and quasi-static cyclic lateral force at the Earthquake Engineering Laboratory of the University of Nevada, Reno. This preentation will provide an overview of the test results and comparison of structural behavior of columns with recyceld and high-end steel fibers.

MS27:5 | Rehabilitation of deteriorated RC beams by applying external post-tension stresses: developing machine learning prediction models of ultimate limit state

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Concrete rehabilitation has become increasingly important due to the need to maintain and improve the performance of existing structures. Among the various techniques available for concrete rehabilitation, active techniques such as prestressing strengthening methods have proven to be highly sustainable solutions. One of the most used prestressing strengthening applications involves placing externally unbonded post-tension tendons on the element due to its ease of construction and cost-effectiveness.
However, external post-tensioning (EPT) strengthening techniques exhibit multiple nonlinear behaviors mainly due to material responses to loading, geometrical disorders during loading, and variations in behavior between unbonded tendons and concrete deformations. These uncertainties can compromise the sustainability of the rehabilitated structure, meaning it may not operate as intended. As a result, numerous studies have been conducted to predict the ultimate tendon stress in EPT beams and determine their flexural strength. However, a more rational, accurate, and functional approach is still needed.
Therefore, this research aims to propose a practical prediction model of the ultimate tendon stress by employing machine learning techniques, specifically tree-based machine learning algorithms. To this end, a comprehensive dataset is created in this research using 32 experimental studies from the literature, which comprises 133

reinforced concrete beams strengthened with unbonded EPT tendons (24 beams were strengthened with FRP tendons while the other 109 were high-strength steel). In addition, a thorough comparison has been made with four design code models and four rational models found in the literature, with theoretical analyses based on specific section or whole member examinations.

Based on this rigorous comparison, the ensemble learning algorithms utilized in this research have demonstrated their reliability. These models have shown high accuracy and low error percentages (MAPE <10%). Furthermore, It has been observed that the variation in tendon eccentricity, along with its initial effective strain, holds significance in many machine-learning prediction models.

MS28: Innovative experimental mechanics for fracture of heterogeneous materials

MS28:1 | Experimental study on joint closure and slip behavior of rock like specimens with non-penetrating long joints under uniaxial compression based on surface displacement monitoring

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This research employs 3D printing and Digital Image Correlation technology to examine the behavior of rock-like specimens with nonpenetrating long joints under uniaxial compression. It analyzes crack propagation and mechanical mechanisms, revealing joint closure and slip behavior during compression by summarizing surface displacement features. Findings demonstrate the significant influence of the number, penetration depth, and arrangement of nonpenetrating joints on mechanical performance. The displacement X field shows high sensitivity to arrangement type and penetration depth, while displacement Z is particularly sensitive to arrangement. Nonpenetrating joints inhibit displacement X discontinuity locally, globally attenuate displacement Y, and promote displacement Z overall. Pre-existing joints are categorized into main and subordinate joints. Joint closure and slip behavior are not primarily at the tips; the main joints exhibit a top-middle-bottom sequence, while subordinate joints show bottom-middle-top. The nonpenetrating constraint effect on joint closure and slip capacity is influenced by the relative penetration depth of horizontally adjacent joints, both main and subordinate. Consequently, under subordinate joint control, wing extension cracks develop, characterized by a pure tensile mechanism and obliquely parallel cracks exhibiting a tensile-shear mechanism, resulting in four distinct failure modes on the frontal face. Nonpenetrating joints, forming the significant spalling surface, induce noncoplanar extension cracks on the lateral face, exacerbating surface spalling on the back face. The presence of Nonpenetrating joints enhances strength in symmetric specimens but weakens it in asymmetric ones. The joint parameter defined by the penetration rate and type exhibits a monotonic negative correlation with peak strength. This study provides compelling evidence that specimens with nonpenetrating joints replicate layered step path failure surfaces.

MS28:2 | On the use of additional sensors during mechanical tests

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In classical mechanical tests, such as tensile tests, elongation and force are measured. Together with the initial length and cross-sectional area, a stress-strain curve is derived. Additional sensors can capture further changes in the material. For example, fractures can introduce elastic waves, which are captured by acoustic emission sensors. We demonstrate how acoustic emission can be applied in mechanical tests using different sensor positions and oscilloscopes. Furthermore, the correlation between mechanical tests and other sensor responses, such as electrical resistivity, temperature, and active ultrasound (combined with coda wave interferometry), is investigated. In the end, we explore the feasibility of controlling the tensile testing process based on sensor signals.

