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List of abstracts

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Generalized continuum models confronted to cell-commensurate instabilities in structured media

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This work focuses on the ability for two generalized continuum models to capture mesoscale cell-commensurate instabilities in structured media using a very simple base model.
Indeed, [1] have shown that a periodic arrangement of atoms, linked by complex interactomic potential could lead to short-wave commensurate and incommensurate instabilities and [3] proposes a quasi-continuum model based on strain gradients able to capture both long and short wavelength instabilities. On the other hands, using non-linear springs, [2] studied the ability of a strain-gradient model to capture long wavelength instabilities. As a consequence, the example of a periodic arrangement of non-linear springs, as presented in Fig.1a) below has been proposed. This simple example has been shown to display both long and short-wavelength instabilities depending on the values of the model's non-linear parameters (Fig.1b)).
Two generalized media have been compared: micromorphic and second order strain-gradient media. It is thus shown that the short-wavelength bifurcation points can only be captured by a micromorphic-type medium while the long-wavelength bifurcation points are captured by both models. This concludes that if short-wavelength instabilities are possible, micromorphic-type media are more appropriate to describe, in a continuous way, the buckling of the mesoscopic stucture.

*Speaker

Buckling analysis of beam-like structures

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In this paper, an homogenized beam model is formulated for buckling analysis of periodic micro-structured beams, uniformly compressed. These are planar grid beams, whose micro-structure consists of a square lattice of equal fibers. The equivalent beam model is derived in the framework of a direct one-dimensional approach and its constitutive law, including the effect of prestress of the longitudinal fibers, is derived through a homogenization approach. Accordingly, micro–macro constitutive relations are obtained through an energy equivalence between a cell of the periodic structure and a segment of the homogenized beam. The model also accounts for micro-warping of the micro-structure, via the introduction of elastic and geometric corrective factors of the constitutive coefficients. The buckling behavior of sample grid beams is presented to validate the effectiveness and limits of the equivalent model. To this purpose, results supplied by the exact analyses of the equivalent beam are compared with those given by finite element models of the planar grid beams.

*Speaker

Multi-scale design of an architected composite structure with optimized graded properties

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A design framework is here presented for the development of an architected solid with targeted mechanical properties thanks to an optimized porosity distribution. A 2D lattice of regular hexagons is considered as core element of a sandwich panel and a Bloch-Floquet-based approach is adopted to derive homogenized equivalent properties. The density distribution of the equivalent continuum is taken as objective function to be minimized in the optimization process. To this end, suitable constraints are designed to avoid empty regions and ensure a minimized density where required by the mechanical actions. A de-homogenization process is carried out on the optimized equivalent continuum to derive the configuration of regular hexagons with optimally varying wall thickness. Static and buckling responses of the optimized architected solid are compared with that of a 2D continuum whose material density distribution is determined through a classical topology optimization. It is shown that the architected 2D solid can absorb higher strain energy, with respect to classically optimized structures, which suffer a buckling-driven collapse below the elasticity threshold. The architected solid is also shown to have an improved energy absorption capability, that may increase considerably its performance, depending on the ductility of the adopted material. Casalotti, A., D'Annibale, F. & Rosi, G. Multi-scale design of an architected composite structure with optimized graded properties. *Compos Struct* **252**, 112608 (2020).

*Speaker

Mechanical metamaterials with local inertia amplification: analytical spectral design

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Abstract: Architected metamaterials yielding superior dynamic performances can be conceived by realizing local mechanisms of inertia amplification in the periodic microstructure [1]. A periodic cellular waveguide characterized by an intracellular pantograph mechanism is considered as minimal physical system simulating an inertially amplified metamaterial [2]. A discrete tetra-atomic model is formulated to describe the undamped free dynamics of the cell microstructure. The ordinary differential equations of motion feature quadratic and cubic inertial nonlinearities, induced by the axial indeformability of the pantograph arms connecting the principal massive atoms with the secondary massive atoms, serving as inertial amplifiers. The transfer matrix of the linearized model is considered to describe the free propagation of small-amplitude harmonic waves. First, the band structure of the complex-valued dispersion spectrum is determined analytically, by properly exploiting the formal (time-to-space) analogy with the Floquet Theory for the stability of non-autonomous dynamic systems (*direct problem*). Second, a spectral design problem is stated and solved by inverting analytically the functions expressing parametrically the boundaries separating attenuation (stop) and propagation (pass) bands in the frequency spectrum (*inverse problem*). The inverse problem solution provides the mechanical parameters of the inertially amplified metamaterial possessing a desired band structure, assigned according to functional design requirements [3]. The existence and uniqueness of the solution in the admissible range of mechanical parameters is discussed. The discussion provides (i) mathematical demonstration for the existence of feasible design solutions or multi-solutions, (ii) complete definition of the physically realizable band structures in the frequency domain, and (iii) alternative criteria to design iso-band structured metamaterials within the admissible domain of mechanical parameters. Different metamaterials purposely designed to satisfy functional or even extreme spectral requirements are finally presented.

