Centre International des Sciences Mécaniques
International Centre for Mechanical Sciences

Rectors:
E. Guazzelli (Marseille) - A. Soldati (Vienna) - W. A. Wall (Munich)

PROGRAMME 2024

" ...The purpose of the Centre is to promote, on a non-profit basis, research in the Mechanical Sciences and related multidisciplinary sciences, favour the exchange, diffusion, and application of the most advanced knowledge in this field, establish active relations with similar national, or international institutions, enlist the cooperation of the most qualified scientists and researchers throughout the world, set up research laboratories and libraries, organize courses and seminars of a high scientific level ..."

from the Statute of the "International Centre for Mechanical Sciences".
CISM, Chap. I, Art. 1.

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PROGRAMME 2024

Udine, Italy

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The Paul H. Steen Session

Drops, Jets and Films

May 6 - 10, 2024

Drops, Jets and Films - their generation, stability, mutual interaction, interaction with their surroundings, as well as their associated transport phenomena with the ambient play a vital role in all aspects of our lives, countless industrial processes and indeed, constitute the natural lifeline not only of humans, but also of all living matter. Research abounds in all of the above-mentioned aspects and the aim of the proposed course is to fill this educational gap specifically for researchers in this domain; hence, the course addresses researchers at the graduate and post-graduate level. Typically, these researchers are coming from the disciplines of engineering, physics, mechanics, mathematics or chemistry, but it is not unlikely that also other natural sciences may be relevant, e.g., biology, medicine, and even forensics.

Research on drops, jets and films has a rich theoretical history, a somewhat younger experimental history and in recent times an indispensable anchor in numerical simulations, with its multitude of computational approaches. The lecturers of the proposed course have been selected to mirror this diverse set of methodologies. A further aim of the course is therefore to demonstrate the strengths and limitations of each method and to underline their complementarity. The course is particularly timely for a multitude of reasons, perhaps the most important being urgency. The COVID pandemic is just one example of how the interaction of aerosols with their environment reaches into all aspects of life, up to the societal-political level. However, of equal if not stronger importance is the enormous economic impact that drops, jets and films have on our industrial world or on health issues, be it combustion, capillary flows, evaporation, coating, painting, liquid deposition, etc.

A further motivating factor for now addressing this topic is the growing maturity and capabilities in all approaches – theoretical, numerical and experimental, as well as the inter-disciplinarity of the subject which encompasses fluid mechanics with free surfaces, electrohydrodynamics, non-Newtonian fluid mechanics and heat and mass transfer, to mention a few topics relevant in the present course. A brief consideration of computing power, refinement of numerical schemes or the speed and resolution of imaging and illumination technologies make this self-evident. We are now offered a direct glimpse into the physics of these phenomena, which heretofore was unattainable. Why is this so important? This allows us to formulate and validate highly refined physical models of the hydrodynamic and thermodynamic processes involved, which are essential for improving predictive capabilities, as well as for development of ‘reduced’ highly powerful analytical models.

The proposed course attempts to address the above issues at various levels comprising historical retrospection, theoretical foundations, experimental and numerical methodologies, but also demonstrating advantages and disadvantages of different approaches through example research problems and solutions. These examples offered by the lecturers are to be complemented by discussion of individual challenges from participants, ideally in the form of poster presentations. An indication of the topical content is already given by the selected keywords: liquid interfaces, interfacial flow, hydrodynamic instabilities, drop impact, atomization. A more detailed description can be extracted from the list of individual lecture titles.

Invited Lecturers:
Daniel Bonn (Amsterdam, NL), Christophe Josserand (Palaiseau, FR), Detlef Lohse (Enschede, NL), Cameron Tropea (Darmstadt, DE), Alexander Yarin (Chicago, USA), Stéphane Zaleski (Paris, FR).

Coordinators: C. Tropea, A. Yarin.

Experimental Substructuring and Transfer Path Analysis for Structural Assemblies

May 13 - 17, 2024

Dividing a complex problem in smaller sub-problems is a typical approach in modern engineering. In numerical substructuring, commonly used to perform model order reduction, components of a large structural model are analyzed separately, reduced according to their fundamental dynamics, then re-assembled.
The same approach can be very useful in experimental dynamics, where components are measured separately, and their experimental model assembled for simulation with experimental (or numerical) models of other components. Such substructure-based experimental (or hybrid) strategies can enable efficient modeling in cases where components can hardly be modelled numerically. Unfortunately, rather simple in theory, using experimentally characterized components is highly challenging because measured dynamics always include errors that in most practical cases make the assembled model useless.
Already in the 70's, first attempts to use substructuring for experimentally measured parts were realized, but with little success. Later, the appearance of affordable and accurate sensors and acquisition systems made it possible to acquire precise transfer function of components at their interface. Over the last ten years, new formulations of the assembly process and advanced signal processing have made measurements suitable for building accurate component models. Also, the concept of blocked forces (known in acoustics for several decades) has recently been properly adapted to structural dynamics and enables a consistent characterization of excitation sources. Proper identification and coupling of substructure dynamics and transfer paths are also essential aspects for hardware-in-the-loop applications. In the field of earthquake engineering, a real-time co-simulation of an experimental and a numerical part is known as "Real-Time Hybrid Substructuring".
In a course of 2018, different aspects of substructuring, both as numerical and as experimental technique, were presented in a graduate course at CISM. In this new course, we will concentrate on experimental substructuring and transfer path analysis, starting from basics and explaining recent advances such as uncertainty quantification, extensions for joint identification (including non-linear joints), specific approaches for high frequency problems (Impulse-based Substructuring) or treatment of complex interfaces

in challenging industrial applications. The course will also discuss industrial applications and some software for experimental substructuring.
The course is intended for graduate students either working in the field of experimental dynamics or interested by the field for their future research. The content is also very appealing for engineers in industry who are involved in challenging NVH problems where substructuring-based TPA can help in efficient analysis and troubleshooting. Since the course will start with the basics of substructuring and summarize important experimental techniques, it can be followed with a good general pre-knowledge in structural dynamics, but no specific expertise in substructuring is required.
The course will include the following parts: 1. Introduction, 2. Experimental identification of substructures, 3. Frequency-based Substructuring (FBS), 4. Modal-based Substructuring, 5. Transfer Path Analysis (TPA), 6. Dealing with real data and uncertainties, 7. Non-linear substructuring, 8. Special methods and outlook. It includes academic and industrial examples and computer (industrial code and an open-source code.

Invited Lecturers:
Matt Allen (Provo, USA), Gregor Čepon (Ljubljana, SLO), Joshua W R Meggitt (Salford, UK), Nevzat Özgüven (Ankara, TK), Daniel Rixen (Munich, DE), Maarten van der Seijs (Delft, NL).
Coordinators: D. Rixen, G. Čepon.