MS28:3 | Rate effects on energy dissipation mechanisms in high-performance concrete

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An experimental fracture study was performed on different types of high performance concrete with the objective of measuring the changes in damage and cracking patterns as a function of loading rate. The specimens were 50-mm diameter cylinders prepared with hooked steel fibers, steel wool fibers, and a combination of both. Specimens were loaded in a split-cylinder configuration at three loading rates ranging from quasi-static to drop weight impact. Each specimen was scanned using x-ray computed tomography (CT) both before and after loading such that internal damage could be measured. Fiber orientation relative to the load axis was measured from the CT images, and for each specimen scanned, an “optimum” and “pessimism” orientation was established, the former being the orientation at which the fibers oriented in a way that best resists crack growth, while the latter is the orientation in which the fibers least resist crack growth. Damage measurements were made through a 3D analysis of load-induced crack area using a hybrid edge-detection/connected components analysis. 3D digital volume correlation was applied to measure strains such that damage below the crack detection threshold could be inferred. Results showed that specimens loaded at higher strain rate produced wider cracks, as compared to the lower strain rate specimens. The pessimism fiber orientation specimens also produced larger cracks when compared to its optimum counterpart. It was also observed that cracking was less continuous in steel wool and fiber reinforced specimens than in the purely fiber reinforced specimens. These quantitative measurements of damage could then be compared to the total energy dissipated by the specimen, as determined by load-deformation or impact energy. Optimum oriented specimens dissipated more energy with smaller total crack area, suggesting a larger amount of micro cracking. Indeed, these specimens had higher amounts of residual strain as measured using digital volume correlation.

MS28:4 | Timelapse X-ray micro-CT imaging: adaptation to damage localisation in fresh cement mortar

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This contribution studies the evolution of internal damage in fresh cement mortar during the 25 hours of hardening using the in situ timelapse X-ray computed micro-tomography (µXCT) imaging method. During µXCT scans, hydration heat was measured, providing insight into internal damage evolution with a link to the development of hydration heat. The measured hydration heat was compared with an analytical model which showed a relatively good agreement with the experimental data. Using 20 CT scans acquired throughout the observed cement hydration, it was possible to obtain a quantified characterisation of the porous space. Furthermore, the use of timelapse µXCT imaging for 25 hours allowed to study crack growth inside the meso-structure including its volume and surface. Using obtained CT data, a digital volume correlation (DVC) was done to calculate boundary conditions, 3D displacements, and 3D strains. The observed results provide valuable information on the shrinkage of cement mortar.

MS28:5 | Quantitative evaluation of fatigue damage in cement mortar: an in-situ approach using XCT

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This paper introduces a novel method for quantitatively assessing fatigue damage in cement mortar by integrating X-ray Computed Tomography (XCT) with Unified Mechanics Theory. Traditional approaches for damage evaluation have relied on empirical equations, lacking mechanistic explanations and requiring extensive experimental data. Computational models offer insight into mechanisms but often lack practical applicability. Unified Mechanics Theory provides a promising alternative, offering a physics-based, non-empirical framework by unifying Newton’s laws and the second law of thermodynamics from first principles.

In this study, we compare various damage measures and employ a Unified Mechanics Theory-based model to predict damage, leveraging time-resolved data obtained through XCT. This approach enhances a fundamental understanding of fatigue damage mechanisms in cement mortar. Future research will focus on refining the method and extending its applicability to a broader range of materials and loading conditions.

MS28:6 | Visualizing corrosion development in cracked reinforced concrete using X-ray tomography

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Corrosion of reinforcement steel in concrete is a common, yet complex, problem. Exposure conditions, such as availability of moisture, chloride, CO2, and oxygen, and local conditions at the steel-concrete interface, influence corrosion development. Furthermore, as the process takes place inside the concrete, the location of the anodic area is seldom known.
During corrosion, corrosion products, often in form of iron oxides, are produced. Iron oxides occupy more volume than the iron they originated from, leading to internal forces and microcracking. Up to the point when corrosion leads to the formation of corrosion-induced cracks, corrosion is difficult to track.
Observing corrosion development at the steel-concrete interface and the consequent fracture of the concrete is challenging. Destructive tests are by far the most common way to assess corrosion damage, thereby not allowing for the collection of data over time in the same sample. Corrosion potential and current are often used for monitoring the risk and progress of corrosion but can only give a rough estimation of damage distribution.
Imaging techniques have the potential to resolve many of these issues. In this study, the authors will make use of X-ray tomography to study the corrosion development at transverse cracks over time in reinforced concrete specimens. The specimens, containing an 8 mm rebar with varying concrete cover, are first cracked in tension and then immersed in a chloride solution. Multiple scans at different time points are to be conducted to allow for the tracking of the formation of corrosion products and the consequent fracture mechanisms.

MS29: Machine learning and artificial intelligence for constrained systems

MS29:1 | Automatic differentiation and neural networks for parameter identification of hysteresis models

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TU Graz, Austria

This contribution focuses on the parameter identification of hysteresis model from measurements by employing automatic differentiation and neural networks. We first introduce the thermodynamically consistent energy based hysteresis model and the parameters which are to be identified. Then we demonstrate how the model can benefit from automatic differentiation. A main step is the parametrization of the hysteresis model based on distribution functions, which makes it possible to treat the identification process as an unconstrained optimization problem. Next, the hysteresis model is sampled, and the generated datasets are used to train neural networks to predict the hysteresis parameters. An important point here is the data generation part. Care needs to be taken so that the generated dataset covers a large space of possible solutions from which the network can learn. The described methods are tested and verified on synthetic as well as measurement data.

