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BOOK OF ABSTRACTS

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Multi-Modal Haptic Actuators

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Commercial virtual-reality technologies based on visual and auditory feedback have achieved remarkable success, yet progress in haptic interfaces remains comparatively limited. This gap is particularly important because haptic systems can access large and mechanically diverse areas of the human body, offering unique opportunities for reproducing, substituting, and augmenting sensory functions. Existing haptic devices, however, are often bulky, difficult to integrate with soft body surfaces, and limited by high power consumption or restricted actuation modes. Here, we present two complementary haptic platforms that address these challenges through theory-guided design. The first platform, reported in *Science*, introduces a full freedom-of-motion actuator capable of delivering multimodal mechanical stimuli from a single compact device, including normal pressure, shear force, and low- and high-frequency vibrations. These capabilities enable selective engagement of multiple classes of human mechanoreceptors, overcoming the limitations of conventional haptic systems that typically provide only one or two forms of mechanical feedback. Analytical electromagnetic models and finite-element simulations were established to determine optimized coil geometries, magnet configurations, and driving conditions for generating programmable shear and normal forces. The second platform, reported in *Nature*, focuses on reducing power consumption through a bistable design. Mechanics and electromagnetic models were developed to reveal the bistable switching behavior under different tissue-coupled conditions, leading to a phase diagram that guides device design, operating regimes, and experimental optimization. Together, these studies establish a mechanics- and electromagnetics-based framework for designing next-generation wearable haptic interfaces, providing versatile solutions for applications in social media, entertainment, rehabilitation, and clinical sensory substitution.

Forward and Inverse Simulations of Pathogen Transport and Environment Design in Enclosed Spaces

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Forward Computational Fluid Dynamics (CFD) simulations have revolutionized our understanding of airborne pathogen transport, serving as a critical tool for predicting disease transmission and engineering safer public spaces. However, while high-fidelity forward modeling is highly effective for risk assessment, using these complex simulations to actively design optimal ventilation environments or back-track unknown pathogen sources typically relies on inefficient, trial-and-error iterations. Furthermore, directly solving the inverse Navier-Stokes equations for fluid flow is numerically ill-posed.

This presentation highlights the powerful impact of forward CFD simulations in analyzing airborne pathogen transmission, and introduces novel inverse simulation strategies to overcome their design limitations. We discuss a modified formulation of the governing transport equations to localize pathogen sources and demonstrate how the adjoint method can be leveraged for optimal environmental design. Crucially, the mathematical structures of these fluid inverse problems characterized by non-linear sensitivity analysis and constrained optimization directly parallel the variational formulations and adjoint-state methods used in nonlinear solid mechanics for parameter identification and optimization. This talk aims to foster cross-disciplinary insights by demonstrating how shared mathematical frameworks can solve complex, non-linear field problems in both fluid and solid systems.

Homogenization of damaged microstructures: Convexification as a local alternative to nonlocal approaches for mesh-independence?

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The simulation of damage evolution plays a key role in numerous applications within engineering. For instance, predicting the service life of products requires the simulation of wear processes governed by subcritical crack growth under cyclic loading conditions. Another example is the treatment of atherosclerotic arteries, where the computationally supported assessment of plaque rupture contributes to improved therapies while simultaneously reducing costs. To achieve this, the stress- and strain-softening mechanisms that occur prior to crack formation and affect crack propagation must be represented accurately, for example through constitutive continuum damage mechanics models. However, the direct application of such models may lead to mesh-dependent numerical results, making simulations difficult to interpret. Various methods have been proposed to address this issue, including nonlocal integral formulations, gradient-enhanced approaches, and Eigenerosion techniques. These methods introduce additional parameters related to characteristic length scales, whose physical interpretation remains an active area of research. An alternative, purely local strategy avoiding such parameters a priori involves the convexification of the corresponding incremental variational problem [1]. This convexification is mathematically challenging and capable numerical algorithms in multi-dimensional problems have only been proposed recently [2]. In addition to that, such algorithms usually come with a tremendous computational effort needed to evaluate the material model at the integration point, significantly increasing the costs for the assembling procedure when used in a finite element calculation. Therefore, the use of alternative mathematical representations of the convex hull in terms of hierarchical sequences has been proposed in [5] to significantly speedup the algorithms based on efficient one-dimensional convexification schemes [3]. This has indeed been a breakthrough as it has made convexification approaches feasible in relevant structural finite element problems using e.g., finite elements. However, most approaches so far have only allowed the description of stress-softening and the reconvexification approach from [4] appears to be the only approach for one-dimensional finite strain problems. Therefore, it remains an open question to what extent such ideas may be extended to multidimensional problems and recent advances will be presented in the lecture.

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Tension Tales of Two-Dimensional Drums

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The atomically thin nature and virtually zero bending rigidity of two-dimensional (2D) materials make tension a central parameter governing their static and dynamic behavior. Indeed, tension emerges not merely as a design parameter, but as a fundamental state variable that governs the behavior of 2D membranes and, as I will discuss in this talk, enables applications ranging from precision frequency control to single-cell diagnostics.

In particular, I will present recent theoretical and experimental advances that exploit tension and tension modulation in suspended 2D membranes. I will begin by highlighting the role of tension in shaping the vibrational spectrum, discussing its influence on resonance frequencies, mode shapes, and wrinkle formation [1, 2]. I will then show how dynamic tension modulation enables parametric excitation and amplification, providing direct access to the nonlinear dissipation mechanisms of 2D resonators [3]. In particular, I will demonstrate how strong nonlinear damping can be exploited to stabilize oscillator dynamics, suppress amplitude fluctuations, and maintain enhanced frequency stability deep within the nonlinear regime [4]. These findings illustrate how nonlinear effects, often viewed as a limitation, can instead be harnessed to improve oscillator performance for precision timing and frequency-control applications.

Moving to slower timescales, I will demonstrate how tension modulation can drive resonators into rich nonlinear dynamical regimes characterized by period doubling and chaotic motion. These phenomena reveal the complexity that can emerge in seemingly simple atomically thin structures and provide new opportunities for understanding and controlling nonlinear dynamics.

Finally, I will show how the extreme sensitivity and low tension of suspended graphene membranes can be harnessed for biological sensing. By utilizing ultrathin (<1 nm) graphene drums, nanoscale oscillations (nanomotion) of a single bacterium can be measured directly in its growth environment [5]. By investigating individual bacterial cells and selectively blocking different pathways contributing to nanomotion, I will discuss the physical origins of these random-like oscillations and the important role of bacterial motility. I will then demonstrate how graphene nanomechanical resonators can detect antimicrobial resistance at the single-cell level, highlighting the prospects of suspended 2D membranes as ultrasensitive platforms for rapid antibiotic susceptibility testing and drug screening.

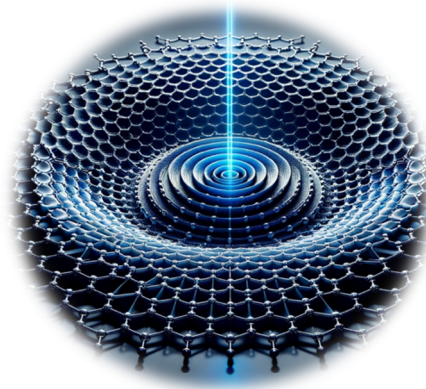


Figure. Artist's impression of a tension modulation in graphene drums.

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The role of Differential Geometry in Continuum Mechanics

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Differential Geometry and Mechanics of Continuous Media share a long history dating back at least to the late 18th century: Euler, Lagrange, d'Alembert, Piola, Cosserat, ... More recently, we could cite Arnold, Marsden, Souriau It seems, however, that a radical break occurred in the 1980s with the development of numerical tools and the rapid advancement of computing capabilities. This upheaval seems to have almost definitively overshadowed the close link between differential geometry and continuum mechanics.

However, there appears to have been a resurgence of interest in the subject over the past decade or so in several directions: one needs to understand what he is doing. For instance, the principle of objectivity, which is of paramount importance for the formulation of constitutive laws, needs to be considered in light of the principle of general covariance derived from General Relativity. Along the same lines, the concept of objective derivatives deserves to be clearly and rigorously defined from a mathematical point of view [3]. In addition, variational principles such as the Principle of Virtual Power should be regarded in a new point of view after the pioneering work of Souriau [5], and especially after the flourishing development of higher gradient media and their application in the conception of new metamaterials.

Finally, it can be interesting to connect Continuum Mechanics with other Physics disciplines such as General Relativity, High Energy Physics and Quantum Mechanics. In such a direction, there is a 4D geometric framework (introduced by Souriau) [4, 2, 1] that allows for a correct formulation of a Relativistic Continuum Mechanics. This general framework is based on Gauge Theory, which serves as the mathematical basis for both Field Theory (and in particular Electromagnetism) and Quantum Mechanics. This 4D approach, which involves general covariance, is indeed essential for better understanding the mechanical/electromagnetic coupling, particularly in large transformations.

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Topic in Geometric Continuum Mechanics

Reuven Segev

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This general presentation will outline the tools used and the results obtained in geometric continuum mechanics—the formulation of continuum mechanics and classical field theory on general domains and fields. For example, one may consider spacetime modeled as a metric-free n -dimensional manifold, bodies with fractal geometry, and stresses and hyperstresses represented by measures. Central notions in the theory are the infinite-dimensional configuration space of a body manifold in space and generalized forces, which are viewed as continuous linear functionals defined on spaces of velocity fields. In addition to the mechanical context, Maxwell's equations of electrodynamics and their generalizations to a general metric-free n -dimensional are considered.

Mini Symposia

MS-1 Dynamics and control of MEMS and NEMS

Dumitru Caruntu (University of Texas Rio Grande Valley, USA), Laura Ruzziconi (eCampus University, Italy), and Mergen Ghayesh (University of Adelaide, Australia)

MS-8 Dynamics and Vibrations of Systems and Structures

Francesco Pellicano (University of Modena and Reggio Emilia, Italy), Marco Amabili (Westlake University, Hangzhou, China)

Dynamic phenomena and complexity in mechanical system

F. Pellicano

Metastable synchronization and dynamical accessibility in nonlinear oscillators

Z. Shi, M. Amabili

Influence of Temperature on the Dynamic Behavior of Beams

S. Doneva, E. Manoach

Linear and nonlinear vibration of a micro-cantilever in a rarefied gas flow

E. Manoach, K. Shterev, S. Doneva

Slow modulation-induced dynamical crises in nanomechanical resonators

P. Belardinelli, F. Alijani

Enhancement of adaptive PID controller parameter learning for selected classes of dynamic systems

T. Nestorović, A. K. Pal

Models of electrostatically fringe field actuated mems resonators: Voltage-amplitude response of parametric resonance

D. I. Caruntu, M. Martinez

Internal resonance couplings of an in-plane arch-shaped MEMS

L. Ruzziconi, Z. Saibaa, N. Alcheikh

Vibration mitigation by hysteretic elements

F. Vestroni

Analysis of nonlinear free vibrations of FGM sandwich shell with auxetic honeycomb core

L. Kurpa, T. Shmatko

Nonlinear vibrations of a bio-inspired metamaterial beam under thermal loading

A. Zippo, F. Pellicano

A coupled spectral element-boundary element (SEM-BEM) method for the hydroelastic vibration analysis of composite laminates in contact with fluid

F. K. Kaya, B. Bediz, M. E. Yildizdag

DYNAMIC PHENOMENA AND COMPLEXITY IN MECHANICAL SYSTEM

Francesco Pellicano

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The Keynote aims to provide an in-depth and comprehensive overview of complex dynamic phenomena arising in mechanical systems of diverse nature and characteristics. Emphasis is placed on understanding how perturbations and imperfections influence the dynamic response of systems characterized by geometric or physical symmetries, often determining their transition toward chaotic behavior. The discussion encompasses the mechanisms through which chaos emerges, its interplay with symmetry breaking, and the resulting qualitative changes in system behavior. Furthermore, additional sources of complexity inherent to strongly nonlinear and externally perturbed systems are addressed, where unexpected and counterintuitive phenomena may occur. Particular attention is devoted to the analysis of nonlinear interactions that give rise to collective behaviors such as synchronization, quasiperiodicity, and Stochastic Resonance. Through theoretical insights and illustrative examples, the presentation seeks to elucidate the fundamental principles governing nonlinear dynamical responses and their implications for real-world mechanical systems. The Keynote will investigate manifestations of complexity in mechanical systems through a synergistic combination of theoretical modeling and experimental analysis. It will address fundamental and applied problems related to dynamic stability, nonlinear vibrations, and the intricate coupling mechanisms characterizing fluid–structure interaction phenomena. Particular emphasis will be placed on the onset and development of chaotic dynamics, highlighting the role of nonlinearity, parameter sensitivity, and bifurcation mechanisms in determining system behavior. By integrating analytical approaches, numerical simulations, and empirical observations, the presentation aims to provide a rigorous understanding of the underlying physical principles governing complex dynamical responses in mechanical and fluid–structure systems.

METASTABLE SYNCHRONIZATION AND DYNAMICAL ACCESSIBILITY IN NONLINEAR OSCILLATORS

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Synchronization is widely exploited to enhance the sensitivity and noise resilience of mechanical sensors, with nonlinear operation commonly assumed to dramatically expand the usable synchronization bandwidth. Here we show that this assumption fails dynamically: in nonlinear self-oscillating systems, most of the nominal synchronization bandwidth is inaccessible under any finite-time tuning. We demonstrate that this breakdown originates from phase inertia, which endows the phase dynamics with an effective second-order response and introduces inertial barriers to phase capture. As a result, nonlinear synchronization is fundamentally divided into a small, dynamically stable locking region and a much larger metastable region where steady-state phase locking is permitted in principle but cannot be realized in practice. Crucially, we show that this metastable regime is not a failure of synchronization but a consequence of inertial continuation. Operating deliberately just outside the locking boundary, phase inertia enforces slow beating dynamics that encode frequency detuning while intrinsically averaging fast phase noise. This inertial-beating transduction provides a continuous, history-independent sensing response precisely where conventional synchronization fails. By reframing synchronization bandwidth as a problem of dynamical accessibility rather than static stability, our work establishes a unified framework that integrates phase locking and inertial beating, fundamentally expanding the operational range, speed, and robustness of nonlinear MEMS/NEMS sensors.

Influence of Temperature on the Dynamic Behavior of Beams

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The effect of temperature on thin-walled structures leads to various changes in the behavior of the system, such as thermal expansion and contraction, variations in material mechanical properties, the development of thermal stresses, and a reduction in stiffness. These effects have a significant impact on the dynamic behavior of structural elements such as beams.

The objective of this study is to analyze the influence of temperature on the dynamic characteristics of the beams, as well as on their nonlinear dynamic behavior.

First, the variation of dynamic characteristics under influence of temperature is examined, with particular attention to changes in natural frequencies and vibration mode shapes. The dependence of the first natural frequencies on the temperature prior to buckling is shown in Fig.1. For larger temperature variations, the beam undergoes buckling, and the natural frequencies increase with the temperature.

Secondly, the combined effect of temperature and dynamic loading on forced, large amplitude vibrations of beams is investigated. Finally, critical phenomena induced by temperature are discussed, including loss of stability (buckling) and structural failure resulting from the combined action of thermal and mechanical loads.

In the present work, two types of beams are considered: a single-layer beam and a composite double-layer beam. Stability analysis and the obtained frequency-response curves reveal different types of stability loss and bifurcations.

A comparative study highlights the differences in the dynamic behavior of the two beam types.

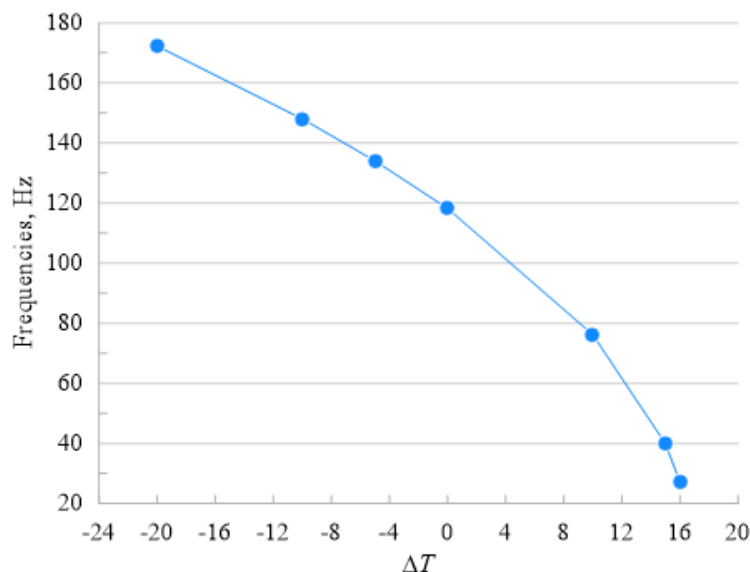


Fig. 1. Variation of the first natural frequency with temperature

LINEAR AND NONLINEAR VIBRATION OF A MICRO-CANTILEVER IN A RAREFIED GAS FLOW

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The fluid–structure interaction (FSI) is one of the most important coupled problems in mechanics. The topic is crucial for many high-technology areas. This work considers the interaction between an elastic obstacle and rarefied gas flow, seeking specifics that arise during this interaction. The Direct Simulation Monte Carlo (DSMC) method was used to model the rarefied gas flow.

DSMC uses a Cartesian uniform mesh in the computational domain and an unstructured mesh near the elastic beam. In cells of a basic mesh, the Transient Adaptive Sub-cells (TAS) technique was used to improve the DSMC spatial accuracy. A 2D adaptive unstructured mesh near the geometry was generated using the Delaunay algorithm by the mesh generator Gmsh (Geuzaine and Remacle 2009) via its C++ API.

The beam motion was modelled using the geometrically nonlinear versions of the Euler-Bernoulli and Timoshenko beam theories. Using the Galerkin approach, reduced models based on three-mode reductions were created. In addition, a 3D model of the micro-beam was created using ANSYS software. The natural frequencies and forced responses of the beam predicted by the theoretical model closely match those from ANSYS. Finally, Euler-Bernoulli beam theory was selected and used for coupling with DSMC code.

The beam was oriented normal to the free stream. The properties of a rarefied gas were selected to obtain a stable Karman vortex street behind the elastic beam. Knudsen number is 0.014, inlet velocity is 0.4 times Mach (148.4 m/s), reference temperature is 288 K, reference pressure is equal to 53.4 kPa, and the length of the beam is equal to 8.89 μm , and the temperature of the beam is constant and equal to the reference temperature.

Many computations were performed using the supercomputer in BAS. Keeping the flow velocity and flow parameters constant, the thickness of the cantilever was successfully increased. In all cases, calculations were performed using small-deflection beam theory (SDBT) and large-deflection beam theory (LDBT).

Increasing the beam thickness decreases its deflection, but when the beam's natural frequency approaches the vortex-shedding frequency, a phenomenon similar to resonance appears, and the vibrations of the thicker beam become large in amplitude. If the beam thickness increases and the natural frequency falls below the vortex frequencies, the deflections decrease rapidly. As the beam's deflections are not very large compared to its thickness, far from the resonance zone, the maximum amplitudes obtained by SDBT and LDBT are very close to each other. Close to the resonance zone, the FRF obtained by LDBT shifts to the left (i.e., to lower frequencies; thinner beam). In addition, the maximum FRF obtained by LDBT is higher than that obtained by SDBT.

This phenomenon could play an important role in the application of a microcantilever interacting with fluid. Sensors could be developed to detect flow velocity or gas properties. For energy harvesting devices based on PZT cantilever and FSI, it is also very important to know at which frequency (or beam dimensions) the resonance will occur.

SLOW MODULATION-INDUCED DYNAMICAL CRISES IN NANOMECHANICAL RESONATORS

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Due to their high sensitivity to environmental changes, suspended two-dimensional materials are promising for a wide range of sensing applications in modern technology. These membranes exhibit large in-plane stiffness while remaining highly flexible in the out-of-plane direction, and consequently display nonlinear behavior even at low actuation powers. Furthermore, owing to their atomic thickness, they are highly susceptible to fluctuating forces arising from coupling to the surrounding environment, making them a unique platform for investigating how fluctuations influence the out-of-equilibrium dynamics. [1].

A small low-frequency signal or a small pulse added to the resonator's drive can significantly raise the likelihood of dynamical switching event. Under the right circumstances, this small signal can improve the signal-to-noise ratio through a mechanism called stochastic resonance, which has been proposed as a sensing method that resembles biological systems.

Single layer graphene resonators exhibit high switching rates close to room temperature, making them promising candidates for sensors based on stochastic resonance [2]. Hence, it is worthwhile to research the impact of superimposing a low-frequency modulation to the drive of nonlinear resonators.

Here, graphene resonators driven into the nonlinear regime are investigated under both direct and parametric driving in the presence of an additional slow parametric modulation. This modulation significantly enriches the phase-space dynamics, leading to increasingly complex trajectories.

The nonlinear dynamics are analyzed via the structure of the basins of attraction, revealing the emergence and disappearance of attractors as the modulation conditions vary. This behavior is interpreted as a manifestation of global dynamical crises induced by the slow drive.

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ENHANCEMENT OF ADAPTIVE PID CONTROLLER PARAMETER LEARNING FOR SELECTED CLASSES OF DYNAMIC SYSTEMS

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Desired behavior of dynamical systems with respect to tracking or stabilization properties in the presence of undesired disturbances can often be achieved only under implementation of appropriate control techniques. Controller parameters require adaptation in dynamical environments, where conventional fixed gain controllers often cannot meet the required closed-loop system specifications. Therefore, the control parameters adaptation according to parameter learning schemes through implementation of neural networks gain more attention. Control parameter learning plays a crucial role in achieving high tracking performance and robustness in nonlinear and uncertain dynamical systems. Conventional PID controllers with fixed gains are often tuned around nominal operating conditions and may exhibit degraded performance or instability when system dynamics vary or uncertainties are present. To address these limitations, we develop a learning-based self-tuning control framework based on a PID controller, with the controller parameters (proportional, integral and derivative gains) being adapted online within the control loop through the controller parameter learning using neural networks. In this work we present parameter learning using radial basis function neural network (RBFNN) enhanced by incorporating a regularization term with the aim to improve numerical robustness and prevent excessive parameter variation.

The system incorporates two neural networks: one of them is used to update (learn) the gains of the PID controller, whereas the other network learns the plant equivalent gain used in the gradient-based update law for the PID gains learning. This way the two neural networks are interconnected, resulting in improved stability and learning reliability. The proposed scheme simultaneously updates the PID controller parameters and refines an internal model of the plant dynamics, enabling effective adaptation under changing operating conditions.

The control architecture is implemented in MATLAB and Simulink and validated on two representative dynamic systems. In the first system, based on identified model of a cantilever beam model the improvement of the step input tracking by RBFNN-based gain learning in comparison with the fixed-gain PID controller is shown. The second system is a strongly nonlinear inverted pendulum-on-a-cart system. For this system, besides the simulation results, a swing-up and balancing performance is verified experimentally using a setup developed at department for Mechanics of Adaptive Systems, Ruhr-Universität Bochum. The system exhibits improved (faster) tracking performance and enhanced robustness compared to a PID controller with fixed parameter. The results indicate that the proposed uncertainty-aware, regularized RBFNN-based self-tuning PID controller is a promising solution for adaptive control of complex mechanical systems.

MODELS OF ELECTROSTATICALLY FRINGE FIELD ACTUATED MEMS RESONATORS: VOLTAGE-AMPLITUDE RESPONSE OF PARAMETRIC RESONANCE

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This paper deals with voltage response of parametric resonance of fringe-electrostatically actuated bio-microelectromechanical (BIO-MEMS) cantilever resonator sensors. The system consists of a cantilever beam above a ground plate with a hole, Fig 1. They are under alternating current (AC) voltage, soft excitations. l , g , W are resonator's length, gap distance and width.

The electrostatic-fringe actuation is based on capacitance formula. Reduced order models (ROMs) are used here. Methods used to solve these ROMs are (1) method of multiple scales (MMS) for ROM with one mode of vibration, (2) continuation and bifurcation (AUTO), and (3) direct numerical integration, the last two for ROM with two modes of vibration.

The voltage response, Fig. 2, shows three bifurcation points: subcritical A, supercritical B and saddle-node C. Also an end point D of the stable branch is present. U_{max} is the amplitude of the tip of the cantilever, and δ dimensionless voltage parameter. In low amplitudes all three methods agree. AUTO better predicts the behavior of the system for all amplitudes.

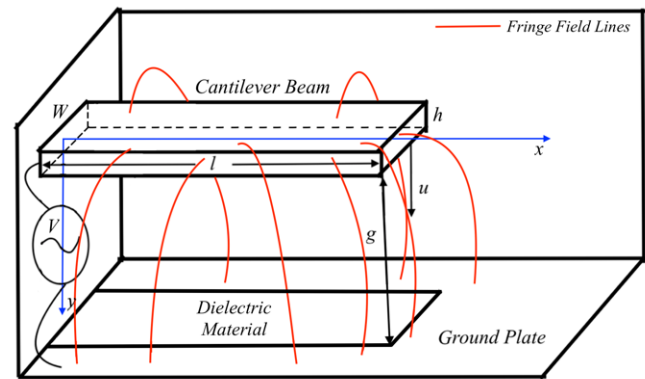


Figure 1: Fringe field electrostatically actuated MEMS cantilever resonator

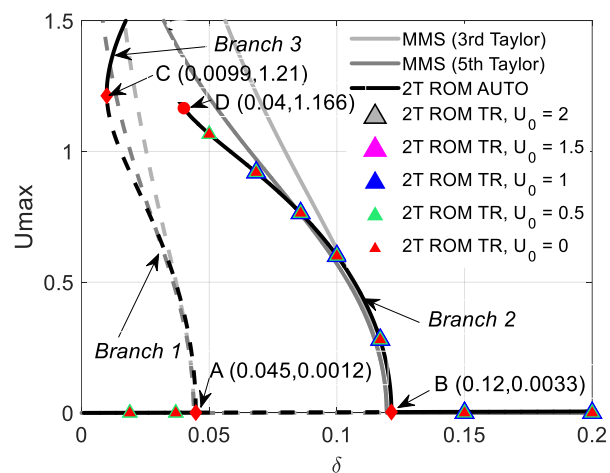


Figure 2: Capacitance model for $b^* = 0.001$, $f = 0.26$, $f^* = 0.29395$, $\sigma = -0.002282$, $\omega_1 = 3.516015$:
Voltage-amplitude response of parametric resonance of fringe-electrostatically actuated MEMS cantilever resonator

INTERNAL RESONANCE COUPLINGS OF AN IN-PLANE ARCH-SHAPED MEMS

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The internal resonance phenomenon [1] arising in micro- and nano-electromechanical systems (M/NEMS) is increasingly considered in the literature for developing novel devices with enhanced performance and functionality [2]. Different patterns can be induced in the MEMS response by internal resonances [3].

The present work investigates the experimental internal resonance couplings arising among the first three modes of an in-plane arch-shaped MEMS device. As sweeping from the first (first antisymmetric) to the second (first symmetric) mode, three sets of frequency sweeps are experimentally acquired at constant V_{DC} loads, via half-electrode configuration. Focus is placed on the experimental intermodal couplings related to the activation of a 2:1 internal resonance. By referring to a Galerkin reduced-order model comprising of the first three modes, simulations are performed and a good matching of the experimental frequency response curves is achieved. Further raising V_{AC} , an additional peak develops in the experimental response, which couples with the main one while involving the same modes.

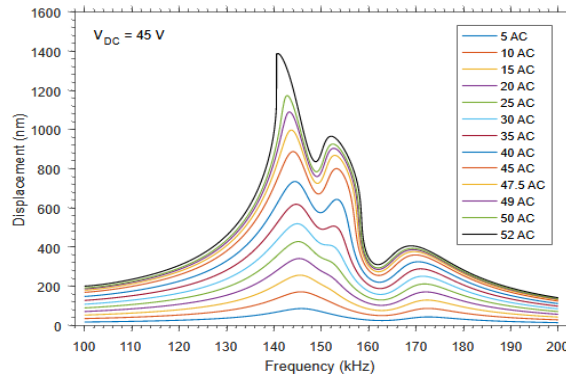


Figure 1. Frequency response diagrams.

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VIBRATION MITIGATION BY HYSTERETIC ELEMENTS

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Recent advances have shown that nonlinearity, often regarded as a source of concern, plays a crucial role in the dynamic response and can even provide beneficial effects [1]. Accordingly, the advantages of incorporating nonlinear elements into structures have been widely highlighted, and several devices have been proposed. Hysteresis is a common feature of many materials and structural elements. The addition of a hysteretic oscillator offers a twofold benefit: it introduces dissipation into the structure, and its nonlinearity promotes energy transfer from the directly excited mode to other modes [2].

The hysteretic vibration absorber (HVA) considered in this study consists of a mass suspended by short cables that exhibit classical hysteretic behavior under flexural deformation. The HVA is mounted on a vertical cantilever beam, representative of barrier structures used along high-speed train lines. Cyclic tests on individual cables were conducted, together with dynamic characterization of the HVA through forced-vibration experiments on a shaking table. Based on the experimental results, the parameters of a Bouc–Wen model describing the restoring force of the device were identified, showing satisfactory agreement between measured and predicted responses.

Experimental free-vibration tests of the prototype structure with the hysteretic cable device installed at its top were performed for various initial conditions. The measured responses were compared with those predicted by the identified two-degree-of-freedom model. The agreement is qualitatively excellent and quantitatively satisfactory. These results confirm the effectiveness of the HVA in significantly reducing the response of the main structure over a wide range of oscillation amplitudes.

Several issues emerging from the experimental investigation are highlighted: the remaining discrepancies in the identified model of the hysteretic absorber, the contribution of viscoelasticity to the dissipation properties, the dependence of mitigation effectiveness on vibration amplitude, and the lack of tools for selecting cables with prescribed characteristics.

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ANALYSIS OF NONLINEAR FREE VIBRATIONS OF FGM SANDWICH SHELL WITH AUXETIC HONEYCOMB CORE

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Auxetic honeycomb materials are widely recognized as modern core materials for advanced sandwich structures. With the increasing use of honeycomb-core sandwich systems in engineering applications, research devoted to the static and dynamic response of auxetic plates and shells has intensified. Consequently, the development and modeling of new auxetic materials and structural configurations have become important topics in contemporary mechanics.

This study presents a model for analyzing linear and geometrically nonlinear vibrations of sandwich shells with a conventional hexagonal auxetic core. The considered shell consists of three layers, including an auxetic honeycomb core and two outer layers made of functionally graded materials (FGM). A numerical-analytical solution approach is proposed by combining the R-functions theory with the variational Ritz method. The main advantage of this technique is its ability to construct admissible functions that exactly satisfy prescribed boundary conditions for shells of practically arbitrary geometry.

Mathematical formulation is developed within the first-order shear deformation theory (FSDT). Nonlinear vibration behavior is analyzed using the Ritz method, Galerkin procedure, and Runge–Kutta integration scheme according to the original methodology developed in this work. Verification through numerical benchmark tests demonstrates the reliability of the proposed approach. New numerical results are reported for FGM sandwich shells with auxetic honeycomb core, including the effects of geometric and mechanical shell parameters, cell geometry, FGM type, and face-sheet-to-core thickness ratio on natural vibration frequencies.

NONLINEAR VIBRATIONS OF A BIO-INSPIRED METAMATERIAL BEAM UNDER THERMAL LOADING

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This work presents an experimental investigation of the temperature-dependent nonlinear dynamics of a bio-inspired metamaterial beam with an architected internal layout inspired by natural compliant–stiff hierarchical systems. The study focuses on the combined effects of thermal loading, geometric nonlinearity, architectural heterogeneity, and temperature-dependent dissipation on structural stability and vibration response.

An extensive experimental campaign was performed using impact hammer testing, broadband random excitation, and stepped-sine base excitation. The specimen was mounted on an electrodynamic shaker inside a climate chamber, allowing controlled tests over a temperature range from -30°C to 35°C . This setup enabled the identification of modal parameters and nonlinear frequency-response curves under varying thermal conditions and large-amplitude oscillations.

The results show a pronounced non-monotonic variation of the fundamental natural frequency with temperature. As temperature increases toward a critical instability threshold, the frequency decreases, indicating effective stiffness softening caused by thermally induced compressive stresses and increased compliance of the internal architecture. Beyond the critical temperature, the frequency partially recovers in the post-instability regime, suggesting a reconfiguration of the load path and the onset of geometric stiffening. In contrast, the damping ratio increases significantly near the instability region, reaching a maximum, which points to enhanced energy dissipation associated with local interactions and strain localization within the architected structure.

Near the critical temperature, nonlinear frequency-response curves also reveal a softening-to-hardening transition, providing experimental evidence of thermally driven nonlinear stiffness modulation in architected metamaterials.

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A COUPLED SPECTRAL ELEMENT-BOUNDARY ELEMENT (SEM-BEM) METHOD FOR THE HYDROELASTIC VIBRATION ANALYSIS OF COMPOSITE LAMINATES IN CONTACT WITH FLUID

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This study develops a coupled spectral element-boundary element (SEM-BEM) framework to analyze the hydroelastic vibrations of laminated composite plates. The structural domain is modeled using a Chebyshev spectral element method based on first-order shear deformation theory, which achieves near-exponential convergence with minimal degrees of freedom. For the fluid domain, a boundary element method is employed, utilizing Green's functions to satisfy the infinite-frequency free-surface condition. To ensure computational efficiency and geometric accuracy, the framework integrates a NURBS-based coarse-quad meshing technique. A key innovation of this approach is the direct placement of BEM collocation points at the SEM sampling points, eliminating the need for time-consuming data mapping between meshes. The framework's accuracy and robustness are validated against existing literature and finite element simulations, demonstrating its effectiveness in predicting the dynamic characteristics of composites in contact with fluid.