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Mechanical metamaterials with local inertia amplification: nonlinear dispersion properties

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Architected metamaterials yielding superior dynamic performances can be conceived by realizing local mechanisms of inertia amplification in the periodic microstructure [1]. A periodic cellular waveguide characterized by an intracellular pantograph mechanism is considered as minimal physical system simulating an inertially amplified metamaterial [2]. A discrete tetra-atomic model is formulated to describe the undamped free dynamics of the cell microstructure. The ordinary differential equations of motion feature quadratic and cubic inertial nonlinearities, induced by the axial indeformability of the pantograph arms connecting the principal massive atoms with the secondary massive atoms, serving as inertial amplifiers. Nonlinear dispersion properties governing the free undamped propagation of harmonic Bloch waves have been investigated by means of a general asymptotic approach in absence of internal resonances [3]. Particularly, the multiple scale method up to the third order is adopted to analytically determine the nonlinear functions relating dispersion properties (wavefrequencies and waveforms) and oscillation amplitude of the propagating wave. Specifically, the nonlinear wavefrequencies and waveforms are determined as analytical closed-form functions of the parameters, quadratically depending on the oscillation amplitudes. The acoustic and optical frequencies exhibit the typical softening behavior caused by dominant cubic nonlinearities in inertially nonlinear systems, even if hardening acoustic frequencies can be identified in particular regions of the parameter space. The invariant manifolds associated with the nonlinear acoustic and optical waveforms show synclastic or anticlastic distortions of the linear (planar) manifolds in the space of principal coordinates. Validation of the analytical outcomes is performed by directly integrating the nonlinear equations of wave motion for different initial conditions. The obtained numerical solutions are shown to lie on the manifold surfaces with fine qualitative and quantitative approximation, confirming the goodness of the analytical approach.

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*Speaker

Parameter Identification and Investigating the Effect of Higher-order Inertia in a Gradient Elasticity Model of Metamaterials in Dynamic Loading

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Abstract: In metamaterials with a complex microstructure, the role of higher-gradient terms in the mechanical response is not negligible. Here, our goal is to identify the parameters of a homogenized model for a type of metamaterials known as pantographic structures. For the description of the pantographic structure, we employ a 2D non-linear second-gradient model which considers the complex structure as a homogenized plate [1]. The parameters of the model are identified for the corresponding structure through an automatized optimization algorithm [2]. We validate the identified parameters for the dynamic regime by comparing displacement plots with experiments [3].

Experimental results are obtained by applying forced oscillations to pantographic specimens made by 3D-printing technology. Qualitative and quantitative analyses for different frequency ranges show a good agreement far away from the eigenfrequencies while discrepancies are present close to the eigenfrequencies. To investigate the effect of microinertia, we include higher-order inertia in the model. As a result, the computations moved favorably toward predicting the mechanical behavior close to the eigenfrequencies. However, the experimental characterization of higher-order inertial terms that exist in theories is not yet understood, therefore there is no clear methodology for determining their values up to now. Further studies in this direction are encouraged.

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Elastic wave propagation in structured plates

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Abstract: A novel concept is introduced and tested for the reduction of the scattering by faults in a flexural lattice. The majority of the relevant published work is based on the so-called "cloaking transformation", based on the idea, which initially came from electromagnetism and optics and linked to the Maxwell system of equations or, in special cases, to the Helmholtz equation [1]. In the present work, we address an elastic system and apply a different principle concerning reinforcement of the boundary and redistribution of mass [2]. We demonstrate that this approach, which is simple in nature, enables one to significantly reduce the coefficients in the multipole expansion of the scattered field. Accurate numerical simulations and quantitative analysis of the scattered fields for 'cloaked' and uncloaked faults are provided.