MS29:2 | Data-driven variational method for discrepancy modeling: application to nonlinear elasticity and viscoelasticity

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This talk presents a data-driven variational method that embeds high-fidelity measured data in the surrogate or deficient models via variationally derived loss functions to enhance the modeling capability of physics-based models. Key idea is the hierarchical mathematical structure of the multiscale method which is exploited to derive residual based closure terms that are comprised of the first-principles theory and sensor-based measurements. Since closure terms represent errors in the system, embedding data through these terms in the variational formulation leads to discrepancy-informed closure models that inject computation-based intelligence in the modeling framework. The resulting method is driven not only by boundary and initial conditions, but also by measurements that are taken at only a few observation points in the target system. Specifically, the data-embedding term behaves like residual-based least-squares loss functions, thus retaining variational consistency. The structure of the loss function is analyzed in the context of variational correction to the modeled response wherein loss function penalizes the difference in the modeled response from the measured data that represents the local behavior of the system. Formulation is applied to time dependent problems and the effect of the variationally embedded loss function on transient response of the system is analyzed under a variety of loading conditions. Specifically, the damped solution and correct energy time histories are recovered by including known data in the undamped situation. The enhanced stability and accuracy of the DDV method is manifested via reconstructed displacement and velocity fields that yield time histories of strain and kinetic energies that match the target systems. The proposed DDV method also serves as a procedure for restoring the eigenvalues and eigenvectors of a deficient dynamical system when known data is taken into consideration. Method is applied to smooth as well as non-smooth model problems and mathematical attributes of the formulation are investigated.

MS29:3 | Influence of hemodynamics and temporal change in intracranial aneurysm shape on machine learning-based rupture prediction

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Recent studies have indicated that intracranial aneurysm rupture is influenced by various factors, including clinical, morphological, and hemodynamic characteristics identified through Computational Fluid Dynamics (CFD) analysis. Based on these insights, there have been endeavors to develop machine learning models capable of predicting aneurysm rupture. Additionally, it has been observed that the risk of rupture increases with the growth of intracranial aneurysms. However, there has been limited research on machine learning models predicting aneurysm rupture while simultaneously considering aneurysm growth in addition to conventional parameters including hemodynamics. In this study, we aim to develop a machine learning model for predicting aneurysm rupture by introducing the temporal change rate in aneurysm size as a new morphological feature, and to evaluate its impact on prediction accuracy. Out of 533 intracranial aneurysms smaller than 10 mm analyzed through CFD (21 ruptured during observation, 512 unruptured), 357 cases were randomly assigned as Training Data and 176 as Test Data. The analysis included 43 features, covering clinical, hemodynamic, and morphological factors, specifically focusing on the temporal change rate in aneurysm length, width, and neck diameter. Two prediction models were developed: Model A, which considered the temporal change rate, and Model B, which excludes it. These models were applied to the Test Data, and their sensitivity and specificity were calculated and compared. Model A exhibited a sensitivity of 89.8% and a specificity of 74.0%, while Model B demonstrated values of 62.2% and 62.3%, respectively. Additionally, in Model A, the temporal change rate in aneurysm length emerged as the most influential morphological factor, alongside significant hemodynamic factors such as the maximum oscillatory shear index (OSI). Both morphological and hemodynamic factors, including the temporal change rate, significantly influenced the prediction of rupture risk for intracranial aneurysms, resulting in improved prediction accuracy.

MS29:4 | Learning mass-spring-damper dynamics via an incomplete equation of motion, Koopman operator and topology

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The nonlinear governing equation of mass-spring-damper dynamics usually consists of a known linear structure and an undetermined complicated component. This work proposes two physics-informed methods to model the unknown component by either a Koopman-guided auto-encoder or a topology-aware graph. Both frameworks show competitive performance for dynamic forecasting under new control inputs in multiple synthetic and experimental case studies, outperforming deep learning and physics-informed benchmarks. A time-series anomaly detection technique based on Jensen-Shannon distance is also proposed. Furthermore, the interpretable graph model can diagnose local system anomalies.

MS29:5 | Physics Extraction Pods (PEP) find statistical closure

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The identification of useful observables that jointly and uniquely characterize their collective behavior is a pressing challenge in data-driven scientific discovery and inference. One such set of observables is clearly the coupled field variables constrained by prevalent conservation laws. This is, however, too much knolwegde to be informed by scant information gleaned from sparse data. Furthermore, reasonable arguments can be made that such an exhaustive characterization, while sufficient, may not be necessary for informing physically-grounded predictions of natural phenomena. The quest for necessary observables and their achievable performance is motivated by the surge of interest in machine learning and digital twins. In this talk I will describe recent efforts in my research group to design data mining and data interpretation paradigms geared towards discovering necessary observables and assessing their mathematical and statistical behavior.