MS-2 Continuum Mechanics and Geometry

Salvatore Federico (University of Calgary, Canada), Alfio Grillo (Politecnico di Torino, Italy), Reuven Segev (Ben-Gurion University, Israel), and G ry de Saxc  (Universit  de Lille, France)

MS-17 Computational, Experimental and AI-Driven Advances in Cardiovascular Hemodynamics

Rosaire Mongrain (McGill University, Canada), Sonia Pinto (Universidade do Porto, Portugal)

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Explicit relationship between exerted couple and microscopic hardening laws for elastoplastic cylinders in torsion: Application to pantographic structures hinges
B. Desmorat

A Gedankenexperiment in micro-robotics: can a charged micro-robot experience the Maxwell–Lodge effect?

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Micro-robots are devices often used in biomechanics [1] and medicine, e.g. for the release of pharmaceuticals [2]. In the context of bio-inspired applications, micro-robots can be shaped as flagella [3] and are thus modeled as slender rods made of viscoelastic materials. A sufficiently deep physical insight into the mechanics of such structures can be gained by regarding them as systems of rigid bars, joined through viscoelastic hinges, and by concentrating the mass of the rods in the midpoints of the bars. The hinges concentrate the distributed elasticity and viscosity of the original structures in selected points of the equivalent systems made of rigid bars.

A mechanical system that may well suit the framework described above is Ziegler’s double pendulum [4, 5]. In our contribution, we consider one such device connected with a cart at one end and featuring a nonholonomic constraint at the other, like in [6]. However, at variance with [6], we assume that the structural element serving as a nonholonomic constraint is electrically charged, and we investigate the dynamic behavior of the considered system under the action of an electric field and of a magnetic field generated by an ideal solenoid. In particular, we propose a *Gedankenexperiment* in which the dynamics of the system, placed in the proximity of the solenoid, is influenced by the electric field outside it. This setting, analyzed in [7], may feature a manifestation of what is known in electromagnetism as the Maxwell–Lodge effect [8].

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COVARIANT FORMULATION OF THE ELECTRO-MAGNETO-MECHANICS COUPLING

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"Smart materials" are studied for health monitoring of structures, since their behaviour involves multiphysics couplings. In the case of the electro-magneto-mechanics coupling, mechanical quantities can be accessed from non-destructive electromagnetic measures, which are especially adapted to the monitoring of existing concrete structures [3]. Although the original formulation of the electro-magneto-mechanics coupling in the 1960s is often attributed to Toupin [13], Tiersten [12] and Brown [1], sixty years later those problematics are still relevant whether it concerns non-linear and finite-strain magnetoelasticity [4], multi-scale problems [10] or description of dissipation [9]. Besides, the electro-magneto-mechanics coupling has been studied in the General Relativity framework since the late 1960s, from magnetoelasticity to electrodynamics [8, 5]. Working in such framework, the present work distances itself from these sources on multiple aspects: not introducing a spacetime at first, requiring *General Covariance*, defining a *matter field* [11, 7] rather than an embedding of a time-body, and using Hilbert's definition of the *stress energy tensor* (in opposition with Noether's definition [6]).

The aim of this work is to define a general covariant Lagrangian (also called Action) which describes the electro-magneto-mechanics coupling for *perfect electrised* matter, name given by Souriau to elastic and non conducting matter, for which a 4 dimensional approach is still relevant, in contrast with conductors which require a 5D Gauge theory framework. The main result consists of a theorem stating the list of suitable arguments for the Lagrangian density (also called Lagrangian) when the Lagrangian is general covariant, taking inspiration from a previous work on gradient theory [2] and Souriau's result for hyperelasticity [11, 7]. The presentation ends up with an application of the Least Action Principle to obtain Maxwell equations, as well as equilibrium equations through the conservation of the stress energy tensor.

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NEURON REORIENTATION AND AXONAL GROWTH ON CYCLICALLY STRETCHED SUBSTRATE

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Experimental evidence highlight that mechanical cues crucially affect both the reorientation and growth of axons. Neurons cultured on periodically stretched planar substrates reorient until they reach a stable equilibrium angle, typically within 60° - 90° relative to the principal stretching direction.

In this context, we propose a novel mathematical model to reproduce *in silico* both neuronal reorientation and elongation under cyclic stretching. The model combines a linear viscoelastic model for growth cone reorientation – augmented by a stochastic component – with a moving boundary model for tubulin-driven axon elongation. Together, these components enable simulations of axonal pathfinding in dynamics mechanical environments.

Numerical simulations were performed for a range of stretching frequencies and strain amplitudes. The results indicate that neurons consistently reorient toward equilibrium angles within the experimentally observed interval. Furthermore, the model reproduces the dependence of reorientation dynamics on stretching conditions, predicting faster alignment at higher oscillation frequencies and strain amplitudes.

Timoshenko beam under finite and dynamic transformations: Lagrangian coordinates and Hamiltonian structures

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We present here a research work on the Hamiltonian structure of the Timoshenko model for finite and dynamic 3-dimensional transformations. This is highly motivated by the development of numerical methods.

Let us first explain why the study of Hamiltonian structures is related to numerics. Numerical methods relying on Hamiltonian structures are promising for two reasons. From a mechanical perspective, conserved quantities have a fundamental meaning because they capture important qualitative properties of the dynamics. From a numerical analysis point of view, these conserved quantities deliver stability results of the numerical method. In the Timoshenko model, one difficulty comes from the fact that the dynamics is infinite-dimensional. In other words, the Hamiltonian equation is a partial differential equation, leading to non-linearities that are hard to tackle. In particular, the Timoshenko model admits non-linear instabilities induced by the coupling between the rigid motion and high frequencies. In this context, the construction of stable numerical methods is intricate. Indeed, many traditional numerical methods dissipate through high frequencies.

Let us now explain our study of the Hamiltonian structure of the Timoshenko model. In the framework of Timoshenko beam, the material parameters are inherently prescribed on the material moving frame. In this regard, we derive the strong and weak formulations of the dynamics under finite transformation in Lagrangian coordinates. Accordingly, analytical mechanics tools are used to deduce a new Hamiltonian formulation of the model which proves to be remarkably simple and synthetic. As a conclusion, we expose some perspectives in numerical analysis opened by this new result.

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Geometric theory of first order generalised continua using moving frames

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The design of materials with complex microstructures (metamaterials, high-contrast composites) requires continuous models capable of capturing size effects ignored by Cauchy's theory of classical continuum mechanics [1]. Even if the ability of generalised continua (micromorphic, Cosserat, strain-gradient) to capture those effects is well established in the literature [2], the proliferation of models with varying kinematic assumptions makes selecting an appropriate formalism for each application a complex task [3].

This work presents a unified geometrical framework for modeling generalised continua in finite strains : in any dimension (rods, shells, 3D media), in any micromorphic theory of order one (micromorphic, Cosserat, micro-stretch, etc) and in any second gradient theory of second grade (strain-gradient, couple-stresses, etc). Central to our approach is the use of moving frames defined at any point in the material, interpreted as generalised configurations. Our framework relies on an intrinsic Lagrangian point of view aligning closely with the original insights of the Cosserat brothers [4].

Our contributions lies in explicitly identifying a gauge invariance principle within this framework, where the arbitrary choice of a reference generalised configuration is treated as a gauge choice. We demonstrate that the standard free energy density for micromorphic media, usually expressed via the micro-deformation [5], emerges naturally from a gauge-invariant energy functional depending on the mapping between frames of generalised configurations [6], the generalised deformation. Using structural group reduction, a tool in gauge theory [7], we provide a systematic classification of all first order sub-models, such as Cosserat or micro-stretch media based on matrix Lie groups. Furthermore, by identifying strain-gradient media as the mapping of convected frames [8], we derive a natural decomposition of the micro-deformation. This result reinforces the link between micromorphic theory and plasticity based on moving frames [9] by providing a kinematic interpretation of the classical gradient decomposition $\mathbf{F} = \mathbf{F}^e \mathbf{F}^p$.

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G-STRUCTURES ASSOCIATED TO COMPOSITES

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We investigate the geometric structures associated to a binary composite. The two Lie groupoids corresponding to each material allows to construct the so-called coarse double groupoid. In terms of G -structures, this leads us to consider reductions of the frame bundle for the group $G_1 \cdot G_2$, where G_1 and G_2 are Lie subgroups of the general linear group, given by each material. We discuss the integrability conditions for such structures and apply the results to composite materials.

Dynamics of solid and fluid Cosserat media

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Our goal in this work is to revisit the theory of generalized continua of the brothers Eugène and François Cosserat [3, 4]. We develop a general approach for the dynamics of material bodies of dimension d represented by a matter manifold $\mathcal{N}$ of dimension $(d + 1)$ embedded into the space-time $\mathcal{M}$. It can be specialized for $d = 0$ (pointwise object), $d = 1$ (arch if it is a solid, flow in a pipe or jet if it is a fluid), $d = 2$ (plate or shell if it is a solid, sheet of fluid), $d = 3$ (bulky bodies).

Among the sources of inspiration of this work, one can quote Jean-Marie Souriau who highlighted the affine character of many features of the Mechanics and proposed a general approach called "Affine Mechanics" and based on tensor-distributions [7]. Starting from this approach, the attention is paid to the concept of affine tensor of which the importance in Mechanics was originally pointed out and developed by Włodzimierz Tulczyjew and his school [8, 6]. We call torsor a skew-symmetric bilinear map on the vector space of affine real functions on the affine tangent space to the space-time.

In the present work, the balance equations are not obtained from the virtual power method but from the concept of parallel transport, using the affine connections as originally developed by Élie Cartan, that is the connections associated to the affine group [1, 2]. We introduce a general principle of covariant divergence free torsor from which we deduce 10 balance equations [5]. We show the relevance of this general principle by applying it for d from 1 to 4 in the context of the Galilean relativity. This change of perspective is fruitful because it allows us to identify new things. That is the goal.

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Geometric Two-Scale Model for Defective Media and Structures

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Over the last few years, we developed a unified geometric theory for materials with two interacting scales: a macroscopic continuum and an attached microscopic structure. Mathematically, the material is treated as an affine bundles $\mathcal{B}$ placed in the ambient space $\mathcal{E} = \mathbb{T}\mathcal{E} \simeq \mathbb{R}^3 \times \mathbb{R}^3$ through a vectorial placement $\mathbf{F} : \mathbb{T}\mathcal{B} \longrightarrow \mathbb{T}\mathcal{E}$ over a punctual placement $\varphi : \mathcal{B} \longrightarrow \mathcal{E}$. This kinematic has two extra levels compared to classical mechanics: a microscopic scale contained in the fibres of $\mathcal{B}$ and $\mathcal{E}$, and a mixed vectorial scale (corresponding to the variation of the micro along the macro) contained in $\mathbb{T}\mathcal{B}$ and $\mathbb{T}\mathcal{E}$. The former can be approximated by the macroscopic gradient; while the latter, which can be seen as an infinitesimal microscopic scale, can be approximated by the microscopic gradient or the macroscopic second gradient. When such approximations are exact, the material is called holonomic. In general φ and $\mathbf{F}$ are anholonomic and may place these scales independently. As a consequence, dislocations and disclinations are not inserted phenomenologically but arise from the geometry itself, through torsion and curvature generated by the kinematics of $\mathbf{F}$ and φ .

The framework is geometrically exact and extends the classical Riemann-Cartan setting (used in Cosserat, Toupin, Eringen) by introducing a new measure of length in such media: a pseudo-metric satisfying some compatibility conditions. In a single object, this pseudo-metric gathers the macroscopic metric, the microscopic metric, and the coupling between the two scales (connection and solder-form). Within this setting, objectivity can be formulated intrinsically, the associated invariants can be computed, and constitutive laws can be expressed without relying on coordinates. Namely, in the case of centered microstructures, the material's energy is function of the material pseudo-metrics. This should be compared to classical theory where the Cauchy-Green tensor plays this role. The variational structure developed in the thesis then yields static and dynamic Euler-Lagrange equations; in linearised regimes, one obtains Helmholtz-type equations linking curvature, torsion, and internal lengths, which we showcased with numerical illustrations of defect-driven responses.

Recent works show that our two-scale formalism recovers several established models: Cosserat media, Mindlin first and second-order strain-gradient media, Toupin couple stresses, Eringen's micromorphic media, Euler-Bernoulli and Timoshenko beams, and any 1D/2D reduction of the above-mentioned 3D models. Putting all those models in a single frame allowed for a deeper study of: their differences in formalism/assumptions, possible continuous transition between them, the possibility to add (other) defects to those models, etc. The talk will present this line of work from the foundational geometric ingredients to its main applications in defective media and beam mechanics.

HIERARCHICAL DESCRIPTORS IN COMPOSITES

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Motivated by the theory of continuous distributions of defects of misalignment in composites and metamaterials, which is briefly reviewed, the underlying hierarchical structure of hypercube skeletons and graphs is shown to spontaneously arise both in the very idea of the set of sub-mixtures of a multi-constituent mixture and in the representation of distant material symmetries in composites by means of n -fold groupoids.

Micro-macro homogenization of a truss-like structure leading to a third gradient 1D continuum: discussion on the homogenisation criteria

Francesco dell'Isola^{*}, Pierre Seppecher[†], Nicola L. Rizzi[‡]

The structure analysed in [1] is modified by introducing perfect hinges in all the (say m) interconnectors, obtaining a mechanism having $m+1$ degrees of freedom (see fig. 1). Now, when all the interconnectors are rigid, the structure has one degree of freedom and a set of configurations (called floppy modes) is identified, which is the same as the one obtained in [1]. When all the interconnectors are modified by inserting perfect hinges and elastic springs are added to the hinges (see fig. 1), generic configurations that do not belong to the floppy set, can be obtained. In this case, a deformation energy is stored in the structure. This energy can be evaluated with geometric arguments, and a detailed discussion of the order of magnitude of the quantities entering its expression is obtained by making the basic assumption that such an energy must be finite, in the limit when the size of the structure's module tends to zero. In particular, we find the critical rescaling power for the rotational springs micro-stiffness and the limit homogenised strain energy density. This identification procedure allows for the determination of a 1D continuum equivalent to the beam-like structure: we observe that the most natural set of kinematical descriptors for such a continuum includes, together with the placement, also a scalar micro-structural parameter, which represents, at the macro-level, the bending of even interconnectors of the considered modified Hart's modules. Some cases are selected, and the numerical results obtained for both the micro and macro models, are compared.

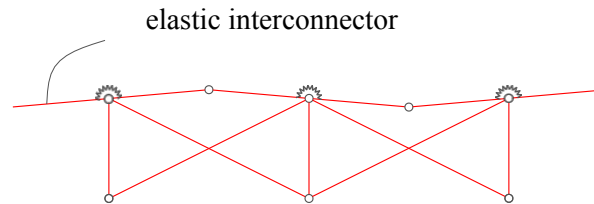


Figure 1: Two-bars linkage with elastic rotational springs

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From articulated-bi-parallelogram trusses to third gradient "beam"

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This article deals with microstructured systems that behave as a 1D third-order gradient continuum. The articulated bi-parallelogram trusses, [1], depicted in the figure below, is one of these peculiar systems since their deformations at constant curvature are free of elastic energy. Inspired by asymptotic homogenization of discrete media, we derived the elastic energy stored in a module of such a truss deformed by gradient of curvature and extension. The corresponding stiffness coefficients are explicitly and analytically linked to the module characteristics and the curvature. The effective behavior is then derived by Euler-Lagrange minimization of the total energy. This discloses the generalized forces in terms of force and couple and double couple together with the associated balance equations and the constitutive laws, [2].

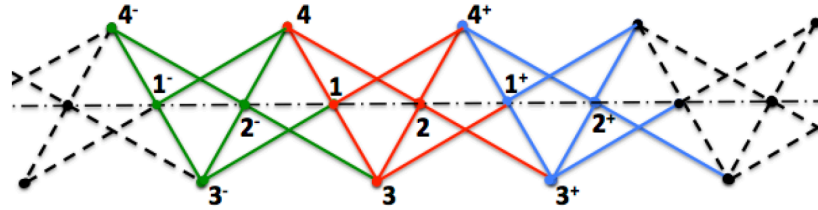


Figure 1: Periodic articulated bi-parallelogram mechanism in straight configuration. The elementary module is made of 4 short bars of length ℓ and of 4 long bars of length $\sqrt{3}\ell$, articulated at the four hinged nodes ($n = 1, 2, 3, 4$).

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CONFIGURATIONAL MECHANICS AND ELECTROPHYSIOLOGY OF MUSCLE CONTRACTION

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Continuum mechanical models of skeletal muscle contraction describe the bulk behaviour of the tissue, and use either an additive decomposition of the stress or a multiplicative decomposition of the deformation gradient [2]. We propose a novel approach, based on the combination of the multiplicative decomposition of the deformation [6], and the Fenton-Karma model of muscle electrophysiology [3, 1].

The deformation gradient $\mathbf{F} \equiv T\phi$, the tangent map of the motion ϕ of the muscle fibre, is decomposed into active (anelastic) and elastic distortions, as $\mathbf{F} = \mathbf{F}_e \mathbf{F}_a$. Both distortions are imposed to be isochoric (i.e., volume-preserving): the passive (elastic) behaviour of soft tissues is known to be incompressible, and the active (anelastic) contraction of muscle is known to be isochoric. The motion ϕ and the active part $\mathbf{F}_a$ are regarded as the standard and configurational kinematical descriptors, respectively. The balance equations are obtained via the principle of virtual work for constrained systems [5]. Under the hypothesis of hyperelastic behaviour, the non-reactive first Piola stress $\mathbf{P}_n$ is obtained from the Helmholtz free energy $W = \hat{W}(\mathbf{F}, \mathbf{F}_a)$. The dissipative part $\mathbf{Y}_{\text{diss;n}} = \mathbf{Y}_n + \mathbf{F}^T \mathbf{P}_n$ of the non-reactive internal configurational force $\mathbf{Y}_n$ is assumed to be proportional to the anelastic distortion rate $\mathbf{L}_a = \dot{\mathbf{F}}_a^{-1} \mathbf{F}_a$. The *external* configurational force $\mathbf{Z}$, representing *muscle activation*, is expressed in terms of calcium concentration, which is in turn a function of the electrophysiological potentials in the muscle [3, 1].

The model correctly predicts isometric (constant length) and isotonic (constant force) muscle contraction, as well as the classical force-length relationship [4].

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Dynamics of a fluttering micro-robot in the proximity of an ideal solenoid: two “virtual” laboratory experiments

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This contribution highlights some specific aspects of another work submitted to the same mini-symposium MS-2 “MS-2 Continuum Mechanics and Geometry”.

Electromagnetism plays an important role in the understanding of many biological phenomena. One common use of electromagnetic fields is found in bio-inspired micro-robotics [1], where Lorentz-type forces can be used to influence significantly, and even control, the movement of robots. However, the magnitude of the correction on the robots’ trajectories due to the electromagnetic interactions depends on the way in which locomotion occurs [2].

One outcome of some locomotion mechanisms, found in the context of micro-swimmers at low Reynolds numbers, is the onset of flutter instability [3]. Fluttering can be generated when the propulsion thrust, exerted e.g. by the fluid surrounding the robot, exceeds a certain threshold.

In this presentation we provide two “virtual” experiments involving a fluttering micro-robot that interacts with an ideal solenoid placed in its proximity [4]. Our goal is twofold: first, to show that, by using micro-robots, it is conceivable to detect an important electromagnetic effect, directly imputable to the vector potential [5], as discussed in [4]; second, to determine how the Lorentz force generated by the ideal solenoid influences the dynamics of the micro-robot. For our purposes, the design of our considered micro-robot takes inspiration from a variant of Ziegler’s double pendulum investigated in a work by Cazzolli et al. [6].

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Frequency-dependent instabilities in Ziegler's double pendulum interacting with a damped oscillator

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In the book by Ziegler [1], attention has been given to a discrete mechanical system featuring two rigid bars connected by a viscoelastic hinge, pinned at one end and subjected at the free end to a concentrated load, designed to be parallel with the latter bar. Depending on the loading conditions, such structure is able to exhibit flutter and divergence instabilities [2].

More recently, Cazzolli et al. [3] examined an extension of such structure in which the double pendulum is mounted on a translating cart and in which the “follower” loading, conceptualized by Ziegler, is concretized as the reaction force to a nonholonomic constraint. By having recourse to theory of bifurcations [4], they predict both theoretically and numerically the onset of stable limit cycles in the phase plots for the two angles characterizing the double pendulum.

Given the premises above, in this presentation we aim at discussing the consequences of “un-fixing” the plate on which the cart, connected to the double pendulum, can slide: indeed, by assuming the plate to be linked at a fixed wall through a viscoelastic spring, we show that the ratio between the fluttering frequency and the frequency of the plate's oscillations can significantly influence the dynamics and the instability properties of the overall system. To do this, we summarize the main findings of [5] by merging together theoretical arguments of dynamical systems [4] with computational techniques of nonholonomic systems [6],

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Chemo-mechanics in lithiation for battery computations

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For energy storage, computational approaches are transforming battery storage technologies. For understanding multiphysics processes, highly accurate and coupled solution algorithms are needed. Specifically for batteries, ions are moving due to chemical potential and thus also stress assisted flux is modeled. Such a coupling between mechanics and diffusion makes numerical difficulties [1].

We discuss a possible framework for such simulations based on continuum mechanics simulations with monolithic methods by using energy based formulations. All computations are done by open-source packages with symbolic derivatives providing high accuracy at the coupling terms [2]. We give examples mimicking phenomena observed in tomography X-ray measurements for Si electrodes.

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Coordinate-Free Finite Element Assembly From Geometry to High-Performance Computing

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The finite element assembly of differential operators on curves and surfaces embedded in higher-dimensional spaces arises in many applications, including surface diffusion, fluid flow, and poroelasticity in fractured media [1, 2]. In particular, the assembly of diffusion and advection operators on such geometries requires the computation of the gradients of the basis functions in the tangent space, which is typically carried out by introducing local coordinate systems.

In this talk, we first review the standard finite element assembly procedure on curves and surfaces in a unified dimension- and element-independent framework. We then present a coordinate-free assembly approach for linear finite elements, which avoids the explicit introduction of local coordinates.

The proposed coordinate-free formulation is validated in several applications related to the simulation of fractured media [3, 4]. We also compare the computational cost of the standard and coordinate-free assembly procedures for linear finite elements. While the two approaches exhibit comparable assembly times in standard implementations, the coordinate-free approach delivers substantially better performance when vectorization is exploited. Moreover, it provides a promising basis for further gains in the context of high-order finite elements.

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A fractional modelling framework for finite viscoelasto-plasticity coupled with Phase Field damage

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This work presents a continuum mechanical formulation of coupled viscoelastic, plastic, and damage phenomena in finite deformation regime.

The kinematics relies on a multiplicative decomposition of the deformation gradient tensor into a viscoelastic, a plastic, and a damage contribution. The damage distortion is prescribed as an isotropic tensor *à la* Mićunović [1].

The main novelty of our approach lies in the coupling of this tensor to the evolution of a scalar phase field. The viscoelastic and plastic tensors have no *a priori* given form but they are restricted to be isochoric processes [2]. Formulated as holonomic, the constraints are rigorously enforced within the variational framework of the Principle of Virtual Power through Chetaev's conditions.

The phase field is incorporated via a grade-one model, thereby enforcing a constitutive dependence on its spatial gradient [3]. Moreover, the model addresses viscoelasticity by considering memory kernels that describe special types of fractional viscoelastic behaviors.

The governing boundary-value problem and its computational background are outlined, followed by the presentation of some relevant numerical results.

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Modelling ionic transport and electrophysiological properties in nervous tissues across scales

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We present a continuum mixture framework for modelling charge transport in nervous tissue upon framing our work within the context put forward by Fried & Sellers [1]. That is, we consider a mixture of $N > 1$ ionic species dissolved in water and use the flux vector $\mathbf{j}_k$, $k = 1, \dots, N$, as the kinematic descriptor for the relative motion of the k -th ionic species with respect to the mixture’s centre of mass. The most fundamental hypothesis that we make, which follows other studies (see, e.g., [2]), is that the mixture under investigation is subjected to the *electroneutrality* constraint. The latter is imposed through the divergence of the total ionic current to be null and handled through a Lagrange multiplier that, once rescaled, acts as an electric potential. Hence, within this approach, the mathematical formulation of the problem is framed to yield two electric potentials: one enforcing electroneutrality and one arising from external body forces interacting with the ions present in the mixture. A specialised case is then examined in which we suppress diffusion-driven ionic transport but allow transport to be driven by the electric field arising from the electroneutrality constraint. In this simplified case, we use asymptotic homogenisation to encode experimentally observed morphological properties of nervous tissue into effective analytical formulae describing the overall electrical behaviour of the tissue.

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Variational formulation of planar linearized elasticity with incompatible kinematics

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We address mechanical equilibrium in the planar strain regime for systems with incompatible kinematic from a variational standpoint. We show that, for non-simply connected domains, the equilibrium problem for a non-liftable strain-stress pair can be reformulated as a well-posed minimization problem for the Airy potential. We characterize the additional compatibility conditions on the internal boundaries of the domain as Volterra dislocations or disclination. Finally, we establish that the minimization problem for the Airy potential can be reduced to a finite-dimensional optimization involving cell formulas.

This is work in collaboration with Pierluigi Cesana and Edoardo Fabbrini.

Symplectic Contact Analysis of Inhomogeneous Media

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The advancement of high-throughput characterization techniques for multi-field coupling in functionally graded materials has propelled the development of materials science. However, quantitatively characterizing fundamental material properties at all sample points precisely and efficiently within a graded specimen remains a significant challenge. This presentation seeks to establish a theoretical foundation for the high-throughput material characterization technologies from the perspective of contact mechanics of inhomogeneous media. In the field of contact mechanics, previous researches have predominantly focused on analyzing half-planes or half-spaces with gradient variations in the vertical direction, with limited theoretical developments addressing gradient variations in the horizontal direction. Furthermore, theoretical studies based on half-plane/half-space assumptions often deviate from physical reality due to the presence of boundary effects. In light of these issues, this presentation introduces the symplectic analysis into contact mechanics, establishing a symplectic framework for contact problems in finite-sized inhomogeneous media. A series of explicit analytical solutions for contact problems are derived and extended to multi-field coupling scenarios. Specifically, for horizontally graded materials, this presentation proposes and rigorously demonstrates that the quasi-Hamiltonian operator and its dual operator conform the dual Hamiltonian transformation, and their eigenvectors satisfy the dual adjoint symplectic orthogonality. The presentation also introduces a strategy for determining the contact area in inhomogeneous media based on the symplectic method. The theoretical results presented above have been validated through finite element simulation, confirming their accuracy and effectiveness.

EULERIAN-LAGRANGIAN TRANSFORMATION OF H -FORCES IN GENERALIZED ELASTICITY BY RECURSIVE PROJECTION AND INTEGRATION

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In the class of high grade materials the elastic energy is assumed to depend not only on the deformation gradient but also on the higher order gradients of the placement function. This circumstance implies, consistently with the principle of virtual work, an enlarged set of admissible external actions.

For deformable bodies with a sufficiently high grade, external H -force densities can be prescribed over the boundary surface, which do work on the H -th derivative of the virtual displacements along the direction of the normal to the face. Analogously, external H -force densities can be prescribed along the curved border edges: these actions do work on the H -th derivative of the virtual displacements along the direction of the normal, of the tangent normal, or a variously ordered sequence of both.

Each Eulerian H -force density of the above typologies turns out to be equivalent to a set of different actions defined in the Lagrangian configuration, acting on the differential borders of order higher or equal and working on the gradients of the virtual displacements of order lower or equal. For a second gradient elastic body, the use of convective coordinates can simplify the task [1]. When the order H is increased, the analytical evaluation of these generalized actions may become prohibitive.

In this study, a recursive procedure is utilized to generate all these irreducible Lagrangian contributions for any H , starting from the Eulerian actions mentioned above. Such an approach rests on complementary edge and surface projectors: their multiple tensor product generates polynomial expressions, which, after symmetrization, can be dealt with as binomial expansions. The proposed method generalizes the integration by parts required in a variational framework, combining it with the divergence theorem extended to differentiable manifolds with codimension one and two [2].

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NEW TRENDS FOR ML-BASED SOLUTION OF SOLID MECHANICS TASKS

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Machine Learning (ML) and Neural Networks (NN) have proven to be highly versatile and applicable to a broad variety of engineering problems in solid mechanics [1, 2]. The present talk gives an overview of recent trends in this field and shows some application examples.

Example 1: The phasefield-based crack simulation is easy to implement into an ML setup due to the inherently energy-based nature of the problem. However, to avoid divergence and overfitting behavior during training, the conventional techniques requires a very high number of collocation points which is further intensified in cases where the necessary NN expressivity is elevated to model discontinuities such as cracks. The work proposes Quadrature-Based Deep Energy Method (Q-DEM) employing a mesh-based discretization analogous to variational Physics Informed NNs (V-PINNs). The method is validated by a case study on a plate made of Al 7075-T6 subjected to traction loading leading to a mixed mode I-II fracture.

Example 2: A new ML architecture, namely the oscillatory Physics-Informed Neural Network (oPINN) has been suggested for the numerical investigation of oscillating continua. The approach carries out a modal analysis of a structure alongside with the transient analysis. Moreover, the potential of transfer learning has been investigated. This step results in a better accuracy and allows to speed up the calculations for a series of related tasks exploiting the similarity between neighbouring solutions and the adaptive nature of NN training. Among others, the numerical results show the great efficiency of the procedure in calculating solutions for comparatively stiff problems.

Example 3: The final example deals with the statistical homogenization methods evaluating the effective response of heterogeneous materials to different cases of loading. A key challenge in applying these methods is the choice of a suitable probability function that accurately captures the material's spatial correlations. By coupling fully connected neural networks (FCNN) and a convolutional neural network (CNN), both trained simultaneously, our adaptable approach significantly reduces the data requirements, allowing for effective training with a comparably small data set.

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A FURTHER CONTINUUM MECHANICS INTERPRETATION OF THE SECOND FUNDAMENTAL LAW OF THERMODYNAMICS

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Within classical thermodynamics, the second fundamental law is typically formulated for the overall entropy of the whole system. Based on the continuum mechanics ideas of Green & Naghdi [1], energy and entropy balances within a continuum can be characterized in fine granularity by applying the transport theorem of Reynolds, the Leibniz rule of integration and the divergence theorem of Gauß. These fine granular energy balances reveal the differences between adiabatic and non-adiabatic systems. Within an entropy balance, the system entropy can be expressed as volume and surface integrals of the internal entropies and other entropy fluxes (given by the quotients of the corresponding heat fluxes divided by the absolute temperature ϑ). This leads, as Green & Naghdi already noted in [1], to much more specific formulations of the second fundamental law of thermodynamics than those expressed in terms of the overall system entropy. In his book [2], Miles Rubin takes up the ideas of Green & Naghdi [1] and derives a further continuum mechanics interpretation of the second fundamental law of thermodynamics, which is based on the material dissipation $\vartheta \dot{\xi}$, the heat produced by the material. In the context of (strain-rate independent) elasto-plasticity, however, not all of the material energy is converted into heat. Instead, in addition to (thermal) material dissipation, some kind of (isothermal) microstructural dissipation occurs: the stored energy of cold work. Unfortunately, Miles Rubin does not mention the stored energy of cold work in his book [2], but he provided me with the following context: the stored energy of cold work consists of an increase in energy from the eigenstress states that result from an increased dislocation density, and it follows directly as $f(\kappa)$ in the presented thermomechanical theory if the von Helmholtz free energy $\psi(\cdot, \cdot, \kappa)$ is a function of the work hardening parameter κ . The stored energy of cold work is not really dissipated, as it can be released again through soft annealing. Moreover, if the velocity vectors $\mathbf{v}_i$ of the atoms of a representative infinitesimal volume element dv (RIVE) consisting of N (thousands of) atoms with masses m_i are expressed as $\mathbf{v}_i = \bar{\mathbf{v}} + \vartheta \mathbf{v}_i$, where $\sum_{i=1}^N m_i \vartheta \mathbf{v}_i = \mathbf{0}$, $\bar{\mathbf{v}} = \frac{1}{dm} \sum_{i=1}^N m_i \mathbf{v}_i$ is the mean velocity and $dm = \sum_{i=1}^N m_i$ is the equivalent infinitesimal mass of the RIVE, then the total kinetic energy dE_k of a RIVE can also be decomposed into a thermal contribution $\frac{1}{2} \sum_{i=1}^N m_i \vartheta \mathbf{v}_i \cdot \vartheta \mathbf{v}_i$ (the internal energy $\mathcal{U}$) and an isothermal contribution $\frac{dm}{2} \bar{\mathbf{v}} \cdot \bar{\mathbf{v}}$ (the mechanical kinetic energy). The corresponding state variables of an infinitesimal mass element dm are the absolute temperature ϑ and the mechanical velocity $\bar{\mathbf{v}}$.

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Thermomechanical formulation of materially uniform amorphous glassy polymers at finite deformations

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Amorphous glassy polymers, for example polycarbonate and poly(methyl methacrylate), are widely used in engineering applications demanding high impact resistance, optical clarity, and structural integrity under different temperatures. Understanding their thermomechanical response under large deformations is essential for reliable material design and failure prediction. This work presents a mathematical framework for modeling the finite viscoplastic behavior of materially uniform amorphous glassy polymers. Following the terminology introduced by Noll, a body is said to be materially uniform if all its material points are materially isomorphic. This concept was later given a geometric formulation by Epstein, in which uniformity is described through the existence of material isomorphisms and an associated uniformity tensor; when this tensor is integrable, homogeneity is recovered. Within this framework, a geometric description of the coupled thermoplastic and viscoplastic behavior of amorphous glassy polymers is developed. Eshelby stress tensors are derived as configurational driving forces governing the local rearrangement of first-order material inhomogeneities. Post-yield softening is captured through internal state variables, while strain hardening is described via a potential function tied to polymer chain orientation and deformation. The predictive capability of the proposed model is assessed through numerical simulations and validated against available experimental data.