Localization and Ductile Failure:
Experimental, Theoretical and Computational Aspects

May 20 - 24, 2024

Ductile fracture is the most common failure mode in metal alloys. Ductile damage in a metal usually starts at an existing flaw, such as a brittle inclusion within a grain, a precipitate at a grain boundary, or a void. Large plastic deformations lead to the progress of this damage under various stress states and through various physical mechanisms. The objective of the course is to present a complete view and the state-of-the-art of the field. Experimental observations, theoretical modeling, and computational aspects will be considered. We will elucidate the following topics:
1. Phenomenological aspects. The main experimental observations under quasi-static and dynamic loadings on structural metals will be given for different stress states, highlighting the underlying physical mechanisms of ductile fracture. The roles played by the stress state will be highlighted.
2. Approaches to ductile damage. Finite strain plasticity, continuum damage mechanics, and porous plasticity will be presented. To get a deeper insight in the ductile failure process, the course also presents micromechanics-based approaches such as unit cell calculations.
3. Localization phenomena in the ductile failure process. Micro-mechanics will be used to describe the two modes of plastic flow localization that commonly occur in the ductile fracture of structural metals, namely macroscopic localization, and void coalescence. Macroscopic localization is typically associated with the softening effect of void nucleation

and growth, in either a normal band or a shear band whose thickness is comparable to the void spacing. Bifurcation and imperfection approaches to strain localization will be described. In the process of void coalescence, which can occur either simultaneously or after macroscopic localization, plastic strain localizes to the ligaments between voids. Experiments have repeatedly reported three distinct types of void coalescence: (i) internal necking, (ii) shear coalescence, and (iii) necklace coalescence.
4. Issues of ill-posedness and length scale aspects in ductile failure. Here, we will explain the theoretical background for the numerical problems usually observed in the simulations and link them to the lack of length scale in the usual local description of the plastic and damage behaviors. This gives some basis for improved modeling of these behaviors including the microstructure of the material.
5. Computational aspects. From the computational point of view, the course will provide the necessary background for the attendees to study and simulate ductile failure with non-linear finite element analyses. The finite element (FE) solver ABAQUS will be used as the main tool both with the explicit and implicit solution methods.
6. Modeling of crack propagation. Finally, all the tools developed above are gathered in the prediction of crack propagation in ductile materials. Crack propagation in ductile metals is truly multiscale, with dislocation activity affecting the micro-mechanics of voids that, in turn, influences the tearing fracture process at the engineering scale.
With these lectures, we aim to attract doctoral students, researchers and engineers interested in ductile failure of structural metals.
The objective is to provide the audience with all the tools necessary to better understand the most recent developments on the subject and so facilitate the technology transfer from research to applications.

Invited Lecturers:
Ahmed Benallal (Gif Sur Yvette, FR), Jonas Faleskog (Stockholm, SE), Odd Sture Hopperstad (Trondheim, NO), David Morin (Trondheim, NO), José A. Rodríguez Martínez (Madrid, ES), Cihan Tekoglu (Ankara, TK).

Coordinators: A. Benallal, O. S. Hopperstad.

Physics of Musical Instruments Applied to Instrument Making

May 27 - 31, 2024

In the last forty years, the field of musical instrument physics has matured significantly, giving rise to a better understanding of the behaviour of the instruments. This has led to advanced manufacturing approaches, ranging from computer-aided design to quality control and process optimisation. Despite these advancements, many craftsmen still rely heavily on empirical methods, overlooking the full potential of research-driven approaches.
The objective of this course is to provide a comprehensive overview of the knowledge in musical instrument physics and its practical application in musical instrument making. The course will focus on three key aspects.

Firstly, the basics of the physics of musical instruments will be described. In other words, the role and properties of each component will be analysed, considering how they all work together. This will be highlighted by the transition from mechanics to sound, the essential characteristics of instruments, with illustrating concepts such as harmonicity, auto-oscillations, and the influence of materials, including composite / synthetic materials. Secondly, the tools developed by physicists and engineers over the past century to enhance instrument design and manufacturing will be reviewed. Topics covered include numerical aspects of instrument virtual synthesis, modelling interactions between interconnected subsystems, solving auto-oscillation processes, optimising instruments, and essential experimental techniques for instrumental characterisation (mechanical and acoustical).
All along the course, applications to real instruments will be given. These case studies will showcase the modelling and optimisation of instruments, historical instrument reconstruction, and the application of acoustic and mechanical measurement tools to control the manufacturing process at different stages.
The course is tailored for doctoral students and young researchers specialising in musical acoustics, as well as senior researchers, engineers in musical instrument manufacturing companies, and instrument makers with a scientific inclination.

Invited Lecturers:
José Antunes (Lisboa, PT), Vasileios Chatziioannou (Vienna, AT), Jean-Pierre Dalmont (Le Mans, FR), Michele Ducceschi (Bologna, IT), Christophe Vergez (Marseille, FR), Romain Viala (Le Mans, FR).

Coordinators: J. Antunes, J.-P. Dalmont.

Hysteresis in Functional Materials:
From Physical Models to Numerical Simulation

June 3 - 7, 2024

The hysteretic behavior of certain materials provides the basis for the design of many of today’s “smart” systems. Prominent examples are ferroelectric and ferromagnetic materials, which have been adopted as sensors and actuators in diverse fields of applications, ranging from microelectromechanical systems (MEMS) for high-precision positioning to vibrational and structural noise control as well as hearing aids. As these materials are taken to their limits by increasing incident fields, frequencies, decreasing size, reaction times as well as transition to large deformation applications, a detailed knowledge on the underlying physics is necessary to enable accurate multi-physics simulations.
The response of ferroelectric or ferromagnetic materials depends on their state of remanent polarization or magnetization and the presence of external electric or magnetic fields. In classical applications, the remanent polarization or magnetization state is assumed as uni-directional and constant. As the operational range of sensors and actuators is extended, this assumption is no longer valid, and an accurate understanding of the evolution of the material’s internal state is imperative. Hysteretic effects observed

in multiferroic materials are usually modelled by means of internal variables. The internal variables can be, e.g., remanent magnetization or polarization, internal strains or phase fractions, and can describe the microstructure at the macroscopic level of the material. The main aim is to provide a comprehensive course teaching the fundamentals of hysteretic material behaviour. The course's content includes the physics of ferroelectrics and ferromagnetics, phenomenological material models, thermodynamically consistent hysteresis models and their mathematical analysis, efficient numerical simulation schemes, and measurement set-ups for deriving the model parameters of real materials. The course will start with an overview of scalar and vector hysteresis models followed by a detailed discussion of variational inequalities as the principal mathematical tool in hysteresis modelling, hysteresis energy balance, and continuous data dependence. Classical elasto-plasticity serves as an exemplary use-case, where thermodynamic potentials and dissipation functions are defined and their relation to commonly used yield conditions and associated flow rules is shown. The concepts developed there provide the basis for modeling ferroelectric material behavior appearing in piezoelectric ceramics. Next, the transition from microscopic to macroscopic level will be discussed for ferromagnetic materials, addressing also the origin of domain structures, domain wall motion and the rotation of magnetization. At this point, the identification of the material parameters based on measurements will be explained. Hysteresis modeling in materials undergoing large deformations, such as polarizable or magnetizable electro-active polymers, will conclude the theoretical part of the course. For all the above applications, theoretical models are complemented by efficient finite element strategies. In a practical session at the end, participants are encouraged to experiment on the behaviour of different hysteresis models in simple computational setups, which will support the understanding of the theories presented throughout the week.
The course will also include two poster sessions, in which the participants are invited to introduce themselves and to present their current research topics.

Invited Lecturers:
Anouar Belahcen (Aalto, FI), Laurent Daniel (Paris, FR), Manfred Kaltenbacher (Graz, AT), Sven Klinkel (Aachen, DE), Pavel Krejčí (Prague, CZ), Astrid Pechstein (Linz, AT).

Coordinators: M. Kaltenbacher, A. Pechstein.