MS29:6 | Statistical surrogate models on small datasets for aeroacoustic computational modeling in liners of turbofan engines

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In modern turbofan engines, notably those with an Ultra High Bypass Ratio (UHBR), fan noise significantly contributes to overall noise levels, characterized by both broadband and tonal noise components. Acoustic liners, designed to mitigate these components, are crucial for effective noise absorption. To ensure their effectiveness, it is imperative to study these liners under various flight conditions. This paper addresses the attenuation of low-frequency tonal noise using adapted acoustic liners. The design of liners needed for targeting low frequencies must have particular geometries and cannot be based on standard geometry acoustic liners. This means that there is a need to optimize these liners on the basis of high-fidelity simulations. However, simulations can be computationally expensive and not always feasible. The challenge lies in developing a model that encompasses both known and unknown variability in operating conditions to ensure robustness against uncertainties. Generating an extensive database through exhaustive exploration of design parameters via high-fidelity simulations is not practical. Thus, a robust statistical metamodel is developed to model a parameterized aeroacoustic liner impedance as a function of frequency and main control parameters using a small dataset from computationally expensive aeroacoustic simulations, requiring the use of an adapted learning algorithm that is chosen as Probabilistic Learning on Manifolds (PLoM). Furthermore, a statistical Artificial Neural Network (ANN)-based metamodel is introduced as another representation, offering greater versatility. It includes a prior conditional probability model for the PCA- based statistical reduced representation of the frequency-sampled vector of log-resistance and reactance. This model imposes statistical constraints, presenting challenges for training the ANN-based model using classical optimization methods. An alternative approach involves constructing a second large dataset using conditional statistics estimated with learned realizations from PLoM.

MS31: Collagen structure and mechanics

MS31-1:1 | A visco-hypoelastic model to describe the rate-dependent tensile responses of individual collagen fibrils

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TU Wien, Austria

Collagen fibrils are the ultrastructural base of biological tissues and exhibit nonlinear rate-dependent tensile behaviour. In this study, we constitute a visco-hypoelastic model to describe the stress-rate-strain-rate responses in accord with the atomic force microscopy (AFM) uniaxial tensile tests on individual collagen fibrils. The model is decoupled into elastic and dissipative (viscous) components: the elastic component is governed by the rate-dependent neo-Hookean model; the dissipative component is postulated as a function of stress and strain rate. We adopt a two-step minimization process to determine the material parameters of the elastic and viscous responses separately. The predicted stress and stretch are computed with an explicit time-integration scheme to the visco-hypoelastic model. Based on the modelling results, we obtain the elastic properties of individual collagen fibrils with 120.9 MPa in shear modulus and approximately 753.2 MPa in tensile modulus under small deformation (2% strain). The dissipation decays quadratically with the increase of the stress level. This study presents a novel visco-hypoelastic model that successfully predicts the nonlinear rate-dependent tensile responses of individual collagen fibrils in both stress-stretch and stress-rate-strain-rate spaces. We additionally characterize the dissipative behaviour of collagen fibrils owing to viscosity and other rate-dependent effects. Additional experiments and data are needed to validate the potential of this model for large deformations.

MS31-1:2 | Collagen fibrillar pre-strain, ordering and internal stress gradients modulating small-scale biomechanics of cartilage and skin

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The collagen fibrillar network in cartilage, skin and bone is a crucial ultrastructural component of the extracellular matrix (ECM). As a principal stiff element in the ECM, collagen fibrils enables a range of tissue-specific biomechanical functions, including shear, multidirectional elasticity, and stiffness. These properties are believed to be achieved by a synergistic action of individual fibril mechanics, interaction with extrafibrillar matrix molecules and inbuilt spatial organisation, interconnection and gradients. However, the nature of these diverse fibrillar-level mechanisms are not fully clear. Here we show how microfocus synchrotron small-angle X-ray scattering combined with in situ mechanical loading can help elucidate these mechanisms across two different tissue types. First, in diarthrodial joints, co-deformation of Type-II collagen fibrils at the bone(hard)-cartilage(soft) interface is crucial to understanding the biomechanical initiation of degenerative changes like osteoarthritis. Using microcompression on cores from metacarpophalangeal bovine joints, we find that loading induces reductions in fibril pre-strain gradients, increases in angular dispersion, and strain variability in the articular collagen. Changes in osmotic stress both in the extrafibrillar and intrafibrillar space are proposed as primary mechanisms for this behavior. Further and notably, the fibril pre-strain reduces in the calcified cartilage, an unexpected result given the presence of a reinforcing mineral phase. Secondly, in cutaneous (skin) wound healing in a mouse model, early-stage collagen fibrils, in the low-stress wound site, exhibit microscale loci of lowered pre-strain and alignment, with clear spatial structure around the wound bed. As natural in vivo stresses return with healing, the inherent tensile pre-strain returns, coupled with increase in matrix mechanics. Our results show the need to understand fibrillar deformation mechanisms both at individual fibril-level and via mechanisms such as reorientation, molecular ordering, and lateral contraction to capture the full functional variability and adaptability of collagen fibrillar mechanics.

MS31-1:3 | Heterogeneous structure and dynamics of water in a hydrated collagen microfibril

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Fibrillar collagen may be viewed as a composite material made of protein, macromolecules (such as glycosaminoglycans and proteoglycans) and water. Yet, the properties of water and the fine interactions of water with the protein constituent of these nanocomposites have only received limited attention. Here, we propose to investigate in-depth water structure and dynamics confined within the microfibril crystal structure of collagen type I to establish its impact on the properties of collagen. We perform large-scale molecular dynamics simulations of a microfibril of collagen [1] at varying degrees of hydration. We found that the properties of water vary strongly with the level of hydration of the microfibril, and spatially along the long axis of the crystal, namely moving from the so-called gap region to the so-called overlap region. In short, at low hydration, water acts as a glue between protein chains; while at high hydration, water acts as a lubricant. Beyond self-assembly and properties of fibrillar collagen, such het- erogeneous structure and anisotropic dynamics may control its biomineralization and the properties of biological tissues such as bone.