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Design of a lattice plate for attenuation and guiding of elastic waves

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Lattice structures are periodic reticulated structures, featuring a cellular architecture stemming from a network of beams that exhibit peculiar dynamic behaviors [1]. These have proven capable of filtering waves at selected frequency components, known as bandgaps, thus impeding their propagation and facilitating the control of their trajectories. Motivated by the growing deployment of lattices in dynamic applications, in this work we numerically investigate the potential of the renowned octet topology [2] and unravel the physics underpinning its attenuation zone. The band structure of this cell [3], computed numerically upon fulfilling Bloch periodicity, unveils a local resonance bandgap tied to the bending resonance of its struts. We leverage the revealed mechanism to design a lattice-based plate equipped with two metadevices for wave mitigation and control, respectively metabarrier and metalens, generated by supplementary masses embedded in the midpoint of the octet struts [4]. We further rely on time-transient simulations to analyze the propagation of flexural waves across the finite plate and corroborate the performance of the engineered devices. The metabarrier allows for protecting a circumscribed region by reflecting the impinging waves with frequency content matching its stop band and preventing their transmission along the plate. The design of the lens, seemingly more complicated, originates from the spatial grading of the masses. This gradual variation tailors the phase velocity of waves traveling within the lattice-based device and shapes their trajectory, eventually steering them toward a specific focal point. The findings of this study reveal the potential of octet lattices in vibration isolation applications, energy harvesting, and focusing and lay the foundation for further in-depth analyses, for instance, including nonlinear effects.

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*Speaker

Oscillatory configurational forces

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Abstract: Eshelby introduced the concept of configurational forces to motivate the change in the defects position within a solid [3]. Over the last decade, this framework has been extended to the mechanics of structures by showing that frictionless sliding sleeves may provide at their exit an 'Eshelby-like' force parallel to the sliding direction [1, 2].

The effect of oscillatory configurational forces is analyzed during the fall of a rod constrained by a sliding sleeve subject to a periodic motion. Time evolution of the system is achieved through numerical integration by means of an in-house Finite Element solver. The dynamic response can be distinguished in three qualitatively different behaviours: (i.) a final complete injection; (ii.) a final complete transverse ejection; and, unexpectedly, (iii.) a steady small amplitude oscillation in the absence of a final injection or ejection of the rod.

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On the geometrically exact nonlinear hyperelastic and hypoelastic granular interactions

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Abstract: This study investigates several granular interaction laws used in the modelling of discrete granular media and the static response of a small assembly of 4 identical grains (diamond pattern). In the considered model, each grain interacts with its neighbour with a coupled shear-normal interaction law. The analysis is performed in a geometrically exact framework allowing large rotation and displacement evolutions, without any geometrical approximations (see also [1] for the granular *elastica* problem). It is shown that most of the granular interaction laws available in the literature are classified as hypoelastic interaction laws [2], [3] (such as the initial interaction models of Serrano and Rodriguez-Ortiz, 1973 or the popular model of Cundall and Strack, 1979 which gives birth to Particle Flow Codes). The interaction is weakly hypoelastic if an integral form exists, whereas it remains strongly hypoelastic when only an incremental formulation is available. Hyperelastic interaction laws may be also considered, that avoid possibly artificial dissipation (model of McNamara et al [4] or model of Turco et al [5]). We also show that along specific loading paths for which the normal and tangential laws are uncoupled, is the behaviour hyperelastic for all the studied models. For the three types of interactions, the modes of instability are then characterized for large displacement of the diamond pattern. We discuss the discrepancies between each granular model during the deformation process of some displacement-based loading tests.

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The Dynamics of a granular based elasto plastic damage model in the strain gradient formulation

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We illustrate a continuum theory for materials having granular microstructure, accounting for tension–compression asymmetry of grain interactions and for dissipative phenomena like damage and plasticity. The dynamics is numerically evaluated and the results show interesting damage and plastic induced anisotropy evolution including the emergence of a type of chiral behavior and formation of finite localization zones. Besides, loading–unloading histories have been considered to elucidate the material hysteretic features of the continuum. We also assess the competition between damage and plasticity, each having an effect on the other. Further, the evolution of the load-free shape is shown not only to assess the plastic behavior, but also to make tangible the point that, in the proposed approach, plastic strain is found to be intrinsically compatible with the existence of a placement function.
In particular, the continuum description is constructed by assuming expressions of elastic and dissipation energies as well as postulating a hemi-variational principle, without incorporating any additional postulates like flow rules. Granular micromechanics is connected kinematically to the continuum scale through Piola's ansatz. Mechanically meaningful objective kinematic descriptors aimed at accounting for grain–grain relative displacements in finite deformations are proposed. Karush–Kuhn–Tucker (KKT)-type conditions, providing evolution equations for damage and plastic variables associated with grain–grain interactions, are derived solely from the fundamental postulates.