Fluid Mechanics of Buildings for Energy, Health, and Well-Being

June 10 - 14, 2024

This course will expose attendees to a holistic overview of environments within buildings and highlight some of the impacts of these environments. Building on robust scientific principles of fluid mechanics, thermodynamics, and the biochemistry of indoor air attendees will be led through considerations of the impacts on energy consumption, thermal comfort, indoor air exposures, disease transmission, and ultimately reflect on linkages to human health, well-being, and productivity. The summer school will comprise of five inter-connected lecture courses. An introduction to urban fluid mechanics will consider the dynamics of flows around buildings, including pollutant sources and dispersion. The thermal performance

of buildings and their energy usage will be considered with a focus on human comfort and performance. How we might ventilate our buildings effectively and using less energy will consider passive strategies and the resulting fluid dynamics. This will be linked to the pollutants we face indoors and our exposures thereto. Finally, solutions for assessing and mitigating the health, productivity, and well-being impacts of buildings will be presented.
Details of the topics covered within the summer school include atmospheric boundary layers and the stability thereof. Introduction to airflows into, and around, urban environments, alongside the impacts of a changing climate and urban heat islands, and mitigation measures will be discussed. Urban pollution sources, and dispersion models, will be introduced. Moving indoors, heat transfer within buildings and the thermo-physiology of humans will be presented in the context of thermal comfort. Links between the indoor environment quality and performance will be evidenced, alongside discussion of measurement methodologies. Heat, moisture, and pollutant balances will be developed to model indoor conditions and inform mitigations, including ventilation and air cleaning. The importance of psychometrics and radiant heat transfer in buildings will be established. The forcing of ventilation flows by natural means will be discussed, and studies of single rooms will be linked to building network flow analysis. The importance of flows with room for the human experience will be emphasised and linked to the role of pointwise monitoring of conditions within rooms. Selected low-energy ventilation and heating/cooling strategies, and associated technologies, will be described. Indoor air pollution, and its implications, will be discussed including both particulate and gaseous pollutants and the transmission of infectious disease. The learning from large-scale studies of indoor air quality will be highlighted. The evidence for health impacts of indoor environments will be introduced, and evidence for infection transmission discussed. Exposure risk models will be presented alongside the practicalities of their deployment. Current topics, and future issues associated with indoor air quality and human exposure will be presented and discussed.

Invited Lecturers:
Bert Blocken (Leuven, BE), Henry Burridge (London, UK), Corinne Mandin (Fontenay-aux-Roses, FR), Cath Noakes (Leeds, UK), Jørn Toftum (Lyngby, DK).

Coordinator: H. Burridge.

Microphysics of Atmospheric Clouds

June 17 - 21, 2024

Clouds determine precipitation and constitute the main component of the hydrological cycle. They can be very beautiful, but also emphemeral in the eyes of people, artists, but also of scientists, thereby creating a fascinating enigma.
The scientific study of clouds began with Luke Howard’s classification in 1803. Throughout the 19th century, the boundary between the arts and sciences, particularly with regard to natural sciences, including meteorology, was much less rigid than it is today. For instance, the great German poet Goethe took particular interest in the scientific classification of clouds. The most original sea-and-sky scape painter of the 19th century, JWM Turner, annotated his copy of Goethe’s ‘Theory of Colors’, and referred to it directly in the title

of one of his paintings (Light and color (Goethe's theory) -The Morning After the Deluge-Moses writing the book of Genesis (The Tate Gallery, London)). And one the finest of all cloud painters, John Constable, was also well aware of the work of Luke Howard, and performed detailed cloud studies in the 1820s over Hampstead Heath.
It is now understood that, paradoxically, the global dynamics of the atmosphere and climate are very much dependent upon the microscale-level processes of clouds. In fact, in addition to convective heating due to the latent heat release associated with the condensation of water vapor, clouds control, to a large extent, the solar and thermal radiation balances of the atmosphere.
The present course mainly focuses on a few of the fundamental aspects concerning clouds:
- Latent heat release, which leads to convective or stratiform heating/cooling, that is, one of the main energy sources of atmospheric motions at spatial scales, ranging from local turbulence and single
clouds to global circulation.
- The condensation of water vapor and the subsequent precipitation within clouds through microphysical processes that take place at cloud particle size scales, ranging from several micrometers to a few centimeters.
- The effects of clouds on radiation caused by cloud coverage, the altitude of the cloud top, the size of the cloud particles, the size distributions, and the phase.
- The effects associated with atmospheric aerosols, which play a key role in determining the properties of clouds and give rise to the formation of water droplets and ice crystals.
- The development of improved observational techniques to study microphysical processes and bulk cloud properties and to measure the physical and optical properties of atmospheric aerosols.
- The interplay between the continuously increasing resolution of large-scale and mesoscale atmospheric models and the treatment of the intrinsic unsteady evolution of individual clouds.
The design of this PhD course in part stems from activities associated with the Marie Sklodowska Curie Action Innovative Training Network, COMPLETE, which was a Cloud-MicroPhysics-Turbulence-Telemetry shared inter-multidisciplinary research training environment for enhancing the understanding and modeling of atmospheric clouds. The network was financed under the Horizon 2020 Framework Program (2016-2021, GA 675675) and coordinated by Daniela Tordella, www.complete-h2020network.eu.

Invited Lecturers:
Annica Ekman (Stockholm, SE), Kalli Furtado (Exeter, UK), Wojciech W. Grabowski (Boulder, USA), Fabian Hoffmann (Munich, DE), Szymon Malinowski (Warsaw, PL), Annette Miltenberge (Mainz, DE), Annika Oertel (Karlsruhe, DE), Daniela Tordella (Torino, IT).

Coordinator: D. Tordella.

Bone Cell and Tissue Mechanics

June 17 - 21, 2024

Bone is a remarkable material: it is strong yet lightweight, can adapt itself to changes in mechanical loading, lasts for a lifetime and can repair itself after a fracture. However, these repair mechanisms can be inhibited by bone disease and aging. Although biology has revealed many secrets of how bone cells can form and remove bone tissue, the mechanisms that control these processes, and the role of mechanical loading in this, are still not well understood, and therefore there is more work to be done to optimise pharmaceuticals, physiotherapy, medical devices and surgical techniques to improve bone repair. The goal of this course is to provide state-of-the-art information on this topic. To do so, the course will review bone cell and tissue mechanics at all three commonly distinguished levels of structural organization: the bone organ, tissue and cell levels; including multidisciplinary topics such as bone biology, imaging and computational modeling.

At the bone organ level, the focus will be on the diagnosis of bone strength using imaging and computational techniques. Bone remodeling at this level is often considered as an optimization process that adapts bone density and shape to the mechanical loading conditions. Hypothetical models that are developed to describe such adaptations of bone will be discussed. At the tissue level, bone can form remarkable complex porous architectures. This capability enables bone to adapt to a wide range of mechanical conditions, reflected by a wide spectrum of architectures and material properties. Methods to visualize and model the complex structures of this living mineral tissue in 3D in-vivo have become available only over the last 25 years. Hypothetical models describing how these structures evolve, adapt to mechanical loading and can be affected by bone diseases will be discussed.

At the level of the cell, promising candidates for the mechanosensory system will be discussed, as well as possible signaling pathways for the communication between bone cells. At this level, the microporosity of the bone tissue becomes an important factor as fluid flow plays an important role in mechanosensation. Recently developed techniques for visualizing such small structures, stimulating and manipulating cells, such as microfluidics devices for bone cell mechanobiology, 3D printing of bone stimulating implants, and tissue engineering of bone to create humanized 3D models be discussed.

It is intended that the course will function as a forum for the exchange of data, philosophy, and ideas across disciplinary divides and so provide further stimulus for a comprehensive approach to the problems of bone mechanics. To further facilitate this, we will organize a student poster-pitch presentation at the end of the first day. There will be a question and answer session at the end of all other days to stimulate discussions. The target audience are graduate students, PhD candidates and early-career faculty members. We expect an audience as diverse in background as the lecturers, that is to say - spanning across the professional spectrum from biomedical and structural engineers, to biologists, veterinarians, and orthopaedic and dental surgeons.