[1] Orgel, J.P.; Irving, T.C.; Miller, A.; Wess, T. J.; Proc. Nat. Acad. Sci. 2006, 103, 24.

MS31-1:4 | Identification and characterization of the MHC immunoglobulin receptor binding site in fibrillar type I collagen

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Collagen type I, the most abundant protein in the animal body, is a critical structural component of tissues like tendons, bones, skin, and lungs. It plays a vital role in maintaining tissue integrity. However, excessive collagen production, often triggered by inflammation, can be detrimental. This overproduction, observed in lung fibrosis, may be linked to autoimmune conditions and long-COVID complications.

Our recent research, utilizing X-ray diffraction (XRD) and Atomic Force Microscopy (AFM), investigated the interaction between antibodies and the structure of collagen and the surrounding extracellular matrix. This exploration led to the discovery of a key immunoreceptor domain within collagen type I. We believe this domain also functions as the major histocompatibility complex (MHC) recognition region. The MHC plays a crucial role in the immune system's ability to differentiate between healthy self-tissues and foreign invaders like bacteria, viruses, and cancer cells. Notably, this immune recognition sequence resides on the most exposed and accessible part of the type I collagen molecule.

MS31-2:1 | Investigating stretched collagen fibrils using polarization-resolved second harmonic generation microscopy

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Understanding the effects of mechanical stretching on all levels of collagen structure is of high importance in understanding the mechanical properties and biological function of collagen. Previously atomic force microscopy (AFM) measurements have been used extensively for investigating the effect of mechanical stretching on individual collagen fibrils. These measurements reveal several important details such as lengthening of the D-Band and stiffening of the fibril due to extension, however AFM provides little detail regarding the effect of stretching on the structure of collagen molecules within the fibril. Here we utilize polarization resolved second harmonic generation microscopy (PSHG) in conjunction with AFM measurements to investigate the effects of stretching on collagen molecular structure. PSHG is an optical microscopy technique with high sensitivity to the molecular structure of helical proteins and can be used to determine the average pitch angle of the collagen triple helix. We demonstrate that there is a continuous unwinding of the collagen triple helix with increasing strain, and that the molecular extension is on the order of double the D-band extension. We additionally show significant changes in collagen molecular density as a result of stretching with density peaking at ~3% D-band strain and then dropping off linearly. A comparison of results obtained for fibrils isolated from functionally distinct tendons will also be presented.

MS31-2:2 | Mechanical behavior of individual collagen fibrils in force-controlled mechanical tests

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Collagens are important structural proteins in the human body playing a key role in specifying mechanical properties of many tissues including tendons, bones and airways. There, collage is mostly found in the form of fibrils with typical diameters around 100 nm and lengths up to several mm. In addition to macro mechanical competence of tissues, collagen fibrils are important for the extracellular matrix (ECM) acting as cell attachment and mechanotransduction. Collagen fibrils exhibit time-dependent material properties and are thought to behave viscoelastic in physiological loading regimes. While experimental techniques for biomechanical characterization of tissues at the macroscale are more or less well established, experiments and data on individual collagen fibrils is scarce. We present experimental data from force-controlled experiments on individual fibrils using dynamic mechanical analysis (nano-DMA) as well as creep tests. Nano-DMA on collagen fibrils from 14 week old wild type mouse tail-tendon in the phase I mechanical regime show loss tangents of up to 0.2 and storage moduli of up to 5 GPa (at 2 µN average force). In addition, loss tangents decreased from the lower (0.1 Hz) to the higher (1 Hz(frequency applied. Creep tests were conducted on similar samples, with half of them cross-linked by incubation with methylglyoxal (MGO). Creep test data from cross-linked and native fibrils were fitted a Burgers material model in Kelvin-Voigt configuration (strain response of fibrils under constant force). Both creep rate of collagen fibrils and residual strain after unloading was reduced by MGO cross-linking. In addition, cross-linked fibrils showed an almost 2-fold increase in tensile modulus. In contrast, cross-linking did not affect transient viscoelastic behavior of collagen fibrils tested. The observed behavior can be explained by cross-linking influencing deformation mechanisms (straightening, uncoiling, sliding) already well below 10% applied strain.

MS31-2:3 | Towards a real-time imaging of the assembly and disassembly of collagen nanofibers

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Collagen type I is the most abundant protein in mammals. It is constituted by molecules known as tropocollagens. Tropocollagen molecules are the building blocks to form collagen nanoribbons and microfibrils. Those structures have a periodic structure known as the D-band [1]. This contribution aims to image in real-time the aggregation of single tropocollagens into collagen microfibrils [2]. High-speed AFM (HS-AFM) was applied to imaging the collagen self-assembly with a spatial resolution of 10 nm and time resolution of 0.3 s. The formation of the microfibril is driven by electrostatic forces between charged aminoacid residues therefore a change in pH leads to the binding and unbinding of the microfibril [3]. By tuning the pH of the buffer solution, it was possible to image either the self-assembly of tropocollagens (pH > 7) or the disassembly of the collagen nanoribbons and microfibrils (pH < 7).