*Speaker

Piola Transformations and contact interactions for Second Gradient Continua and some related remarks on history of mechanics

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The recently obtained Piola transformations for second gradient continua are presented. They prove that edge and surface contact forces in Lagrangian description do not depend only on their Eulerian counterparts but also
on Eulerian contact double forces.
A careful discussion about the limited validity of so-called Cauchy postulate for stress induces some remarks on
relevant aspects of history of mechanics and in particular on the development of the concepts of force, stress and couples.

*Speaker

Variational formulation for the form finding of light-weight structures

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In this work a new variational principle for the form finding of membranes and cable nets is presented. In the case of minimal surfaces the principle offers the interpretation of a minimal surface, as an equilibrium surface with a vanishing Elsheby stress tensor.
The proposed approach generalizes the force density method presenting a non singular Hessian at the optimal solution. Application to metamaterials is one of the scope of the research

*Speaker

On the constitutive assumptions for the recombination term for the R-D-D equations for scintillators

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Abstract: The evolution equations for inorganic scintillators (which converts ionizing radiations into visible light) were obtained in [1] (see also [2], [3]): they are Reaction-Diffusion-Drift equations, coupled with the Poisson equation of electrostatics and Neumann boundary conditions, in terms of the m-dimensional *charge carriers vector* $n \equiv (n_1, \ldots n_m)$:

$$\begin{aligned} \operatorname{div}(D[\nabla n] + MN[q \otimes \nabla\varphi]) + r(n) = \dot{n}\,, \\ -\epsilon\Delta\varphi = eq \cdot n\,, \end{aligned} \tag{1}$$

here D and M are the $m \times m$ *diffusivity* and *mobility* semi-positive definite matrices, $N(n) = \operatorname{diag}(n_1, \ldots n_m)$, φ is the *electric potential*, ϵ the *permittivity* of the crystal, e the elementary charge, $q \in \mathbb{Z}^m$ the *charge numbers vector* and finally $r(n)$ the recombination term which accounts for the visible photons production. Equation $(1)_1$ was obtained by the means of a microstructured continuum model, in the sense of [4], where the rate-of-change of the m- dimensional *director* is the *scintillation potential* $g(n) = eq\varphi(n) + F(n)$, where $F(n) > 0$ is a term of entropic nature.

Here we shall deal with various constitutive assumptions for the recombination term $r(n)$ and show how, when $F(n)$ is the Gibbs-Boltzmann entropy, we can recover the cubic polynomial expression used *e.g.* in one of the few previous existing phenomenological models [5]. Further we shall how a polynomial representation can be obtained as a limit of a Markov process and also explore the instance in which $F(n)$ is represented instead by the Fermi-Dirac potentials.

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A non homogeneous Timoshenko beam subject to the effects due to a diffusion of a fluid

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A variational method for a non homogeneous Timoshenko beam with the inclusion of the phenomenon of the diffusion of a fluid is proposed. The axial and bending cases have been analyzed.
In addition to the classic kinematic descriptors, such as the axial displacement w, the transversal displacement u and the rotation theta of the section, also the concentration c of the fluid inside the beam has been considered.
The proposed assumption for the elastic strain energy implies the defnition of: (i) the duals, distributed (b^{ext}_c) and concentrated (F^{ext}_c0 and F^{ext}_cL), of the descriptor c = c(X; t), (ii) the diusion stiffness K_{DIF} , (iii) the fluid elasticity K_F , (iv) the axial-fluid stiffness interaction K_{FN}, (v) the shear-fluid stiffness interaction K_{FT} and (vi) the bending-fluid stiffness interaction K_{FM}.
The dynamic case, with damping by means of the Rayleigh functional, has been considered introducing the damping factors relative to the time derivative of: axial displacement (c_w), the transversal displacement (c_u), the rotation of the section (c_{theta}) and the concentration of fluid (c_c).
Subsequently it will be possible to consider the case of plasticity and damage whose extension to the 2D case will be used in the study of the ageing phenomena of dams.

*Speaker

A Cosserat model of elastic solids reinforced by a family of curved and twisted fibres

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We outline a Cosserat model for fibre-reinforced solids in which the fibers are modelled as continuously distributed spatial Kirchhoff rods with intrinsic flexural, torsional and extensional elasticity. The basic kinematical variables are a deformation field and a rotation field that describes the local fibre orientation. Constraints on these fields are introduced to account for the materiality of the fibres with respect to the underlying continuum deformation, with the associated Lagrange multipliers interpreted as transverse shear tractions acting on the fibre cross sections. The theory is illustrated via simple examples involving finite deformation.