Invited Lecturers:

Georg Duda (Berlin, DE), Peter Fratzl (Potsdam, DE), Jenneke Klein-Nulend (Amsterdam, NL), Ralph Müller (Zürich, CH), Gwendolen Reilly (Sheffield, UK), Marco Viceconti (Bologna, IT).

Coordinator: G. Reilly.

Multi-Field Problems Across Different Scales - Materials for the Development of Green Technologies

27th CISM-IUTAM International Summer School

June 24 - 28, 2024

Breakthroughs in materials science and engineering are needed to meet the demands of a sustainable society. Required for this are developments in materials technology for efficient energy applications, such as energy conversion (e.g., high-tech magnets), storage (e.g., batteries, hydrogen tanks), and smart devices.

The functionality and mechanical stability of advanced materials for sustainable energy supply rely on the effective coupling of different physical fields, including electromagnetic, electro-mechanical, and chemo-mechanical interactions. However, many of the underlying mechanisms in this area have yet to be studied experimentally, and predictive theoretical and numerical models are currently being developed worldwide. Moreover, such mechanisms occur at different time and length scales, which poses another challenge to the data analysis and the design of advanced materials. Of course, sustainability also translates into the need to address the durability of structures and devices, accounting for the specific challenges derived from multi-field effects in materials, such as battery failure for electrolyte cracking or hydrogen embrittlement in steels.

This course delves into essential aspects of materials science and engineering, with a specific focus on modeling multi-field phenomena across various scales. Consequently, several challenges arise, including:

1. Mathematical modeling of single-phase and multi-phase materials for coupled problems.
2. Scale-bridging techniques, spanning from the nano- to the micro- to the macro-scale.
3. Data analysis and design strategies for multi-field materials customization.

Ariadne’s thread of this course will be the analysis of the energy transfer mechanisms across scales to promote an experimental and in silico material design for a sustainable “Energiewende”. To achieve this, the course will explore experimental, theoretical, and computational methodologies, offering a comprehensive and cross-disciplinary perspective in the field.

Key topics include:

1. Continuum thermodynamics of coupled responses, encompassing thermo-, electromagneto-, and chemo-mechanical aspects.
2. Numerical approaches for multi-field problems and machine learning technologies for data analysis.
3. Homogenization techniques for complex microstructures and multi-field phenomena.
4. Experimentally study of magnetism on atomic and macroscopic length scales
5. Understanding the molecular basis of coupled mechanisms, ab initio methods.

6. An exemplary case study on the workflow from experiments to macroscopic characterizations using ab initio methods for hysteresis design aspects of magneto-mechanical coupled materials in high-tech magnets applications.
7. Applications focusing on the coupled response of materials for the green economy, including the study of hydrogen embrittlement in steels, failure of solid electrolyte Li-ion batteries, and multi-responsiveness of functionalized hydrogels.

This course is intended for graduate students and postdoctoral fellows from academia and industry interested in an interdisciplinary perspective of constitutive modeling of multi-physics mechanisms at different scales. A background in engineering or materials science is recommended for participants.

Invited Lecturers:

Vikram Deshpande (Cambridge, UK), Michele Marino (Rome, IT), Jörg Schröder (Essen, DE), Laurent Stainier (Nantes, FR), Heiko Wende (Duisburg, DE), Hongbin Zhang (Darmstadt, DE).

Coordinators: J. Schröder, M. Marino.

Variational Fracture Mechanics and Phase-Field Models

9th CISM-ECCOMAS Summer School

July 1 - 5, 2024

The goal of this course is to provide to graduate students, young researchers and engineers a complete and multidisciplinary presentation of the variational phase-field approach to fracture.

This new paradigm for the theoretical and computational treatment of damage and fracture has emerged in the past two decades as a game changer for both theory and applications and has attracted large attention in the broad fracture mechanics community as well as from industry. The lecturers will present phase-field fracture modeling in the framework of the variational Griffith' theory of fracture mechanics and its variational regularization, of gradient damage models, as well as of phase-field modeling for phase transformations widely used in material science. Overviews of current research topics and open issues will be provided. Lectures on the theoretical and mathematical aspects will be complemented by hands-on tutorials introducing the participants to appropriate numerical methods.

The variational phase-field modeling of fracture can be seen as the regularization of the variational approach to fracture (Francfort and Marigo 1998). The lectures by Blaise Bourdin will introduce the basic concepts of the variational formulation of brittle fracture. Flaviana Iurlano will give a general introduction to the mathematical notions needed to establish the link between the sharp-crack model and its regularized counterpart (Gamma-convergence). The lectures, addressed to an audience of non-mathematicians, will also highlight the most important mathematical aspects in the larger context of free-discontinuity problems.

The variational phase-field model of fracture can also be constructed as a special class of

gradient damage models, thus establishing the link with continuum damage mechanics. The lectures of Laura De Lorenzis and Corrado Maurini will be devoted to the variational derivation of the set of equations which govern the quasi-static evolution of damage in a body, their stability, and the discussion of the related crack nucleation criteria. Reference analytical solutions and extensions to elastoplastic couplings will be presented.
Phase-field modeling as a general framework entails the regularization of problems involving moving interfaces and is a very active area in the larger context of computational material science, fluid mechanics and topology optimization. The lectures by Peter Vorhees will provide a broad overview of the phase-field method, starting from its thermodynamics, and will highlight different classes of models involving conserved and unconserved phase-field variables.
A primary advantage of the phase-field framework lies in its flexibility and performance in numerical computations. Ensuring robust computations and obtaining accurate results is not trivial. Numerical aspects will be the focus of the lectures by Jack Hale. He will first introduce basic concepts of linear and non-linear solvers and parallel computing, then focus specifically on non-linear coupled phase-field computations involving incremental constrained minimization, and finally provide hands-on numerical examples using the FEniCS Project finite element framework.

Invited Lecturers:
Blaise Bourdin (Hamilton, CAN), Laura De Lorenzis (Zurich, CH), Jack S. Hale (Esch-sur-Alzette, LU), Flaviana Iurlano (Paris, FR), Corrado Maurini (Paris, FR), Peter W. Voorhees (Evanston, USA).

Coordinators: L. De Lorenzis, C. Maurini.

Mechanics of Active and Biological Structures: from Fundamentals to Recent Results

10th CISM-AIMETA Summer School

July 8 - 12, 2024

The aim of this course is to provide participants with a fast track to frontier research of great contemporary interest starting from the revisiting of foundational aspects of the Mechanics of Solids and Structures. The course primarily targets beginning graduate students and young researchers who want to get an accelerated introduction to recent progress in the analysis of the response and failure of advanced materials and active systems, including biological ones.
A. De Simone and P. Reis will lecture on the mechanics of slender structures (rods, plates and shells), both active and passive, and applications to adaptive structures and to soft and bioinspired robotics. L. De Lorenzis and K. Ravi-Chandar will lecture on Fracture Mechanics, from modern experimental and theoretical foundations to recent advances on phase-field modeling and computation, and applications to biological tissues and porous media.
A. Goriely and Ellen Kuhl will lecture on the mechanobiology of growth and morphogenesis, and applications to quantitative modeling of the human brain.