MS31-2:4 | Linking the electrostatic and mechanical properties of collagen

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Single collagen fibrils were stretched along their entire length by depositing them on a highly stretchable foil of polydimethylsiloxane (PDMS). Kelvin-probe Force Microscopy (KPFM) was then performed on strained fibrils to probe their electromechanical response. Native fibrils and fibrils exposed to glutaraldehyde, which is a typical protein cross-linking agent for cell cultures, were compared. The results show that their surface potential increases towards more positive values for up to 10% strain and then decreases again at even higher strains. We interpret this phenomenon as breaking of cross-links, which exposes positive charges at the surface of collagen fibrils. This trend correlates with the stiffness of collagen fibrils, where fibrils strain-stiffen for strains up to roughly 15%, and then strain-soften for greater strains. The change in charge described here could affect the interaction of collagen with cell-adhesion proteins and the calcification of fibrils, thereby ultimately affecting collagen-cell interactions and cell behaviour. Using the same experimental approach, individual collagen fibrils were deposited on a pre-strained PDMS foil. By releasing the PDMS foil from its initial strain, the attached collagen fibrils spontaneously buckled. AFM imaging was then used to determine the shapes of individual, buckled fibrils. The data obtained allows calculation of the fibrils' tensile moduli using the well-known column-buckling theory from mechanical engineering without the need for force measurements. Comparison of our calculated moduli with data obtained by AFM nanoindentation and more sophisticated techniques show that our results are in good agreement. The great advantage of our approach, however, is that it is much easier to use and can be implemented by any lab to quickly determine the mechanical properties of a large number of fibrils without requiring specially built instrumentation.

RS01: Various topics

RS01:1 | Analysis of the behavior of the structure under internal ANFO explosion

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Although extensive explosion related researches were performed in past several decades, almost no researches have focused on internal blast. However, research on the internal blast is needed to understand about the behavior of a containment structure or building under internal blast loading, as in the case of the Chernobyl and Fukushima nuclear accident. Therefore, the internal blast study concentrated on reinforced concrete (RC) structures is performed. The test data obtained from RC tubular structure applied with an internal explosion using ammonium nitrate/fuel oil (ANFO) charge are used to assess the deformation resistance and ultimate failure load based on the structural stiffness change under various charge weight. For the internal blast charge weight, ANFO explosive charge weights of 15.88, 20.41, 22.68 and 24.95 kg were selected for the RC tubular structures, which were detonated at the center of cross section at the mid-span with a standoff distance of 1,000mm to the inner wall surface. Then, the test data were used to predict the internal charge weight required to fail a real scale reinforced concrete containment vessels (RCCV), which were reported in Choi.S (2022). In addition, an analysis model based on LS-Dyna was developed to verify the experiments of the scaled down model of the containment building. An ANFO explosive charge weight of 15.88 kg was selected for the analysis, as reflected pressure data was only available for this experiment. Recently, a study on the selection of TNT equivalence factor for ANFO explosives was conducted experimentally. Therefore, internal explosion analyses were performed with equivalence factors of 0.52, 0.62, 0.72, 0.82, and 0.92. By comparing experimental and analytical results, TNT equivalence factor for ANFO explosives is presented. The results of the study are discussed in detail in the paper.

RS01:2 | Bay Bridge

J. S Plachta

ASCE, United States of America

San Francisco Bay Bridge has been has recognized by ASCE as the 7th Engineering Wonder of the World. There was a great need for a bridge to connect the densely populated areas of San Francisco and Oakland. Because of soil conditions in the bay area, the great depth of water and the distance, this was a very difficult and complicated task.

This is a two-level bridge with initially six lanes of vehicular traffic and the lower level for the tracks of the interurban electrical trains. The most difficult parts of the construction were the foundations for the western part of the bridge. The large cellular reinforced concrete caissons were the largest ever built. At one of the piers bedrock was at a depth of 220 feet.

The Loma Prieta earthquake of October 17, 1989, with a magnitude of 7.1, caused a collapse of a short span at the eastern bay crossing. The governor of California, concerned for similar damage in case of future seismic shaking, called a special commission to investigate the damage and provide recommendations. After several years of discussions, it was decided on a total replacement of the eastern bay crossing.

New span has been designed in such a way as to be immediately available after a large seismic event. The single steel tower consists of four pentagonal-shaped shafts that are interlinked with shear links

September 2, 2013 there was an opening ceremony of the rebuilt east span. This was a very small ceremony open only to local politicians, a huge difference from the 1936 ceremony that lasted four days and was witnessed by hundreds of thousands of people. This project became the nation's great engineering embarrassments and one of its most infamous infrastructure case histories.