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The Jeffery equation—Revisited after 100 years

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Jeffery published his famous paper “The motion of ellipsoidal particles immersed in a viscous fluid” more than 100 years ago [1]. Since then it has been the starting point of many investigations in the field of non-Newtonian fluid mechanics. When Jeffery wrote his paper, tensor calculus and direct notation were at their infancy. Consequently, his paper is very difficult to read. In our presentation we shall, first, derive his famous equation in a modern notation using a Newtonian background fluid. Second, we shall present analytical solutions, of which many versions can be found in the (recent) literature, for example, [2], many of which contain typos and make a discussion of the solution difficult—to say the least. We will try to avoid typos and discuss it in detail. Third, we will discuss the limitations of the solution when studying the flow of blood, in which we are particularly interested. Fourth, we will present an extension of Jeffery’s equation to a micropolar background fluid and compare our results to those from very recent publications [3], [4], [5], [6].

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Double groupoids of composites: new notions of uniformity

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Abstract

This talk will be devoted to introduce a novel geometric framework to analyze the uniformity properties of composite materials by means of material double groupoids. This structure allows for the systematic study of the interaction between different constitutive responses within a composite body. Building upon the classical notion of uniformity in simple materials, characterized by the transitivity of the material groupoid [2], we extend this concept by introducing a rich taxonomy of uniformity conditions, derived from the various types of transitivity and “*filling conditions*” inherent in double groupoids [1]. These include horizontal, vertical, weak, and strong uniformities, each corresponding to physically meaningful compatibility properties between the constituents. Our approach not only generalizes existing theories but also provides a flexible tool to model and compare different configurations of composites, with potential applications to different kinds of materials. The idea of studying composite materials using the notion of double groupoids was first suggested by a series of articles [3, 4, 5].

Keywords— Double groupoids; Composite materials; Uniformity

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From Saint-Venant compatibility conditions to effective integration of hypoelasticity

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The exterior derivative of alternate forms is constructed by derivation and antisymmetrization, yielding a new alternate form. Iterating this process leads to a graded sequence of alternate forms spaces forming the De Rham complex.

In a similar spirit, we use the Dubois–Violette theory [1, 2] to construct a differential complex for linear elasticity. The associated differential operator is obtained by derivation and symmetrization, reflecting the symmetries of elasticity tensors. A homotopy formula then yields the Saint-Venant compatibility condition for an infinitesimal strain tensor to derive from a displacement, which is shown to be both necessary and sufficient. As a consequence, we recover the Cesàro–Volterra integrator [3, 4], providing the displacement field associated with a compatible infinitesimal strain.

We then propose a geometric reformulation of hypoelasticity in terms of covariant tensor fields on the manifold of Riemannian metrics, within the intrinsic Lagrangian framework of continuum mechanics [5, 6]. In this setting, the problem of integrating a hypoelasticity law into an elasticity law is reformulated through a differential complex similar to the previous elasticity complex, but now defined on an infinite-dimensional manifold.

The same homotopy approach provides a necessary and sufficient integrability condition, which can be viewed as an infinite-dimensional analogue of the Saint-Venant compatibility condition. Finally, we construct an explicit integrator calculating the elasticity law from a given integrable hypoelasticity law, in a form analogous to the Cesàro–Volterra formula..

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Equilibrium and Interaction Regimes in Mixed Disclination–Dislocation Systems

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Dislocations and disclinations are the classical lattice asymmetries introduced by Vito Volterra in 1907. Dislocations are translational topological defects characterized by a Burgers vector and exhibit infinite elastic energy in a continuum setting. Disclinations are rotational defects defined by a Frank angle and generate singular stresses while possessing finite though large elastic energy. Understanding their interaction in both static and dynamical regimes is essential for modeling inelastic behavior in materials such as graphene, crystalline membranes, and metallic alloys. While dislocations have been widely studied, disclinations have received significantly less attention. Recent developments in shape memory alloys and magnesium based alloys have renewed interest in their rigorous mechanical modeling, particularly regarding their dynamics, equilibrium configurations, and influence on material properties such as strengthening and hardening.

This work is part of an ongoing collaboration between research groups in Italy and Japan devoted to the mechanical modeling and mathematical analysis of systems of disclinations with particular focus on their interaction with edge dislocations [1, 2, 3, 4]. We analyze the interaction between a single wedge disclination and a single edge dislocation confined in a circular domain within linearized elasticity under plane strain conditions. Our main objective is to identify the mechanical regimes and energy scalings under which these defects effectively interact, a nontrivial issue due to their fundamentally different energetic behavior. By studying the dissipative evolution of finite defect systems in a circular geometry, we obtain explicit solutions and precise estimates of collision times and equilibrium configurations. Through asymptotic analysis and suitable rescaling, we identify regimes where a single disclination and a single dislocation exhibit effective interaction, with measurable influence on their velocities. We also present numerical simulations for more complex defect configurations, revealing rich dynamical behavior including attraction, repulsion, and hybrid interaction regimes.

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Controlling Growth: A Geometric Control-Theoretic Framework for Volumetric Evolution in Continua

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In this work, relying on Geometric Control Theory, we develop a novel theoretical approach to investigate the controllability of volumetric growth in deformable media.

Volumetric growth is here modeled through the multiplicative decomposition of the deformation gradient [2], capturing the interplay between elastic response and growth-induced structural rearrangement. Within this setting, we reinterpret non-mechanical interactions –such as biochemical or environmental stimuli–as control inputs acting on the growth dynamics [4].

Two complementary perspectives on controllability are discussed. The *a priori controllability* approach, [6, 5], assumes the existence of growth-driving non-mechanical forces and prescribes their expressions in advance, typically based on phenomenological or experimental considerations. In contrast, we develop an *a posteriori controllability* framework–novel in the context of growth mechanics–in which such forces are not assigned a priori but are instead determined as control functions that steer the system toward desired configurations. By exploiting tools from geometric control theory [1, 3, 4], we derive analytical conditions for controllability in terms of the material parameters characterising the medium’s elasticity and growth.

The proposed approach extends classical growth theories by embedding them into a control-theoretic framework, enabling the systematic design of growth pathways. A benchmark problem of growth in a constrained geometry is analyzed to validate the theory and illustrate the emergence of closed-form controllability conditions. This work opens new perspectives in continuum biomechanics, active materials, and the design of growth-driven systems, offering a unified language to study and control complex inelastic processes.

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MULTISCALE MODELS OF BONE FRACTURE AND DAMAGE

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The yield and failure properties of trabecular bone are of key interest in understanding and predicting the fracture of bones and bone implant systems. The discrete homogenization technique is presently developed as a convenient micromechanical approach to construct the plastic yield surfaces of 2D and 3D bending-dominated periodic lattices of articulated beams considered as prototype topologies for cancellous bones. Thereby, the initial trabecular lattice is substituted by an effective Cauchy continuous medium at an intermediate scale, endowed with effective properties representative of an identified representative unit cell within the structure. The cell walls of the bone microstructure are modeled as Timoshenko thick beams taking into account stretching, transverse shearing, and bending deformations. In the case of plastic yielding, the cell struts of trabecular are assumed to behave in an elastic-perfectly plastic manner. The effective strength of trabecular bone is evaluated in the two situations of fully brittle (fracture with no tissue ductility) and fully ductile failure (yield with no tissue fracture) of the trabecular tissue. A size-dependent non-classical plastic yield criterion is developed relying on the reduced Cosserat theory to capture the size-dependency of the trabecular bone structures. Size effects appear when the characteristic size of the bone sample is comparable to the bending length. In the second part of the presentation, we propose a two-dimensional constitutive model for trabecular bone combining continuum damage with embedded strong discontinuity. The model is capable of describing the three failure phases of trabecular bone tissue which is considered herein as a quasi-brittle material with strains and rotations assumed to be small and without viscous, thermal or other non-mechanical effects. The performance, accuracy and applicability of the proposed model for trabecular bone fracture are evaluated and validated against experimental measurements. These comparisons include both global and local aspects through numerical simulations of three-point bending tests performed on ten single bovine trabeculae in the quasi-static regime.

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VARIATIONAL METHODS AND INTERNAL CONSTRAINTS IN POROELASTIC THEORIES

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This contribution aims to merge two lines of research that have characterized our group in the last few years and that have the mechanics of volumetric growth as common target: one research line frames growth within the theory of mixtures in order to account for the multi-phasic nature of biological tissues, while the other uses analytical mechanics to approach growth variationally.

After providing a critical revision of the studies conducted by Grillo et. al [1] and Licari [2], we discuss a possible generalization of the results reported therein. We show how, under certain hypotheses, the mechanics of growth in multi-constituent systems can be described through an initial and boundary value problem deduced from an extended Hamilton–Suslov Principle [3] in which the “*growth laws*” [4] are interpreted as nonholonomic constraints.

Taking inspiration from [4, 5], we propose a model for the microstructural evolution of an idealized biological medium, described as a mixture in which the solid phase undergoes growth and remodeling. We start from an *ad hoc* multiplicative decomposition of the deformation gradient tensor [1, 2], and we compel the factor pertaining to the growth-induced distortions to obey the nonholonomic constraints provided by the imposed growth laws. Then, we append these constraints to a Lagrangian density function, by which we construct the action functional of the growing medium. The action is varied according to the prescriptions of the Hamilton–Suslov Method and its variation is balanced by the virtual work done by non-potential forces.

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Analogy of the space-time as an elastic medium – Selected Geometric Aspects of General Relativity from the Standpoint of Continuum Mechanics: Implications for Measurements by Virgo- and LISA-Type Interferometers

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Abstract

Gravitational waves reveal that space-time exhibits measurable strains of 10^{-21} , suggesting that the vacuum behaves as an elastic medium. Building on my Ph.D. thesis defended in November 2025 and published in leading international journals in physics and mechanics, this work develops an analogy between general relativity and continuum mechanics, modeling space-time as an extremely rigid elastic material governed by Hooke's law in four dimensions. Locally and dynamically, gravitational waves induce an isotropic transverse response, and the perturbation tensor of the metric is linked to strain components in a quadratic form, introducing nonlinear effects consistent with the theme of nonlinear solid mechanics. We propose two extensions to Einstein's theory: (i) an elastic stress-energy tensor accounting for intrinsic strain energy of the vacuum, and (ii) geometric torsion (Einstein–Cartan approach) to reassemble foliated space-time sheets into a continuous medium. These hypotheses lead to three falsifiable tests:

1. Lateral motions of interferometer arms, predicted by the link between the metric perturbation tensor $h_{\mu\nu}$ and strain tensor $\varepsilon_{\mu\nu}$;
2. Complementary gravitational wave polarizations in the propagation direction if geometric torsion is included;
3. A cosmological Bragg law derived from the CMB power spectrum, interpretable as the diffractogram of a cosmic crystal, suggesting a large-scale foliation of space.

Beyond its predictive power, this analogy offers a didactic framework linking gravitational phenomena to mechanical concepts such as rigidity, creep, and instability, opening new perspectives on dark energy and dark matter as manifestations of thermal curvature and long-term deformation of the vacuum.

Keywords: gravitational waves, nonlinear elasticity, isotropic transverse medium, geometric torsion, interferometry, cosmological Bragg law.

A Numerical Analysis of Simple Collagen Fibril Entanglements in Cardiovascular Tissue

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Introduction: Collagen fibrils within the extracellular matrix are critical determinants of the mechanical properties of the arterial wall [1]. High-resolution imaging show complex fibril entanglements, in particular, the fibrotic layer of an atherosclerotic plaque is similar to a basket-weave network of collagen fibers which gets looser in time [3]. FEA is used to analyze observed collagen entanglements, including parallel, helical and wrapped.

Methods & Results: FEA was performed with LS-Dyna to assess the mechanical stresses associated with the different entanglements (Fig 1). Each configuration was modeled with two simple interacting collagen fibrils. The fibrils were stretched by 10% with an elastic constant of $E=10$ MPa [4] and the corresponding stresses were calculated. From the stress results (Fig 1), we find that the higher is the contact angle between the fibrils, the higher is the stress. On average, the relative stresses to the parallel configuration for the different entanglements are: parallel 1.00, helical: 0.80 and wrapped: 0.27.

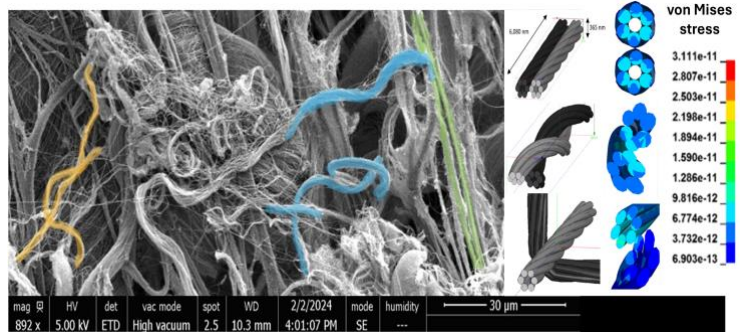


Figure 1. SEM image of aortic tissue showing the parallel (green), helical (orange) and wrapped (blue) entanglements and the their FEA models and results, (b) The corresponding von Mises stresses (average stresses ratios to the parallel configuration are parallel 1.00, helical: 0.80 and capstan: 0.27

Conclusion & Discussion: The results show that all configurations bear comparable fraction of the loads and stresses highlighting potential comparable mechanical roles for tissue integrity. Interestingly, the wrapped fibrils can also be modeled with the simplified Capstan equation [3]: $T_A = T_B e^{\mu_s \theta_{BA}}$, where, T_A is the applied load on the fibrils, T_B the balancing load on the wrapped fibril, μ_s coefficient of friction and θ_{AB} the contact angle. In future work, FEA results will be compared to the Capstan model to simplify the analysis.

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DEEP LEARNING SURROGATES FOR AORTIC ANEURYSM HEMODYNAMICS: A PHYSICS-INFORMED APPROACH

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Accurate assessment of patient-specific hemodynamics, particularly velocity, pressure distributions, and wall shear stress, is vital for predicting disease progression and rupture risk in Abdominal Aortic Aneurysms (AAA). Traditional modeling tools face significant limitations: 4D flow Magnetic Resonance Imaging (MRI) often suffers from limited resolution in complex flows, while high-fidelity Computational Fluid Dynamics (CFD) simulations are computationally expensive and demand boundary conditions that are difficult to obtain clinically. This work explores physics-informed deep learning techniques as data-assimilating alternatives to overcome these bottlenecks. Building upon our recent works [1, 2], we investigate the application of Physics-Informed Neural Networks (PINNs) and Physics-Informed Deep Operator Networks (PI-DeepONets) to predict both steady and unsteady 3D vascular flows within an idealized AAA model. By integrating the 3D Navier-Stokes equations directly into the network's loss function, these models are constrained by the fundamental laws of fluid dynamics alongside sparse observational data. To address the persistent architectural challenges posed by the modeling of complex flows, we analyze recent techniques designed to improve model convergence and handle disparate physical constraints without relying heavily on dense labeled data. The proposed methodologies are validated against standard CFD simulations, demonstrating a good agreement across benchmark datasets. By combining deep learning with fluid mechanics, this approach offers an accurate and computationally efficient alternative for modeling in biomechanics. This work advances the application of Scientific Machine Learning in cardiovascular disease modeling, serving as a crucial step toward real-time, non-invasive clinical diagnostics in realistic physiological scenarios.

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NUMERICAL ESTIMATION OF THE FFR IN PATIENT-SPECIFIC CORONARY ARTERIES: FROM CFD TO AI

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The numerical analysis of blood flow in stenotic coronary arteries (CAs) may aid in the diagnosis of cardiovascular diseases in a non-invasive and cost-effective manner. For coronary artery disease (CAD) assessment, cardiologists measure the fractional flow reserve (FFR) to assess the functional severity of stenosis. The measurement procedure is costly, time-consuming and requires specialized equipment, as well as a potential risk to patients with diseased vessels. Thus, the use of computational methods to calculate the FFR has been the target of scientific studies in an attempt to predict it non-invasively.

The authors have developed a tool to numerically predict the FFR by simulating realistic blood flow in ANSYS® Fluent by incorporating accurate models with patient-specific parameters measured at the Unidade Local de Saúde de Gaia e Espinho (ULSGE) and evaluated it in all 22 CAs. The numerically predicted FFR shows an average relative error of 13.1% when compared to the invasive FFR. In comparison, the relative error between the invasive FFR and the ones predicted by HeartFlow® is 17.7%. HeartFlow® does not disclose how the FFR is predicted, it is costly and does not return FFR values lower than 0.5. Our tool offers an open-source, free and transparent methodology with the ability to compute the full range of FFR values (0 to 1).

The numerical predictions of this parameter must be quick and accurate for hospital implementation, which is not possible through numerical simulations because they require the recreation of the arteries in a 3D environment through the usage of image segmentation algorithms. In addition, running numerical simulations takes 8-12 hours. Hence, alternatives such as deep learning (DL) are on the rise.

These require an extensive database of high-quality medical imaging and patient data from different hospitals (public and private) for generalization. Thus, the authors aim to use the developed and validated numerical tool to assemble a database of FFR values of patient-specific coronary arteries, in order to develop a DL algorithm to predict the FFR. Running these algorithms requires only seconds to minutes, making them a promising tool used in hospitals with the goal of aiding the diagnosis of CAD, improving patient outcomes, and saving costs and resources.

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Explicit relationship between exerted couple and microscopic hardening laws for elastoplastic cylinders in torsion. Application to pantographic structures hinges.

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It has been recognized recently that, in order to get the synthesis of higher order continua, micro-architectures including elastic hinges are necessary. As 3D printing technology made possible the construction of specimens whose micro-architecture is very complex and includes cylinders undergoing torsional deformation, it became necessary, in micro-macro identification process for getting homogenized behavior of metamaterials, to detail the study of the elastoplastic behavior of cylinders in torsion. Assuming that the linearized form of displacement classically found for cylinders in torsion is valid also when plastic phenomena arise, we find a set of conditions to be verified by the function associating to the torsional angle the exerted torque if a well behaving hardening law models plasticity phenomena at micro-level. In the class of plasticity-admissible torque/angle dependency, which we have established, we have found a novel hardening rule using which we could perfectly fit experimental data obtained in bias tests for pantographic sheets. We propose to use this novel hardening rule for the novel materials produced with 3D printing processes, whose characterization is often very difficult to obtain. In particular, we claim to have found a way for mechanically characterizing two 3D printed materials constituting some experimentally tested specimens.

MS-4 Multiscale and Multiphysics Modelling for ‘Complex Materials (MMCM 20)’

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On ellipticity and hyperbolicity within nonlinear strain gradient elasticity

V. A. Eremeyev

Bounds for Multimaterial Composite Properties

A. Cherkaev

Hidden Variables and Nonlocality in Multiscale Composite Materials

E. Cherkaev

Wave attenuation in lattice metamaterials with additive manufacturing geometric imperfections

D. Addessi, A. Paoloni, L. Parente, R. Zuppi

Semi-Analytical Finite Element Modeling of Nonlinear Nanoshells

C.A. Yan, N. Fantuzzi, R. Vescovini, R. Luciano

Two times scale modelling of cyclic deformation and damage in plates with auxetic core

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Jeffery’s equation for a micropolar background fluid and its use for the rheological modeling of blood

F. P. L. Massing, E. N. Vilchevskaya, W. H. Müller, V. A. Eremeyev

Modeling metamaterials by second-order rate-type constitutive relations between only the macroscopic stress and strain

V. Průša

Parameter calibration of micropolar yield criteria for composites via a multiscale discrete-continuum approach

M. Colatosti, P. Trovalusci, B. Carboni and S. Forest

A Generalized Macrohomogeneity Condition for Micropolar Continua

P. Trovalusci, M.L. De Bellis, G. Ongaro

Finite element analysis of crack growth near the tin phase transition in composite PCMs

Y. Viazovychenko, K. Naumenko, E. Gariboldi

Data-driven framework for rapid prediction of impact-induced deformation

X. Zhang, S. Chen, G. Lu

Mode transition of Kagome-based flexible metamaterials

R. Bao, J. Li, W. Chen

The effect of porosity on dynamic crack propagation in functionally graded materials using peridynamics

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ON ELLIPTICITY AND HYPERBOLICITY WITHIN NONLINEAR STRAIN GRADIENT ELASTICITY

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We discuss the hyperbolicity properties of the equations of motion for generalized models of structures and continua, such as strain-gradient elasticity, and their relation to the ellipticity of equations of statics. Unlike classical elasticity theory for simple materials, hyperbolicity does not automatically follow from ellipticity here, so further analysis is required. For example, we consider the one-dimensional case of an elastic bar and demonstrate some special cases.

Bounds for Multimaterial Composite Properties

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Abstract

This paper discusses bounds on the energy of periodic multicomponent composites made of linear materials. The bounds are defined by several prescribed parameters: the moduli of the constituent materials, their volume fractions, and the applied loading. Since all possible geometries are admissible, the optimal fields in the constituent materials are characterized by constant components that depend on the given parameters; thus, the optimization problem is finite-dimensional.

Each material is represented by an energy “well” that consists of its quadratic energy density and its cost. The minimal energy of a composite corresponds to the quasiconvex envelope of a Lagrangian defined as the minimum of several wells. The structure of the Lagrangian allows us to order the optimal fields in the materials and find explicit constraints on them. These inequalities are combined with the translation method, producing a modified procedure that we call the *constrained translation method*.

The resulting bounds depend on the active inequalities, which, in turn, are determined by the problem’s parameters. Consequently, the bounds admit different analytic expressions over different regions of the parameter space. The ordering of optimal fields provides insight into the geometry of optimal microstructures. In particular, they indicate that the topology of optimal composites alternates as the volume fractions of the constituent materials vary. In particular, they indicate the regions of parameter space where the constraints are inactive, and the traditional Hashin–Shtrikman and translation bounds are sharp; they also suggest improved, tighter bounds in the remaining regions.

Hidden Variables and Nonlocality in Multiscale Composite

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The microgeometry of the material determines its overall effective behavior in response to applied static or dynamic loadings. The influence of the processes on the microstructural level is captured by internal or hidden variables which are introduced to properly formulate problems governing the behavior of the fields and waves propagating in multiscale materials and heterogeneous media with microstructure. The talk discusses a set of internal variables that are naturally related to the structure of a composite material [1]. These hidden variables determine the characteristic internal scales in the composite corresponding to the micro-level processes of different characteristic wavelengths. The wave propagation in such materials is influenced by these micro-level processes; it is characterized by frequency dispersion and energy dissipation that result in a material with memory described by a time- and space-domain convolution kernel. For instance, in a non-dispersive homogeneous medium, a packet of sinusoidal wave functions of different frequencies travels without changing its shape, as all waves in the packet propagate at the same speed. In a medium with microstructure, every wave in the packet experiences multiple scatterings from the boundaries of inclusions; these effects lead to the dissipation of the wave's energy, which depends on the wavelength. As a result, waves of different frequencies travel at different speeds, and the shape of the wave packet is changing with time. We show the relationships between the internal hidden variables and the characteristic internal scales in the composite that determine the dispersion and dissipation phenomena in wave propagation through a micro-structured medium. The parameters of the composite's microgeometry are incorporated into the internal variables through the spectral measure in the Stieltjes analytic representation [2,3] of the effective properties of the composite; this spectral measure determines the equations for the evolution of the internal variables. The spectral measure contains all information about the geometry of the media on the microscale and links it through the hidden variables to the behavior of the material on the macroscale. We discuss an extension of the approach to the viscoelastic peridynamic model characterized by a non-constant complex-valued micro-modulus function.

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Wave attenuation in lattice metamaterials with additive manufacturing geometric imperfections

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Lattice metamaterials offer advanced capabilities for controlling wave propagation and mitigating vibrations through the tailored design of their internal geometry [1]. However, most modeling strategies rely on ideal periodicity, whereas structures fabricated via additive manufacturing inherently exhibit geometric defects. Assessing the impact of such imperfections on wave attenuation mechanisms is essential for the reliable design of architected materials [2]. This work investigates the wave propagation in 3D printed lattice metamaterials through a systematic comparison between ideal periodic models and as-built configurations. The study focuses on one-dimensional beam-like lattices obtained by the periodic repetition of selected two-dimensional unit cells (UC), examining how different geometric configurations affect dispersion characteristics and attenuation properties.

Dispersion relations and band gap properties of ideal lattices are first evaluated using Bloch-Floquet theory. Manufacturing defects are then introduced by developing finite element models based on real geometries of printed specimens. For finite structures, frequency response functions (FRF) are computed to directly quantify wave attenuation in the presence of weak and spatially distributed geometric disorder.

An experimental campaign is carried out on lattice specimens manufactured in thermoplastic polymers via fused deposition modelling (FDM). Experimental measurements are used to identify attenuation trends and validate the numerical predictions [3].

The outcomes highlight that even small geometric imperfections can significantly influence the wave propagation properties of lattice metamaterials, emphasizing the necessity of accounting for manufacturing effects during both modeling and design stages [4].

Keywords: 3D printing, metamaterials, unit cell geometry, wave propagation, geometric imperfections

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Semi-Analytical Finite Element Modeling of Nonlinear Nanoshells

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The nonlinear response of shell structures is highly sensitive to geometry, loading and imperfections. These effects are even more pronounced passing at micro- and nano-scale, where size-dependent phenomena also play an important role on the mechanical response. Capturing the combined effects of nonlinearity and nonlocality remains a major modeling challenge, requiring specialized and sophisticated computational tools.

To address this need, the present work introduces a new nonlinear finite element formulation for nanoshells which is capable of accounting for both geometric nonlinearities and nonlocal scale effects. The framework is implemented within the Kirchhoff–Love shell theory where geometric nonlinearities are introduced through the von Kármán hypothesis. Size dependency is incorporated via the second-order strain gradient constitutive model, leading to a final set of nonlinear partial differential equations of order six.

The solution of these equations is achieved through a combination of finite elements and perturbation approach. In this solution strategy, the generalized displacements of the shell are interpolated using a novel hierarchical Hermite polynomial space which satisfies the high continuity requirements of the nonlocal shell model. Subsequently, the finite element coefficients are expanded into an asymptotic series, leading to a semi-analytical solution of the nonlinear governing equations. This combination enables efficient and accurate prediction of postbuckling and nonlinear vibration responses of nanoshells.

Numerical results demonstrate the capability of the proposed framework to accurately capture the coupled effects of nonlinearity and nonlocality. Our results show significant deviations from classical models and highlight the importance of incorporating size-dependent effects in nonlinear nanoscale shell analysis.

TWO TIMES SCALE MODELLING OF CYCLIC DEFORMATION AND DAMAGE IN PLATES WITH AUXETIC CORE

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Three-layer (sandwich) plates are widely used as structural elements in aircraft. Their operating conditions are characterized by cyclic loading and thermal effects. Recent design solutions have led to the use of thin-walled elements with auxetic properties in their inner cores. This creates a need to develop approaches and methods for modeling such structural elements, taking into account nonlinear effects in deformation processes and the accumulation of hidden damage in the material.

The paper presents an approach for modeling nonlinear irreversible deformation and damage accumulation in cyclically loaded three-layer plates with an inner auxetic core. The method is based on a two-time-scale description of the plate's motion, using small parameters and subsequent averaging over a period of oscillation or loading–unloading. To describe the material behavior, constitutive and evolution equations developed for the averaged representation of cyclic loading or heating are employed. Their derivation is likewise based on the use of the asymptotic methods with small parameters and subsequent averaging over the periods of loading or heating/cooling. To adequately describe the nonlinear behavior of inner core material, the obtained constitutive and evolution equations for the damage parameter were verified using experimental data obtained on one-dimensional specimens for different values of stresses and temperatures.

The formulated averaged boundary–initial value problem is solved using a finite difference scheme, with finite element modeling performed at each time step. The computational method is implemented for both general three-dimensional modeling and plane stress/strain conditions.

Numerical results are compared with experimental data obtained under various loading conditions for both three-layer plates and their separate inner-core components. Problems of cyclic deformation, which in some cases are accompanied by the cyclic heating and cooling of the plates, and with consideration of hidden damage in the cells of the inner layer, are considered and discussed.

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JEFFERY'S EQUATION FOR A MICROPOLAR BACKGROUND FLUID AND ITS USE FOR THE RHEOLOGICAL MODELING OF BLOOD

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Cardiovascular diseases are still the leading cause of death worldwide. Consequently, research on blood in general and more specifically in the field of medical technology is highly active. For instance, knowledge about the hydrodynamic properties of blood is required for the design of medical devices such as blood pumps. Blood itself consists of white blood cells, platelets, and Red Blood Cells (RBCs) suspended in blood plasma. The deformable RBCs make up the majority of particles, while plasma is the major constituent within the suspension with approximately 55%. Plasma was considered an isotropic, incompressible Newtonian fluid model for many decades, whereas recent findings indicate a viscoelastic behavior under certain conditions. This can be attributed to proteins such as fibrinogen in plasma on a microscale. Hence, the plasma microstructure has a prominent effect and should not be neglected in material models for blood.

We consider blood as a concentrated suspension of RBCs that are idealized as rigid, spheroidal particles. In order to draw conclusions regarding the concentrated suspension, it is useful to start from a simplified, dilute system, that is, single spheroidal particles suspended in a fluid. Jeffery famously laid the foundation for equations governing the motion of such particles in a simple shear flow of an incompressible Newtonian fluid. These equations are expanded by additionally considering a background fluid with a microstructure to account for the microstructural nature of plasma. To this end, the background fluid is considered a micropolar fluid. In contrast to Newtonian fluids, the micropolar stress tensor consists of a symmetric Newtonian part, and a skew-symmetric part due to the friction caused by a microstructure rotating at an angular velocity different to the fluid vorticity. The spin balance is no longer fulfilled identically, and must be solved explicitly to obtain the fluid's micro- and macromotion. It depends on the macroscopic stress and couple stresses, which comprise the material's internal moments. Whereas classical micropolar fluid theory does not incorporate any viscoelastic features, several generalized theories exist to model more complex material behavior, *e.g.*, viscoelastic micropolar or micromorphic theory. The presented equations will therefore serve as a starting point for the motion of complex fluids containing structures on both the meso- and microscale.

The particle kinematics are investigated for single particles as well as particle ensembles. Additionally, effective rheological properties are derived. The differences from the original Jeffery equations with respect to oscillation periods, flow alignment, and effective viscosity are carved out. The effect of length scale ratios between particles on the meso- and the macroscale is analyzed. Results are further compared to experimentally obtained rheological properties of human blood from literature. Existent similarities are presented and steps necessary to improve the agreement between reality and model are proposed.

MODELING METAMATERIALS BY SECOND-ORDER RATE-TYPE CONSTITUTIVE RELATIONS BETWEEN ONLY THE MACROSCOPIC STRESS AND STRAIN

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Following [2], we discuss a novel thermodynamically based approach for constructing effective rate-type constitutive relations describing finite deformations of *metamaterials*. The effective constitutive relations are formulated as *second-order* in time rate-type Eulerian constitutive relations between only the Cauchy stress tensor, the Hencky strain tensor, and objective time derivatives thereof. In particular, there is no need to introduce additional quantities or concepts such as “micro-level deformation”, “micromorphic continua”, “enriched continua”, or elastic solids with frequency dependent material properties.

The linearisation of the proposed fully nonlinear (finite deformations) constitutive relations leads, in Fourier space, to the same dispersion relations as those commonly used in metamaterial theories based on the concepts of frequency dependent density and/or stiffness. From this perspective the proposed constitutive relations reproduce the behaviour predicted by the frequency dependent density and/or stiffness models, but yet they work with constant — that is motion independent — material properties. The behaviour predicted by the linearised models is documented through numerical experiments exploiting the dispersion-relation preserving discretisation proposed in [1].

Finally, we argue that the proposed fully nonlinear (finite deformations) second-order in time rate-type constitutive relations do not fall into the traditional classes of models for elastic solids (hyperelastic solids/Green elastic solids, first-order in time hypoelastic solids), and that the proposed constitutive relations embody a new class of constitutive relations characterising elastic solids.

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Parameter calibration of micropolar yield criteria for composites via a multiscale discrete-continuum approach

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Keywords: Yield criteria parameters, Micropolar continua, Multiscale discrete-continuum modelling, optimisation strategy

The macroscopic mechanical response of composite materials is significantly affected by microscale heterogeneities, such as voids, cracks, and inclusions, which complicate classical macromechanical descriptions. To effectively including microstructural size effects, this work utilises micropolar theory, through a two-level descriptions. The material is analysed both as a discrete system of rigid particles interacting via non-linear interfaces and as a corresponding non-linear continuum, assuming elasto-plastic behaviour. While elastic constitutive parameters are derived via a multiscale identification procedure [1], the parameters defining the yield domain [2] are measured using an optimisation strategy based on a genetic algorithm [3-4]. In this context, the micropolar model is calibrated using measurements extracted from the discrete system analysis. Numerical studies show the efficacy of this methodology in bridging discrete and continuum descriptions, facilitating the identification of several constitutive parameters that are typically unknown or limited to parametric sensitivity analyses. Consequently, the proposed framework supports the practical application of equivalent micropolar models for materials with complex microstructures and establishes a basis for future experimental validation.

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A Generalized Macrohomogeneity Condition for Micropolar Continua

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Keywords: Micropolar continua, Homogenization, Skew-symmetric strain and stress, Dirichlet and Neumann boundary conditions

Multiscale homogenization is a well-established framework for predicting the effective response of complex materials in both linear and nonlinear regimes. Within this context, the present contribution proposes a generalized Hill-type macrohomogeneity condition for the homogenization of heterogeneous micropolar continua [1–3].

Within a unified tensorial framework, energetically consistent Dirichlet and Neumann boundary conditions are derived from power equivalence, ensuring scale-consistent energy balance and providing a coherent setting for homogenization of materials whose response is strongly influenced by internal microstructure and associated rotational degrees of freedom.

The proposed framework is assessed through finite element analyses performed on both homogeneous and periodic heterogeneous media, demonstrating the effectiveness and energetic consistency of the formulation [4]. The methodology offers a solid basis for future developments, including applications to composite materials with random microstructures.

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FINITE ELEMENT ANALYSIS OF CRACK GROWTH NEAR THE TIN PHASE TRANSITION IN COMPOSITE PCMs

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Phase Change Materials (PCMs) are widely employed in thermal energy systems owing to their latent heat effects during phase transformations. A key limitation of composite PCMs is liquid-phase leakage, which in some systems appears already during the initial thermal cycles. Despite its technological relevance, the microstructural mechanisms governing leakage pathway formation remain insufficiently resolved.