The detailed plan of the lectures is the following.
Mechanics of 2d rods from Euler's elastica to robotic arms and elephant trunks (ADS)
Kinematics and equilibrium of active planar rods in the large deformation regime; variational methods: the principle of virtual power and the finite element method.
Applications 1: shape control of structural systems with cables and tendons;
applications 2: shape control through active bending (snakes and elephant trunks);
applications 3: spontaneous oscillations in biological filaments and growing plant shoots.
Mechanics of 3d rods, plates and shells (PR)
Mechanics of rods – Kirchhoff's rod theory: Kinematics & Equilibrium. Examples and Applications; Plates I: Pure bending deformation. Wrinkling; Plates II: Föppl-von Kárman (nonlinear) theory of plates. Plate buckling; Shells I: Linear pressure vessels, A primer on differential geometry, Dimensional reduction (3D-2D). Linear shell theory; Shells II: Nonlinear DMV shell theory. Shell buckling; Magneto-active Rods, Plates, and Shells.
Fracture Mechanics (KRC)
Griffith theory of fracture – the global approach; Engineering fracture mechanics – the local approach; Experimental fracture mechanics; Mixed-mode fracture – crack path selection; Elastic plastic fracture; Dynamic fracture.
Variational phase-field modeling of fracture (LDL)
The variational approach to brittle fracture; the phase-field regularization: main modeling components; crack nucleation vs. propagation, energy decomposition; computational aspects; phase-field modeling of ductile fracture; applications to anisotropic tissues and porous media.
The mathematics and mechanics of biological growth (AG)
The problem of growth; Growing in 1D: rods and filaments; Growing in 2D: membranes, plates, and shells; Growing in 3D: nonlinear elasticity and theory; Growing in 3D: applications (plants, arteries, and the brain); From 3D to 1D: dimensional reduction with applications.
Integrating mechanics and computation to understand the human brain (EK)
Introduction to Neuromechanics; Elasticity of the brain - Characterizing brain stiffness dead and alive; Growth of the brain; Understanding neurodevelopment; Damage of the brain - Traumatic brain injury and neurodegeneration; Machine learning and the brain; Integrating neuroimaging and mechanics. - Automated model discovery - Learning models for human brain.

Invited Lecturers:
Laura De Lorenzis (Zurich, CH), Antonio De Simone (Pisa, IT), Alain Goriely (Oxford, UK), Ellen Kuhl (Stanford, USA), Krishnaswamy Ravi-Chandar (Austin, USA), Pedro Reis (Lausanne, CH).

Coordinators: A. De Simone, P. Reis.

Computational Modelling of the Heart: from Fundamentals to Clinical Applications
CISM-EUROMECH Summer School

July 8 - 12, 2024

Recent progress in the fields of computational modeling, data science, and artificial intelligence have shaken the landscape of cardiovascular research. In parallel, state-of-the-art medical imaging technologies now provide streams of patient data of unprecedented volume and detail. The convergence of these advances with the growth in processing power and communication infrastructure has made it possible to run patient-specific models of high fidelity or in large numbers, and empowered inter-disciplinary collaborations that are accelerating further developments of multi-scale, multi-physics models.

These synergies are driving a revolution in cardiovascular science by offering increasingly realistic digital twins to investigate disease mechanisms, facilitate medical device design and implantation planning, search for therapeutic targets, and improve diagnosis. However, the translation of computational advances to improve clinical decision support systems also faces significant challenges. It is necessary to be able to handle and manage vast amounts of data, coming from various sources and with different formats. Running patient-specific models with high fidelity requires significant computational resources. The development of multi-scale and multi-fidelity models requires significant integration efforts. Furthermore, the models need to represent the intricacies of the cardiovascular system by parameters that are often difficult to measure. Before clinical support systems can be implemented, rigorous validation against real-world clinical data is required. Other challenges are related to regulation, ethics or gaining the trust in the models of healthcare professionals, such as doctors and nurses, among others. Overcoming these challenges is essential to realize the full potential of current cardiovascular research and requires a new generation of scientists trained in all these aspects.

This course will review core competencies and novel developments in cardiac computational modeling. Particular attention will be given to multi-physics, multi-scale model development, digital twins and model-aided patient phenotyping, incorporating patient-specific data beyond vessel or chamber geometry, and simulation pipeline automation and integration into clinical decision support systems. The course curriculum will cover fundamental topics in cardiac biomechanics and state-of-the-art modeling techniques. It will also discuss machine learning and AI tools for image analysis and provide examples of computational models adopted into clinical decision support systems.

The course is aimed at graduate students of applied sciences and engineering interested in all aspects of cardiac bio-electro-mechanics, including imaging and computing. Researchers specializing in one field (e.g., electrophysiology) interested in branching out to other areas (e.g., fluid-structure interaction) are also welcome to attend this course. The course will feature poster sessions to spark cross-disciplinary communication among participants.

Invited Lecturers:
Christoph Augustin (Graz, AT), Javier Bermejo (Madrid, ES), Patrick M. Boyle (Seattle, USA), Juan Carlos del Álamo (Seattle, USA), Manuel Garcia-Villalba (Wien, AT), Maria J. Ledesma-Carbayo (Madrid, ES).

Coordinators: J. C. del Alamo, M. Garcia-Villalba.

Inverse Problems for Mechanical Systems: Methods, Simulations and Experiments

July 15 - 19, 2024

Inverse problems are encountered in several areas in applied science and technology. When one studies a physical phenomenon which is governed by the equations of mathematical physics, the application of the model to real life situations often requires the knowledge of constitutive and/or geometrical parameters which in practice may not be completely known or are inaccessible to direct measurements. Other applications involve the development of non-destructive methods for identifying damage or defects in mechanical systems or for the identification of unknown forcing terms. Generally speaking, one has to deal with a class of problems in which the roles of the unknowns and the data is reversed, at least in part, with respect to the direct problems.

The analysis of inverse problems has inherent mathematical interest since, when compared with the corresponding problems of the direct theory, they do not usually satisfy the Hadamard postulates of well-posedeness and are highly non-linear, even if the corresponding direct problem is linear. In most cases, in order to overcome these analytical obstacles, it is impossible to invoke all-purpose, ready-made, theoretical procedures. Instead, it is necessary to single out a suitable approach and trade-off with the intrinsic ill-posedeness by using original ideas and a deep use of mathematical methods from various areas. Another important aspect of the study of inverse problems concerns with their numerical treatment, and the need of figuring out ad-hoc strategies for the implementation of robust solving algorithms, considering the presence of noise, measurement errors and the probabilistic character required in some contexts. The above critical issues are further amplified when inverse methods are applied to the study of full-scale mechanical systems, as additional obstructions arise because of the complexity of mechanical modelling, the inadequacy of the analytical models used to describe the physical phenomena, and the incompleteness of the field data.

In this course we aim to provide a review of recent developments of inverse problems for mechanical systems. The topics will range from advanced techniques for damage detection and source identification in structures, dynamic methods for model updating and active vibration control, photo-acoustic imaging using resonating nanoparticles, the use of nanostructures as mass resonant sensors, probabilistic and deep learning-based methods, with attention to the computational and experimental aspects relevant for practical applications. With this lecture series, we mainly aim to attract doctoral students and researchers interested in working in inverse problems in the areas of civil and mechanic engineering, mathematical physics, and applied mathematics. The objective is to provide the audience with a solid theoretical framework, mathematical tools needed to tackle specific classes of inverse problems, computational tools, and experimental evidence to better understand the most recent advances on the subject including those involving probabilistic deep learning.

Invited Lecturers:

Sifeng Bi (Glasgow, UK), Alexandre Kawano (São Paulo, BR), Antonino Morassi (Udine, IT), John Mottershead (Liverpool, UK), Assad A. Oberai (Los Angeles, USA), Efim Shifrin (Moscow, RU), Mourad Sini (Linz, AT).