RS01:3 | Numbers, structure and insight

K. W. Breitung

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In structural reliability a fundamental problem is failure probability estimation. But what is the goal here? To find probabilities/numbers or obtain some understanding what causes failure? Methods of failure probability estimations should give insight in the failure mechanisms, however many focus on numbers only. In the standard normal space it can be shown using the divergence theorem that the failure probability is determined by the shape of the limit state surface. So all information obtained by observing the limit state function inside the safe domain is more or less irrelevant. By studying the limit state surface one can get additional information about the sensitivity of the failure probability. There are several popular methods which seem not to use the limit state surface: subset simulation, polynomial chaose expansion, important direction and Bayesian learning. However in reality all these concepts are related to the structure of the limit state surface. In this presentation these relations will be studied. It will be shown that asymptotically all algorithms end up in the neighborhood of the design points. So from this follows the question: is it more efficient to start from the origin calculating iteratively integrals or to make approximations starting from the design points using line sampling or thermodynamic integration instead of simple FORM/SORM?

PS01: Poster Session

PS01:1 | Integrated evaluation of blast loads on reinforced concrete structures: a strength and ductility approaches

Y. Kim, S. Kim, J. Shin

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This study delves into the effects of blast loads on reinforced concrete columns, utilizing both Ductility-based and Residual Strength-based Evaluation Methods to assess their impact. The investigation specifically focuses on how the ratios of longitudinal and transverse reinforcement, as well as axial load ratios, influence the structural blast resistance. It was found that increased longitudinal reinforcement markedly enhances blast resistance, effectively reducing both displacement and strength damage. Similarly, a higher ratio of transverse reinforcement significantly boosts the lateral resistance of the columns. Conversely, elevated axial load ratios were observed to heighten displacement-based damage, attributable to the P-Δ effect, thus complicating the structural response to blast impacts. A comparative analysis between the two evaluation methods reveals a low consistency in their results, suggesting discrepancies that could impact the reliability of structural assessments under blast conditions. This inconsistency highlights the necessity for an integrated evaluation approach that combines both ductility and strength aspects to provide a more reliable and comprehensive assessment of blast resistance. Such an approach is essential for advancing current methodologies and ensuring the safety and integrity of structures subjected to explosive loads.

Acknowledgments: This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (RS-2024-00348713).

PS01:2 | Machine-learning based optimum retrofit scheme for reinforced concrete frame structures: a case study on 1980s school buildings

S. Kim, Y. Kim, J. Shin

Gyeongsang National University, Korea, Republic of (South Korea)

Numerous educational facilities remain at risk from seismic activity, having been erected prior to the institution of obligatory seismic design regulations. The focal point of this paper is the deployment of machine learning techniques to establish a swift and efficient reinforcement planning algorithm. This algorithm leverages minimalistic data inputs to ascertain the optimal fortification approach for school buildings from the 1980s that do not meet contemporary ductile design standards. By integrating a decision tree (DT) model, this investigation provides a conservative yet precise prediction of potential failure modes in concrete columns. The study further refines a strategy for determining optimal reinforcement tactics, taking into account the ductility enhancement through confinement ratio (CR) and the increase of stiffness via stiffness ratio (SR). The assessment of column failure types in relation to variations in CR and SR facilitates the formulation of a comprehensive retrofit plan for schools with masonry infill walls, delineating the upper limits of applicable SR and the permissible increment range based on CR thresholds. Compared to conventional analytical methods, the proposed retrofit planning technique significantly expedites the retrofit process, ensuring safer educational environments in seismically active zones. This work contributes to the field by providing a novel framework for seismic retrofitting that can be applied to vulnerable structures, as part of broader efforts to enhance seismic resilience in legacy building stock.

PS01:3 | Neural network-driven representation and computational particle mechanics via signed distance fields

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We introduce a novel approach, the Neural Network-Encoded Signed Distance Field (NetSDF), for the representation of shapes and computational particle mechanics in granular materials. Our method utilizes a neural network to learn and depict a Signed Distance Field (SDF), which defines a mapping from a point to a signed distance. Specifically, the neural network takes point coordinates and a latent code representing a single shape as inputs, generating the signed distance from the point to the particle surface. The sign distinguishes between the interior and exterior of a particle, making the zeroth isosurface of the SDF an accurate representation of the particle surface. Upon training the NetSDF with a designated set of particle samples, it can effectively represent an entire class of particles exhibiting the characteristic morphology of the granular material. Our results demonstrate the NetSDF's proficiency in accurately representing irregular-shaped particles and generating virtual particles within the same class. Moreover, the NetSDF seamlessly integrates with the SDF-based discrete element method (Lai et al., 2022, Computational Mechanics), showcasing notable advantages in terms of memory consumption and computational efficiency.

Lai, Z., Zhao, S., Zhao, J., & Huang, L. (2022). Signed distance field framework for unified DEM modeling of granular media with arbitrary particle shapes. Computational Mechanics, 70(4), 763-783.

PS01:4 | Shape-based vision system optimized for seismic damage detections of nonstructural components in buildings

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Seismic damages of nonstructural components such as partition walls and ceilings installed in buildings can be monitored to increase occupant safety and to perform immediate repairs. Since damaged locations of the nonstructural components are difficult to predict compared to structural components, traditional vision-based displacement sensors (VDSs) with markers limited to single-point measurement are not suitable for detecting the seismic damages. This study aimed to develop a shaped-based VDS measuring multi-points displacement optimized for seismic damage detections of the nonstructural components. Using shape information (i.e., convex hull) of the nonstructural components in region of interests to extract and track multiple feature points at user-desired locations, the seismic damage of the nonstructural components can be detected and monitored with a single camera. From the shake table test on a two-story moment frame installed with partition walls and ceiling, the applicability of the proposed vision system is investigated and discussed. The result demonstrates that the proposed vision system can detect the damage location of the nonstructural components without any additional equipment.