Thermal cycling induces localized thermomechanical stresses due to mismatches in thermal expansion and elastic properties between the PCM matrix and embedded inclusions. In the tin-containing composite system considered here, attention is focused on the temperature range near the tin phase transition, where changes in volumetric response and mechanical properties modify the driving forces for defect evolution in the matrix–inclusion region.

The present study investigates a crack-growth mechanism for leakage initiation at the microstructural level. A two-dimensional finite element model of a representative composite element containing a tin inclusion and an initial crack is developed to resolve thermally induced stress–strain fields during heating and cooling across the tin phase transition.

Within the framework of linear elastic fracture mechanics, the temperature dependence of the mode-I stress intensity factor K_I is quantified as a function of crack length and geometry. This analysis identifies temperature intervals associated with peak K_I values, determines defect sizes for which the stress intensity factor reaches the critical fracture toughness K_{Ic} , and characterizes the sensitivity of the response to variations in microstructural parameters.

The results establish a mechanistic link between stress amplification near the tin phase transition and crack-growth activation, providing a microstructural basis for subsequent three-dimensional and multiscale thermomechanical analyses of composite PCMs.

DATA-DRIVEN FRAMEWORK FOR RAPID PREDICTION OF IMPACT-INDUCED DEFORMATION

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Rapid and reliable prediction of structural deformation under impact loading is critically needed for impact-resistant design and safety assessment, particularly in scenarios where extensive experimental testing is impractical. This study proposes a machine-learning-based collaborative framework that integrates impactor material classification with plate deformation prediction, enabling efficient and accurate estimation of the maximum central deformation of plates subjected to impact.

An impact database is established by integrating experimental data from multiple impact scenarios, covering a wide range of velocities and material responses. To improve model generality and reduce platform-dependent variability, physically motivated dimensionless parameters are introduced alongside conventional geometric and material descriptors. These parameters are incorporated into multiple input schemes for machine learning models, including ensemble methods and neural networks.

The results demonstrate that prior classification of impactors based on their dominant mechanical response significantly enhances deformation prediction accuracy. Compared with direct regression approaches and conventional semi-empirical models, the proposed framework achieves improved predictive performance and robustness. Further analysis reveals that the inclusion of dimensionless groups is critical for capturing the underlying impact mechanics and improving model interpretability. The potential of data augmentation techniques for small-sample impact datasets is also investigated.

The proposed framework provides a practical alternative to extensive experimental testing, enabling rapid estimation of deformation limits and offering insights into impactor target material interactions. This work highlights the capability of data-driven methods to complement classical impact mechanics and supports their application in transportation, aerospace, and infrastructure safety design.

Mode transition of Kagome-based flexible metamaterials

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Abstract

Mechanical metamaterials are artificially engineered and structured materials designed with intricate building blocks to achieve special properties that surpass the inherent characteristics of the base materials, showcasing diverse static and dynamic characteristics. The dynamic and static characteristics of a class of mechanical metamaterials with elastic hinges are systematically investigated by using theoretical, numerical and experimental tools in this work. Focusing on the elastic wave propagation and nonlinear deformation behavior of the structures, the unusual wave phenomena, nonlinear responses, structural instability properties and deformation mode transitions in mechanical metamaterials are explored, which provide ideas for tuning elastic waves, manipulating deformation modes, and realizing vibration control in engineering.

Some simplified models are proposed for a class of mechanical metamaterials with elastic hinges aid in simplifying computations, discovering, and analyzing the rich dynamic phenomena and complex static behaviors for the system. Such analytical approach can be utilized not only for the issues addressed in this dissertation but also for investigating the dynamic and static properties of a broader range of mechanical metamaterials. The ZGV modes, solitary wave propagation, static bifurcation behavior, as well as wide and low-frequency bandgap characteristics in the mechanical metamaterials with elastic hinges proposed in the work, offering innovative ideas and solutions for engineering applications and frontier research areas such as energy harvesting, impact control, programmable metamaterial design, and noise reduction.

THE EFFECT OF POROSITY ON DYNAMIC CRACK PROPAGATION IN FUNCTIONALLY GRADED MATERIALS USING PERIDYNAMICS

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Crack initiation and propagation under impact loading have been extensively studied due to their critical role in engineering applications. Although brittle materials are widely used for their hardness and wear resistance, their low toughness and sensitivity to internal defects limit their structural performance. In particular, porosity—often present at small scales—can significantly influence fracture behavior and should not be neglected in mechanical analyses. This study investigates dynamic fracture behavior in porous brittle materials by incorporating functionally graded material (FGM) concepts. A bond-based Peridynamic (PD) framework is employed to model crack initiation and propagation under impact loading conditions. The material gradation is defined through spatial variation of mechanical properties, enabling the assessment of how gradual transitions in stiffness affect crack evolution. A two-dimensional representation is utilized to systematically analyze the influence of porosity and material gradation on fracture response. The findings highlight the importance of both porosity and material gradation in governing crack propagation characteristics, demonstrating the potential of PD-based approaches for the design of more damage-tolerant structures.

MS-5 Mechanics of Thin Films and Interfaces

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Constitutive Modeling of Heat- and Solvent-Driven Shape Memory Behavior in Thiol-Ene/Acrylate Polymers

S. Xu, R. Xiao, J. Song

Intrinsic Indefatigability of Monolayer Two-Dimensional Covalent Crystals

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High-precision subtle gesture recognition based on stretchable ultrasonic sensor

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Kirigami-based reconfigurable metasurfaces for selective electromagnetic transmission modulation

C. Wang

Advanced transfer printing techniques based on tunable adhesives

J. Song

Fracture and Delamination of Film/Substrate Systems in Nuclear Reactors under Complex Service Conditions

W. Zhang, M. Han, S. Luo, Y. Zhang, T. Bao, X. Huang

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Multiscale Biomechanical Modeling of Ciliary Muscle Contraction and Its Influence on Corneal Deformation

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Phase Transition Adhesion Control for Transfer Printing of Locally Melted Liquid Metal Stamps

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Constitutive Modeling of Heat- and Solvent-Driven Shape Memory Behavior in Thiol-Ene/Acrylate Polymers

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Thiol-ene/acrylate shape memory polymers (SMPs) are attractive for biomedical and soft-device applications since their recovery behavior and mechanical properties can be tuned under physiologically relevant conditions. In this work, a constitutive model is developed for a thiol-ene/acrylate network. The model combines a finite deformation generalized Maxwell model with a temperature- and concentration-dependent shift factor derived from free-volume theory, allowing solvent uptake through diffusion process to modify local relaxation kinetics in a physically transparent manner. Model parameters are identified from standard material characterization, and the governing equations are solved within a fully coupled chemo-mechanical setting. Predictions are validated against uniaxial tension and bending recovery experiments conducted at 37 °C in air and in 0.9 wt% NaCl solution. Good agreement is obtained for both dry thermal recovery and solvent-assisted actuation. The proposed framework provides a physically grounded and computationally tractable route for predictive analysis of solvent-responsive SMPs.

Intrinsic Indefatigability of Monolayer Two-Dimensional Covalent Crystals

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Two-dimensional (2D) materials have shown enormous potentials in the application of electronics, electromechanical systems, and composite materials. Of particular importance is to understand the fatigue behavior of 2D materials for their performance optimization and reliability evaluation. However, the damage mechanisms of 2D materials under cyclic loading are currently unclear and there exists a debate upon whether they exhibit the fatigue phenomenon. Furthermore, due to their small size and low dimensionality, it remains a daunting challenge in terms of clamping and loading of 2D materials, let alone the accurate characterization of their deformation and failures. To this end, here we present the fatigue studies of freestanding 2D materials based on atomic force microscopy, and the indefatigability of monolayer crystals is demonstrated according to the temperature dependence of service lifetime interpreted by the modified Arrhenius model. Our work not only provides deeper insights into the atomistic failure mechanism of these atomically thin materials but also guides the optimization of mechanical reliability of 2D materials-based devices.

Keywords: Nanomechanics; 2D materials, fatigue, atomic force microscopy

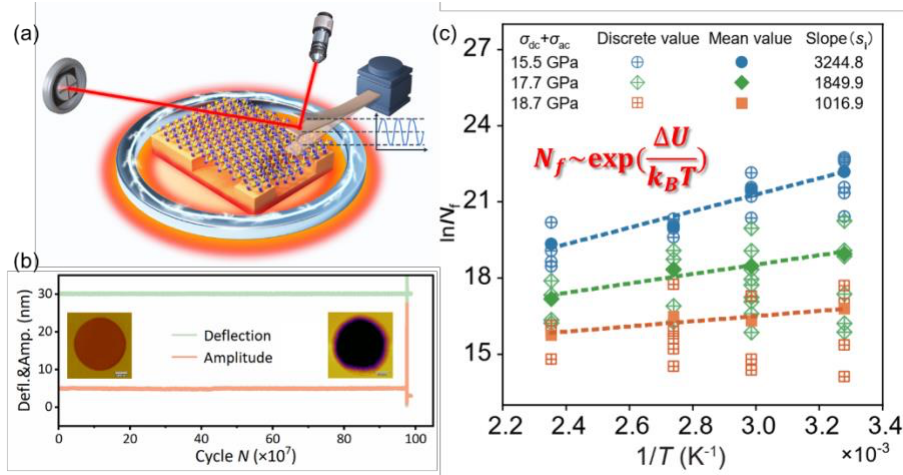


Figure 1. (a) Schematic of the AFM-based experimental setup equipped with a thermal control stage. (b) Representative plots showing the probe deflection and tip oscillation amplitude as a function of the number of loading cycles, where sudden jumps indicate the damage in the tested sample. (c) The life to failure as a function of temperature under different loading conditions, following an exponential correlation.

High-precision subtle gesture recognition based on stretchable ultrasonic sensor

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Subtle gesture recognition is fundamental for natural human-computer interaction, yet existing solutions suffer from inherent limitations. Herein, we propose a stretchable ultrasonic sensor (4 functional sites, 16 piezoelectric modules) with a fan-shaped design (30% stretchability), enabling close conformity to diverse users' forearms and precise attachment to target muscle regions. Experimental and numerical results verify its sub-millimeter spatial resolution and superior signal-to-noise ratio. Integrated with a 1D convolutional neural network (1D-CNN), the system reaches 98.75% recognition precision for subtle metacarpophalangeal joint movements ($<5^\circ$ angular changes), which is unattainable by existing approaches. The multichannel design ensures high classification precision, good classification balance, low user dependence, and strong robustness to sensor placement variations, offering insights for more reliable and adaptive human-computer interaction systems.

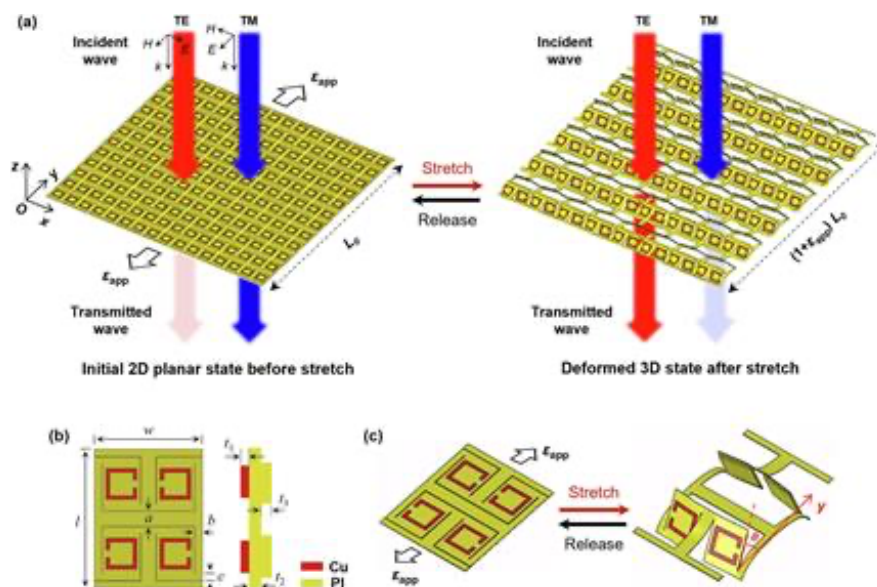
Kirigami-based reconfigurable metasurfaces for selective electromagnetic transmission modulation

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Tunable three-dimensional (3D) electromagnetic metasurfaces are essential for achieving selective modulation of polarized waves, but they usually require complex designs and the use of smart materials, posing great implementation challenges. Here, we propose a novel kirigami-based reconfigurable electromagnetic metasurface, which consists of a kirigami-based deformable thin polyimide substrate and periodically arranged copper split-ring resonators. By simple stretch, the two-dimensional (2D) planar metasurface can be uniformly transformed into a 3D state, enabling it to effectively and selectively modulate linearly and circularly polarized waves. Experimental and numerical results reveal the mechanical deformation and transmission characteristics of the metasurface under applied strains. It is shown that the metasurface exhibits good selective transmission tunability while the resonant frequency remains basically unchanged for both transverse electric and transverse magnetic polarized waves. Furthermore, the selective tuning mechanism and the influence of geometrical parameters are also illustrated by the equivalent circuit analysis.



Reference

He, S., Wang, C., Tao, J. et al. A kirigami-based reconfigurable metasurface for selective electromagnetic transmission modulation. *npj Flex Electron* 8, 48 (2024).

ADVANCED TRANSFER PRINTING TECHNIQUES BASED ON TUNABLE ADHESIVES

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Transfer printing is an emerging deterministic assembly technique, which enables the heterogeneous integration of classes of materials into desired functional layouts. It creates engineering opportunities in flexible and stretchable inorganic electronics and next generation Micro-LED display technology. The key for a successful transfer printing is the ability of adhesion switch from strong state for pick-up to weak state for printing. Here, we will present our recently developed advanced transfer printing techniques with extraordinary capabilities of deterministic assembly based on the design of tunable adhesives.

Fracture and Delamination of Film/Substrate Systems in Nuclear Reactors under Complex Service Conditions

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Abstract:

Film/substrate systems are widely employed in nuclear reactor structures, such as chromium coatings on fuel cladding for corrosion resistance in pressurized water reactors and oxide films formed on cladding surfaces in lead–bismuth fast reactors to mitigate liquid metal corrosion. During service, these systems are subjected to coupled multi-physical fields, including neutron irradiation, thermo-mechanical loading, and fluid erosion. The resulting failure modes, such as cracking and delamination, critically affect reactor safety and service life. To address this issue, this study systematically investigates the coupling between irradiation effects and interfacial mechanics. First, a strength-based numerical framework is developed to analyze the influence of neutron irradiation on film cracking behavior. The results show that irradiation-induced hardening of the substrate enhances interfacial shear transfer, leading to a reduction in crack initiation strain and an increase in saturated crack density. Furthermore, to overcome the limitation of conventional shear-lag models in describing crack-free film states, an elastoplastic shear-lag model is established, in which both the film and substrate are treated as ideal elastoplastic materials. Analytical solutions for stress distributions and crack density under different elastoplastic regimes are derived. A crack initiation criterion governed by the competition between yielding and fracture is proposed. In addition, considering fluid erosion effects, an interfacial stress model for partially debonded film/substrate systems and a film delamination kinetics model are developed. Meanwhile, strain rate plays a crucial role in interfacial mechanical responses, with interfacial strength, toughness, and delamination behavior exhibiting pronounced rate dependence. In summary, this work systematically investigates the failure behavior of film/substrate systems under complex service conditions through numerical simulation, theoretical modeling, and mechanistic analysis. It advances the fundamental understanding of interfacial mechanics under irradiation and multi-field coupling, and provides a unified theoretical framework for describing cracking and delamination in film/substrate systems.

Keywords:

Film/Substrate Systems, Surface Cracks, Delamination, Neutron Irradiation, Flow Erosion, Rate Dependence

Unusual stretching-twisting of liquid crystal elastomer bilayers

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Liquid crystal elastomers (LCEs), as a unique class of smart soft materials combining the properties of liquid crystals and hyperelasticity, are capable of rapid, anisotropic, and reversible deformations in response to mechanical, thermal or optical stimuli. Here, we report a hitherto unknown stretching-induced twisting behavior of LCE bilayer strips. Under uniaxial stretching, we reveal that due to the spontaneous mismatch strain arising from interlayer anisotropy, the bilayer strips exhibit notable twisting deformations. We develop an LCE bilayer strip model based on semi-soft elasticity to quantitatively understand and predict such intriguing tension-twisting response. Based on our experiments and theoretical analyses, we systematically explore how the liquid crystal director orientation, geometric dimensions and material parameters of the strips would affect the twisting behavior. We find that when the alignment of directors of bilayer are symmetric about the stretching direction, a larger deviation angle of the initial directors results in a more significant twisting deformation. Additionally, a longer, narrower and thicker strip has a more pronounced twisting effect. Furthermore, the material anisotropy encourages the twisting, while the feature of semi-soft elasticity discourages it. The findings not only reveal the tension-twisting coupling behavior of LCE bilayer strips, but also offer new insights into the design of LCE actuators, intelligent structures and soft robots.

Tunable Flexible Capacitive Sensor for Dynamic Pressure Monitoring

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Flexible capacitive pressure sensors have gained widespread application in health monitoring, robotics, and structural diagnostics. However, conventional designs that rely on flat or micropatterned dielectric layers typically offer high sensitivity only at low pressures and possess limited tunability, which makes them unsuitable for dynamic or harsh environments. In this study, we present a tunable capacitive pressure sensor fabricated via buckling-guided assembly and laser cutting, which transforms 2D precursors into 3D cage-like architectures. The sensor exhibits pressure-dependent sensitivity, characterized by low sensitivity under small loads and significantly enhanced sensitivity at higher loads due to nonlinear variations in electrode spacing. It achieves outstanding performance, including high durability over 6000 cycles, a low detection limit (~ 2 Pa), minimal hysteresis ($\sim 4\%$), and rapid response and recovery times (131/140 ms). Finite element analysis and experimental validation confirm the tunable mechanical response and accurate electromechanical behavior enabled by geometric design. The sensor also allows reversible tuning through lateral strain and liquid encapsulation, enhancing environmental robustness. Moreover, a compression-induced rotation mechanism further improves sensitivity by increasing electrode overlap during loading. Wind tunnel experiments validate the sensor's performance under extreme conditions, demonstrating strong potential for practical applications.

Nanohelical Electronics Assisted by Mismatch-Stress-Driven Buckling

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Air- and moisture-permeable stretchable electronics are highly desirable for epidermal devices, yet achieving permeability together with strain-invariant electrical performance remains a fundamental challenge in thin-film mechanics. Here we report a materials-agnostic strategy to fabricate nanohelical electronic films through mismatch-stress-driven buckling of pre-stretched electrospun nanofilms. Guided by thin-film instability and interface-mediated deformation, initially planar fibrous films evolve into three-dimensional helical architectures with high permeability, low effective stiffness, and exceptional deformability. Mechanically, the nanohelical topology introduces spring-like deformation and twist-bend coupling, which redistribute strain, alleviate local stress concentration, and suppress electromechanical drift under large stretching. Finite-element analysis captures the roles of geometric nonlinearity, buckling evolution, and interfacial mechanical coupling in governing the observed strain-insensitive behavior. Because the approach relies on structural transformation rather than material-specific processing, it can be broadly applied to metals and organic/inorganic semiconductors. The resulting nanohelical thin-film systems enable stable operation of epidermal electrodes, deformable interconnects, electroluminescent devices, and multimodal sensors, offering a general mechanical framework for permeable and robust soft electronics.

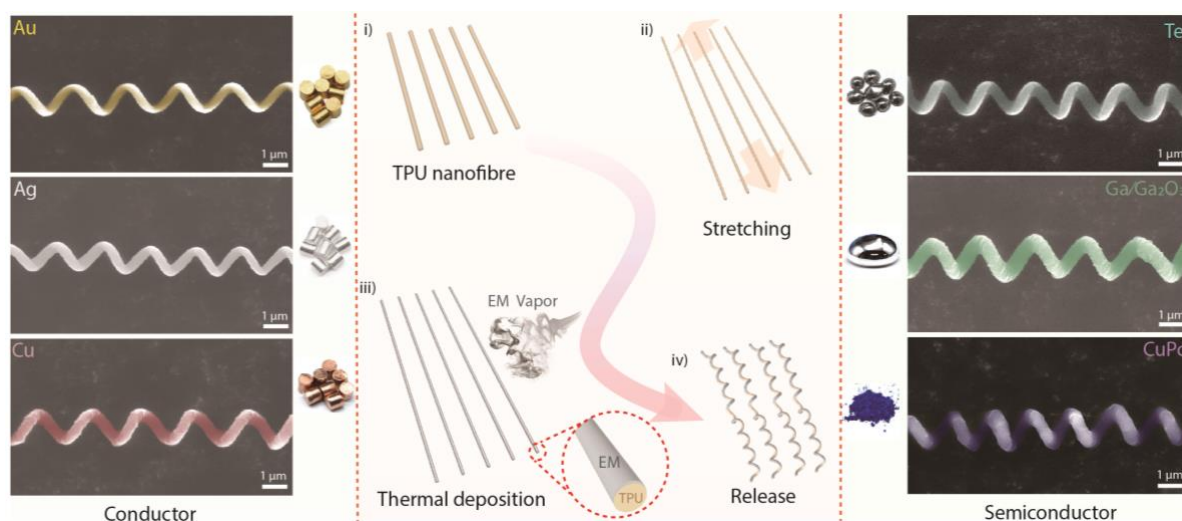


Figure: Schematic diagram of the preparation of the nanohelical structures with various electronic materials on the surface. e, Helices of alternating chirality connected by perversions along an individual nanomembrane.

Multiscale Biomechanical Modeling of Ciliary Muscle Contraction and Its Influence on Corneal Deformation

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Understanding the biomechanical role of the ciliary muscle in accommodation is essential for elucidating the pathogenesis of myopia, particularly its mechanical influence on the cornea as a thin membranous structure. In this study, a population-averaged axisymmetric finite element model of the human eye was developed, where the ciliary muscle was characterized using a microstructure-based (MB) constitutive model incorporating matrix, collagen fibers, and myocytes, with active contraction simulated via an electro-chemo-mechanical coupled model; the cornea was modeled using ex vivo lens observation and uniaxial tensile testing on corneal lenticule strips from 60 patients combined with numerical simulations, while other tissues were modeled with a neo-Hookean hyperelasticity; intraocular pressure (IOP) and aqueous humor circulation were integrated using fluid cavity and transport methods. During simulated near vision, active contraction of ciliary muscle myocytes generated nonlinear contractile stress that increased rapidly before plateauing, with the circular component contributing most significantly. This contraction induced anterior displacement of the corneal apex (axial elongation) and oscillatory movement of the posterior pole, while IOP showed a gradual increase that initially rose positively and then reversed direction. Notably, the model did not predict posterior displacement of the fundus during near vision, likely due to the exclusion of zonule-lens mechanical interactions. In conclusion, this study presents the first multiscale finite element model of the human eye that captures the active contraction of the ciliary muscle and its direct influence on corneal apex displacement, suggesting a biomechanical pathway for myopia progression and providing new insights into IOP dynamics during accommodation; future work will focus on parameter calibration, incorporation of initial ocular geometry, inclusion of zonular fibers, and experimental validation.

Phase Transition Adhesion Control for Transfer Printing of Locally Melted Liquid Metal Stamps

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Abstract: Transfer printing, a key heterogeneous integration technique, has recently gained much attention due to its crucial role in enabling unconventional layouts and developing high-performance electronic systems. A significant challenge is the potential destruction of ultrathin membranes during the pick-up and print processes due to the contact force of traditional elastic stamps, which becomes particularly critical when handling fragile inorganic nanomembranes. Herein, we present a precision-induced localized molten technique, employing either laser- induced transient heating or hotplate-induced directional heating to precisely melt solid gallium (Ga), which leverages the fluidity of localized molten liquid metal (LM) to avoid damage on fragile thin films. The proposed localized molten stamp features a gentle contact force and exceptional conformal adaptability, yet it improves operation reliability when compared to the fully liquefied Ga stamp. Furthermore, the phase transition of metal Ga provides reversible adhesion with high adhesion switchability. Once solidified, the Ga stamp hardens and securely adheres to the micro/nano-membrane during the pick-up process, demonstrating an outstanding adhesive strength. The Ga stamp also exhibits the capability to maneuver arbitrarily shaped objects by generating a substantial grip force through the interlocking effects. Such a robust, damage-free, simply operable protocol illustrates its extraordinary capabilities in transfer printing diverse ultrathin membranes and objects on complex surfaces for developing high- performance unconventional electronics.

MS-6 Biomechanics

Marco Amabili (Westlake University, Hangzhou, China), Michele Tepedino (Università degli Studi dell'Aquila, Italy)

MS-9 Computational models of bone remodeling and healing at different scales

Michał Nowak (Poznan University of Technology, Poland), Jean-Francois Ganghoffer (Université de Lorraine, France)

Mechanical Characterization of Skeletal Muscle in Neurological Disorders

K. Belghith, A. Aghaei, W. Maktouf, M. Zidi

Sensitivity analysis as a verification tool for annulus fibrosus material modeling in finite element studies of lumbar disc degeneration

O. Ardatov, S. R. Fernandes, A. Kilikevicius, V. Alekna

Next-Generation Clear Aligners: Integrating Electromagnetic Force Systems with Enhanced Biocompatible Materials

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Smart Mandibular Advancement Devices for Obstructive Sleep Apnea: Integrating Sound and Temperature Sensors for Continuous Therapeutic Monitoring

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Beyond the Virtual Plan: Mechanics of Unplanned Forces in Aligner Therapy

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From Biology to Mechanics: Understanding and Optimising Orthodontic Tooth Movement with Clear Aligners

M. Tepedino

Variational analysis of the Canham-Helfrich energy functional

L. Lussardi

A novel constitutive model for vascular smooth muscle contribution into mechanical response of aortic tissue

G. Prezioso, I. D. Breslavsky, M. Zingales, M. Amabili

Biomechanics and the Mechanics of Living Systems

Y. Rémond

A multiscale research protocol for the study of craniofacial growth in orthodontics

A. Pasqualini, G. Caldarelli, L. Putignani, G. Di Carlo

Structural optimization principles as guidelines for trabecular bone treatment models

M. Nowak, K. Sędlak

From mechanical to biomechanical: A biomimetic framework

K. Sędlak, M. Nowak

A Reduced-Order Hyper-Viscoelastic Framework for Corneal Biomechanics and Shear Wave Propagation

P. Mazinani

Mechanical Characterization of Skeletal Muscle in Neurological Disorders

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This study is part of a research project focused on characterizing the muscle–tendon complex, with special attention to skeletal muscle. This soft biological tissue is essential for movement, force generation, and stability, and is notable for its hierarchical structure and capacity to store mechanical energy. Despite these strengths, skeletal muscle is highly susceptible to injury, particularly in neuromuscular disorders and central nervous system trauma, such as stroke.

To address this important challenge, our recent work has combined fundamental analysis with biomechanical assessment and clinical application. By integrating computational modeling, numerical analysis, and experimental measurements, we aim to better understand tissue mechanics and muscle degeneration, with the broader goal of improving rehabilitation strategies following central neurological disorders.

The main objective is to conduct a multiscale analysis and quantify the biomechanical properties of healthy and pathological muscles, from their microscopic components to the whole tissue level. To this end, advanced methods are used to characterize the mechanical behavior of biological tissues both *in vivo* and *in vitro*. Mechanical tests, including tensile and stress-relaxation experiments, are performed on healthy and pathological muscles to evaluate their visco-hyperelastic properties, as well as changes in the density and organization of muscular microstructures.

These approaches are complemented by non-invasive techniques such as elastography, which relies on the propagation and measurement of shear waves propagations to provide real-time assessment of muscle mechanical properties. Combined with numerical methods, this technique also makes it possible to evaluate stress distribution within the muscle, thereby improving our understanding and supporting more personalized treatments.

Overall, our results indicate that pathological muscle manifests structural and mechanical alterations, including atrophy, connective tissue remodeling, increased collagen accumulation, and changes in viscoelastic and anisotropic properties, along with increased stress concentration.

SENSITIVITY ANALYSIS AS A VERIFICATION TOOL FOR ANNULUS FIBROSUS MATERIAL MODELING IN FINITE ELEMENT STUDIES OF LUMBAR DISC DEGENERATION

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Finite element (FE) modeling is widely used to investigate the biomechanics of lumbar intervertebral disc degeneration; however, the predictive reliability of such models remains strongly dependent on material assumptions, particularly for the annulus fibrosus. Due to the absence of standardized experimental benchmarks and the inherent limitations of biological tissue testing, direct validation of disc material models is often infeasible. In this context, sensitivity analysis provides a critical alternative framework for assessing model robustness, parameter influence, and internal consistency. The present study extends previous investigations of degeneration-dependent loading strategies by focusing on the sensitivity of nucleus pulposus mechanical response to different constitutive descriptions of the annulus fibrosus.

Three commonly used material models for the annulus fibrosus were examined: linear elastic, Mooney–Rivlin hyperelastic, and Ogden hyperelastic formulations. Each model was implemented within an identical three-dimensional FE representation of a lumbar spinal segment with progressive disc degeneration. Sensitivity analyses were performed by systematically varying key material parameters within physiologically reported ranges for each constitutive model, while maintaining consistent geometry, boundary conditions, and loading configuration. The primary outcome measures were changes in stress and strain distributions within the nucleus pulposus, as well as global reaction forces, enabling assessment of how annulus material uncertainty propagates into nucleus mechanics.

The results demonstrate that the sensitivity of nucleus pulposus stress state is strongly dependent on the selected annulus material formulation. Linear elastic models exhibited the lowest parameter sensitivity, with relatively modest variations in nucleus stress under parameter perturbations, but showed limited ability to capture nonlinear load redistribution associated with degeneration. In contrast, hyperelastic formulations revealed substantially higher sensitivity, reflecting their stronger coupling between annulus deformation and nucleus confinement. Among these, the Ogden model displayed the greatest influence of parameter

variation on nucleus stress and strain, particularly under advanced degeneration, while the Mooney–Rivlin model exhibited intermediate sensitivity and more stable trends across degeneration stages.

These findings highlight that the apparent robustness of a model may depend not only on the magnitude of predicted stresses but also on how strongly outcome variables respond to plausible parameter uncertainty. From a methodological standpoint, high sensitivity is not inherently detrimental; rather, it indicates that the model is responsive to material changes that are biomechanically relevant. However, excessive sensitivity may compromise interpretability when experimental constraints on material parameters are weak. Therefore, the choice of annulus fibrosus material model should be guided by the intended research objective: linear elastic formulations may be sufficient for qualitative trend analysis, while hyperelastic models are more suitable for mechanistic investigations, provided their sensitivity is explicitly quantified.

The study further argues that sensitivity analysis represents a practical and necessary component of model verification and indirect validation in spinal biomechanics. Experimental validation of disc tissue properties is constrained by limited specimen availability, altered post-mortem conditions, non-physiological testing environments, and the inability to perform repeated measurements on the same sample. Under these conditions, demonstrating that a model exhibits stable, explainable, and degeneration-consistent responses to parameter variations becomes a critical indicator of credibility.

In summary, this work underscores the importance of integrating sensitivity analysis into FE studies of intervertebral disc degeneration and provides comparative insight into how different annulus fibrosus material models influence nucleus mechanics. The presented framework supports more transparent model selection, improves interpretability of computational predictions, and contributes to the development of more robust and verifiable biomechanical simulations.

Next-Generation Clear Aligners: Integrating Electromagnetic Force Systems with Enhanced Biocompatible Materials

V. Grassia

This report explores the potential integration of innovative force-control systems in orthodontic therapy using clear aligners, with a focus on enhancing biomechanical efficiency and biocompatibility. Contemporary aligner-based treatments rely heavily on composite attachments bonded to tooth surfaces to facilitate controlled tooth movement. While these attachments have proven clinically effective, they present certain limitations related to aesthetics, patient comfort, plaque accumulation, and the precision of force application. In parallel, the thermoplastic materials currently used in aligner fabrication, although widely accepted, may not represent the optimal solution in terms of long-term biocompatibility and environmental sustainability.

The present work investigates the feasibility of replacing conventional attachments with alternative systems characterized by electromagnetic properties. Such systems could allow for a more dynamic and programmable control of orthodontic forces, potentially enabling clinicians to modulate force magnitude, direction, and timing with greater accuracy than is currently achievable. By embedding micro-scale electromagnetic components either within the aligner structure or as minimally invasive elements associated with the tooth surface, it may be possible to generate controlled force fields that guide tooth movement in a more efficient and predictable manner. This approach could also reduce the need for visible attachments, thereby improving the aesthetic appeal of the treatment and patient compliance.

In addition to force-control innovations, the report examines the possibility of substituting traditional plastic aligner materials with more advanced biocompatible alternatives. Emerging materials, including bioinert polymers, biodegradable composites, or hybrid biomaterials, may offer improved interaction with oral tissues, reduced risk of allergic or inflammatory responses, and enhanced mechanical properties. Such materials could also address concerns related to microplastic release and environmental impact, aligning orthodontic practice with broader sustainability goals.

The combination of electromagnetic force systems and novel material science represents a paradigm shift in aligner therapy. However, significant challenges must be addressed before clinical implementation. These include ensuring the safety and stability of electromagnetic components in the oral environment, developing reliable methods for their activation and control, and validating their effectiveness through rigorous experimental and clinical studies. Furthermore, regulatory considerations, cost implications, and patient acceptance must be carefully evaluated.

This report aims to provide a conceptual framework for future research and development in this field, highlighting both the opportunities and the limitations of such an approach. By rethinking the fundamental mechanisms through which orthodontic forces are generated and delivered, it may be possible to overcome current constraints and achieve a higher level of precision, efficiency, and patient-centered care in aligner-based orthodontics. Ultimately, the integration of advanced technologies and materials could redefine the standards of modern orthodontic treatment, paving the way for more personalized and biologically compatible therapeutic solutions.