*Speaker

Bio-inspired phononic crystals and elastic metamaterials

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Abstract: Phononic crystals and acoustic metamaterials can be considered as composites with ad-hoc designed architectures made of periodic, quasi-periodic or even randomly disposed building blocks (unit cells) exhibiting extraordinary dynamic properties, such as frequency-dependent directionality and band gap (BG) behavior. Since their introduction a few decades ago, researchers have tried to explore more and more configurations exhibiting low and broad-band frequency effects without recurring to unpractical increases of the unit cell size or stiffness decreases [1].

On the other hand, Nature has always represented a formidable source of inspiration to solve mankind's scientific challenges and engineering tasks. For instance, it has been shown that a hierarchical organization over multiple length scales allows enhanced quasi-static mechanical properties, while the relative orientation of adjacent chiral centers strongly affects the physical properties of a polymer, to cite a few examples [2]. In this talk, we discuss how bio-inspiration may be used to enhance the potential of phononic crystals and acoustic metamaterials [3, 4]. Specifically, a comparison of the dynamic behavior of conventional and bio-inspired phononic crystals / metamaterials is presented through the evaluation of the corresponding dispersion diagrams and / or transmission properties.

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Transient waves in 1D oscillating media: second-order homogenization and interface conditions

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We consider waves propagating in one-dimensional elastic media, whose properties are periodically varying and which may be bonded by homogeneous (or other heterogeneous) media. The goals of the study was to (i) design a model capturing the dispersive effects of the microstructure and (ii) write adequate boundary and transmission conditions at the interfaces for other media to finally (iii) present a full model and a stable numerical scheme.
For long wavelengths, the asymptotic homogenization procedure provides a family of effective models, which can be interpreted as "strain" or "stress gradient"-type enrichments of the classical elastic model. We select one of these models to achieve a better agreement with the dispersion curve of a given material. Corresponding boundary and interface correctors are then established in the time-harmonic case. They are finally extended to the transient setting, along with a reformulation of the enriched wave equation as an hyperbolic system whose stability is proven. The final model efficiency is illustrated by numerical simulations.

*Speaker

Effective dynamics for low-amplitude transient elastic waves in a 1D periodic array of non-linear interfaces

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This presentation focuses on the time-domain propagation of elastic waves through a 1D periodic medium that contains non-linear imperfect interfaces, i.e.~interfaces exhibiting a discontinuity in displacement and stress governed by a non-linear constitutive relation. The array considered is generated by a, possibly heterogeneous, cell repeated periodically and bonded by interfaces that are associated with transmission conditions of non-linear "spring-mass" type. More precisely, the imperfect interfaces are characterized by a linear dynamics but a non-linear elasticity law. The latter is not specified at first and only key theoretical assumptions are required. In this context, we investigate transient waves with both low-amplitude and long-wavelength, and aim at deriving homogenized models that describe their effective motion. To do so, the two-scale asymptotic homogenization method is deployed, up to the first-order. To begin, an effective model is obtained for the leading zeroth-order contribution to the microstructured wavefield. It amounts to a wave equation with a non-linear constitutive stress-strain relation that is inherited from the behavior of the imperfect interfaces at the microscale. The next first-order corrector term is then shown to be expressed in terms of a cell function and the solution of a linear elastic wave equation. Without further hypothesis, the constitutive relation and the source term of the latter depend non-linearly on the zeroth-order field, as does the cell function. Combining these zeroth- and first-order models leads to an approximation of both the macroscopic behavior of the microstructured wavefield and its small-scale fluctuations within the periodic array. Finally, particularizing for a prototypical non-linear interface law and in the cases of a homogeneous periodic cell and a bilaminated one, the behavior of the obtained models are then illustrated on a set of numerical examples and compared with full-field simulations. Both the influence of the dominant wavelength and of the wavefield amplitude are investigated numerically, as well as the characteristic features related to non-linear phenomena.