Coordinators: A. Kawano, A. Morassi.

Dense Particulate Flows: From Micromechanical to Macroscopic Modeling

July 22 - 26, 2024

Particles in dense suspensions give rise to a multifaceted change in flow behavior that are relevant in process and civil engineering but also play key roles in environmental processes. Prominent examples are the discontinuous shear thickening of corn starch, the destructive potential to move large boulders in debris flows, and the shear thinning of quicksand, to name just a few. Understanding the flow behavior of dense suspensions as a function of the material properties of the particles and the fluid is therefore of fundamental interest in engineering and physics.

The key challenge to understand these changes in flow behavior is to link the micromechanical interactions of the particles to the macroscopic flow behavior of the suspension. Depending on the situation and the analysis of the system, this results in an effective viscosity, which is larger than the clear fluid viscosity, often showing anisotropic behavior that is dictated by the shear rate. Such anisotropic behavior is also expressed in terms of a macroscopic friction coefficient and an effective volume fraction. As such, the rheology of a suspension plays a key role as a constitutive equation in larger scale models of engineering. The rheological behavior of a suspension is determined by a wide host of stress scales, e.g., short range lubrication and far-field viscous effects, contact and friction, particle inertia, cohesion and yield stress as well as a combination of all these stresses. Even though substantial progress has been made in recent years to understand the relevance of those different properties on the complex flow behavior of dense suspensions, a comprehensive rheological framework is still lacking, which limits the predictive capacity of the larger scale models.

Consequently, the Advanced School aims to provide an overview of the state-of-the-art research on the rheological behavior of dense suspensions from different perspective covering applications from process engineering, civil engineering and material science, as well as geophysical applications. The courses will provide a solid background in the theory of the rheology of dense suspensions and will give a broad overview of applications, for which subscale rheological processes are relevant. The lectures will cover examples from the laboratory, numerical simulations and field scale applications, where a focus will be given to imitating assumptions of the underlying modeling approach and potential to connect the different applications to a unifying framework.

Invited Lecturers:

Pascale Aussillous (Marseille, FR), Elisabeth Guazzelli (Paris, FR), Douglas Jerolmack (Philadelphia, USA), Wilson Poon (Edinburgh, UK), Franco Tapia (Dresden, DE), Martin Trulsson (Lund, SE), Bernhard Vowinckel (Dresden, DE).

Coordinators: P. Aussillous, B. Vowinckel.

The Gianpietro Del Piero Session

Contact Mechanics in Multibody Dynamics: From Modeling to Applications

September 2 - 6, 2024

The course will address the scientific topics that contribute to the mechanical and computational challenges to handle contact mechanics in the context of multibody dynamics. The reviewing of the classic theories in elastic and plastic contact, the computational algorithms for their efficient use in the framework of multibody dynamics applications, the tribology aspects characteristic of many of the mechanical systems of interest, the consequences of wear both in the response of the system and in the use of the background contact theories are just some of the aspects of relevance that justify a closer look. The application of the theories, methods and algorithms, and their inherent numerical issues, to road and railway vehicle dynamics, general mechanical systems, biomechanical and biomedical systems are just few of the areas in which the overview of the computational methods associated to contact mechanics are of major importance.
This course provides a comprehensive state-of-the-art overview of the fundamental aspects related to contact-impact events in multibody dynamics, for both rigid and flexible elements. The well-established formulations to deal with contact problems in dynamical systems and the ongoing research domains are presented and discussed with different cases of application. The course is organized around several complementary and interconnected lectures, delivered by well-known experts in each of the scientific areas addressed. A complete framework of the contact mechanics topics is provided, including constitutive laws, numerical issues, time integration, rolling contact, contact with flexible elements and with rigid elements, complementary contact formulations, penalty based contact formulations, finite element contact, application in vehicle dynamics, biomechanics, general mechanical systems, etc.
This framework requires a computationally efficient implementation of the contact detection with regards to the contacting surfaces using different search algorithms for various sizes of contact problems. The interaction between the system components is addressed alternatively via both non-smooth mechanics formulations, penalty formulations or augmented Lagrangian approaches. The particular issues associated with the contact detection between finite element meshes, used to model flexible multibody components, is also the focus of more specialized methodologies.
The characterization of the normal and friction forces is also focused in the description of the contact interaction. The temporal integration of the multibody systems in the presence of contact-impact becomes of particular relevance not only for the stability of the dynamic analysis process but also for its computational efficiency. The contact involving flexible multibody dynamics, in which the finite element method is used to describe the system components, or rigid bodies or a mixture of both, lead to more specialized methods when dealing with the interaction forces developed in the contact. Such issues are addressed and solutions proposed. In the process, not only constitutive laws for particular types of contact, such as rolling contact in the wheel-rail interface or for tire-road, are briefly addressed but also issues such a normal and friction force contact models are presented.

The course is designed to give an integrated theoretical, numerical and application perspective on most recent advances in contact dynamics, as well as potential future research directions in this scientific domain. With this purpose in mind, this course brings together lecturers with different background and schools of thought and for the purpose of presentation, discussion, refinement of a comprehensive work on different methodologies. The foreseen participants constitute a diverse, but consistent, group of researchers, specialists, advanced students, young faculty or post-doctoral researchers, dealing with the methodological and application aspects of contact mechanics and computational multibody dynamics.
During the second day, a workshop will be organized when the participants introduce themselves and their current interests in terms of research.

Invited Lecturers:
Jorge Ambrósio (Lisbon, PT), Bernard Brogliato (Grenoble, FR), Paulo Flores (Minho, PT), Josep Font-Llagunes (Catalunya, ES), Christian Hesch (Siegen, DE), Alessandro Tasora (Parma, IT).

Coordinators: P. Flores, C. Hesch.

Model Reduction and Machine Learning for Solids, Fluids and Controls
CISM-EUROMECH Summer School

September 9 - 13, 2024

The complexity of physical processes of interest to contemporary science and engineering continues to grow. As a result, one needs to describe these processes with high-dimensional governing equations, which sometimes are not fully known. For the analysis, prediction, design and control of such processes, there is a broad need for reduced-order models capturing the core of the underlying physical phenomena from equations or data. However, most of these phenomena are characteristically nonlinear, and hence there is no generally applicable mathematical procedure to separate their core behavior from the rest.
This proposed summer course brings together experts in model reduction to introduce participants to the current state of the art in equation-driven and/or data-driven nonlinear model reduction. The emphasis will be on applications of practical relevance, as opposed to simple toy examples. Students will gain insights into at least three major reduced-order modelling approaches: advanced projection-based methods, invariant manifold methods and neural-network based methods. The lectures will touch on both the theoretical basis and the numerical implementation of these approaches. The lecturers include Professors Balakumar Balachandran, Charbel Farhat, Michael Graham, George Haller, Shobhit Jain and Gianluigi Rozza.
Some of the introductory lectures will cover the notion of various low-dimensional invariant manifolds (such as inertial manifolds, attractors and spectral submanifolds) that provide a mathematical foundation for model reduction in high-dimensional nonlinear dynamical systems. A separate tutorial will be offered to the course participants on the use of available open-source codes that can be used to compute reduced-order models from

equations (SSMTool) and data (SSMLearn) for various problems in solid mechanics, fluid dynamics, and controls. Several lectures will cover contemporary, neural-network-based modelling techniques for applications in fluids, solids, and controls. As opposed to providing black-box-type approaches, this course will feature systematic uses of neural networks in the discovery and interpolation of low-dimensional invariant sets, such as inertial manifolds or chaotic attractors. Further lectures will be devoted to the use of neural networks in model-based prediction of critically important societal phenomena, such as the spread of infections in a pandemic or the emergence of highly destructive rogue waves in the ocean. Physics-informed neural networks and their applications to the reduced-order numerical solutions of continuum motion modelled by PDEs will be discussed. Additionally, certified reduced basis methods will be introduced to the students with applications to transport and continuum mechanics. Recent reduction methods aimed at very large systems, such as hyperreduction and moment-matching methods, will also be surveyed.