Smart Mandibular Advancement Devices for Obstructive Sleep

Apnea: Integrating Sound and Temperature Sensors for

Continuous Therapeutic Monitoring

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Obstructive sleep apnea (OSA) is a common sleep-related breathing disorder characterized by recurrent episodes of upper airway collapse during sleep, causing hypoxemia, sleep fragmentation, and excessive daytime sleepiness. When associated with other comorbidities, the condition is more appropriately defined as obstructive sleep apnea syndrome (OSAS). OSA is increasingly recognized as a relevant public health issue because of its high prevalence, frequent underdiagnosis, and significant systemic consequences, including neurocognitive impairment, reduced quality of life, cardiovascular morbidity, and increased occupational and road accident risk. The pathogenesis of OSA is multifactorial and involves upper airway anatomical susceptibility, altered neuromuscular control, and sleep-related changes in ventilatory regulation. Major risk factors include obesity, craniofacial anomalies, adenotonsillar hypertrophy, smoking, alcohol use, sedative medications, and family history. Clinical evaluation may be supported by validated screening tools, including the Epworth Sleepiness Scale and STOP-Bang questionnaire, while definitive diagnosis is based on polysomnography or cardiorespiratory sleep monitoring. Therapeutic management includes continuous positive airway pressure, surgical interventions, and mandibular advancement devices, which are particularly indicated in mild to moderate cases. Despite their clinical usefulness, the follow-up of MAD therapy is often limited by the cost and restricted availability of sleep laboratory investigations. In this context, the development of sensor-integrated MADs represents a promising innovation. The incorporation of sound and temperature sensors may allow continuous monitoring of respiratory flow dynamics during sleep, offering a practical tool for therapeutic assessment and personalized management. This technological evolution may contribute to improved treatment adherence, lower healthcare costs, and better risk stratification in patients with OSA.

Review of Mechanical aspects of Dental Adhesives and Dentin-Adhesive Interfaces

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The dentin-adhesive interface is critical to the success of composite tooth restoration. The durability behavior of this narrow interface is impacted by complex bio-chemo-mechanical environment that the interface experiences. From the viewpoint of composition and structure, the interface is highly heterogeneous irrespective of the scale of observation. Moreover, the characteristics of this interface evolve with time as it is subjected to time and rate-dependent loading. These features offer challenges not only for the laboratory analytical techniques, but also for mathematical modelling. This presentation will describe physico-mechanical characterization of synthetic components and biological tissues forming the dentin-adhesive interfacial complex and the role of modelling in elucidating these complex phenomena.

Keywords dentin; dentin-adhesive interface; numerical modelling.

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A TWO-DIMENSIONAL MODEL CONNECTING MICRODAMAGE WITH BONE REMODELING

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The accumulation of microdamage renders bone tissues more vulnerable to excessive fatigue loading, which could potentially lead to fragility fractures. There is a need for an effective and noninvasive approach for predicting damage-prone regions. The literature lacks investigation into quasibrittle damage-informed remodelling, which is hypothesized to accurately capture the damage state. The present study aims to formulate a strain-driven microdamage-informed remodelling framework to accurately depict the quasibrittle nature of bone and to predict damage and adaptation state of a two-dimensional proximal human femur. Additionally, the potential of the proposed approach was assessed under the effects of the key remodelling parameters. Results imply that insufficient magnitude of remodelling, rapid stimulus diffusion, excessively fast remodelling, and inadequate diffusion coefficient promote substantial damage accumulation. The choice of adequate parameters reduces the femur fracture risk. The proposed model can serve clinicians as a predictor of likely femur fracture regions in elderly populations.

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Beyond the Virtual Plan: Mechanics of Unplanned Forces in Aligner Therapy

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Clear Aligner Therapy is now the global benchmark in orthodontics, with over 17 million cases treated annually. However, despite the precision of digital planning, clinicians often face a challenge known as "tracking failure": a gap between predicted and actual tooth movement that can affect up to 45% of complex cases.

Why do teeth sometimes fail to follow the virtual plan? The core of the issue lies in "unplanned forces", biomechanical interactions that current software cannot yet predict. Three key clinical areas will be discussed: unplanned tipping, accidental intrusion and extrusion, and arch-level effects.

Identifying these computational modeling gaps represents a new frontier for the industry, providing insights for a more predictable and collaborative future in clinical orthodontics.

From Biology to Mechanics: Understanding and Optimising

Orthodontic Tooth Movement with Clear Aligners

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Orthodontic tooth movement is a complex biological and mechanical process in which controlled mechanical stimuli are applied to the dentition in order to progressively displace teeth towards a desired position. In contemporary clinical practice, clear aligner therapy has emerged as one of the most widely adopted orthodontic treatment modalities, offering aesthetic and practical advantages over conventional fixed appliances. However, despite their growing clinical prevalence, clear aligners continue to pose significant biomechanical challenges that remain only partially resolved.

This lecture aims to introduce the biological and mechanical framework governing orthodontic tooth movement, with the dual objective of contextualising the clinical problem and identifying the key areas where rigorous mechanical modelling and mathematical optimisation could contribute to meaningful improvements in treatment outcomes.

The presentation will first outline the biological mechanisms underlying tooth displacement, with particular emphasis on the role of the periodontal ligament (PDL) as the primary mechanosensitive interface between the applied mechanical loads and the bone remodelling response. The mechanobiological cascade — from mechanical stimulus to cellular activation and ultimately to bone apposition and resorption — will be described in terms accessible to a non-clinical audience.

The mechanical framework will then be examined, addressing the behaviour of clear aligners as elastic shells interacting with a complex, heterogeneous, and anisotropic biological system. The forces and moments generated by the aligner on each individual tooth, their dependence on material properties, geometry, and staging parameters, as well as the current limitations in their precise quantification, will be discussed.

Finally, the lecture will highlight the open scientific and clinical challenges where the contribution of physics and applied mathematics appears most promising: the development of predictive patient-specific numerical models, the optimisation of force systems for targeted tooth movements, and the integration of mechanobiological parameters into computational frameworks capable of guiding clinical decision-making.

VARIATIONAL ANALYSIS OF THE CANHAM-HELFRICH ENERGY FUNCTIONAL

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The Canham-Helfrich energy is widely used to describe the elastic properties of biological membranes at the subcellular level. The membranes are modeled as surfaces in the three-dimensional space and their shape minimizes an energy which penalizes the curvatures of the surface. A suitable multiphase energy permits to model also heterogeneous biological membranes. I will discuss existence of single and multiphase minimizers under area and enclosed volume constraints in the varifolds setting (joint work with K. Brazda and U. Stefanelli, [1]) and in the current setting (joint work with A. Kubin and M. Morandotti, [2]).

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A novel constitutive model for vascular smooth muscle contribution into mechanical response of aortic tissue

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Aortic dissection is one the most lethal cardiovascular disease. It consists of a tear of the innermost layer of the aortic wall, i.e. the tunica intima, with leakage of the blood into the outer layers and creation of a “false channel”, parallel to the original one. This condition is usually treated with emergency surgery through the substitution of the damaged part of the vessel with a synthetic graft made in Dacron, which however is poorly biomimetic. Consequently, the main aim of the current research is the efficient biomechanical characterization of the aortic tissue in order to guarantee the development of biomimetic graft.

Aortic tissue has been extensively studied in terms of quasi-static passive mechanical response to the blood flow during the systolic phase. In particular, some in vitro tests were carried out on human samples of aortic tissue, in order to extract the parameters for the development of structurally-motivated theoretical models based on the Holzapfel-Gasser-Ogden (HGO) formulation, slightly modified to take into account the dispersion of collagen fibers and their progressive recruitment with increasing loads [1].

However, the description of the quasi-static active mechanical response, in terms of Vascular Smooth Muscle (VSM) cells response to the action of chemical stimuli, remains considerably more complex, mainly due to the challenges associated with developing an appropriate experimental setup. A pioneering study in this context [2] provided the necessary experimental data by proposing a suitable protocol for testing human aortic samples; however, from a theoretical modeling perspective, it focused only on the development of a model able to fit the total mechanical response of the tissue, obtained as superposition of active and passive responses.

As a result, the main aim of this study turns out to be, starting from the previously obtained experimental data, the development of a theoretical model able to fit the active mechanical response of the aortic vessel. More in detail, to guarantee a huge flexibility of the model, the active strain energy density function is represented in terms of sum of exponential terms and not in a polynomial form. Finally, a genetic algorithm is employed to extract the material parameters of the model, from the experimental results, in order to assess the goodness of the proposed formulation.

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BIOMECHANICS AND THE MECHANICS OF LIVING SYSTEMS

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This presentation offers a synthesis of the major advances achieved over the past decade in French laboratories in the fields of biomechanics and the mechanics of living systems. Without aiming for exhaustiveness, we focus on four domains that have undergone particularly significant developments. We first discuss the revolution brought about by microfluidics and nanofluidics, ranging from heterogeneous microsystems to organoids. We then highlight recent progress in metrology and modeling, including the systematic exploration of tissues and organs. The third part addresses the emergence of “*Theramechanics*” and its ambitions for developing new therapeutic strategies grounded in mechanical principles. Finally, we examine recent advances in real-time simulation across these domains.

A MULTISCALE RESEARCH PROTOCOL FOR THE STUDY OF CRANIOFACIAL GROWTH IN ORTHODONTICS

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In the field of orthodontics, craniofacial growth has been extensively investigated over the past century, primarily through the development of distinct theoretical models that have progressively emerged over time. A common feature of these interpretative approaches lies in the attempt to account for the complexity of craniofacial growth processes within a single theoretical framework. Moreover, most of these theories have been formulated with almost exclusive reference to the postnatal growth period.

Concurrently, traditional research has predominantly focused on the analysis of craniofacial and biological characteristics at the macroscopic level, whereas in contemporary literature there remains a limited integration with biological processes occurring at the micro- and nanoscale. The aim of the present contribution is to propose a research protocol designed to describe craniofacial growth through an integrated approach, linking anatomical knowledge of growth with the cellular dynamics and genetic mechanisms that regulate its development.

Within this framework, the present project adopts a multidisciplinary perspective aimed at advancing the understanding of the role of oral microbiota in the treatment of dentoskeletal malocclusions during growth and development. Data are analysed using advanced mathematical tools, particularly those derived from network theory, situating this approach within the emerging field of network medicine. This paradigm has been enabled by the increasing availability of large-scale biomolecular and diagnostic datasets, together with the integration of quantitative computational methodologies and data science approaches. Such tools offer significant potential for the advancement of personalised medicine, allowing the application of statistical models and network-based analyses to assess patient-specific risk and to predict individual developmental trajectories.

This approach is particularly relevant in paediatric orthodontics, where the limited availability of longitudinal patient data may hinder timely and effective therapeutic interventions. The proposed methodology aims to identify which skeletal disharmonies are modifiable during growth by integrating a large number of cephalometric predictors with microbiota-related variables through statistical and network-based modelling, thereby supporting clinical decision-making.

STRUCTURAL OPTIMIZATION PRINCIPLES AS GUIDELINES FOR TRABECULAR BONE TREATMENT

MODELS

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A central challenge in osteoporosis treatment is understanding bone remodeling and assessing whether trabecular architecture is mechanically adequate under loading conditions. This cannot be neglected, as micro-structural adaptation to external forces is essential for maintaining mechanical competence. Consequently, explicit representation of the spatial trabecular architecture is crucial in theoretical and computational studies of load transfer and adaptation mechanisms.

This paper presents an approach for numerical simulation of trabecular bone remodeling using real tissue micro-structural configurations. The proposed framework integrates the actual micro-architecture of remodeling tissue with the governing remodeling mechanisms into a unified model. This yields a simulation tool for “*in silico*” analysis of whole-system remodeling responses to pharmacological interventions under varying external loads. The approach extends established physiological knowledge by reformulating bone homeostasis in terms of structural optimization principles.

Within this framework, structural optimization principles serve as guiding rules for trabecular bone treatment models, interpreting remodeling as an adaptive process driven by mechanical efficiency and structural adequacy. Numerical examples illustrate model behavior under different loading and remodeling scenarios. The resulting methodology, together with the associated computational tools and simulation capabilities, provides a platform for studying and developing treatments for chronic bone diseases, particularly osteoporosis, characterized by trabecular microarchitectural degradation and loss of mechanical integrity. In this context, disease progression is interpreted as a disturbance of mechanical homeostasis.

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FROM MECHANICAL TO BIOMECHANICAL: A BIOMIMETIC FRAMEWORK

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Trabecular bone exhibits a highly adaptive architecture driven by mechanical stimuli, and its accurate modeling is essential for understanding bone quality, disease progression, and implant integration. This work presents a research and implementation project focused on adapting a biomimetics-based computational framework, originally developed for mechanical engineering, for direct biomechanical applications.

The research phase includes analysis of functional requirements and user contexts, incorporating competency modeling, cognitive load, and usability constraints. A gap analysis informs the definition of measurable adaptation objectives and guides the redesign of system architecture toward modularity, scalability, and interoperability.

A key contribution is the development of adaptive mechanisms, including configurable workflows, role-based interaction models, and user-specific personalization strategies. These are implemented through software reconfiguration and user interface redesign to enhance accessibility, efficiency, and learning.

The study further investigates the impact of different mechanical stimuli on remodeling predictions, comparing Rankine (maximum principal stress), von Mises (distortion energy), and strain energy density (SED) hypotheses within a unified computational framework.

Results demonstrate that the adapted system bridges advanced modeling and practical biomechanical use while supporting diverse user profiles. The work underscores the importance of integrating mechanical rigor with user-centered design to promote broader adoption of computational tools in interdisciplinary contexts.

Nowak M., Sokołowski J., Żochowski A., Polak J., On compliance minimization by biomimetic regularization method, Bulletin of the Polish Academy of Sciences Technical Sciences, vol. 74, 1/2026, pp.e155900, <https://journals.pan.pl/dlibra/publication/155900/edition/136926/content>, 2026

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A Reduced-Order Hyper-Viscoelastic Framework for Corneal Biomechanics and Shear Wave Propagation

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Understanding the nonlinear mechanical behavior of soft biological tissues is essential for both biomedical mechanics and clinical diagnostics. In the human eye, the cornea plays a crucial biomechanical role, governing the structural stability and optical performance of the ocular system. Mechanical alterations in the cornea are strongly associated with pathological conditions such as Keratoconus and influence the interpretation of modern diagnostic techniques including shear wave elastography. Consequently, accurate mechanical modeling of the cornea represents an important challenge at the interface between nonlinear solid mechanics and biomedical engineering.

Recent studies have introduced several continuum-mechanics-based descriptions of corneal tissue, including three-dimensional Cauchy continuum formulations, hyperelastic constitutive laws, and viscoelastic models capable of capturing time-dependent behavior. However, many existing approaches remain fragmented: structural models describing equilibrium deformation are typically developed independently from dynamic formulations used to analyze wave propagation. This separation limits the ability to consistently interpret elastographic measurements and to capture the coupled effects of geometric nonlinearity, viscoelasticity, and dynamic loading.

In this context, recent developments in generalized continuum mechanics have provided promising reduced-order frameworks for thin biological structures. In particular, the nonlinear surface formulation offers a geometrically consistent reduction of three-dimensional energy densities into effective surface models suitable for thin tissues. Building upon this theoretical foundation, the present work discusses an integrated structural–dynamic modeling strategy for corneal biomechanics. The proposed perspective combines reduced-order continuum descriptions with hyper-viscoelastic constitutive modeling and dynamic wave-propagation analysis, drawing on recent developments by the author on shear-wave-based characterization and viscoelastic modeling of corneal tissue.

The resulting framework aims to bridge the gap between structural mechanics and elastographic dynamics by enabling the simulation of shear wave propagation within geometrically nonlinear, hyper-viscoelastic corneal models. Such an integrated approach has the potential to improve the interpretation of elastography measurements, enhance predictive modeling of corneal diseases, and provide new insights into the nonlinear mechanics of ocular tissues.

MS-7 Mechanics of Soft Materials

Yihui Zhang (Tsinghua University, China), Tongqing Lu (Xi'an Jiaotong University, China)

Mechanics-guided 3D assembly for electronics and microsystems

Y. Zhang

Origami/Kirigami Reconfigurable Functional Metastructure

L. C. Wang

Stretching-induced twisting of liquid crystal elastomer bilayers

Y. Wen, Z. Dai, Z. Chen, Y. Chen, Y. Yang

Rational design of soft network materials towards biomedical applications

S. Cao

A large-strain incompressible hyperelastic beam theory

I. D. Breslavsky, M. Amabili, H. R. Moghaddasi

Inverse design for the mechanically guided assembly of three-dimensional structures

Z. Fan

Mechanical Design of Passive Electronic Microfliers

K. Li

Soft Network Materials with Unusual Mechanical Properties over Large Deformations

J. Liu

Mechanics-Regulated Lithium Deposition in Lithium Metal Batteries

R. Xu

Defect-Insensitive Mechanical Responses of Random Network Materials with Horseshoe-shaped Microstructures

Y. Xiao

Mechanics-guided 3D assembly for electronics and microsystems

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3D micro-/nano-structures have widespread applications in a broad spectrum of cutting-edge areas, such as bio-integrated electronics, microrobots, tissue engineering, among others. Existing manufacturing approaches to form such 3D micro-/nano-structures, however, can only be used directly with a narrow range of materials and/or 3D geometries. A grand challenge in the field is in the development of schemes that allow construction of 3D structures in device-grade crystalline inorganic materials essential for high-quality electronics and microsystems. In this talk, I will introduce a mechanics-guided assembly approach that exploits controlled buckling to construct complex 3D micro/nanostructures rapidly from patterned 2D micro/nanoscale precursors. This approach applies to a broad set of materials (e.g., semiconductors, polymers, metals, and ceramics) and even their heterogeneous integration, over a wide range of length scales (e.g., from 100 nm to 10 cm). Development of a rational microlattice design allows transformation of 2D films into programmable 3D curved mesosurfaces through this assembly approach. Analytical modeling and a machine learning-based computational approach serve as the basis for shape programming and determine the heterogeneous 2D microlattice patterns required for target 3D curved surfaces. By studying fundamental aspects of adhesion and delamination in the film/substrate system, general design diagrams are developed to serve as guidelines for the selection of engineering parameters to avoid interface-related failure. A wrinkling-assisted strategy is also proposed to substantially facilitate the delamination at desired regions of the film/substrate system. The compatibility of the approach with the state-of-the-art fabrication/processing techniques available in semiconductor industries, allow transformation of diverse existing 2D microsystems into 3D configurations, providing unusual design options in the development of fundamentally new devices. I will introduce a few examples of unusual bioelectronic devices and bioinspired microrobots enabled by the mechanics-guided 3D assembly.

Origami/Kirigami Reconfigurable Functional Metastructure

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Origami/kirigami metastructures exhibit promising application prospects in multifunctional devices due to their unique reconfigurable properties. This work focuses on the design, mechanics, and functional realization of flexible reconfigurable functional metastructures, with a focus on their reconfigurable characteristics and engineering applications.

Based on the Square-Twist (S-T) origami configuration, reconfigurable control of the in-situ force-displacement curve under uniaxial tension is achieved by establishing an equivalent theoretical model combined with finite element analysis and experimental verification. A single structure can display five distinct force-displacement behaviors, including monostable and bistable responses, providing a new route for the design of mechanical metamaterials.

For the folded stable states of S-T origami, a prestressed out-of-plane compression finite element model is established to reveal the three-stage compressive mechanical behavior dominated by surface contact and surface-substrate contact. By optimizing structural redundancy, a non-planar foldable modified S-T configuration is proposed, which features a more direct force transmission path and enables on-demand reconfigurable stable bearing under out-of-plane compression.

Heterogeneous S-T origami is fabricated via multi-material 3D printing. By integrating its triple-stable characteristics and thermally driven self-deployment, a Z-shaped dipole antenna is designed to achieve frequency reconfiguration with five operation modes, while a coded multiple-input multiple-output system improves communication capacity and reliability.

A flexible 3D large-deformation thermal insulation metastructure is developed using origami, extending its application to ultra-high-temperature extreme environment protection. In addition, a kirigami-based radar absorbing metastructure is innovatively designed. Precise tuning of the kirigami pattern and assembly realizes excellent stretchable conformability and tunable microwave absorption performance.

The results provide key technical support for the engineering applications of reconfigurable functional metastructures in mechanical engineering, communication technology, protective materials, and related fields.

Stretching-induced twisting of liquid crystal elastomer bilayers

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Liquid crystal elastomers (LCEs) represent a distinctive category of smart soft materials that merge liquid crystalline order with hyperelastic behavior, enabling rapid, anisotropic, and reversible deformations under mechanical, thermal, or optical stimuli. In this work, we report an as-yet undocumented phenomenon: the occurrence of twisting in LCE bilayer strips when subjected to uniaxial stretching. Our investigations reveal that this deformation arises from a spontaneous mismatch strain between layers, originating from interlayer anisotropy. To quantitatively describe and predict this stretch-induced twisting response, we establish a theoretical model grounded in semi-soft elasticity. Through a combination of experiments and analysis, we systematically examine the influence of key parameters, such as liquid crystal director orientation, geometric dimensions, and material properties, on the resulting twist. Our results show that when the alignment of directors of bilayer are symmetric about the stretching direction, a larger deviation angle of the initial directors results in a more significant twisting deformation. Moreover, strips with greater length, narrower width, or increased thickness exhibit amplified twisting behavior. Material anisotropy is found to promote twisting, whereas semi-soft elasticity tends to suppress it. These findings not only uncover a novel tension–twisting coupling in LCE bilayers but also provide valuable insights for the design of advanced LCE-based actuators, intelligent structures, and soft robotic systems.

Rational design of soft network materials towards biomedical applications

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Soft network materials (SNMs) are innovative metamaterials designed to replicate the nonlinear mechanical behaviors of soft tissues, such as skin, tendons, and ligaments. These materials, which consist of filamentary microstructures arranged in periodic lattice patterns, exhibit J-shaped stress-strain curves that mimic the mechanical responses of biological tissues. Despite their potential, the design of SNMs has been constrained by the complexity of existing models, which often require multi-stage design processes and subjective parameter selections. To address these challenges, we developed a novel phenomenological framework and an evolutionary algorithm, integrated with finite element analysis (FEA), to enable the optimization of SNMs with diverse curved microstructures and lattice topologies (Figure 1A). This approach facilitates the rational inverse design of SNMs that closely replicate the mechanical properties of soft tissues. *In vitro* experiments demonstrated that these SNMs under cyclic tensile stimulation supported the proliferation of L929 fibroblasts and induced tenogenic differentiation of tendon-derived stem cells (TDSCs, Figure 1B), as evidenced by elevated tenomodulin expression. Furthermore, *in vivo* rat defect models of sciatic nerve and Achilles tendon injuries showed that SNM-based scaffolds (Figure 1C) outperformed conventional electrospun scaffolds in terms of tissue regeneration (Figure 1D&E), offering regenerative outcomes comparable to autologous tissue grafts. These findings underscore the potential of SNMs in advancing soft tissue engineering and regenerative medicine.

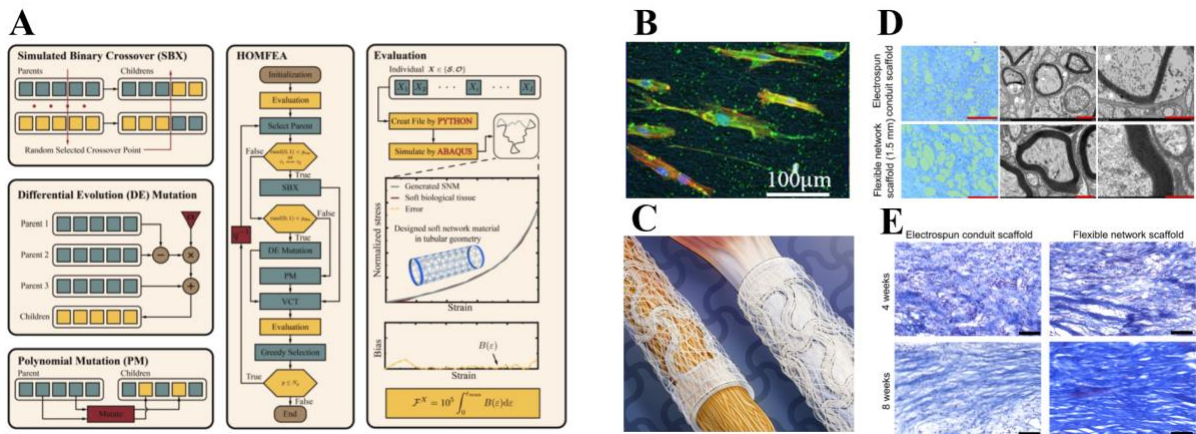


Figure 1 **A** Rational design of SNM assisted by evolutionary algorithm and FEA; **B** *In vitro* dynamic culturing of TDSCs; **C** SNM-based scaffold for sciatic nerve and Achilles tendon regeneration; **D** & **E** Representative regenerative outcomes of sciatic nerve and Achilles tendon.

A LARGE-STRAIN INCOMPRESSIBLE HYPERELASTIC BEAM THEORY

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Incompressible hyperelastic materials are widely used to model soft polymers, elastomers, and biological tissues. While numerous beam formulations exist for elastic structures, many classical beam theories are not well suited for incompressible materials undergoing large deformations. In particular, traditional approaches often neglect the coupling between bending deformation and transverse strains, such as thickness and width changes, which can become significant in incompressible solids. As a result, these simplified models may provide inaccurate predictions of deformation and stability behaviour when large strains occur.

In this study, a large-strain beam theory for incompressible hyperelastic beams is developed. The formulation is derived starting from the three-dimensional equations of nonlinear elasticity. A displacement field is assumed that allows for bending, axial deformation, and uniform width change of the beam cross-section. The corresponding Green–Lagrange strain components are obtained and the incompressibility constraint is enforced through the third invariant of the right Cauchy–Green deformation tensor. The stress field is derived using a hyperelastic constitutive model, and the traction-free conditions on the surfaces of the beam are incorporated. This procedure results in a system of equations relating the generalized displacement variables of the beam.

The theory is applied to incompressible neo-Hookean beams subjected to transverse and axial loads. Several representative problems are studied, including simply supported beams with both immovable and movable ends. Numerical results are compared with finite element simulations using three-dimensional solid elements. The comparison demonstrates that the proposed beam formulation accurately captures the nonlinear deformation behaviour of incompressible beams even for relatively large deflections, while classical beam theories may significantly underestimate the response.

The proposed formulation provides a consistent framework for analysing large-strain behaviour of incompressible beams while retaining the computational efficiency of beam models. The theory can be useful for studying soft structural elements made of elastomers and biological materials, where large deformations and incompressibility play an essential role.

INVERSE DESIGN FOR THE MECHANICALLY GUIDED ASSEMBLY OF THREE-DIMENSIONAL STRUCTURES

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Due to the significant applications of three-dimensional micro/nanostructures in fields such as biomedical devices, optoelectronics, energy storage, and metamaterials, their design and fabrication have garnered increasing attention. Recently, mechanically guided assembly methods have emerged as an effective approach for fabricating complex three-dimensional microstructures through large post-buckling deformations of thin-film structures. This method imposes minimal restrictions on material types, enabling the use of advanced materials including metals, polymers, and semiconductors. It is applicable across a wide range of characteristic scales, from micrometers to millimeters, demonstrating considerable application potential. However, owing to the highly nonlinear nature of post-buckling deformations, current research on this method relies heavily on extensive numerical simulations for initial structural design, highlighting the need for an inverse design strategy that proceeds from target configurations to initial structures. This report focuses on three-dimensional ribbon and curved surface structures, proposing inverse design strategies based on variable thickness and porosity. These strategies allow the geometric design parameters of the initial two-dimensional precursors and the corresponding loading conditions to be derived directly from the geometric features of the target structures. The approach has successfully realized dozens of typical three-dimensional configurations, thereby laying a theoretical foundation for the application of mechanically guided assembly methods in three-dimensional structural fabrication.

Mechanical Design of Passive Electronic Microfliers

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Abstract

Miniaturized aerial devices harbor transformative potential for large-scale environmental monitoring, distributed sensing, and Internet of Things (IoT) networking. However, conventional micro-air vehicles (MAVs) remain constrained by their reliance on active drive modules—plagued by inherent limitations including poor miniaturization scalability, excessive energy consumption, and compromised concealment in real-world deployment. Addressing this critical bottleneck, this talk introduces a paradigm shift in microflier design: bio-inspired three-dimensional (3D) electronic microfliers that harness passive wind dispersal as a core flight mechanism, enabling unprecedented long-duration and long-range aerial operation without the need for active propulsion. This work bridges mechanics, flexible electronics, and aerodynamics, offering a scalable, low-power solution for next-generation distributed sensing systems.

Biography



Kan Li is a Professor in School of Mechanical Science and Engineering, Huazhong University of Science and Technology. He received his bachelor degree from Tsinghua University, Tsien's Excellence in Engineering Program. Dr. Kan Li obtained his PhD in Theoretical and Applied Mechanics from Northwestern University in 2019. He conducted postdoctoral research at the University of Cambridge in the Department of Engineering. His research focuses on the mechanical design of flexible electronics, stretchable electronics and electronic microfliers. He has published extensive papers in top journals, including Nature, PNAS, Advanced Materials, etc., as of 2025. He serves as the Associate Editor for the Mechanics of Materials journal, and an editorial member of Mechanics and Materials of Complex Systems.

Soft Network Materials with Unusual Mechanical Properties over Large Deformations

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Soft network materials consisting of well-organized wavy microstructures capable of precisely replicating the nonlinear stress-strain responses in diverse biological tissues or organs, thereby possess significant potential for a broad spectrum of applications, such as bio-integrated devices and tissue engineering. Notably, previous studies on soft network materials mostly focused on the biomimetic J-shaped stress-strain curves, while the unconventional mechanical properties that can surpass those of natural biological materials remain to be explored. This report aims to systematically present the design methods and mechanics models of soft network materials, provide combined theoretical, computational and experimental studies of the unusual mechanical properties of the proposed soft network materials, as well as demonstrate their potential applications. Specifically, three types of soft network materials will be mainly introduced in this report: those with a relatively constant negative Poisson's ratio under large deformations, those combining high stretchability and high tensile strength, and those with imperfection-insensitive properties under monotonic/cyclic loads.

Mechanics-Regulated Lithium Deposition in Lithium Metal Batteries

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The mechanical integrity of SEI plays an essential role in determining the performance of Li metal batteries. However, the mechanical integrity of SEI faces great challenges when Li metal is introduced into batteries. The SEI on Li metal anode can crack easily as the non-uniform Li plating can impose large local strains on the SEI film. The cracks of SEI can act as hot spots to intensify the non-uniform Li plating and stripping, which promotes the unfavorable formation of Li dendrites. Currently, no sophisticated model can capture the dynamically evolving interplay among Li plating/stripping, SEI growth, SEI cracking, and battery performance. In this work, we aim to build a fully coupled electro-chemo-mechanical (ECM) model to understand the Li deposition behavior under various electrochemical conditions, and more importantly, to elucidate how the ECM interplay regulates the morphological evolution of deposited/stripped Li and thereby determines battery performance.

Defect-Insensitive Mechanical Responses of Random Network Materials with Horseshoe-shaped Microstructures

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Advancements in soft network materials featuring strategically distributed wavy microstructures have enabled many attractive applications in bio-integrated electronic devices, since these materials can be programmed to precisely replicate nonlinear mechanical responses of soft human tissues and organs. In practical scenarios, soft network materials usually serve either as the encapsulation or the substrate of bio-integrated electronic devices. However, unforeseen imperfections may significantly reduce the ductility of periodic network materials, thereby setting limitations on their potential applications. Therefore, it is essential to develop defect-insensitive network materials, and investigate the underlying mechanisms that confer resistance to defects. In this work, we report a class of random network materials consisting of horseshoe microstructures, which could be generated using a consistent numerical method. An in-depth investigation on the effects of randomness on key mechanical parameters was performed, including the critical strain, Poisson's ratio, fracture strength, and fracture strain. Henceforth, we propose a design methodology capable of generating random network materials with optimal fracture strength. Finally, we engage in a comprehensive analysis regarding the influence of defect orientation, quantity, and spatial distribution on the fracture behavior. The fracture strength of a periodic network materials exhibits a notable reduction when a horseshoe microstructure is absent, in comparison to the case of a fully intact one. However, the absence of a single horseshoe microstructure does not reduce the strength evidently for random network materials. The defect-insensitive response of random network materials can be attributed to the mechanism that the presence of randomness tends to mitigate stress concentration surrounding defects.

MS-10 Stability and dynamics of structures

Francesco D'Annibale (Università degli Studi dell'Aquila, Italy), Francesco Dal Corso (Università di Trento, Italy) and Yury Vetyukov (TU Wien)

Self-tuning resonators from variable-length structures

F. Dal Corso

Energetic Exhaustiveness: tracing energy derivatives from nonlinear homogeneous deformations

F. O. Falope, L. Lanzoni, A. M. Tarantino

Homogenized model of a prestressed ladder beam – Application to buckling

A. Rallu, S. Antczak, C. Boutin

Thermal post-buckling of induction-heated thin sheets

V. Filkin, Y. Vetyukov, F. Toth

Vibration control of taut strings via a distributed piezoelectric damper

A. Casalotti, F. D'Annibale

Tension-twisting coupling in liquid crystal elastomer bilayers

Y. Wen, Z. Dai, Z. Chen, Y. Chen, Y. Yang

Multiscale Modeling of Textiles

P. Sočo, M. Krier, J. Orlik

Damping-induced stabilization and destabilization in non-holonomic systems

G. Migliaccio, F. D'Annibale, D. Bigoni, F. Dal Corso

Bending behaviour of lightweight 316L stainless steel structures produced by MIM-like additive manufacturing: effect of infill density and wall thickness

S. Badin, V. Magnier, J.-F. Witz, D. Najjar

Elastic-invisibility-enabled metastructure with mechanically programmable nonlinear resonators for vibration mitigation and energy harvesting

D. Misseroni

SELF-TUNING RESONATORS FROM VARIABLE-LENGTH STRUCTURES

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A frictionless sliding sleeve is a mechanical constraint that allows only relative sliding motion between the sleeve and the constrained element, creating an effective system with variable domain. When the flexibility of the constrained component is considered, a curvature discontinuity typically arises at the sleeve exit and a tangential concentrated force, nonlinear and repulsive, is generated there.