PS01:5 | Theoretical study on soil deformation induced by shield tunneling through soil-rock composite strata

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In the construction of shield tunnels traversing upper soft and lower hard soil-rock composite strata, surface subsidence is a common occurrence, which may lead to safety hazards. In this special strata, the influence mechanism of shield tunneling on soil deformation will be different from that in soft soil strata. This study investigates the displacement patterns of soil resulting from shield tunneling in such complex strata by analyzing the convergence behavior of the shield excavation face. The research accounts for the variations in the slopes of the tunnel and the rock-soil interface along the excavation direction. A formula to compute the tangent of the principal influence angle (tanβ) at varying depths within layered strata was developed. Utilizing the principles of the stochastic medium theory, expressions for soil displacement at different stratum depths were derived. Surface subsidence was computed and evaluated using three engineering case studies. The findings suggest that the surface subsidence curves generated by this computational approach closely align with the measured data, thereby providing a reliable method for predicting soil displacement in practical engineering contexts. When tunneling through composite strata, the tunnel linings are prone to an upward floating motion, leading to a convergence pattern in the cross-section that tends toward a non-uniform radial movement, with the top section being tangential. Within the same project context, the grouting filling rate (δ) diminishes as the hard rock ratio (B) increases, exhibiting an approximate linear correlation. The hard rock ratio significantly influences the extent of lateral and longitudinal surface subsidence. An increase in the hard rock ratio results in reduced values for lateral and longitudinal subsidence, the width of the lateral subsidence trough, and the main impact zone of the shield tunneling operations.

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MAPS

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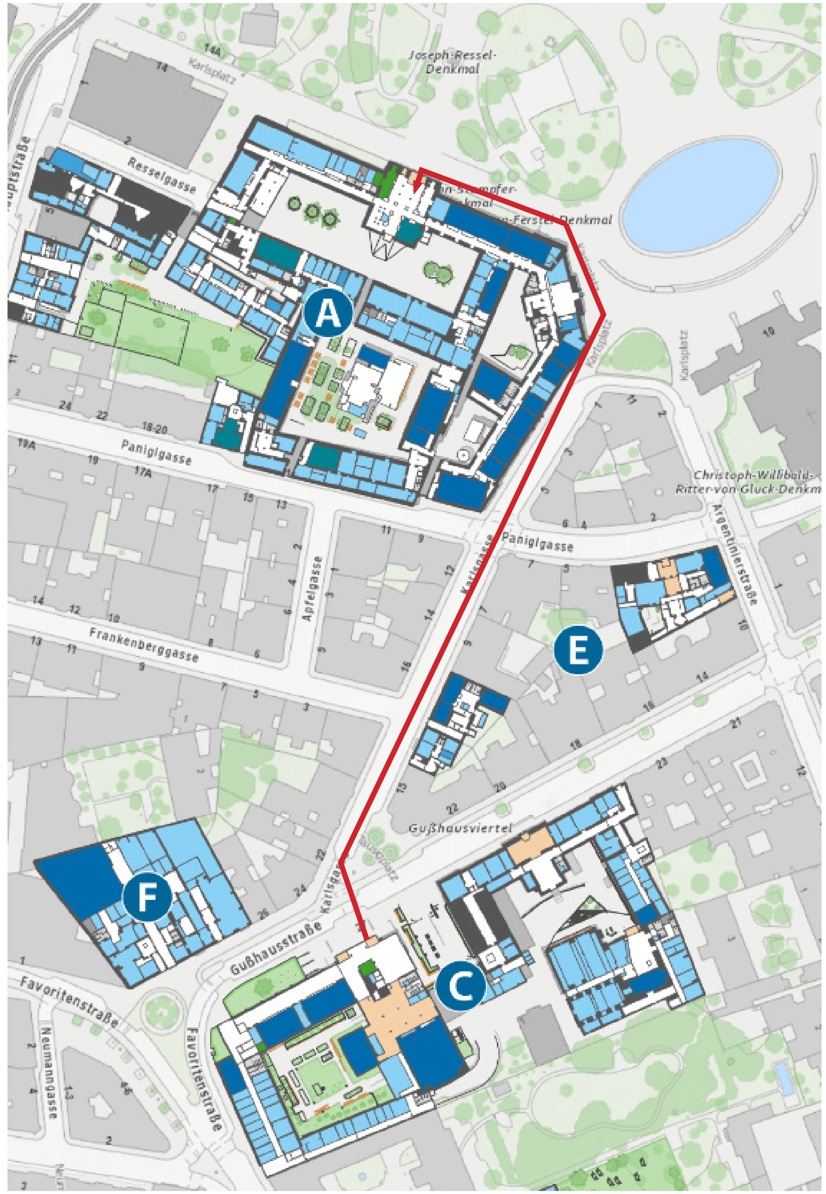

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