*Speaker

Antiplane surface waves in the framework of strongly anisotropic surface elasticity

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We discuss a new model of surface elasticity based on a certain heuristic homogenization of inhomogeneous microstructured coatings. The motivation of these surface structures is at least twofold. The first relates to polymeric brushes. These coatings consist of a system long ordered polymeric chains. At the molecular level the interactions between chain links is described by Stockmayer potential, which is a generalization of the Lennard-Jones potential considering dipole-dipole interactions. The interest to modelling of coatings made polymeric brushes relates to recent developments in superhydrophobic and superoleophobic surfaces used for manufacturing of so-called self-cleaning and bactericide coatings. Another example of such coating is hyperbolic metasurfaces.
First we briefly recall discuss the structure of a coating. Then we present a continuum model with surface energy density. From the physical point of view this model corresponds to a coating made of a family of parallel long fibers which possess bending and extensional stiffness in one preferred direction only. Finally, with the use of the variational Lagrange principle we derive the equilibrium equations and the corresponding natural boundary conditions. The presented 2D model can be treated as a highly anisotropic 2D strain gradient elasticity. The surface strain energy contains both first and second derivatives of the surface field of displacements. So it represents a class of 2D models of the surface elasticity which is intermediate between the Gurtin-Murdoch and Steigmann-Ogden ones. Finally, we discuss the propagation of antiplane surface waves.
Eremeyev, V.A., 2020. Strongly anisotropic surface elasticity and antiplane surface waves. *Philosophical Transactions of the Royal Society* A, **378**(2162).

*Speaker

Perfect absorption of flexural waves: complex frequency plane interpretation and experimental validation

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Abstract: In this work we discuss the possibilities and the limits of perfect absorption of flexural waves by open lossy resonators. By applying the analysis of the eigenvalues of the scattering matrix in the complex frequency plane we present the limits of absorption in the reflection and transmission problems for one- and two-dimensional problems. Analytical models based on transfer matrix method of multiple scattering theory are used to show obtain the scattering parameters. For the case of 1D systems, the hypotheses on which the analytical model relies, are validated by experimental results. The open lossy resonators considered in this work, present both energy leakage and inherent losses due to the viscoelastic damping. Wave absorption is found to be limited by the balance between the energy leakage and the inherent losses of the open lossy resonator. The perfect compensation of these two elements is known as the critical coupling condition and can be easily tuned by the geometry of the resonator. On the one hand, the scattering in the reflection problem is represented by the reflection coefficient. A single symmetry of the resonance is used to obtain the critical coupling condition. Therefore the perfect absorption can be obtained in this case. On the other hand, the transmission problem is represented by two eigenvalues of the scattering matrix, representing the symmetric and anti-symmetric parts of the full scattering problem. In the geometry analyzed in this work, only one kind of symmetry can be critically coupled, and therefore, the maximal absorption in the transmission problem is limited to 0.5. The results shown in this work pave the way to the design of resonators for efficient flexural wave absorption.

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Damped Bloch waves in viscoelastic beam lattice metamaterials via state-space formulation

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Abstract: Beam lattice materials are characterized by a periodic microstructure which realizes a geometrically regular pattern of elementary cells. The linear dispersion properties governing the free propagation of elastic harmonic waves can be studied by formulating parametric discrete models of the cellular microstructure and applying the Floquet-Bloch theory [1]. Within this framework, controlling the wave propagation by means of energy dissipation mechanisms is a major issue of theoretical and practical interest. To this end, a general dynamic formulation is presented for determining the dispersion properties of mechanical metamaterials modeled, in a two-dimensional space, as locally resonant beam lattices with generic coordination number. The mechanism of local resonance is realized by tuning periodic auxiliary oscillators viscoelastically coupled with the beam lattice microstructure. The free propagation of the damped waves of the translational and the rotational motions is described by an enlarged linear homogeneous system of equations obtained – first – by approximating the kernel of the 3 integral-differential viscoelastic relationships with a Prony series truncated at the nth term and – second – by adding $3n$ viscoelastic states whose dynamics are governed by auxiliary first order differential equations [2]. The complex-valued branches of the dispersion spectrum are determined and parametrically analyzed for a beam lattice characterized by periodic hexagonal cells [3]. The occurrence of $3n$ pure-damping spectral components, associated with waveforms strongly polarized in the added states, is highlighted and discussed. Finally, the forced responses to harmonic monofrequent external excitations due to point forces and couples, respectively, are investigated in the frequency and time domains. The metamaterial responses to non-resonant, resonant and quasi-resonant external forces and couples, are then compared and discussed from a qualitative and quantitative point of view.