In this presentation, I will demonstrate how fundamental structural systems characterized by a simple, yet distinctive constraint can be exploited to realize self-tuning metastructures.

Specifically, we consider a rod in a gravitational field constrained by a sliding sleeve. The constraint is oriented such that the sliding direction is parallel to gravity, allowing the rod to freely slip through the sleeve when the latter is at rest. In this configuration, the rod undergoes free fall until the rod is fully inserted into the constraint.

However, transverse harmonic oscillations of the sliding sleeve can hinder this motion. We demonstrate the existence of self-tuning dynamics, associated with specific average rod lengths that yield stable motion within certain frequency ranges. Furthermore, when distributed mass is considered, a mode-jumping phenomenon emerges, enabling automatic transitions from the $(n+1)$ -th mode to the n -th mode as the oscillation frequency of the constraint decreases.

These results lead to the concept of self-tuning resonators, whereby a single device spans a wide frequency range otherwise requiring multiple classical (fixed-length) resonators.

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Energetic Exhaustiveness: tracing energy derivatives from nonlinear homogeneous deformations

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The mechanical characterization of soft materials is traditionally performed by fitting stress components or resultants obtained from standard states of deformation, such as uniaxial tension/compression, biaxial tests, torsion, or shear. Once a constitutive framework is assumed, the identification process focuses on determining the corresponding material parameters. An alternative and more direct approach consists in experimentally tracking the two- or three-dimensional behavior of the derivatives of the energy function, for incompressible and compressible materials, respectively. Depending on the choice of deformation invariants [1] and on the adopted experimental protocol, homothetic tests can be classified into three families [2]: energetically exhaustive, partially exhaustive, and non-exhaustive tests. A test is defined as energetically exhaustive when its matrix formulation yields a determined system of equations for the unknown derivatives of the energy function.

Within this framework, the unequal-biaxial test is shown to possess a remarkable characterization capability, as it alone allows for the direct identification of the functional form of the energy derivatives. The theoretical basis of this property is discussed, and dedicated experimental design tools are proposed. Experimental results obtained from unequal-biaxial tests on three different rubber-like materials are presented and analyzed.

These experiments reveal two unexpected findings. First, two commonly adopted empirical inequalities fail to describe the behavior of two of the tested materials, despite the fact that the classical Baker–Ericksen inequalities are satisfied. Second, alternative formulations of the Baker–Ericksen inequalities [3] are proposed, together with a new hierarchical empirical inequality, providing fresh insights into the constitutive behavior of hyperelastic isotropic materials.

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Homogenized model of a prestressed ladder beam– Application to buckling

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We present an asymptotic method that allows to describe the macroscopic mechanical behavior of a prestressed periodic reticulated structure, based on the asymptotic homogenization of periodic discrete media. In this case, the structure is a 1D periodic ladder beam with a frame unit cell.

The discrete equilibrium equations are written in a deformed configuration of the prestressed structure, in the context of in-plane displacements and linear elasticity. Under the assumption of scale separation between the unit-cell size and the characteristic length of variations in the displacement envelope of the deformed structure, a continuous equivalent beam model is then derived. The formulation considers asymmetries in the loading and the ladder itself, as well as low-to-high stiffness contrasts between the structural elements. A generic model is then deduced for the prestressed ladder beam, valid for a wide range of contrasts between the stiffnesses of the elements, and showing that the derived stiffnesses of the equivalent beam depend on the loading.

This framework is then used in the case of buckling analysis of a ladder beam. In this context, this method allow the prediction of critical buckling loads and modes of the structure. Experiments conducted on 3D-printed ladder beams confirmed the buckling modes and loads predicted by the analytical models. These models are also validated against finite element calculations.

The original contributions are: (i) the ability to consider different stiffness ratios between the elements of the structure, (ii) the derivation of effective beam models whose parameters depend on the prestress loading, (iii) the consideration of both symmetric or asymmetric loadings, and (iv) formulations with mono- or multi-cell periodicity, enabling the identification of both short- and long-wavelength buckling modes.

THERMAL POST-BUCKLING OF INDUCTION-HEATED THIN SHEETS

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Induction heating of thin sheets is widely used in industrial applications such as metal forming, heat treatment, and manufacturing processes. During induction heating, strong and non-uniform temperature gradients can develop in the heated parts. These gradients generate thermal stresses that can cause thin structures to buckle.

Once buckling occurs, the geometry of the structure changes significantly. This geometric change alters the electromagnetic field distribution around the sheet and, as a result, modifies the induced currents and heat generation. The altered temperature field further affects the mechanical response of the structure. Therefore, the problem involves a strong two-way coupling between electromagnetic, thermal, and mechanical fields.

Analytical studies indicate that this coupled system can exhibit not only classical thermal buckling but also post-buckling behavior characterized by transcritical bifurcation (“snap-through” and “snap-back” phenomena) [1]. Such effects may lead to sudden changes in deformation and temperature, which are important for the safe and reliable design of induction heating systems.

We study an application-oriented example both computationally [2, 3] and experimentally, and relate our findings to analytical modeling [1]. The analytical models provide insight into the governing mechanisms and stability behavior. Numerical simulations capture the fully coupled nonlinear response, while experimental observations are used to validate the models. The results improve the understanding of coupled thermal–electromagnetic–mechanical interactions and provide guidance for the design and control of induction heating processes involving thin structures.

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Vibration control of taut strings via a distributed piezoelectric damper

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Several engineering fields, such as civil, offshore, aerospace, and mechanical engineering [1], exploits cables thanks to their highly efficient structural performance. Continuous efforts are carried out to enhance the design potential of such elements. In this context, numerical as well as perturbation approaches [2] are adopted to investigate cables with lengths both greater and less than the distance between their supports, representing suspended and taut configurations, respectively. In the recent years, various applications ranging from the actuation, sensing and energy harvesting [3] have seen the development piezoelectric devices to improve the performance. Among those studies, an interesting approach is the use of embedded piezoelectric layers onto cable- [4] and beam-like structures to enhance their mechanical behavior also in the case of non-autonomous systems [5].

Here, the study is focused on the design of a smart Piezo-Electro-Mechanical (PEM) system aiming at developing an innovative metamaterial with enhanced mechanical behavior. The work deals with the development of a viscoelastic taut string endowed with a system of distributed piezoelectric layers shunted to an ad hoc designed electrical circuit. The final objective is to improve the capability of the taut string in mitigating its own oscillations induced by external forces. The equations of motion are derived via a variational approach and then discretized with the Galerkin method. The system is subject to external periodic loading that induces primary resonance and therefore numerical time history analyses are carried out to find suitable ranges in which the controller is capable of mitigating the system response.

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Tension-twisting coupling in liquid crystal elastomer bilayers

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Liquid crystal elastomers (LCEs) are smart soft materials that merge liquid crystal properties with hyperelasticity, enabling rapid, anisotropic, and reversible deformations under various stimuli. In this study, we report a previously unknown phenomenon: uniaxial stretching induces twisting in LCE bilayer strips. Our experiments reveal that this twisting arises from spontaneous mismatch strain caused by interlayer anisotropy. To quantitatively capture and predict this tension-twisting response, we develop a bilayer model based on semi-soft elasticity. Through systematic analysis, we explore how director orientation, geometry, and material parameters affect the twisting behavior. Our results show that when the director alignments in the two layers are symmetric with respect to the stretching direction, increasing the initial director deviation angle enhances the twisting magnitude. Moreover, longer, narrower, and thicker strips exhibit more pronounced twisting. Additionally, while greater material anisotropy promotes twisting, the characteristic of semi-soft elasticity suppresses it. These findings not only elucidate the tension-twisting coupling mechanism in LCE bilayer strips but also provide fresh perspectives for designing LCE-based actuators, intelligent structures, and soft robots.

Multiscale Modeling of Textiles

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Textiles are multiscale materials. At the microscale, their structure consists of thin elastic yarns in contact, arranged in periodic patterns. At the macroscale, the textile behaves like an effective anisotropic 2D manifold. The relation between these two scales is not straightforward. The effective macroscopic behavior – governed by coupled tension, bending, shear and torsion – depends on the microstructure’s periodic geometry and on the loading regime relative to stiffness and thickness [1, 2, 3]. Simultaneous homogenization and dimension reduction of the thin 3D periodic domain provides a natural mathematical framework for deriving effective 2D constitutive laws and their parameters [1, 4].

In our presentation, we show a mechanical multiscale model for the structures and their numerical treatment, illustrating the computation of effective model parameters by simulations on the microscale and their effect in draping and put-on scenarios on the macroscale.

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Damping-induced stabilization and destabilization in non-holonomic systems

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The intricate interaction between nonlinear dynamics, stability, and non-holonomic constraints in elastic systems is investigated through a representative double pendulum, which is subjected to a conservative force at one end, while a non-sliding wheel is present at the other. Notably, and in contrast to the classical Ziegler's double pendulum [1], this configuration can exhibit dynamic instabilities, such as flutter, even under purely conservative loading. Flutter instabilities in elastic systems are traditionally associated with non-conservative follower forces, which are also known to produce counterintuitive effects like Ziegler's damping destabilization paradox. Such phenomena have long been considered exclusive to non-conservative systems. However, recent studies indicate that similar behaviors may also arise in the presence of conservative forces when non-holonomic constraints are introduced [2], underscoring the significant role of non-holonomic constraints in shaping the nonlinear dynamic response of elastic systems. In this work, the nonlinear dynamics of a double pendulum with a non-holonomic constraint at one end and a conservative loading mechanism at the other is examined analytically. By employing the Method of Multiple Scales [3], the limit cycles emerging near Hopf bifurcation points are determined, providing deeper insight into the system's nonlinear dynamic behavior. The analysis demonstrates that Hopf bifurcations can occur in elastic systems under purely conservative loading when non-holonomic constraints are present. The resulting limit cycles are derived analytically. Moreover, damping is shown to play a dual role: it can either stabilize or destabilize the system, potentially transforming stable limit cycles into unstable ones. This analytical framework paves the way for the design of advanced mechanical systems for locomotion, in which non-holonomic constraints and dynamic stability play a fundamental role.

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Bending behaviour of lightweight 316L stainless steel structures produced by MIM-like additive manufacturing: effect of infill density and wall thickness

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Metal additive manufacturing by material extrusion (MIM-like) enables the production of lightweight, partially hollow 316L stainless steel structures at significantly reduced equipment cost compared to Laser Powder Bed Fusion (LPBF). This study investigates the flexural behaviour of beam specimens sintered under vacuum in a laboratory furnace, with two structural variables at constant mass: infill density (50%, 62.5%, 75%) and number of perimeter walls (1, 3, or 5). Specimens are labelled RXX-NP, where XX denotes the infill percentage and N the number of perimeter walls (e.g., R50-5P: 50% infill, 5 walls; R75: 75% infill, 1 wall). Three-point bending tests were combined with in-situ Digital Image Correlation (DIC) using a dense optical flow algorithm, providing full-field strain maps from the elastic regime through large plastic deformation.

At equivalent mass, the five-wall low-infill design (R50-5P) consistently outperformed the high-density single-wall design (R75): R50-5P specimens sustained forces exceeding 50 kN without fracture versus ~ 17.5 kN for R75, with superior energy absorption evidenced by pronounced central necking. This result is rationalised by Steiner’s theorem: outer walls, being furthest from the neutral axis, increase the average second moment of area more efficiently than raising infill density. Furthermore, crack initiation was systematically located at positions of minimum local second moment of area along the beam axis, providing a direct geometric predictor of structural weakness.

DIC measurements revealed two unexpected features. First, the neutral fibre shifted toward the tension side in single-wall specimens – attributed to the compressibility of the porous lattice rather than material asymmetry. Second, the neutral fibre effectively disappeared in multi-wall specimens, with tensile strains extending across the entire cross-section height. Both observations invalidate the classical Euler-Bernoulli assumptions, and shear effects were found to be non-negligible, pointing to the need for Timoshenko-type models.

These findings provide clear design guidelines: for a given mass envelope, combining low infill density with thick outer walls yields higher stiffness, higher fracture load, and better energy absorption than a dense thin-walled configuration. The local second moment of area distribution is identified as a key structural integrity indicator for MIM-like printed components.

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ELASTIC-INVISIBILITY-ENABLED METASTRUCTURE WITH MECHANICALLY PROGRAMMABLE NONLINEAR RESONATORS FOR VIBRATION MITIGATION AND ENERGY HARVESTING

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Recent progress in elastic invisibility concepts and nonlinear resonators is opening new opportunities for designing structures that can simultaneously reduce vibrations and harvest energy. In this work, we propose an elastic-invisibility-enabled metastructure that embeds compact nonlinear magneto-piezoelectric oscillators within a meta-beam. The beam features a series of uniform voids, each hosting a nonlinear piezoelectric beam that contributes to broadband vibration attenuation while also enabling energy harvesting.

To prevent the voids from altering the dynamic response of the structure, we implement an elastic invisibility strategy based on boundary reinforcement and mass redistribution. This approach allows the perforated beam to preserve the same modal properties as an equivalent continuous beam, thereby maintaining structural integrity while retaining tunability and high performance.

The proposed system is studied through theoretical modeling, numerical simulations, and non-standard vibration experiments, all of which confirm the predicted behavior. The results highlight the potential of this elastic-invisibility-enabled metastructure as an efficient and reliable platform for vibration control and energy management, with promising applications in future smart structural systems.

MS-11 Nonlinear mechanics of beam, plate, membrane and shell structures: models and methods

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MS-14 Discrete-to-Continuum Modeling: Theory, Scale Effects, Uncertainty, and Computation

Gabriele La Valle (Université Gustave Eiffel, France), Christian Soize (Université Gustave Eiffel, France), Ivan Giorgio (University of L'Aquila, Italy) and David J. Steigmann (University of California, Berkeley, USA)

Spherical B-spline in Lie groups: A mixed $\mathbb{R}^3 \times SO(3)$ isogeometric Cosserat rod formulation
L. Greco, D. Castello, A. Cammarata and M. Cuomo

Beam-to-beam contact interaction for Cosserat rods based on geodesic interpolation
A. Cammarata, D. Castello, and L. Greco

Spherical B-spline interpolation for the nonlinear dynamic analysis of 1D Cosserat rod
D. Castello, S. Morganti, A. Cammarata and L. Greco

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A statistical framework for complex systems with a small number of simulations: from complex plasmas to continuum mechanics
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Spherical B-spline in Lie groups:

A mixed $\mathbb{R}^3 \times SO(3)$ isogeometric Cosserat rod formulation

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Polar thin structural theories in general present a configurational space given by the product of the Lie groups $\mathbb{R}^3 \times SO(3)$. An isogeometric formulation adopting geodesic B-spline representations, i.e. polynomial B-spline in the section $\mathbb{R}^3$ and Spherical B-spline in the section $SO(3)$ is presented. In this way, an objective and path-independent multiplicative numerical scheme is designed, as in [1-4]. The case of the uni-variate interpolation case is considered in order to analyze the static of a 1D Cosserat continua. A mixed formulation is adopted in order to avoid locking phenomena since a displacement based on a $\mathbb{R}^3 \times SO(3)$ formulation is not able to reproduce constant finite strains.

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BEAM-TO-BEAM CONTACT INTERACTION FOR COSSERAT RODS BASED ON GEODESIC INTERPOLATION

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Beam contact applications range from wire ropes and cables, where it is used to understand how individual strands interact and rub under tension, to civil infrastructure, for analyzing the behavior of reinforcement bars within concrete or the intersections of steel trusses. In textile engineering, modeling these interactions allows for the simulation of microscopic fiber contact to predict fabric durability. Furthermore, in the field of medical devices, beam contact is essential for ensuring the structural integrity and successful deployment of vascular stents, while in robotics, it informs the design of soft links that may collide during operation. Describing all these key scenarios requires a robust formulation that can identify potential contacts while ensuring a uniform distribution of contact pressures. Precisely to meet these requirements, beam-to-beam formulations have recently attracted more attention than node-to-node ones. In this work, the geodesic interpolation for finite rotations in Cosserat beam models, previously devised by the authors in [2, 3, 4], is complemented by a beam-to-beam contact formulation. The contact identification algorithm is based on two phases. The broad phase relies on a spatial hashing search for potential contacts between elements. The narrow phase, on the other hand, extends to each Gaussian point of the mortar elements of the potential contact pairs selected by the broad phase and is based on identifying the closest contact point on the non-mortar element. Our model adapts that proposed in [5] that performs no computation of the integration boundaries. However, to reduce the number of unknowns and increase the computational speed, we preferred to use a penalty formulation with the regularization proposed in [6]. To verify the robustness and performance of the method, three classical benchmarks were implemented.

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SPHERICAL B-SPLINE INTERPOLATION FOR THE NONLINEAR DYNAMIC ANALYSIS OF 1D COSSERAT ROD

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In this contribute the configuration space of 1D Cosserat continuum is modelled as $\mathbb{R}^3 \times \text{SO}(3)$. Two-node geodesic interpolation in $\text{SO}(3)$, i.e. spherical linear interpolation (SLERP), has been adopted in [1,2] in order to interpolate the cross section orientation of the beam ensuring objectivity and path independence properties of the numerical formulation.

B-spline interpolations have demonstrated significant advantages with respect to C0 FE-formulation in terms of accuracy and robustness. In this work higher order spherical B-spline of order $p \geq 2$ is developed in order to interpolate the cross-section orientation of the Cosserat rod, following [3,4], furthermore, the time integration proposed in [5] is adopted.

Benchmark problems confirm the effectiveness of the proposed formulation in terms of robustness and accuracy.

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Mixed Eulerian–Lagrangian modelling for steady-state elastic-plastic bending of an axially moving rod

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Continuous metal forming processes feature axially moving continua that sustain persistent plastic deformations on the way through a series of forming stands. The practically important steady-state is identified by the structure in *contour-motion* with material particles travelling through a spatially fixed configuration. This state is best captured by a mixed Eulerian–Lagrangian kinematic parametrisation [1], which entails a transition to spatial control volumes with correspondingly modified variational principles [2].

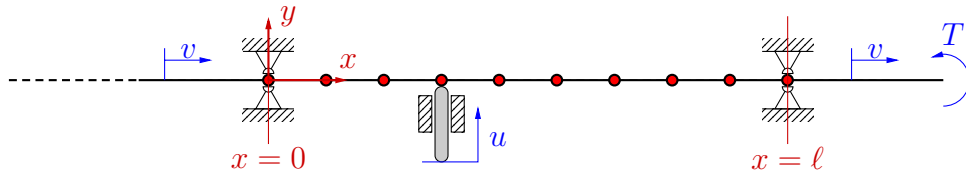


Figure 1: Continuous elastic-plastic bending of a moving semi-infinite rod.

To exemplify, we consider the problem of continuous elastic-plastic bending of a semi-infinite rod subjected to an external moment T at the free end, see Figure 1. The unshearable rod is moving at material transport rate v and elastic-plastic bending between the supports is imposed by deflections u of a rigid stamp; frictionless contact is assumed and plasticity is modelled with a stress-resultant model for pure bending [3]. Geometrically linear and nonlinear problems are considered and reference solutions for the semi-infinite material domain are provided to verify the results obtained for the spatial control domain $x \in [0, \ell]$. The solution methods comprise semi-analytic treatments and finite element simulations.

The study gives insight into the consistent modelling of continuous forming processes and shows the utility of a non-material kinematic framework with respect to: the resolution of spatial constraints and plastic states, the computation of steady-state solutions and the identification of driving forces to compensate for the power consumption of the dissipative process.

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CRUSHING CHARACTERISTICS AND ENERGY ABSORPTION BEHAVIOUR OF ORIGAMI-INSPIRED BIO- BASED SANDWICH STRUCTURES WITH CURVED GEOMETRY

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Lightweight, sustainable, and high-performance energy-absorbing structures are increasingly sought across modern engineering applications. This study investigates the crushing characteristics and energy-absorption behaviour of a novel thin-walled sandwich structure that employs thin laminated wood sheets bonded to a lightweight origami paper core, shaped into a curved sandwich tessellation. By integrating geometric design principles of origami folding with the inherent anisotropy and eco-friendliness of wood and paper, the concept offers an efficient and low-impact alternative for load-carrying and crashworthy applications.

The curved origami sandwich configuration enables controlled deformation mechanisms, promoting stable progressive folding and superior energy dissipation. Experimental quasi-static compression tests were conducted to assess the key performance parameters, including peak load, mean crushing force, specific energy absorption (SEA), and crushing force efficiency (CFE). The influence of geometric parameters such as curvature, fold angle, and wall thickness is systematically examined through a Finite element (FE) model validated against experimental results.

Results demonstrate that the origami-inspired curvature significantly improves crushing stability compared to flat-faced sandwich panels. The structures exhibit a desirable progressive collapse mode characterised by sequential folding and limited catastrophic failure. The wood-based face sheets improve stiffness, energy dissipation, and sustainability due to their fiber orientation and renewable nature. Therefore, the synergistic combination of bio-based materials and origami geometry demonstrates tunable mechanical behaviour and strong potential for lightweight, crashworthy, and eco-conscious structural systems.

Overall, this research highlights the potential of combining origami-inspired design with bio-based materials to develop efficient, lightweight energy absorbers. The findings provide valuable insights for applications in automotive crashworthiness, protective structures, and sustainable engineering systems, where controlled energy dissipation and environmental considerations are critical. Future work will focus on dynamic impact testing, numerical modelling, and optimisation of geometric parameters for real-world implementation.

Keywords: Origami-inspired curved sandwich structures, Bio-based composite, Energy absorption, Finite element analysis, Crushing analysis.

Nonlinear Bending Behavior of Plate and Truss-Based Lattice Metamaterials: A Strain Gradient Homogenization Approach

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This study investigates the bending behavior of beams made of lattice metamaterials, with attention to geometric nonlinearity and size-dependent effects. The lattice topologies considered in this research are broadly classified into plate-based cells and truss-based cells, allowing for a systematic investigation of their structural response.

To reduce the computational cost typically associated with detailed lattice modeling, a homogenization approach is proposed. In this method, complex lattice structures are represented as equivalent homogenized continuum beams, modeled using Euler–Bernoulli and Timoshenko theories enhanced by strain gradient elasticity to capture size effects. A second-order asymptotic homogenization scheme is employed to derive effective higher-order material properties.

A geometrically nonlinear numerical method is used to carry out three-dimensional nonlinear bending simulations of the lattice beams. The resulting response is used to evaluate the effective bending rigidity in the nonlinear regime. These results are then directly compared with those obtained from linear bending analyses, highlighting the influence of geometric nonlinearity on the overall stiffness and deformation behavior.

The study also examines the validity of homogenized beam models by comparing their predictions against detailed finite element results. It is shown that lattice metamaterials exhibit pronounced size effects, which are not captured by classical beam theories. In contrast, strain gradient beam models provide accurate predictions across different lattice types, thicknesses, and length scales.

Overall, the findings underline the importance of incorporating size effects when modeling lattice metamaterials. The proposed approach offers an efficient tool for the analysis and design of lightweight, high-performance structures, with potential applications in areas such as aerospace and automotive engineering.

EXPERIMENTAL AND MODELLING ISSUES

FOR FIBER METAL LAMINATES UNDER IMPACT

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In the aviation industry, the so-called impact of small accidental or man-made sources on aircraft elements, in service or also during maintenance operations, encompasses several scenarios of practical interest, see [1]. As a first objective, this study aims at characterizing the dynamic response of Fiber Metal Laminates (FMLs), manufactured ad hoc by the authors with different stacking sequences. Both the low-velocity impact (under 10 m/s) of a dropping weight, in accordance with ASTM D7136 standards, and the ballistic impact (at speeds ranging from 90 to 145 m/s) of a 25 g, 9 mm radius steel sphere on an FML target have been carried out. In the latter configuration, the collision caused diverse complex scenarios, with the projectile passing through and continuing its trajectory, remaining stuck in the sample (embedment), or even being bounced back (ricochet). As a second objective, the experimental data were utilized to validate an accurate heterogeneous model of the samples developed in ABAQUS software, discretized by finite elements in explicit dynamics and including geometric nonlinearity and contact [3]. A satisfactory agreement of the finite element predictions was found, in qualitative terms, with the deformation patterns and the damage mechanisms identified by post-mortem visual inspection of the samples, and, in quantitative terms, with the reaction force and the displacement history of the impactor or the outlet speed of the bullet, for the low- and ballistic-impact tests, respectively.

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Non-equilibrium thermodynamics of oriented particles

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The continuum thermodynamics responses of non-spherical oriented particles show additional complexity due to the microstructure orientational freedom of the particles to align with the deformation, loading and boundaries. It was observed that the thermodynamical responses have strong coupling with the microstructure particle orientations, where the evolution of the microstructure gives rise to emerging anisotropy in all quantities.

In this presentation a continuum thermodynamics model for oriented particles is presented. The formulation is a generalization of the constitutive laws of spherical particles that includes an explicit dependency on the microstructure orientational. It is shown that linear dependency is sufficient to well capture the anisotropic coupling between the stress and the microstructure orientational.

As microstructure orientational is an additional field, an associated balance law must be proposed. The formulation of the orientation balance law is presented that includes production and non-convective flux. Consideration of the interaction with the boundary suggests the formulation of the orientation boundary conditions.

The performance of the proposed continuum model is compared with numerical microscopic simulations and experiments to evaluate its accuracy as well as to determine the phenomenological transport coefficients used in the model. It will be shown that the proposed model is capable to well capture the continuum thermomechanical and the microstructure orientational response under various loading and boundary conditions.

A STATISTICAL FRAMEWORK FOR COMPLEX SYSTEMS

WITH A SMALL NUMBER OF SIMULATIONS: FROM

COMPLEX PLASMAS TO CONTINUUM MECHANICS

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This work aims to enhance the limited amount of data obtained from numerical simulations through statistical methods, with the goal of improving the analysis of underlying physical properties. While the present study focuses on plasma behavior, particularly electron density and electron temperature in the boundary region of a tokamak, which are key observables influencing transport properties and confinement regimes, the proposed approach is not restricted to plasma physics. Instead, it is formulated as a general framework applicable to complex systems governed by continuum mechanics. Although the simulations considered here are fully deterministic, we reinterpret them as samples drawn from underlying random fields, enabling the extraction of statistical information. This perspective allows for the construction of marginal and joint probability density functions (PDFs), providing insights beyond standard deterministic analyses and capturing structural features of the system. In the plasma context, this includes the role of triangularity, the impact of the diffusion coefficient, and their implications for boundary behavior. Numerical simulations are performed using the Gkeyll gyrokinetic code. Despite their high resolution, the computational cost severely limits the number of available simulations, motivating the need for advanced techniques capable of extracting meaningful information from small datasets. To address this challenge, we adopt a statistical framework based on probabilistic learning on manifolds (PLoM), a nonparametric approach specifically designed for inference in small-sample regimes [1]. Beyond the specific application to tokamak plasmas, the methodology naturally extends to a broad class of problems in continuum mechanics, where governing equations are deterministic, but data availability is constrained. In this sense, the proposed framework provides a general tool for statistical characterization and uncertainty-aware analysis of complex physical systems from a small number of simulation data.

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DISCRETE-BASED MODEL FOR BI-MODULUS (META)MATERIALS

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Many common materials exhibit different elastic behaviour in tension and compression [1]. A key challenge in modelling such behaviour lies in formulating a consistent bi-modulus continuum theory, in particular, in identifying the quantity that governs the transition between tensile and compressive regimes and, consequently, determines the corresponding elastic moduli responsible for the material duality. For isotropic materials, the most widely known approach is the theory proposed by Ambartsumyan [2], who phenomenologically assumed that the transition is controlled by the signs of the principal stresses. Some recent works use, e.g, a deviatoric-volumetric split assumption of the strain energy function [1] and a granular micromechanics approach [3].

In this contribution, we propose a discrete-based constitutive material model that captures tension-compression asymmetry within a strain-driven framework, whereby the elastic response depends on the sign of a specific combination of principal strains. We consider a series of benchmark problems, namely a pure shear load, volumetric load, and uniaxial load cases, and discuss (1) the decomposition of elastic strain energy, (2) the principal directions of the stress and strain tensors, and (3) the concept of classical Young's modulus and Poisson's ratio applied in the framework of bi-modulus materials.

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An Objective FE-Formulation for Cosserat Shells Based on Spherical Bézier Interpolation

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ABSTRACT

An objective Bézier Finite Element (FE) formulation for geometrically exact Cosserat shell structures undergoing large deformations is presented. The approach extends classical bilinear interpolation [1] in $\mathbb{R}^3$ to a spherical bilinear interpolation on the rotation manifold $SO(3)$, further generalized to high order than 1 by means of the De Casteljau's algorithm, as in done [2,3]. This enables the use of high order bi-variate Bézier surface representations for both the mid-surface (in $\mathbb{R}^3$) and the frames (or unit matrices in $SO(3)$), ensuring an objective and path-independent multiplicative up-dating iterative numerical scheme.

Recursive expressions are derived for the interpolation of finite rotations, as well as for the spin and curvature vectors, resulting to a generalization of Bézier basis functions in $SO(3)$. To mitigate locking effects, a mixed formulation is employed.

Several numerical examples are investigated in order to highlight the convergence, objectivity and path-independence properties of the proposed formulation.

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MS-13 Nonlinear Mechanics of Advanced Materials and Nanostructures

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On spacetime evolutive equilibrium of 1-D elastic structures

D. Ussorio, M. S. Vaccaro, R. Barretta, R. Luciano

Dispersive waves in cubic lattices with short- and long-range interactions

G. Ruta, N. Challamel, H.P. Nguyen, C.M. Wang

To be announced

E. Barchiesi

A hemivariational model for fatigue damage–elasto-plastic Mode-II interfaces

A. Montanino, L. Placidi, F. Fabbrocino

ON SPACETIME EVOLUTIVE EQUILIBRIUM OF 1-D ELASTIC STRUCTURES

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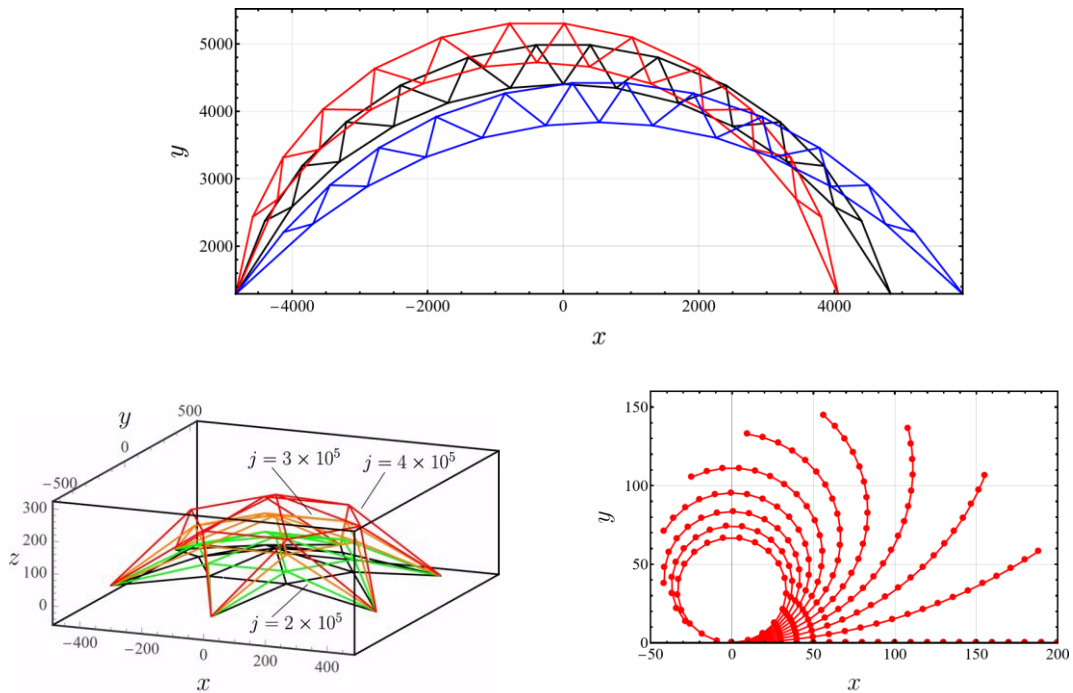
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Nonlinear mechanics of 1-D elastic structures is effectively investigated at different scales in a geometrically consistent 4-D spacetime framework. The 4-D trajectory manifold becomes the object of interest on which the motion can be experienced. The Rate Virtual Power Principle is exploited and the variationally effective stress rate leveraged. Distinction between material and spatial fields is clarified and material tensors at different instants are compared in a natural way by push along the motion. Constitutive relations are formulated as instantaneous incremental responses to a finite set of material tensor state variables and to their time convective rates along the motion. A computationally efficient incremental solution procedure is implemented to effectively address problems of multiscale 1-D elastic structures undergoing large displacements. Elastic and non-elastic effects are considered. Numerical results for emblematic case-studies are presented. Contributed outcomes support the implementation of the presented approach for resolution of geometrically nonlinear structural problems, especially when non-elastic effects are taken into account. Notably, results indicate strong potential for extending the proposed approach to geometrically nonlinear elasto-viscoplastic structural problems, circumventing long-known and debated issues that affect finite deformation approaches.

Keywords: Rate elasticity · Geometric continuum mechanics · Nonlinear mechanics



Dispersive waves in cubic lattices with short- and long-range interactions

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The justification of linear, non-linear, local, and non-local elasticity in homogeneous continuous bodies may be derived from the asymptotic limit of discrete bunches of particles interacting by standard central or non-central forces, in the wake of the path initiated by the French mechanicians Cauchy and Poisson, followed by the Italian Piola, in the early 19th century [1], and re-considered by Born, Von Kármán, Gazis, and many more, in the last century [2]. Following some previous investigations on one- and two-dimensional discrete lattices composed of geometrically regular arrangements of point-like material particles interacting by both central and non-central forces [3-5], in this contribution we examine three-dimensional (3D) cubic elastic lattices composed of such particles, imagined as located at the lattice vertices and spaced by an equal amount along the three characteristic directions of the cube.