Invited Lecturers:
Balakumar Balachandran (College Park, USA), Charbel Farhat (Stanford, USA), Michael Graham (Madison, USA), George Haller (Zürich, CH), Shobhit Jain (Delft, NL), Gianluigi Rozza (Trieste, IT).

Coordinators: G. Haller, J. Shobhit.

Tensegrity Systems: From Biomechanics to Mechanical Metamaterials

September 16 - 20, 2024

Tensegrity structures are prestressable truss structures, obtained by connecting compressive members (bars or struts) through pre-stretched tensile elements (cables or strings). The interest in such structures has been motivated by nature: Tensegrity concepts are ubiquitous and can be found, in every cell, from the microstructure of spider silk to the arrangement of bones and tendons, to name but a few examples. This course is aimed at illustrating the peculiar mechanical behavior of tensegrity systems in the large displacement regime and their application for the development of mechanical metamaterials, space structures, and mechanical models of biological systems.
The course will cover the following thematic blocks:
1. Basic concepts and calculation methods of tensegrity systems: tensegrity principles (classification and case studies), linear theory (force density method, self-stress), stiffness and stability (geometric stiffness, the stress matrix, prestress stability and superstability), form-finding problems and methods, static response, bistable regimes, basic concepts of tensegrity dynamics, tensegrity space structures (case study of a tensegrity ring for a deployable mesh reflector).
2. Tensegrity metamaterials and tensegrity-based mechanical systems: tensegrity metamaterials (basic concepts and casuistry), bandgap response (dispersion relation of tensegrity mass-spring chains, role of prestress), wave dynamics of stiffening-type tensegrity metamaterials (propagation of solitary compression waves), softening-type tensegrity metamaterials (propagation of rarefaction solitary waves), origami

tensegrities (deployability, collapsibility and stiffness), seismic protection devices (displacement capacity, superelastic response, energy dissipation properties).
3. Tensegrity structures for space applications and 3D tensegrity metamaterials: post-buckling response of tensegrity planetary landers, 3D tensegrity metamaterials (unique properties in the post-buckling regime), reduced-order models for the dynamic and post-buckling behavior of tensegrity structures, computational implementation (modelling bars and cables, solution techniques for statics and dynamics), advanced Machine Learning (ML) methods for tensegrity.
4. Extremal mechanical properties of tensegrity metamaterials and structures: basic concepts of extremal mechanical properties of materials and structures, tensegrity meta-systems (discrete and continuum models), scale effects (identification of extremal mechanical properties of tensegrity systems in structural scales), 2D and 3D tensegrity modules and lattices with extremal properties.
5. Biotensegrities: overview of biotensegrities (tensegrities mimicking biology systems), biotensegrities mimicking the anatomy and physiology of living organisms, form-finding in the linear regime of self-equilibrated biotensegrities, mathematical modelling of the shape change of biotensegrities (initial, deformed, shape change, and target state), computational approaches and numerical examples.
6. Nonlinear biomechanical character of tensegrity: nonlinear biotensegrities (the role of structure in evolution, triangulation and trusses, non-linearity), soft matter mechanics in living organisms, the fascia connection (ubiquitous of the fascial connections, kinematic chains), muscles mechanics (internal vs external forces), biotensegrity dynamics (instability vs superstability, energy source and storage), mechanics of walking and running in a biotensegrity model.
The course is addressed to doctoral students, young researchers, practicing engineers, medical doctors, and architects, interested in tensegrity systems.

Invited Lecturers:
Anna Al Sabouni-Zawadzka (Warsaw, PL), Fernando Fraternali (Salerno, IT), Andrea Micheletti (Rome, IT), Chai Lian Oh (Shah Alam, MY), Julián Rimoli (Irvine, USA), Graham Melvin Scarr (Nottingham, UK).

Coordinators: F. Fraternali, J. Rimoli.

Computational and Geometric Mechanics of Discrete and Continuum Systems

September 23 - 27, 2024

Rising interest in non-holonomic mechanical systems has initiated a large body of research that exploits what is often called ‘non-holonomic’ geometry. More precisely the geometric setting is that of (principal) bundles, which serve as configuration space, and the connection on the bundle plays a key role as it encodes constituent kinematic and dynamic relations. This not only provides a beautiful holistic approach to multi-physical systems it also gives rise to consistent compact and efficient computational formulations for complex systems. Renewed interest in concepts from geometric mechanics for modelling and computation arises in various scientific and engineering communities. In robotics, geometric mechanics approaches have become a corner stone of what is sometimes called 'modern robotics', where Lie group formulations are now established for kinematics and dynamics modeling, and the bundle view is central for locomotion planning and control of floating-base systems, e.g. humanoids, legged robots, and space robots. Computational multibody dynamics is another area that has embraced geometric methods for the consistent modeling of constrained systems comprising rigid and flexible bodies, and also geometric integration schemes are now established for the numerical analysis of such systems. In the last decade, significant progress was made in the field of computational geometric approaches to discrete and continuous mechanical systems, in particular for the dynamics simulation and control of articulated rigid body systems, and of solid and fluid systems in a consistent geometric framework as well as fluid-structure interaction and particle methods.

Recently geometric modeling of discrete and continuous systems finds their fruitful application also in the domain of artificial intelligence, where manifold learning, structure-preserving integration schemes, and computational Lie group formulations enhance efficiency and robustness of learning methods. Geometry based reduced-order modeling of complex systems, especially nonlinear dimensionality reduction techniques exploiting the topology of the underlying manifolds, provide new perspectives in this emerging field. Hybrid surrogate models of continuum and discrete systems, merging physics-based sub-models and data-driven representations, are combined to co-simulate complex mechanic and thermodynamic phenomena by incorporating the geometric structure of information manifolds. Contemporary machine learning algorithms start using methods originated from physics and statistical mechanics even on the conceptual level as geometrical structures and principles provide insight into formulations and algorithms used in artificial intelligence. This course will introduce attendees to fundamental concepts and mathematical formulations of geometric mechanics and provide a panoramic overview of current state of research and applications of geometric modeling. It covers theoretical and mathematical foundations, computational methods that allow for practical application to multibody system dynamics, as well as cutting-edge multidisciplinary research.

Invited Lecturers:
Géry de Saxcé (Lille, FR), Frédéric Boyer (Nantes, FR), Andreas Müller (Linz, AT), Radu Serban (Madison, USA), Zdravko Terze (Zagreb, HR).

Coordinators: A. Müller, Z. Terze.

Time and Rate-Dependent Damage Evolution and Fracture in Advanced Composites

September 30 - October 4, 2024

Novel and advanced multiphase materials are required by various innovative industrial applications, e.g. in aerospace, military, aeronautics, automotive, civil, and other applications. The basic question in designing new composites is how to optimally arrange the reinforcing phase to get the required material response to the applied load. The most important of these are fibrous composites, laminates, and complex multiphase materials, including interpenetrating and functionally graded composites, with complicated architectures of an internal structure consisting of porosity, and different types of reinforcement. It is widely recognized that important macroscopic properties like macroscopic stiffness and strength are governed by multiphysics processes that occur at one to several scales below the level of observation. A thorough understanding of how these processes influence the reduction of stiffness and strength is key to the analysis of existing, and the design of improved, complex materials.