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Dispersive wave propagation in magneto-electro-elastic waveguides with periodic microstructure

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Abstract: Magneto-electro-elastic waveguide devices boast a large variety of applications in many sectors of engineering [1]. Field equations of a magneto-electro-elastic (MEE) waveguide characterized by a periodic microstructure are given and complex variables are introduced to simplify their expression. In this framework, a MEE layered periodic material is considered and the propagation of electro-magneto-mechanics waves travelling along the direction perpendicular to the material layering is investigated. Afterwards, field equations for the MEE layered material are rewritten in terms of the Bloch amplitudes and the frequency band structure is retrieved according to the transfer matrix procedure [2] and by imposing the Floquet-Bloch boundary conditions. Finally, the eigenproblem governing the free progation of bulk waves in the microstructured periodic material is sort out by exploiting the symplecticity properties of the transfer matrix and the associated fourth-order palindromic characteristic polynomial. The proposed approach is tested on illustrative examples where total band gaps in the Floquet-Bloch spectrum can be observed and the stability, depending on the coefficients of the characteristic polynomial, is discussed. Finally, the exact dispersion functions are compared with the approximate ones stemming from asymptotic perturbation methods [3].

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Acoustics of permeo-elastic media according to their morphology

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Abstract: This paper highlights the main acoustic characteristics of permeo-elastic media. These porous media consist of a rigid porous skeleton on which are fixed highly flexible elastic films that interact with the fluid saturating the pores [1, 2]. They may correspond, for example, to foams, with the thin membranes acting as films and the rigid structure being formed by their thicker struts.

Permeo-elastic media are characterised by the fluid/film interaction at the pore scale which, compared to conventional porous media, enriches the flow physics with an elastic component. Consequently, the acoustic characteristics of permeo-elastic media can deviate considerably from those of conventional porous media due to the interaction of the elastic and kinetic energy of the films with the viscous and kinetic energy of the fluid, [1, 2].

The theoretical description is established by the two-scale asymptotic homogenization method. The resulting effective behaviour takes into account membrane and/or bending effects at the pore scale in the films. It is shown that the film effects depend strongly on whether the pores or membranes are partially or fully connected. Hence, different wave propagation regimes are identified according to the nature of the local flow. In details, we successively examine the cases of permeo-elastic materials with pores that are: :

- Fully connected, i.e. no pores are closed by the films.
- Unconnected, i.e. all pores are closed by films,
- Partially connected, i.e. some pores are closed by the films.

In these different cases, a mapping of the effective behaviour is established as a function of two characteristic frequencies associated with visco-inertial and visco-elastic effects. It reveals under which conditions a fluid-film interaction phenomenon appears at the pore scale and significantly influences the macroscopic acoustic behaviour. In particular, it is shown that, depending on the morphology, the conductivity or the compressibility (or both) can present singularities at specific frequencies due to local internal resonance or anti-resonance phenomena. This induces frequency bands of ”anomalous” effective sound velocity. Finite element calculations and laboratory experiments [1] have confirmed these phenomena.

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One dimensional wave dynamics in elastically asymmetric media

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Abstract: A relatively novel class of architected materials based on specifically designed internal contacts is developed. Because of the unilateral and discontinuous properties of the contact interaction, the resulting materials possess a strong and tunable elastic asymmetry [1]. This asymmetry results in different wave speeds of tensile and compressive components of elastic waves. The faster component can overtake the slower one resulting in their dissipative annihilation through energy cascades. Efficient absorbing assemblies are presented and analysed numerically. The length of the asymmetric part needed to damp a harmonic signal is determined analytically and validated numerically. Transmission properties for random self-affine wave-packets are studied: a universal scaling for the transmission factor variation with the length of the asymmetric part was established [2, 3].

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Elastic wave propagation in non-centrosymmetric and chiral architectured materials: insights from strain gradient elasticity

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The study of elastic wave propagation is a fundamental tool in different fields, from non-destructive damage evaluation (NDE) to ultrasonic imaging. Usually NDE and characterisation techniques rely on inversion methods based on homogenised theories, that are valid only when the wavelength of the perturbation is considerably larger than the characteristic size of the heterogeneities of the materials. When the wavelength approaches this characteristic size, an upscaling occurs and mesoscopic effects can be transferred to the macro-scale. In this case, classic models used in the aforementioned inversion procedures can fail to predict the correct response [1] and they need to be improved [2].

In this work, we address those architectures for which the unit cell does not have any centre of inversion (non-centrosymmetric) nor symmetry plane (chiral). It will be shown that unconventional effects, in terms of dispersion and polarisation, can be observed even for large wavelengths. We will also show that, in order to describe these materials using an equivalent homogeneous continuum, the use of an enriched or generalised theory, such as the strain gradient elasticity, is mandatory. Moreover, the analysis of the generalised acoustic (or Christoffel) tensor defined in this framework can give a useful insight on the dynamic features of the architectured material. The delastodynamic behaviour of representative triply periodic cubic architectured materials will be detailed.