Each particle is assumed to interact with the neighbours up to order p (i.e., in principle we investigate interactions with molecular action extending up to a p -neighbourhood) through short- and long-range central (segmental) and non-central (angular) forces. As the inter-particle spacing (i.e. the cube edge length) tends to zero, the lattice asymptotically converges to a continuum. At the first order (i.e., for next-neighbour interactions), the lattice parameters can be calibrated to reproduce a homogeneous, linear elastic, isotropic medium with unconstrained Poisson's ratio. Higher-order asymptotic limits lead to either gradient-enhanced or non-local elastic continua.

It is customary in such cases to investigate the elastic wave transmission in space and time. Here, the wave dispersion characteristics of the lattice are analysed for the simplest case of short-range interactions ($p = 1$, nearest-neighbour interactions only), and in a more general case (for p interactions), with particular emphasis on the role of the discrete interaction kernel. It is shown that the iso-frequency surface for each mode (transversal or longitudinal) belongs to the class of Goursat surface for the second-order asymptotic medium.

Keywords: Discrete vs. continuum elasticity; 3D lattices; Dispersion properties

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A hemivariational model for fatigue damage–elasto-plastic Mode-II interfaces

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We present a variationally consistent model for a one-dimensional continuously distributed interface undergoing Mode-II-type fatigue damage and elasto-plastic evolution. For the sake of simplicity, and in order to emphasize the mechanical consequences of the proposed approach, the two materials across the interface are represented in a deliberately minimal setting: one material is assumed to be rigid, whereas the other is modeled as an elastic axially deformable beam. Equivalently, the system can be interpreted as an elastic truss anchored to a fixed environment through a bed of axially distributed damage–elasto-plastic springs.

The interface is endowed with two plastic accumulation fields, one for each direction of the one-dimensional space, and with a scalar damage field. The activation thresholds of damage and plasticity are not independent, but are coupled within the dissipation potential. This constitutive coupling makes each loading cycle slightly irreversible and progressively more damaging, so that fatigue effects emerge from the structure of the model rather than from an externally prescribed cycle-counting rule or from an assigned S–N law. The evolution problem is formulated as a hemivariational inequality, which ensures thermodynamic admissibility and irreversibility of the internal fields.

Numerical simulations show that the proposed formulation is able to reproduce a pull-out test, progressive narrowing and degradation of hysteretic loops, monotonic growth of damage and dissipation along the interface, failure propagation, and the identification of Paris-law-type parameters. Wöhler curves are also obtained from the simulated evolution, allowing the identification of Basquin-type relation parameters. The proposed formulation can therefore be regarded as a minimal, yet mechanically interpretable, framework for the unified description of plasticity, damage, hysteresis, fatigue and debonding propagation in distributed interfaces.

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MS-15 Modelling interface and contact problems

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Numerical modelling of coupled Cahn–Hilliard diffusion and strain gradient elasticity

S. Khakalo, O. Kranzsch, A. Morozov

Axisymmetric contact and patch-loading problems for a semi-space with a surface energetic boundary

A.Y. Zemlyanova

Vibro-impacts of a visco elastic beam under rigid obstacles: from Euler–Bernoulli to enhanced Timoshenko formulations

C. Pozzolini

Modeling axisymmetric contact problems within strain gradient elasticity

L. Schek, A. Morozov, S. Khakalo, W. H. Müller

Dynamics of a Hybrid Tunable Granular Chain

I. Berinskii

NUMERICAL MODELLING OF COUPLED CAHN–HILLIARD DIFFUSION AND STRAIN GRADIENT ELASTICITY

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Coupled diffusion with elasticity models are utilized in various applications, *e.g.*, the phase decomposition and coarsening of solder alloys [1] and microphase separation in hydrogels [2]. Extensions to the classical Cahn–Hilliard equation incorporating elasticity have already been discussed and formalized in a more general sense, often referred to as the Cahn–Larche system [3]. The arising set of coupled equations has been studied numerically for the cases of small and large elastic deformations [4]. However, the coupling with gradient elasticity lacks numerical investigations in literature, despite its relevance for problems where classical elasticity is known to give qualitatively different predictions, *e.g.*, under bending loading conditions.

In the present contribution, we consider a coupled mechano-diffusion problem that combines Mindlin’s strain gradient elasticity with the Cahn–Hilliard diffusion model [5]. This augments the modelling capabilities by incorporating elasticity-related length scales reflecting microstructural effects at the continuum level. The higher-order boundary value problem is formulated in a variational form within a proper Sobolev space setting. Conforming Galerkin discretizations for numerical results are obtained via an isogeometric analysis approach. We first assess the numerical formulation through a one-dimensional benchmark problem, verifying the implementation and establishing convergence properties. We then analyse size effects in 2D phase separation and coarsening, with particular emphasis on bending-type boundary conditions under which classical and strain gradient elasticity predict qualitatively different mechanical and microstructural behaviour. The simulations reveal how gradient elasticity modifies the evolution of the microstructure during coarsening and clarify the relation between the various length scales involved.

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Axisymmetric contact and patch-loading problems for a semi-space with a surface energetic boundary

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Two axisymmetric problems for a semi-space with a surface-energetic boundary are considered: a frictionless contact of a rigid stamp and a patch-loading problem for nano-sized penny-shaped material surface. The surface-energetic boundaries are modeled using the Steigmann-Ogden form of surface energy. The problems are solved by using the Boussinesq potentials represented by the Hankel transforms of certain unknown functions. With the help of these functions, the problems can be reduced to integral equations. Solvability of these integral equations is studied. Two types of material surface tip boundary conditions are considered for the patch-loading problem: free tip conditions and conditions with compensated surface prestress term. The numerical solutions of the integral equations are obtained by expanding each unknown function into a series based on Chebyshev polynomials. Then the approximations of the unknown functions can be obtained from a system of linear algebraic equations. Accuracy of the numerical procedure is studied. Various numerical examples for different values of the surface energy parameters are considered. It is shown that both the surface parameters and the type of tip conditions have significant influence on the behavior of the material system.

VIBRO-IMPACTS OF A VISCO ELASTIC BEAM UNDER RIGID OBSTACLES: FROM EULER-BERNOULLI TO ENHANCED TIMOSHENKO FORMULATIONS

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In many practical applications, especially in the nuclear industry, viscoelastic beam-like components are exposed to dynamic loadings that may generate repeated impacts against rigid stops. These interactions produce strongly nonlinear responses characterized by unilateral contact, discontinuities in velocity, and intricate energy dissipation mechanisms. This talk investigates the vibro-impact dynamics of a viscoelastic Euler–Bernoulli beam subjected to external forcing and unilateral, frictionless contact with two rigid obstacles. A rigorous continuous formulation is first introduced based on Signorini contact conditions. The problem is naturally expressed as a time-dependent variational inequality. Spatial discretization is performed using the finite element method, leading to a semi-discrete system of second-order differential inclusions. The resulting time-dependent problem is then addressed using the singular mass method [1] combined with a generalized Newmark integration scheme. Special attention is devoted to the influence of the time step, the convergence behavior of classical penalty-based contact formulations, and the capacity of the proposed scheme to maintain physically meaningful energy dissipation over long simulation horizons. The results demonstrate the emergence of complex dynamic behaviors, including bifurcations, transitions between periodic and quasi-periodic responses, and chaotic vibro-impact regimes. A key conclusion is that the qualitative structure of the dynamics depends not only on the physical parameters and contact configuration, but also strongly on the numerical discretization and the time integration strategy. This observation underscores the crucial role of modeling choices in non-smooth dynamical systems. From a theoretical perspective, impact modeling has historically relied on Newton's restitution law: $v(t^+) = -e v(t^-)$, rigorously formalized in the 1970s by Moreau and Schatzman within the framework of differential measurement inclusion theory. In the specific case of a point mass impacting a rigid obstacle, the existence of solutions for external $L^1(0,T)$ -forces was established by M. Schatzman, using penalization techniques, in his doctoral thesis. However, uniqueness is generally compromised, as demonstrated by the counterexample of Bressan and Schatzman for regular loading. Interestingly, Percivale later showed that uniqueness is restored when the forcing term is analytical. A significant open problem concerns the extension of Newton's impact law to thin structures. For these structures, elastic waves cannot propagate through the thickness, making the definition of a coefficient of restitution challenging. A mathematically consistent generalization guaranteeing existence, uniqueness, and energy consistency for thin structures remains to be solved and constitutes a stimulating research area at the interface of analysis, mechanics, and numerical approximation. Finally, these results encourage the development of more advanced strategies, such as contact approaches based on the Nitsche model or enriched beam kinematic theories [2], which appear promising for performing reliable long-term simulations of industrial structures subjected to repeated impacts.

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Modeling axisymmetric contact problems within strain gradient elasticity

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Experimental testings indicate that the effective hardness of materials, as measured in normal contacts, depends on the size of the indenter. While this effect cannot be described by classical continuum theories, such a size-dependence can be modeled with generalized continuum theories. In this study, the application of simplified strain gradient elasticity in describing frictionless normal contacts is investigated. Axisymmetric contact problems for indenters of different shape are modeled within the framework of simplified strain gradient elasticity using a rigid body penalty-based contact approach in isogeometric analysis. The numerical implementation is verified using an existing semi-analytical solution for strain gradient elasticity. This study reveals significant deviations from classical theory, particularly in the form of the pressure distribution under the indenters. It is shown that the stress singularity present in the classical solution to the indentation test of a flat cylinder vanishes in the case of strain gradient elasticity. Furthermore, the importance of gradient elasticity for describing scale effects of normal contacts with indenters is demonstrated. The presented results are based on work recently published by the same authors in [1].

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Dynamics of a Hybrid Tunable Granular Chain

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Granular metamaterials – engineered assemblies of discrete particles – offer a uniquely tunable platform for wave control. Their dynamics, governed primarily by contact mechanics, can be dialed from weakly to strongly nonlinear by varying precompression. In the absence of pre-stress, one-dimensional chains enter the “sonic vacuum” regime with no linear sound and with strongly nonlinear solitary waves. Precompression adds linearity to the system, however it is fully pre-defined by the granular elastic properties.

We propose a hybrid linear–Hertzian chain in which linear springs connecting the spherical beads provide a stable, bidirectional small-signal pathway while Hertzian contacts supply amplitude-dependent hardening. This dual-knob architecture decouples baseline stiffness (set by springs and/or pre-stress) from nonlinear tuning (set by contact mechanics). The resulting structure is simultaneously predictable (well-defined dispersion for homogenization), tunable, and robust (connectivity retained). We show how the parameters of stiffness and space between the granular beads affect the regimes of wave propagation and related phenomena.

MS-16 Mechanics of Flexible Electronics

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Finite deformation theory for growth-inspired conformal integration

X. Feng

Conformal vibration-coded metamaterials for structural health monitoring of low-altitude aircraft

C. Li, Y. Lu

Wearable ultrasound arrays: fabrication and therapeutic application in bone fracture and ischemic stroke

H. Liu

Stretchable Multilevel Mesh Brain Electrodes for Neuroplasticity in Glioma Patients Undergoing Surgery

Y.-F. Liu

Multisensory electronic skin with decoupled pressure–temperature-sensing capabilities for similar object recognition

J. Ji

Bioinspired balloon catheter integrated with stretchable “flounder” electrodes under high voltage for uniform pulsed field ablation

X. Shen, Y. Chen, X. Feng

Mechanics of shape-reprogrammable soft surface

H.L. Wang

Mechanics in electronically controllable micromachines

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Elastic snap-through buckling via designed magnetic actuation

Y. Zhang

A reduced-order model for thin magneto-elastic plates

D. Yan, K. Zhang

Wave Propagation in One-Dimensional Third-Gradient Continua for Metamaterial Design

A. C. Rapisarda, E. Barchiesi, L. Placidi

Finite deformation theory for growth-inspired conformal integration

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Conformal integration enables planar bodies to operate on curved, living, or engineered surfaces where performance relies on intimate geometric and mechanical compatibility. In practice, fabrication and patterning remain largely planar, motivating post-fabrication integration to non-developable targets. The central challenge is that geometric incompatibility demands in-plane metric change, which often triggers wrinkling, delamination, or fracture. Nature offers a guiding principle: growth programs the in-plane metric to fit complex geometries without loss of continuity. Translating this concept to engineered systems exposes a gap. Existing studies have mainly focused on forward modeling of growth-induced morphologies or inverse shape design within reduced plate or shell models, while computational-graphics approaches, such as discrete conformal and bounded-distortion mappings, address related metric design problems primarily from a geometric perspective.

We develop a finite deformation theory for growth-inspired integration that co-designs the local map and stress state within a unified framework. Closed-form analytical results are derived and illustrated through a canonical disc-to-sphere attachment problem. Grounded in differential geometry, the inverse design is formulated through two invariants, quasi-conformal (QC) dilatation, which measures angle distortion, and areal stretch, which quantifies local area change. Canonical mappings—conformal, QC, and constant-area—are formulated to respectively preserve local angles, bound anisotropy, and maintain local area. An optimal graded-QC strategy is introduced to balance angle fidelity and area uniformity. The Cauchy stress field is decoupled from the chosen in-plane mapping, yielding a phase diagram that links membrane tension and interfacial traction and provides guidelines for wrinkle-resistant and delamination-free integration. This framework establishes a unified basis for coupled geometric and mechanical design and shows potential for programmable integration and morphing in soft materials, biological tissues, and curvy electronics.

Conformal vibration-coded metamaterials for structural health monitoring of low-altitude aircraft

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Accurate vibration sensing is central to structural health monitoring of low-altitude aircraft, especially in the fast-growing low-altitude economy of Hong Kong and the Greater Bay Area. Yet current systems face three mechanical limits: the need for dense sensor networks to locate faults, a strict trade-off between sensitivity and sensing bandwidth, and the mismatch between continuous elastic dynamics and discrete high-rate sampling. Here we introduce conformal vibration-coded mechanical metamaterials that integrate information processing into the elastic dynamics of aircraft-like structures. These metamaterials are geometrically conformal to curved airframes and act as mechanical “front-ends” that pre-condition vibration signals before they reach conventional electronics. First, we design information-driven elastic programmable metamaterials that tailor guided-wave propagation so that the position and strength of a vibration source can be identified from a single measurement point. Second, we realize purely mechanical frequency-division multiplexing metamaterials that decompose broadband vibrations into multiple narrow frequency channels, overcoming the usual sensitivity–bandwidth trade-off in vibration sensing. Third, we create wave-based analog computing metamaterials that perform spectral operations directly on propagating elastic waves, mitigating the mismatch between continuous physical dynamics and discrete sampling. Experiments and simulations on representative low-altitude aircraft structures demonstrate robust source localization, sensitive yet wide-band detection, and efficient spectrum extraction. This mechanics-centric, conformal metamaterial platform offers a scalable route to intelligent, vibration-based health monitoring for next-generation low-altitude aircraft in emerging urban air mobility ecosystems.

Wearable ultrasound arrays: fabrication and therapeutic application in bone fracture and ischemic stroke

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Ultrasound is an effective non-invasive biomedical therapy, while traditional rigid probes have inherent limitations that restrict clinical application. Here, we fabricated wearable ultrasound array devices with identical material components for bone fracture and ischemic stroke therapy, using 1-3 piezoelectric composites, bridge-island serpentine metal interconnects and soft elastomeric membranes. The devices exhibited >20% stretchability, stable electromechanical performance and tight tissue conformal integration, overcoming the drawbacks of rigid probes. In rat femoral delayed union models, 6-week intervention achieved complete osseous healing, with bone modulus, bone mineral density and trabecular thickness increased by 615%, 30.2% and 35.7% via upregulating OPN/RUNX2 to promote osteoblast differentiation. For ischemic stroke, the ultrasound arrays adapted to mouse brain curvature was validated on MCAO mice, effectively targeting ischemic brain regions and significantly facilitating structural and functional repair of lesion areas. This work develops versatile flexible ultrasound arrays with clinical potential, providing new engineering strategies for flexible ultrasonic technology in biomedical therapy.

Stretchable Multilevel Mesh Brain Electrodes for Neuroplasticity in Glioma Patients Undergoing Surgery

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Brain disease surgical treatment usually leads to neurological dysfunction. Electroencephalogram (EEG)-based neuroplasticity study may facilitate patient nerve function recovery from injury, allowing a return to normal activities. Due to the limitations of wound infections and hair barrier effects, a traditional brain-computer interface system is not applicable to patients after tumor resection. Here, stretchable multilevel mesh brain electrodes with reconfigurable interfaces are developed. The electrode has a multilevel mesh and malleable structure to avoid hair blockage between the electrode and scalp, realizing the conformal attachment of the stretchable multilevel mesh brain electrodes to a nondevelopable curved brain surface. Moreover, the thermally reversible hydrogel forms a good reconfigurable interface contact between the electrode and scalp, reducing postoperative infection and secondary injury risks to ensure the high-quality acquisition EEGs. In this study, a newly invented stretchable multilevel mesh brain electrodes is applied to test the preoperative and postoperative EEGs of recurrent glioblastoma patients for the first time. The obvious inhibitory effects of tumors on brain activity (a-wave signals) are discovered. More importantly, the EEG signals gradually enhance with postoperative recovery, which is mutually confirmed with the Karnofsky score results, showing the possibility of neural function remodeling neurological rehabilitation in adults. The main text, like the author names used Times New Roman font, 14 points for the Author names and 12 points for the remainder of the abstract. Type or paste your text into this file but remember to keep the page margins the same as is set here which is 2.5 cm all round. Paragraphs are justified (straight-edged) on both left and right.

Multisensory electronic skin with decoupled pressure– temperature-sensing capabilities for similar object recognition

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Multisensory electronic skin (e-skin), which mimics the tactile capabilities of human skin, plays a pivotal role in enabling advanced perception in robotic systems. Despite numerous advances in multifunctional perceptions, e-skin with combined mechano- and thermosensation capabilities is still challenging, particularly for recognizing objects with similar physical characteristics.

Here, we report a multisensory e-skin featuring a bioinspired multilayer strain-regulating mechanical design for smart perceptions. A patterned protrusion texture is introduced to tailor strain distribution and enhance pressure sensing sensitivity, while the temperature-sensing layer is mechanically isolated from deformation under pressure loading. This multilayer architecture allows pressure- and temperature-induced responses to be distinguished with minimal cross-interference over a wide operating range.

Owing to its excellent decoupled sensing performances of pressure and temperature, this multisensory e-skin enables the development of a haptic perception system for evaluating some discernible characteristics (e.g., shape and size) and experience-driven features (e.g., modulus and thermal conductivity) of objects through a simple grasp. Demonstrations of accurate recognition of various objects even with extremely similar surface features highlight the significant potential of this multisensory e-skin in applications such as intelligent soft robotics, prosthetics, and other related fields.

BIOINSPIRED BALLOON CATHETER INTEGRATED WITH STRETCHABLE “FLOUNDER” ELECTRODES UNDER HIGH VOLTAGE FOR UNIFORM PULSED FIELD ABLATION

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Atrial fibrillation leads to severe diseases such as heart failure and strokes. While catheter ablation is prevalent for the treatment, hardly can existing techniques achieve both tissue selectivity and ablation uniformity. Here, we propose a bio-inspired strategy for balloon-based pulsed field ablation (PFA) systems based on “flounder” electrodes. Inspired by flounder skeleton and citrus peels, the microfabricated electrodes are ultrathin, stretchable and scattered-configured, withstanding large balloon deformation (87% compression), high voltage (1200 V) and owning exceptional tissue conformability (720° twists). Mechanical-electrical coupled stimulation optimizes balloon electrodes with hemispherical electric field uniformity. A water lily-inspired transfer printing method enables one-step integration of multi-electrodes with the balloon. A comprehensive PFA system is complemented, achieving ablation depths of 3.8 mm (potato), 3.1 mm (rabbit) and 2.3 mm (swine) with good uniformity and electrophysiological isolation. These results shed light on quantitative design of PFA systems, with high potential for more precise, safe, and effective catheter ablation therapies.

Mechanics of shape-reprogrammable soft surface

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Shape-reprogrammable structures capable of morphing into various configurations in response to spatiotemporally distributed actuation exhibit emerging applications in soft robots, smart medicine and human-machine interfaces. Previously reported shape-reprogrammable structures encounter difficulties in reproducing multiple target shapes and continuous shape-shifting processes, due to the lack of strategy to determine the distribution of actuations for the structure to morph into targets (i.e., the inverse problem). In this presentation, a mechanics model in concise form is developed for the out-of-plane deformation of the electromagnetically actuated network structure. It shows that the overall large deformation obeys the same rule as that of a tensioned membrane under out-of-plane pressure in linear regime, yielding analytical solutions to the relationship of displacement vs. electromagnetic force. The model is validated by FEA and experiments for various typical deformations. It leads to a model-based solution to the inverse problem, predicting the actuations for the structure to morph into target shapes without referring to expensive numerical approaches. In addition, the model reveals the mechanism of the shape reprogrammable network structure and provides design guidelines. These findings pave the way for the application of shape programmable soft surface, especially for scenario that demands the accurate control of the shape-shifting process.

Mechanics in electronically controllable micromachines

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Micromachines, with characteristic dimensions on the order of 100 micrometers, exhibit unique mechanical behaviors. Their motion mechanisms, structural deformations, and fluid interactions follow physical laws that are distinctly different from those governing macroscopic machines. This report introduces our series of research progress on mechanical issues in micromachines.

First, to address the challenge of controllable deformation at the microscale, we have developed design and fabrication methods for deformable structures based on electrochemical microactuators. By combining mechanical analysis with nanofabrication techniques, we achieved controllable deformation through electrochemical reactions, thereby enabling mechanical motion and fluid pumping.

We then discuss the mechanical principles underlying microarchitected structures, including the use of origami techniques to create three-dimensional microstructures and the study of their fundamental mechanics. Specifically, we designed a metamaterial robot platform capable of shape morphing and mechanical motion. By addressably controlling subregions of the robot, we achieved multiple distinct shapes within a single device; cycling through these shapes enables the robot to locomote in desired directions. Applying a similar shape-morphing concept, we employed an artificial cilia platform for fluid pumping. We demonstrate that a single-degree-of-freedom cilium can achieve non-reciprocal motion through fluid-solid interaction, with the pumping direction influenced by boundary conditions. Furthermore, we show that hinged cilia can achieve efficient bidirectional pumping via electronic actuation.

Second, we address the challenge of coordinated motion in large-scale robot swarms. By establishing a signal transmission mechanism based on local electronic pulse coupling among microrobots, each robot can perceive and exchange information with its neighbors, achieving collective clock signal synchronization.

Overall, this report demonstrates the central role of mechanical issues in the research of micromachines, from the deformation mechanisms of individual actuators to the cooperative dynamics of large-scale swarms. A mechanical perspective provides indispensable tools for understanding and designing these emerging systems.

Elastic snap-through buckling via designed magnetic actuation

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Hard magnetic elastomers (HMEs) are formed by incorporating hard magnetic particles into a soft elastomer, resulting in a magneto-responsive continuous medium. This study establishes an equivalent point-force model for slender hard magnetic elastica under external magnetic fields and conducts a systematic investigation focusing on elastic snap-through instability in bistable structures. A classical bistable model is constructed using HMEs and an Euler buckling structure, which systematically reveals the fundamental characteristics of snap-through instability and achieves multiple distinct elastic snap-through modes, including asymmetric, symmetric, and high-order symmetric modes. Although symmetric snap-through is theoretically realizable and offers advantages for practical applications, it has rarely been reported in bistable systems. We also introduce a design concept of “magnetized interfaces”, where alternately magnetized regions are prefabricated in HMEs, generating a series of staggered equivalent force pairs under an applied magnetic field. While preserving the intrinsic symmetry of the system, this configuration establishes an internal “force-field competition mechanism”: the driving force induces snap-through instability, whereas the equivalent resistance effectively suppresses the formation of asymmetric modes. Using this “distributed regulation” strategy, the stable excitation of symmetric snap-through instability paths under quasi-static conditions is realized for the first time, and a universal design method applicable to more complex bistable systems is established. Furthermore, based on a five-interface system, a complete “snap-through phase diagram” is constructed in this study, clarifying the correspondence between interface parameters and structural instability behavior, and revealing a quasi-linear scaling law of critical magnetic fields between different orders. This provides a theoretical foundation and design basis for the precise control of complex bistable systems.

A REDUCED-ORDER MODEL FOR THIN MAGNETO-ELASTIC PLATES

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Slender plate-like structural elements are widely employed in both traditional engineering structures and advanced functional devices. Their counterparts made of magnetically-active elastomers can provide fast and reversible shape-morphing through contactless remote actuation. Several promising applications involving magnetic plates have been recently proposed in the literature, albeit with designs that have been primarily driven by intuition. As such, there is a striking lack of formal theoretical tools to aid in the predictive and rational design of this class of magneto-elastic slender structures.

Here, we develop a 2D theory for the mechanics of thin hard-magnetic plates based on a modified torque-based 3D continuum theory. Following a dimensional reduction procedure akin to that of classic Föppl–von Kármán plates, we reduce the system’s 3D energy functional, including the magneto-elastic coupling, into a 2D description with respect to the plate’s mid-surface. The reduced-order model is then employed to predict the plate deformation under a combination of mechanical and magnetic loading conditions. Our theoretical framework, comprising a 3D continuum model and a 2D plate model, is validated thoroughly using experiments.

Wave Propagation in One-Dimensional Third-Gradient Continua for Metamaterial Design

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Understanding wave transmission in higher-order continua is essential for modeling advanced microstructured systems and designing new metamaterials. In this work, we investigate the behavior of plane waves in a one-dimensional third-gradient continuum under small deformations, focusing on the dynamic effects introduced by higher-order terms.

The analysis is grounded in a variational approach, from which we derive the governing equations using the principle of stationary action. The third-gradient terms naturally appear from the homogenization of architected structures, and are key to describing systems with complex internal geometry. The resulting dispersion relations reveal multiple wave modes—both propagating and attenuated—governed by internal length scales introduced by the higher-order contributions.

We derive the boundary conditions directly from the variational principles, ensuring physical consistency, and examine the transmission and reflection of waves at interfaces between continua of different order, particularly when third- and second-gradient materials are coupled. These boundary interactions play a critical role in controlling how wave transmission.

By computing the time-averaged energy flux, we obtain explicit expressions for transmission coefficient. Our results show that third-gradient effects significantly modify the propagation behavior, offering control over energy flow that can be exploited in impact protection and vibration filtering. This line of research is directly motivated by the development of new metamaterials, such as the recently studied ZAPAB (Zigzagged Articulated Parallelograms with Articulated Braces structure), which exhibit higher-order mechanical responses. The model presented here provides a robust theoretical foundation for designing materials with tailored dynamic performance.

MS-18 Models for Damage and Plasticity in Advanced Materials

Anil Misra (Florida International University, USA), Luca Placidi (Pegaso University, Italy)

MS-19 Methods for data-driven design of materials through optimizing microstructures and processes

Daniel Balzani (Ruhr-University Bochum, Germany), Markus Kästner (Technische Universität Dresden, Germany)

Toward digital twins: the case of the Palmavera nuraghe (Alghero) for a structural vulnerability assessment

M. E. Yildizdag, I. Trivelloni, R. Busonera, E. Barchiesi, E. Turco

2D and 3D Granular Micromechanics Simulation of Ultra-High Performance Fiber-Reinforced Concrete (UHP-FRC) under Non-Homogeneous Loading in Compression, Tension, and Three-Point Bending Test

A. Kandalafi, A. Misra, L. Placidi, F. Fabbrocino

From Hinge Failure to Continuum Damage: Experimental Identification in Pantographic Metamaterials via Model-Driven DVC

A. Ciallella

Computational modelling of magnesium alloy corrosion: A microstructural approach

F. Karamifard, T.J. Vaughan and P.E. McHugh

Systematic general inelasticity

V. N. Khiêm and A. J. Gil

Thrust-line assessment in masonry arches using a granular micromechanics model

M. M. Nayeban, C. Olivieri, F. Fabbrocino, A. Misra, L. Placidi

Planar Chiral Metamaterial with Granular Motif: Constitutive Parameter Identification using Numerical Experiments

N. Yilmaz, L. Placidi, A. Misra

Slope stability in granular micromechanics

L. Placidi, A. Montanino, F. Fabbrocino, M. Nayaban, C. Olivieri

To be announced

E. Barchiesi

Damage Analysis of Beam Structure Based on Peridynamics Theory

Z. Yang and K. Naumenko

Mechanics driven route toward functional assembly of 2D materials

C. Cao

Inverse materials design – data-guided from property to structure

M. Kästner, A. Otto, A. Raßloff, M. Rosenkranz, T. Schneider

Inverse Microstructure Design of Tool Steels for Enhanced Indentation Resistance Using Compact Statistical Descriptors

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Bayesian-guided inverse design of hyperelastic microstructures: Application to stochastic metamaterials

H. Danesh, H. Wessels

Microstructure-Damage Relationships in SMC Composites

M. Shirinbayan

Analysis of Welding Deformations and Stresses Accounting for Structural Transformations

O. Dzidzava and O. Kikvidze

TOWARD DIGITAL TWINS: THE CASE OF THE PALMAVERA NURAGHE (ALGHERO) FOR A STRUCTURAL VULNERABILITY ASSESSMENT

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The use of computational models represents an important approach for investigating degradation processes and structural behaviour in historic architecture exposed to natural and anthropogenic factors. This paper explores the theoretical basis for a digital-twin approach applied to dry-stone masonry structures through the discrete element method. In this framework, individual stones are modelled as rigid blocks connected by nonlinear interfaces, enabling the simulation of structural interactions and damage evolution. Nuragic architecture in Sardinia provides a particularly suitable context for this research. The large number of nuraghi distributed across the island, together with their recurring architectural and construction features, offers an ideal basis for testing computational models and assessing structural vulnerability. The growing interest in the conservation and enhancement of Nuragic heritage further highlights the relevance of developing advanced tools for analysis and monitoring. The Nuraghe Palmavera complex was selected as a pilot case study because of its clear architectural configuration, extensive archaeological documentation, and recent restoration activities. The study aims to contribute to the development of methodologies for the digital analysis and conservation of historic dry-stone architecture.

2D and 3D Granular Micromechanics Simulation of Ultra-High Performance Fiber-Reinforced Concrete (UHP-FRC) under Non-Homogeneous Loading in Compression, Tension, and Three-Point Bending Test

May 18, 2026

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Abstract

A granular micromechanical framework is proposed to describe and predict the mechanical response of Ultra-High Performance Fiber-Reinforced Concrete (UHP-FRC) subjected to heterogeneous loading conditions, including compression, tension, and three-point bending. The formulation is built on an explicit representation of grain-pair interactions, where orientation-dependent contributions are integrated over the full configurational space to recover the macroscopic behavior from underlying microstructural activity. Within this setting, the model reproduces the progressive development of damage and plastic deformation in a directionally dependent manner, naturally giving rise to anisotropic response characteristics as an emergent phenomenon of the microstructure.

The theoretical formulation establishes a direct link between discrete granular mechanics and continuum-scale response through the application of Piola's ansatz, while kinematic consistency is ensured via objective measures of grain-to-grain relative motion under finite deformation. Constitutive evolution is defined through thermodynamically consistent laws derived from Karush–Kuhn–Tucker (KKT) conditions, which enforce irreversibility and govern the coupled evolution of damage and plasticity at the grain level.

For numerical implementation, the model is embedded in a dedicated computational environment developed in MATLAB and COMSOL Multiphysics, allowing both two-dimensional and three-dimensional simulations of the granular system. This framework is used to reproduce laboratory-scale experiments, where predicted force–displacement responses are systematically validated against measured data. A complementary parametric analysis is conducted to investigate the influence of key microstructural and constitutive parameters on the global response, providing insight into their role in governing the observed macroscopic behavior.

UHP-FRC is finally framed as an advanced cement-based composite material that has undergone significant development over the last two decades, distinguished by high tensile and residual strength, efficient crack mitigation, and strong resistance to crack propagation. These attributes enhance structural durability and reliability, and, in combination with the proposed multiscale modeling approach, underscore its suitability for next-generation resilient structural applications.

Keywords: UHP-FRC, granular micromechanics, damage, plasticity, anisotropy, PP fibers, Karush–Kuhn–Tucker conditions, hemivariational approach, concrete modeling, multiscale simulation

From Hinge Failure to Continuum Damage: Experimental Identification in Pantographic Metamaterials via Model-Driven

DVC

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Pantographic metamaterials, composed of two families of fibers interconnected by pivots or hinges, exhibit remarkable resilience under large elastic deformations and are capable of sustaining significant loading paths even in the presence of localized damage. Due to the high concentration of deformation energy in the relatively small volumes occupied by the pivots, these interconnections are the preferential sites of plastic and damage phenomena. Their placement therefore constitutes the key macro-kinematical parameter governing the overall mechanical response of the structure, consistently with the predictions of second-gradient continuum models.

The experimental characterization of damage evolution in such microstructured systems presents specific challenges. Micro-computed X-ray tomography combined with global Digital Volume Correlation (DVC) provides full-field three-dimensional displacement measurements, but the periodicity of the mesostructure, the limited gray-level contrast of 3D-printed polymeric materials, and the large displacement regimes encountered during testing hinder a straightforward application of standard DVC pipelines. Mechanical regularization, while necessary to stabilize the inverse problem, introduces continuity constraints that generate kinematic artifacts in the presence of broken hinges, effectively masking the damage it should help characterize.

To address these issues, a model-driven initialization strategy is adopted, in which a calibrated 3D continuum finite element model provides the initial displacement guess for the DVC analysis at each loading step. The hinge centers, identified as the representative kinematical points of the pantographic block, are used both to drive the initialization and to localize damage: broken hinges manifest as outliers in the joint distribution of maximum principal strain and gray-level residuals evaluated at the hinge level. At each loading step, identified broken hinges are removed from the finite element mesh and the DVC analysis is re-run on the updated mesh, yielding an artifact-free reconstruction of the displacement field.