The aim of this course is to present a series of lectures by researchers specialized in (1) multiscale modelling of complex materials, and (2) developing novel experimental methods of observation of damage and fracture processes in these materials subjected to high strain rate loading. The basic principles will be formulated of multiscale modelling strategies towards modern complex multiphase materials subjected to dynamical or impact loadings.

The study of how these various length scales and multiphysical processes (1) can influence damage and fracture processes of advanced composites and (2) can be bridged or considered simultaneously during a time- and rate-dependent material loading. They have a well-defined architecture or internal structure at the nano-, micro-, and mesolevels. For this reason, advances in multiscale modelling and analysis made here, pertain directly to classes of materials that either have a wider range of relevant microstructural scales, such as polymers, and metals, or have random microstructures, e.g. metal-matrix composites, fiber-reinforced laminates, interpenetrating phase composites, FGMs or cellular materials and voided solids.

With regard to ceramic composites (CCs) and ceramic matrix composites (CMCs) the damage and fracture processes will be described with a triple-scale approach. The important problem of the damage process of interfaces surrounding particles, grains, whiskers or fibres included in composites will be analysed for different properties of the inclusions and in different scales.

The challenge in modelling time-dependent problems is to solve space and time multiscale, multiphase, and multiphysics initial-boundary value problems. Therefore, various methods applicable to time- and rate-dependent problems in novel composite materials will be discussed during the course including FEM, phase-field, or peridynamics.

The experimental part of the lectures includes a description of the newest achievements in (1) micro-CT assessment of internal structures of complex composites, (2) testing under low-velocity impact including temperature effects, and (3) high-velocity strains experiments with application Split Hopkinson Pressure Bar.

Invited Lecturers:

Holm Altenbach (Magdeburg, DE), René de Borst (Sheffield, UK), Christophe Czarnota (Lorraine, FR), Liviu Marsavina (Timisoara, RO), Tomasz Sadowski (Lublin, PL), George Z. Voyiadjis (Baton Rouge, USA).

Coordinators: T. Sadowski, H. Altenbach.

Dynamics of Human Balancing

October 14 - 18, 2024

The interdisciplinary nature of how the nervous system controls balance forms a barrier for mathematically oriented researchers. It is not only necessary for researchers to appreciate the physiology and anatomy of human balance control, but also researchers must be fluent in the analysis of time-delayed dynamical systems. The starting point is to understand how the inverted position of a pendulum can be stabilized. Two “human-in-the-loop” applications of the inverted pendulum paradigm are pole balancing at the fingertip and postural sway during quiet standing. While pole balancing is a voluntary motor skill, quiet standing is achieved through the operation of “hard wired” neural reflexes. The main question in pole balancing is how it is possible to balance short poles. In case of postural sway, the challenge is to understand how balance can be maintained by an aging nervous system, to identify the nature of its failures and to reduce the risk of falling. Naturally, the question arises: does the nervous system face the same challenges controlling balance that a mechanical engineer faces in stabilizing mechanical structures?

This school brings together internationally recognized experts in the experimental and mathematical analysis of human balancing tasks. From different perspectives, each of them has reached the conclusion that the controller for human balance is time delayed and acts intermittently. The lectures are self- contained and are structured in a manner to give the audience an appreciation of the interplay between mathematics and experimental observations that led to the demonstration that balance control is intermittent. Where possible theoretical concepts will be illustrated with hands-on demonstrations, e.g., measurement of time delays, stick balancing, numerical analysis of delay differential equations.

The course is organized with the premise that the audience has little or no experience with the analysis of time delayed dynamical systems and the physiology and anatomy of human balance mechanisms. The course begins by first examining the evidence for time-delayed feedback control in humans and the experimental evidence that supports the intermittent nature of neural control in stick balancing, human postural control and balance control in the elderly. These lectures are followed by mathematical considerations of the stability of delay differential equations in the presence of sensory uncertainty. The approaches are then extended to other human balancing tasks.

The school is addressed to MSc and PhD students as well as to post-docs, early career researchers, and also to engineers working at the R&D departments of companies with interest in understanding human motion control. The course is designed for participants working primarily in the field of biomechanics, collaboration of human and machines. However, the course is addressed also to those generally interested in dynamical systems involving time delays, control theory and numerical analysis and/or experimental vibration measurement techniques.

Invited Lecturers:

Tamás Insperger (Budapest, HU), Ian Loram (Manchester, UK), John Milton (Austin, USA), Pietro Morasso (Genoa, IT), Taishin Nomura (Osaka, JP), Gabor Stepan (Budapest, HU).

Coordinators: T. Insperger, J. Milton.

Domain Decomposition and Multigrid Methods
for Computational Structure Mechanics

October 21 - 25, 2024

The increased sophistication of materials (e.g., composites, 3D printed microstructures) and the extension of their range of use (e.g., complex triaxial state of stress induced by complex geometry) threaten to render obsolete the traditional "rules of thumb" used by designers and issued from decades of experience. Simple engineering optimization approaches are no longer applicable. Moreover, the complexity of failure scenarios makes it difficult to predict accurately the resilience of structures which is crucial when aiming at virtual testing and certification.

The solution to these difficulties lies in the ability to conduct reliable simulations at the scale of the whole structure. In this context, reliability implies to be able to use fine scale models that accurately reproduce nonlinear critical phenomena like plasticity, cracking, delamination. This in turns implies to use fine adapted meshes potentially containing billions of degrees of freedom.

Modern cluster hardware made out of thousands of multicore processors connected by a fast network makes it in theory possible to bear such a computational load. But only few solvers are capable of correctly exploiting these resources. Indeed, problems from structure mechanics possess many unfavorable features associated with the use of unstructured finite element discretization, the presence of strong heterogeneity, the history-dependent nonlinearity (elastoviscoplasticity, damage, cracking). The mechanical engineering community is deeply influenced by legacy commercial software which relies on direct solvers which, in spite of their impressive recent progress in terms of parallelism, are not able to scale up to the desired complexity.

However, domain decomposition and multigrid methods have been the object of important studies and developments in the last 30 years, and thanks to recent improvement regarding their robustness, they have reached a remarkable level of maturity. In addition to their strong mathematical foundations, these methods possess essential mechanical interpretations and offer new modeling opportunities (e.g., non-overlapping domain decomposition for the contact between subdomains, multigrid methods to handle nested models).

This course aims at presenting state-of-the-art domain decomposition and multigrid solvers for solid mechanics. The course will balance theoretical and practical aspects, as well as mathematical and mechanical points of view. The course will also discuss the open source software libraries which propose implementations of the methods.

The course is intended for graduate students working in computational structure mechanics, numerical analysis of partial differential equations, and high-performance computing. The content will also be very appealing for mechanical or civil engineers from industry seeking high performance, where the characteristic size of critical phenomena is very small compared to the structure. This framework encompasses composite structures (aerospace industry), microstructure-driven metallic parts (rolling elements in trains and cars), reinforced concrete buildings, bio-medical applications...

Invited Lecturers:
Pierre Gosselet (Lille, FR), Axel Klawonn (Köln, DE), Matthew Knepley (Buffalo, USA), Radek Kučera (Ostrava-Poruba, CZ), Oliver Rheinbach (Freiberg, DE), Nicole Spillane (Palaiseau, FR).

Coordinator: P. Gosselet.

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