The approach is demonstrated on a 3D printed pantographic block subjected to a shear test, with micro-CT scans acquired at successive loading stages. Pre-existing printing defects are identified via a backtracking procedure comparing the as-printed configuration with the nominal geometry. The progressive evolution of hinge failure across loading stages is tracked and visualized, providing a direct experimental characterization of damage at the mesoscale. Future developments will focus on exploiting this identification framework to calibrate and validate damage-plasticity models for generalized continua describing pantographic metamaterials.

COMPUTATIONAL MODELLING OF MAGNESIUM ALLOY CORROSION: A MICROSTRUCTURAL APPROACH

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Magnesium (Mg) alloys are promising bioresorbable medical implant materials, that safely degrade after healing [1]. However, Mg alloys typically corrode too rapidly in physiological environments [2]. Experiments show that this corrosion does not progress uniformly through the material, and that the progression depends on the material's polycrystalline grain structure [3]. In the present work microstructural corrosion in an Mg alloy (WE43) is simulated using computational modelling. A polycrystalline Mg alloy (WE43) microstructure is modelled where each grain has a distinct lattice orientation, allowing corrosion to vary with local crystallography. Mg crystals have a hexagonal-close-packed (HCP) structure, and experiments have shown [3] that basal-oriented grains (i.e. grains with the basal plane parallel to the corrosion surface) are more susceptible to corrosion, and this is implemented in the corrosion model. The surface-based corrosion model is implemented in Abaqus, incorporating the evolution of a scalar damage (corrosion) variable and element removal. The approach is a development on our previously published pitting corrosion model [2, 4] where in that previous work the material was considered to be homogeneous and isotropic. In the present work, 2D geometries are assumed. Diffraction Contrast Tomography (DCT) was used to characterize the Mg WE43 microstructure. Simulations are performed using DCT-based and regular hexagonal grain models with random crystal orientations in 2D. Results indicate the non-uniformity and grain structure dependence of corrosion in the microstructure (Fig. 1 (a, b) vs (c, d)). However, overall corrosion rates are similar where the average grain size and average grain orientation correspond. Simulations for models with finer grain structures indicate slower overall corrosion progression (Fig. 1(e)). Overall, the modelling approach provides useful insights to aid microstructural design of bioresorbable implant materials. Future work will extend this approach to fully 3D microstructure models, both regular and DCT-based.

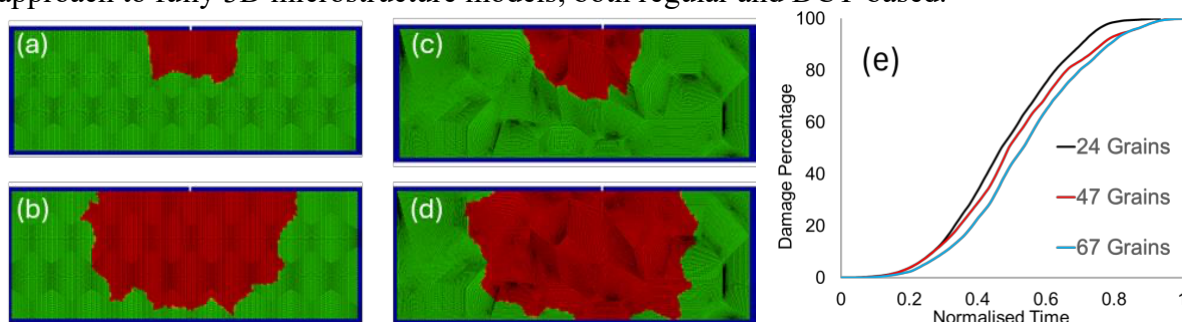


Fig. 1: Simulated corrosion (red) in the model reference region at two time points from an initial pit for two models with the same average grain size and orientation: regular (a, b) and DCT-based (c, d); (e) overall corrosion evolution for models with different numbers of grains in the model reference region.

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Systematic general inelasticity

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Continuum inelasticity describes the transmission of deformation and internal forces in materials that undergo irreversible processes. Recent experimental evidence from advanced material systems calls for a theoretical framework that can capture anisotropic behavior, a requirement that classical inelasticity theories fail to achieve without relying on ad hoc constructions.

In this contribution, we develop a rigorous thermodynamic and mathematical framework for continuum inelasticity based on the principle of maximum internal dissipation, formulated in terms of the thermodynamic driving force rather than the stress. The theory relies on only two fundamental ingredients: (i) a generally anisotropic Helmholtz free energy, expressed via irreducible invariants of frame-indifferent quantities; and (ii) a generally anisotropic yield function, derived from representation theorems in terms of the thermodynamic driving force. This formulation enables a unified treatment of anisotropic inelasticity as well as irreversibility driven by multiphysics couplings.

The proposed framework is further equipped with a newly proposed inelasticity theorem that provides a general guideline for constructing inelastic theory such that the entire framework is inherently thermodynamically consistent. Applications to new families of polymeric and composite materials demonstrate that the theory yields closed-form expressions for the internal variables, drastically reducing computational cost compared with stress-based yield formulations. At the same time, it offers a clear physical interpretation of complex phenomena such as mechanoresponsive light emission, damage cross-effects, and deformation-induced phase transitions.

Thrust-line assessment in masonry arches using a granular micromechanics model

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Abstract

A continuum formulation based on granular micromechanics is proposed for the analysis of masonry arches with tension/compression asymmetry. The approach aims to bridge classical thrust-line analysis and standard finite element analysis within a unified constitutive framework. The formulation is based on the homogenization of orientation-dependent pairwise interactions, leading to a continuum elastic energy density in which distinct tensile and compressive stiffnesses are introduced through a bimodulus parameter n .

The method enables the reconstruction of the thrust line a posteriori from the computed stress field through the eccentricity relation $e = M/P$, allowing direct comparison with classical Heyman-type solutions. Unlike purely geometric limit-analysis approaches, the proposed framework also provides access to stress distributions and principal stress trajectories within the arch domain.

A series of benchmark case studies is considered, including semicircular and segmental arches subjected to self-weight, distributed horizontal loading, and concentrated vertical loads. The bimodulus parameter is calibrated through the minimum-thickness semicircular arch benchmark and subsequently transferred to different geometries and loading conditions. Numerical results show that increasing n progressively reduces tensile effects and leads to thrust-line configurations in good agreement with classical no-tension solutions, while also capturing thrust-line migration and stability sensitivity under varying load conditions.

The proposed framework preserves the interpretability of thrust-line concepts while extending the analysis toward constitutive modeling and finite tensile effects, providing a mechanics-based tool for the assessment of masonry-like structures under complex loading scenarios.

Planar Chiral Metamaterial with Granular Motif: Constitutive Parameter Identification using Numerical Experiments

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Cosserat or micropolar continuum models for planar (2D) media have been shown to predict mechanical chirality due to coupling between material stretching and micro-rotation [1]. This type of mechanical chirality appears in 2D materials with granular microstructures because of specific interactions between grains. Such a behavior cannot be described by the classical Cauchy continuum model. However, extended continuum models derived using granular micromechanics approach (GMA) predict such material behavior [2-4]. These models provide a link between grain-scale behavior and the overall material response, such that the methodology can be applied to conceive granular motif metamaterial that exhibit the desired chirality. Using this approach 2D microstructures for granular metamaterial are designed, one with a square motif and the second with a hexagonal motif. For the complete identification of the micropolar model stiffness parameters of the conceived metamaterial a numerical simulation methodology is developed. The parameter identification methodology is agnostic to the anisotropy class of the given metamaterial. The numerical simulation utilizes micro-scale finite element simulations based upon the classical continuum model and exploits deformation energy correspondence between the micropolar model and the micro-scale finite element simulations. This presentation will describe our approach for parameter determination and show results that emphasize the need for appropriate generalized continua to describe material behavior.

Keywords chiral behavior; granular micromechanics; cosserat continua; numerical modelling.

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Slope stability in granular micromechanics

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We present a slope-stability analysis based on granular micromechanics. The material is described as a purely linear elastic continuum with tension–compression asymmetry, obtained by assigning lower stiffness in tension and higher stiffness in compression for each interaction orientation. This choice allows us to account, in a simple but mechanically meaningful way, for one of the characteristic features of granular geomaterials.

Instability is searched by means of a Mohr–Coulomb criterion adapted to granular micromechanics, from which a safety factor is defined. The proposed framework recovers the expected result that steeper slopes are associated with lower safety factors. At the same time, the analysis highlights the influence of the compression-to-tension stiffness ratio: the symmetric case gives a reference estimate, whereas increasing the ratio changes the predicted safety factor and may lead to significant deviations from standard stability assessments. These results suggest that the proposed approach can be of practical interest for engineering applications. As a perspective, the framework will be extended to include plastic deformations in granular micromechanics and irreversible evolutions governed by suitable dissipation functionals.

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Damage Analysis of Beam Structure Based on Peridynamics

Theory

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Peridynamics (PD) is a non-local continuum mechanics theory that describes long-range forces between material points through integral equations. By overcoming the limitations of traditional differential equations in handling discontinuity problems, it is well-suited for analyzing material fracture, damage, and multi-physics field coupling.

In this study, a mathematical model for composite beam structures was established based on peridynamics theory, and a damage model was constructed using the maximum strain energy density criterion. The model was validated through the bending failure of sandwich and laminate composite beam structures, successfully accomplishing crack initiation, propagation, and arrest phenomena in alternating soft and hard materials. A key advantage of this model is its ability to visualize two-dimensional damage evolution within a one-dimensional framework, significantly reducing computational time and modeling costs.

Mechanics driven route toward functional assembly of 2D materials

C. Cao

McGill University

Two-dimensional materials promise exceptional performance, but turning near-theoretical atomic strength into real, manufacturable structures remains a central challenge. In this talk, I will show our efforts in linking fracture and interfacial mechanics of graphene oxide across length scales to a new additive manufacturing platform for 2D materials-based nanocomposites. At the atomic and nanoscale, we quantify how chemistry, functionalization, and hierarchy control strength, toughness, and interlayer shear—from monolayer graphene oxide with strengths approaching tens of GPa, through nanosheets that approach monolayer performance, to functionalized multilayers where crack-arrest mechanisms more than double fracture toughness compared to pristine graphene. We then leverage these insights to design inks and curing strategies for a reaction-based direct ink writing process, enabling freeform, support-free printing of lightweight 2D material-based nanocomposite architectures with programmable mechanical response.

Bio



Dr. Cao is an Associate Professor and Canada Research Chair (Tier 2) in small-scale materials and manufacturing, in the Department of Mechanical Engineering at McGill University. He earned his Ph.D. in Mechanical Engineering from the University of Toronto and was a postdoctoral fellow at MIT before joining McGill. His research interests include experimental nanomechanics of advanced materials, development of additive manufacturing mechanisms, N/MEMS, and transfer printing technologies. He is the Associate Editor of *Microsystems and Nanoengineering* (Springer Nature) and has also been recognized with the Young Leaders Award and Young Leaders International Award from TMS, the Young Scientist Award from Springer Nature, and Stony Brook University 40 under 40, etc.

INVERSE MATERIALS DESIGN – DATA-GUIDED FROM PROPERTY TO STRUCTURE

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Being able to design the microstructure of a material to achieve a desired macroscopic behavior is a key enabler for materials innovation. Achieving this goal requires detailed knowledge of how the local material structure influences effective mechanical properties such as stiffness, strength, or ductility. Ideally, experimental data and numerical simulations are combined to establish robust structure–property (SP) linkages. A central challenge then lies in inverting these linkages to identify microstructures that realize a prescribed set of target properties—an approach commonly referred to as inverse materials design.

In this contribution, we employ stochastic descriptors to characterize complex microstructures across multiple length scales. Examples include volume fraction, generalized spatial n -point correlation functions, and Gram matrices derived from pre-trained convolutional neural networks. Corresponding statistically representative volume elements (SVEs) are generated using differentiable microstructure characterization and reconstruction (DMCR). Compared to other efficient reconstruction techniques, DMCR enables the prescription of generic, potentially high-dimensional microstructure descriptors, provided they are differentiable. The reconstructed microstructures are subsequently analyzed using numerical homogenization techniques to compute effective material properties, which are then combined with the microstructural descriptors to establish SP linkages.

Since engineering data – particularly high-fidelity simulations and experiments – are generally costly to generate, inverse design must operate effectively in data-scarce regimes. We therefore investigate both direct and indirect inverse design strategies tailored to limited data availability. The presented methodology is demonstrated for two representative and complementary application domains: (i) spinodoid-based mechanical metamaterials, where complex yet smooth morphologies can be described using low-dimensional stochastic descriptors; and (ii) microstructures of secondary aluminum alloys contaminated by iron and silicon, where microstructural variability and defect populations critically affect mechanical performance. These examples highlight the versatility of the proposed framework for data-driven exploration of SP landscapes and inverse microstructure design in modern materials research.

Inverse Microstructure Design of Tool Steels for Enhanced Indentation Resistance Using Compact Statistical Descriptors

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High-speed steels (HSS) are widely used tool steels, as they exhibit application-specific favorable properties such as superior hardness, which are usually the result of pronounced microstructures consisting of carbide inclusions within a martensitic matrix. HSS contain a variety of different alloying elements posing challenges with regard to recyclability and, in addition to that, the carbides make use of critical alloying elements such as tungsten (W) or molybdenum (Mo). Hence, reducing the number of alloying elements and substituting the critical with less critical ones, such as vanadium (V), is necessary for more sustainable HSS. To assess the influence of microstructure morphology and phase properties on the overall performance, a virtual, data-driven workflow is advantageous. The validity and efficiency of such workflows depend on (i) a minimal yet expressive set of microstructural design parameters, (ii) appropriate 3D microstructure reconstructions, and (iii) numerical simulations that capture the mechanical response with high accuracy.

Here, a workflow is presented which takes into account higher-order statistical descriptors, as used in so-called statistically similar representative microstructures [1], as they are expected to be necessary to unambiguously describe HSS microstructure morphology. However, their high dimensionality makes them unsuitable as design variables for the later optimization. Therefore, we propose an approach to significantly reduce the design-parameter space by distilling characteristic features from the higher-order statistical measures. Still, an artificial three-dimensional microstructure needs to be reconstructed from the designed statistical descriptors, for the framework MCRpy [2] is used. With reconstructed microstructures at hand, numerical micro-indentation simulations are performed using a contact implementation [3] in the finite element framework Ferrite.jl [4]. This allows the hardness of the designed material to be computationally assessed, such that an optimization scheme can be employed for the identification of the particular material design leading to the highest hardness.

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Bayesian-guided inverse design of hyperelastic microstructures: Application to stochastic metamaterials

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From a given pool of all feasible design variants, our aim is to identify a structure that achieves a target macroscopic stress response. For each candidate design, the response is obtained from a high-fidelity oracle, in particular, time- and resource-intensive computational homogenization or experiments. We consider the case where (i) the geometry cannot be conveniently parameterized, rendering gradient-based optimization inapplicable, and (ii) brute-force evaluation of all candidates is infeasible due to the cost of oracle queries. To tackle this challenge, we propose a Bayesian-guided inverse design framework that proceeds as follows. First, the dimensionality of the design variants is reduced through statistical feature engineering, and the resulting low-dimensional descriptors are mapped to effective constitutive parameters describing the macroscopic hyperelastic response. This mapping is modeled using a multi-output Gaussian process surrogate that accounts for correlations between the parameters. The surrogate is trained using uncertainty-driven active learning under severe budget constraints, allowing only a very limited number of high-fidelity oracle evaluations. Based on surrogate predictions, a finite number of promising candidates are shortlisted. Since the surrogate accuracy is inherently limited, the final selection of the optimal design is performed through high-fidelity oracle evaluations within the shortlist. In numerical test cases, we consider a dataset of 50,000 candidate structures. Active learning requires labeling less than half a percent of the full dataset. Bayesian-guided inverse design under unseen loading conditions reaches a prescribed error threshold with only a handful of oracle evaluations in the majority of cases.

Microstructure-Damage Relationships in SMC Composites

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Sheet Molding Compounds (SMCs) are increasingly used in lightweight structural applications, where their performance is governed by a complex interplay between microstructural architecture, constituent materials, and manufacturing-induced heterogeneities. This work examines the mechanical behavior and damage development of three SMC grades - Standard SMC, Advanced SMC (A-SMC), and Low-Density SMC (LD-SMC) - subjected to quasi-static, dynamic, and fatigue loading conditions. To capture the effect of loading rate on damage initiation and propagation, tensile tests were performed over a broad range of strain rates, from quasi-static conditions up to 100 s^{-1} . Particular attention was paid to the influence of fiber orientation and microstructural anisotropy on the mechanical response. A dedicated Interrupted Dynamic Tensile Test (IDTT) device was developed to investigate damage accumulation during high-rate deformation and to provide access to intermediate damage states prior to final failure.

A multiscale experimental methodology combining mechanical testing, microscopic observations, anisotropy characterization, and interrupted tests was employed to identify the governing failure mechanisms. The analysis revealed a progressive transition involving matrix cracking, fiber/matrix interfacial debonding, fiber fracture, and pseudo-delamination phenomena. The role of hollow glass microspheres, characteristic of LD-SMC materials, was also assessed in relation to stiffness, strength, and damage resistance.

The results highlight significant differences between the investigated SMC systems. A-SMC exhibits markedly enhanced tensile performance and improved damage tolerance compared with conventional SMC, whereas LD-SMC provides an attractive compromise between weight reduction and mechanical performance. Furthermore, all materials demonstrated pronounced strain-rate sensitivity, indicating that visco-damage mechanisms strongly influence failure processes under dynamic loading. By establishing clear links between microstructural features, damage scenarios, and macroscopic behavior, this study provides valuable insights for predictive multiscale modelling and the design of next-generation SMC structures operating under severe service conditions.

Keywords: SMC; strain rate; fatigue; microstructure-dependent damage; multi-scale.

Analysis of Welding Deformations and Stresses

Accounting for Structural Transformations

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During the welding of metal structures, irreversible volumetric deformation occurs, which affects the level of welding displacements and stresses, as well as the strength of the welded joint. In the temperature range of structural transformations, deformation changes non-monotonically as the temperature increases. Consequently, the thermal linear expansion coefficient is a complex function of temperature. Constitutive equations that relate strain increments to stress components are used to determine stresses. The equation of state is selected according to the theory of structural parameters.

Based on the processing of experimental dilatometric curves, dependencies of the thermal linear expansion coefficient on temperature have been obtained. The study of displacement and deformation during the welding of rod structural elements has been conducted. Numerical calculations were performed using the Mathcad software.

MS-22 Mathematical models in Engineering and applied sciences

Alberto Maria Bersani (Sapienza Università di Roma, Italy), Micol Amar (Sapienza Università di Roma, Italy)

Multiscale analysis in composite materials with rough imperfect interfaces

M. Amar, D. Andreucci C. Timofte

The effect of almost-periodic microstructures in phase separation

L. D'Elia

Axisymmetric nematic soap films

L. Lussardi

Homogenization of non-linear free boundary-value problems in composite materials

S. Monsurrò

Homogenization of a nonlinear elliptic problem with imperfect interface

C. Perugia

Multiscale analysis in composite materials with rough imperfect interfaces

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In the last years, the improvements of industrial techniques has permitted to obtain more efficient materials constructed by assembling different constituents, whose physical properties are definitely superior than the ones of the single components. However, this bonding does not give rise in general to perfect contacts between the different components, so that discontinuities in the involved physical fields can appear.

Also the study of boundary value problems in composites with rough boundaries or interfaces is a topic that has recently attracted a significant interest due to their applications in many areas of natural or engineering sciences, such as fluid mechanics, materials science, biology, etc.

In this talk, we present some recent results concerning the study of problems where imperfect contact conditions couple with oscillating interfaces.

More precisely, we consider a stationary heat diffusion problem in a two-component material, which exhibits an imperfect contact across an oscillating interface separating the two constituents. At the microscopic scale, it is mathematically described by an elliptic boundary value problem stated in each of two connected components. The heat potential is continuous across the interface, while its flux jumps according to suitable prescribed conditions, which lead to different macroscopic models, obtained through an asymptotic analysis.

The effect of almost-periodic microstructures in phase separation

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Many of the new media needed by and sought for in the applications are heterogeneous materials. Being able to describe and predict stable equilibrium configurations of phases is thus fundamental in order to take full advantages of these materials.

In this talk, we will work within the gradient theory of phase separations, namely using a van der Waals–Cahn–Hilliard type of energy. We consider the case where the material has a microstructures that can be described by an almost-periodic function. This is intended to model quasi-crystalline materials, whose properties are in between periodic and random materials. We will discuss the effect of these types of microstructures in the sharp interface limit of the energy.

This work is in collaboration with R. Cristoferi (Radboud University).

AXISYMMETRIC NEMATIC SOAP FILMS

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Nematic films are thin fluid structures, ideally two dimensional, endowed with an in-plane nematic order. Some variational models for nematic films have been introduced by Gomi in 2012 and by Napoli and Vergori in 2018. At equilibrium, the shape of the nematic film results from the competition between surface tension, which favors the minimization of the area, and the nematic elasticity, which instead promotes the alignment of the molecules along a common direction. The main difference between the two mentioned approaches is the way to compute the surface derivative of the nematic vector field. In this seminar I will briefly describe the physical models, and I will present a variational analysis of the proposed models for revolution surfaces spanning two coaxial rings. This talk is based on joint works [1]-[2] with Giulia Bevilacqua (Venezia), Chiara Lonati (Torino) and Alfredo Marzocchi (Brescia).

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HOMOGENIZATION OF NON-LINEAR FREE BOUNDARY-VALUE PROBLEMS IN COMPOSITE MATERIALS

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Signorini-type boundary conditions appear in many problems in applied mathematics that model phenomena arising in engineering and materials science. Examples include lubrication and filtration processes, hydrodynamics, plasticity, crack theory, and optimal control problems. The weak formulations of such kind of problems involve variational inequalities corresponding to nonlinear free boundary-value problems.

Aim of the talk is to describe some homogenization results for Signorini-type problems in periodic two-component domains. In particular, the Signorini condition is expressed in terms of two complementary interfacial conditions involving the jump of the solution on the interface and its conormal derivatives via a parameter γ . These problems can model the heat exchange in a medium hosting a periodic array of thermal conductors. Actually, in nature the presence of impurities distributed in some regions of the interface may give rise to a discontinuity of the temperature field. The Signorini interface condition seems more realistic to describe such real phenomena since, from a physical point of view, it expresses the fact that there exist a zone of the interface of perfect conduction i.e. absence of jump, and one characterized by an imperfect contact transmission condition. In the latter, the thermal flux is proportional to the jump through a coefficient depending on the period and on the parameter γ representing the order of magnitude of the resistance with respect to the period. According to the values of γ different limit behaviours are obtained.

HOMOGENIZATION OF A NONLINEAR ELLIPTIC PROBLEM WITH IMPERFECT INTERFACE

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As a first approximation, a biological tissue can be considered as an electrolyte. Its dielectric properties can be interpreted by analyzing the possible effects of the interaction of an electromagnetic radiation with the tissue components at the cellular and molecular levels. The earliest investigation on the electrical properties of these tissues was conducted by Schwan in [4]. Eventually in [2] it was experimentally proven that three kinds of dispersions occur according to the frequency: the ionic diffusion, the interfacial polarization and the dipolar orientation. Here we are concerned with the interfacial polarization taking place in the radio-frequency range and deriving from the conductive properties of cellular membranes, which may have a nonlinear behaviour. This is also known as the Maxwell-Wagner effect and it is typical of non-homogeneous dielectrics. Thereby, it seems natural to model such phenomena in the context of the homogenization of boundary value problems in composite materials in presence of nonlinear conditions on the interface. Aim of the joint work [3] is to find out the effective dielectric properties of a biological tissue made up of two phases separated by a dielectric interface taking into account the conductive properties of its components and of the interface. More precisely, inspired by [1], from a mathematical point of view, we consider an elliptic problem with a nonlinear lower order term set in an open bounded cylinder of $\mathbf{R}^N$, $N \geq 2$, divided into two connected components by an imperfect rough interface. We assume that at the interface the flux is continuous and proportional, via a nonlinear rule, to the jump of the solution. According to the amplitude of the interface oscillations and the proportionality coefficient, we derive different homogenized problems:

- A) the interfacial polarization phenomenon is preserved at the limit and, via an interface nonlinear condition, takes into account the dielectric properties and the geometry of the interface.
- B) the Maxwell-Wagner effect gives rise, at the limit, to an isolating interface separating the two different phases of the dielectric.
- C) the limit model is the same which would occur in absence of the interfacial polarization.

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Posters

MS-5 - *Multi-Physics Coupled Electrical Contact Model Considering Contact Asperity Interaction*
F. Shen, Y.-H. Li, L.-L. Ke

MS-5 - *Nonlinear Deformation and Chip Formation in Orthogonal Cutting of Aluminum Alloys:
Role of Johnson-Cook Constitutive Parameters*
F. Pan, A. Hartmaier

MS-8 - *Nonlinear bending deformation of active metabeam*
J. Jiang, X. Zhang, M. Amabili

MS-8 - *Mechanical Integrated Computing Architecture for Extreme Environment Applications*
C.Niu and H. Jiang

MS-17 - *Learning to optimise energy: AI-driven control for hybrid PV-battery systems*
J.F. Pereira, M. Fernandes, I. R. Silva, C. Neiva, S.I.S. Pinto

Multi-Physics Coupled Electrical Contact Model Considering Contact Asperity Interaction

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Electrical contact refers to the phenomenon where two conductors are connected to transfer electric current or signals, widely present in electronic, power, and communication systems. It involves a multi-physics coupling phenomenon including electrical, thermal, and mechanical disciplines. The presence of rough surfaces introduces greater complexity, as interactions occur between asperities. The deformation of each asperity is influenced not only by compression but also by the deformation behavior of its neighboring asperities. This paper establishes a theoretical and numerical multi-physics coupling electrical contact model on rough surfaces, determining the electrical contact behavior that accounts for interactions between contact asperities and elastoplastic deformation.

Theoretical Model: First, the boundary element method is employed to determine the surface contact morphology considering interactions. Geometric analysis is then performed on each contact spot to calculate the critical deformation amount (using an ideal elastoplastic model). For elastically deformed rough peaks, the area calculated by the boundary element method is used as the elastic deformation area. For plastically deformed rough peaks, the plastic deformation area is calculated using a fitting formula. The electrical contact area is then further determined. The electrical contact results for the rough surface are determined through a summation method based on the electrical contact behavior of each contact asperity.

Numerical Model: A boundary element method combined with the fixed-point method is employed for modeling electrical contact on rough surfaces, offering higher computational efficiency compared to the finite element method. First, the Boussinesq-Cerruti fundamental solution is employed to obtain contact behavior considering contact asperity interaction. The DF-SANE algorithm computes the strain based on contact pressure increments. The Mindlin fundamental solution accounts for plastic deformation and the influence of the temperature field on the overall deformation. Finally, iterative solution is achieved using the fixed-point method to obtain the overall electrical, thermal, and mechanical behavior.

Analysis reveals that considering multi-physics coupling, contact asperity interaction, and elastoplastic deformation is crucial for accurately describing electrical contact behavior on rough surfaces and should not be neglected in related research.

Nonlinear Deformation and Chip Formation in Orthogonal Cutting of Aluminum Alloys: Role of Johnson-Cook Constitutive Parameters

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Metal Machining is a representative nonlinear solid mechanics problem involving severe plastic deformation, high strain rates, strong thermo-mechanical coupling, and severe strain localization. Accurate constitutive descriptions are therefore essential for predictive simulation. The Johnson-Cook (JC) constitutive model is an empirical material model that incorporates strain hardening, strain-rate sensitivity, and thermal softening, which is widely applied in machining simulations. This study systematically investigates the influence of JC constitutive parameters on orthogonal cutting outcomes, with a particular focus on chip formation and machined surface roughness.

A literature-based JC parameter set for aluminum alloys was established, and a full-factorial design with three levels for each of the five JC parameters was constructed. An automated Python-Abaqus workflow was developed for two-dimensional orthogonal cutting simulations and post-processing. Statistical analysis indicates that the cutting force is predominantly influenced by the strain hardening coefficient. Chip formation and surface roughness are primarily influenced by the yield strength, strain hardening exponent, and their interaction. Further in-depth analysis reveals that a periodic shear instability develops during chip formation, with periodicity mainly controlled by yield strength, strain hardening coefficient, and strain hardening exponent. Variations in these parameters alter the flow stress and strain hardening behavior of the material, thereby modulating the stability, intensity, and spectral purity of the periodic adiabatic shear bands. To physically quantify this morphological transition, a dimensionless Serration Tendency Index, formulated from yield strength and strain hardening reserves, is proposed. This index effectively differentiates between continuous and serrated chips under the investigated conditions. The periodic shear mechanism leads to fluctuations in the cutting force and transmits a mechanical signal through the tool-workpiece system, directly influencing the geometric profile of the machined surface.

These findings provide a physics-based perspective on the nonlinear deformation mechanics in cutting, offer actionable guidance for selecting and calibrating JC parameters for predictive simulations, and support strategies aimed at improving surface quality.

Nonlinear bending deformation of active metabeam

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Beams constitute the backbone of structural engineering, serving as fundamental load-bearing elements that determine system integrity and performance. The incorporation of active control mechanisms has revolutionized beam behavior, creating structures with unprecedented deformation characteristics that fundamentally challenge conventional analytical paradigms. These active metamaterials exhibit high adaptability and can transform traditional structures into metamaterials. The introduction of external energy makes these active metamaterials particularly interesting, enabling controlled propagation gain/loss while facilitating Π -T symmetry breaking [1, 2], and acquiring self-adaptive functionality [3]. However, active forces create new constitutive relationships which bring nonlinear deformation behaviors. When deforming, active forces change with the structure while external forces remain the same. In other words, unlike external loads in the deformation equilibrium equations, active force influences the unit deformation in a coupled manner.

Therefore, this paper first proposes a state-space methodology for deriving the governing equations of active beams, which deals with this nonlinearity in a non-iterative way. The effectiveness of this approach is demonstrated through an active unidirectional coupling based on the Timoshenko beam model. Case studies under various boundary conditions reveal that the novel odd-elastic constitutive relationships not only enable significant bending deformation control but also introduce a novel stiffness—active stiffness. This active stiffness introduces nonlinearity and challenges the conventional perception that bending deformation is merely related to bending stiffness.

This novel design and analysis methodology address a significant research gap in the systematic analysis of active metabeam systems. The active nonlinear deformation mechanism enables a passive beam with highly adjustable stiffness, allowing the beam to achieve shape control capabilities with non-destructive modifications while maintaining load-bearing capacity. In this way, it can be used for cases like temperature deformation compensation, self-adaptive aerodynamic components, and fluid propulsors. This methodology presents a new and effective approach for precise control of equipment and structures in aerospace and advanced manufacturing applications.

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Mechanical Integrated Computing Architecture for Extreme Environment Applications

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Abstract

Conventional microelectronic technologies, based on P-N junction operation, face fundamental performance degradation in extreme environments due to thermally induced carrier effects and radiation-induced damage. Despite advances in wide bandgap semiconductors and advanced packaging strategies, computing architectures with intrinsic resilience to such conditions remain limited. Here, we report a mechanical integrated computing (MIC) architecture enabled by mature MEMS technology, in which logic operations are realized through controlled mechanical motion rather than charge transport. This approach mitigates key failure mechanisms associated with electron-hole dynamics under extreme conditions. The MIC system maintains full functionality over a wide temperature range from 83 K to 773 K and sustains γ irradiation with a total dose exceeding 10 kGy. Through a programmable node design, the architecture supports implementation and scalable fabrication of universal logic gates, achieving operating frequencies up to 10 kHz and stable operation over more than 1×10^9 cycles at the micrometre scale. Scaling analysis further suggests that nanoscale implementations could enable operating frequencies up to 0.25 GHz, with energy consumption as low as 6.5×10^{-26} J per cycle. These results establish mechanical integrated computing as a viable pathway for robust information processing in extreme environments, bridging the gap between conventional microelectronics and mechanically based computing systems.

Keywords

Extreme environment; Mechanical computing; Vibration; Signal processing; Dynamic control

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LEARNING TO OPTIMISE ENERGY: AI-DRIVEN CONTROL FOR HYBRID PV-BATTERY SYSTEMS

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The increasing penetration of renewable energy sources, particularly photovoltaic (PV) systems, introduces operational challenges due to their variability and intermittency. In grid-connected environments, efficient Energy Management Systems (EMS) are required to balance energy flows, reduce costs and ensure reliability. While optimization-based approaches such as Mixed-Integer Linear Programming (MILP) provide optimal strategies, their computational complexity limits real-time applicability.

This work proposes a machine learning-based EMS framework using policy approximation to replicate optimal decisions generated by a MILP model. The case study considers a grid-connected PV system with a redox flow battery, simulated in the System Advisor Model (SAM). A day-ahead forecasting approach is adopted, using real meteorological data for PV generation and synthetic load profiles.

The MILP model generates optimal control actions, forming a supervised dataset used to train multiple machine learning models, including Random Forest (RF), Extreme Gradient Boosting (XGBoost) and deep learning architectures such as CNN-LSTM. These models are evaluated for both policy approximation and forecasting tasks. A physics-informed layer is incorporated to enforce constraints such as battery state-of-charge and power balance. In parallel, reinforcement learning (RL) agents are being developed as a benchmark to compare RL and policy approximation approaches, particularly in handling uncertainty.

Results obtained under simulated conditions, show that the proposed EMS achieves less than 4% performance degradation relative to the MILP optimum, while improving costs by approximately 11.4% compared to a rule-based controller, with significantly lower computational effort. These results are obtained in a partially realistic environment, as load profiles are synthetic.

Future work will focus on validation with real consumption data and on evaluating the robustness of RL and policy approximation approaches under uncertainty, including forecasting errors and measurement noise.

The proposed framework demonstrates a scalable pathway toward real-time EMS solutions for renewable-integrated smart grids.

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