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*Speaker

Waves over a periodic progressive modulation

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Reciprocity is a principle of the if-you-can-hear-me-then-I-can-hear-you category that governs wave propagation in linear media. Reciprocity is robust as it holds in the presence of inhomogeneities or linear losses. However, it fails when the properties of the medium are modulated in function of time. Here, we report on some aspects of non-reciprocity in time-dependent media when the modulation is periodic and progressive. Such modulations create a bias whereby the waves traveling with and against the modulation do not behave in the same fashion. In some cases, waves will only be able to travel one way. We investigate how this bias manifests itself in the dispersion diagram as well as in the effective homogeneous behavior for low enough frequencies. We finally comment on some issues involving numerical simulations as well as on a number of experimental demonstrations.

*Speaker

Controlling seismic waves with structure geometry and material properties in large scale metamaterials

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Controlling seismic waves with structure geometry and material properties in large scale metamaterials is a short overview of the results of a collaboration between mathematicians, physicists, and civil engineers and an introduction on some different themes like seismic & acoustic metamaterials, the topological beam splitting & the topological rainbow effect for the localization of the symmetry protected edge waves, the Zero frequency bands gaps and the Inertial amplification.

*Speaker

Studying the nucleation and propagation of cracks by a gradient damage method with a novel family of degradation functions

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The phase-field method or gradient-damage is now widely used in modeling and simulating cracks in different materials and/or structures. This method turns out to be particularly efficient for dealing with crack initiation and propagation in complicated situations. The regularization length involved in this method, which can be interpreted as a material parameter, plays a key role and must be small enough to reflect the fact that a crack is a sharp discontinuity. In the works reported in the relevant literature on the phase-field method applied to study crack problems, the smallness of the regularization length makes that the mesh size of finite elements has to be also sufficiently small, so that computational costs are very high. In the present work, we use the phase-field method with a family of degradation functions introduced by Sargado et al. in the elastic strain energy of elastic brittle materials, and investigate the nucleation and propagation of cracks in such materials. We show that, owing to this novel family of degradation functions, the mesh size in the area where a crack passes through can be much coarser and the computational cost can be considerably reduced without changing the path of the crack as well as the global and local mechanical behaviors. In the case where experimental results are available for plaster specimens subjected to compressive loadings, the results obtained by the phase-field method together with the new family of degradation functions are compared and discussed with respect to those provided by the ones with the classical quadratic degradation function.

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*Speaker

Damage mechanics by a phase-field approach in strain gradient elasticity

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Inherent substructure causes a material to deviate from conventional elasticity response. Such mechanical metamaterials are modeled by generalized mechanics, one possible version is the strain gradient theory. Especially in damage mechanics, such a generalization is difficult to acquire. We exploit the action formalism for a formulation in generalized damage mechanics for metamaterials [1]. The key point is using so-called auxilliary variables in order to involve the first rate of damage variable into the action formalism. In this way, the presented action formalism with auxilliary variables generates the weak form necessary for the numerical implementation. A finite element method based approach is used by means of open-source packages FEniCS (see [2] for engineering examples). Probably for the first time, three-dimensional simulations in metamaterials damage mechanics are demonstrated for simple geometries.

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*Speaker

Low Cycle Fatigue Analysis of Architectured Materials: Incorporating Theory of Critical Distance with Elastoplastic Homogenization

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Computational homogenization is an efficient tool for the analysis of architectured materials. However, standard effective quantities obtained from homogenization are insufficient for analyzing phenomena such as fatigue due to localized stress/strain concentrations. To address this issue, in the context of elastoplastic homogenization, the information of the local plastic strain in the critical region of the representative volume element is captured using the theory of critical distance for fatigue-life predictions. This theory provides an efficient method for fatigue analysis, and is introduced here for the fatigue analysis of architectured materials. Fatigue is one of the challenges in the industrial applications of such materials in presence of cyclic loading. The method, being generic, has been applied here to 2-D auxetic and 3-D kelvin lattices.

*Speaker

Failure analysis for the pre-cracked materials based on the regularized FE solutions of strain gradient elasticity theory

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In this work, we use the feature of the strain gradient elasticity theory (SGET) related to the regularization of classical singularity problems. We suggest that the structural analysis of pre-cracked materials can be reduced to failure analysis within SGET by using the appropriate failure criteria formulated in terms of the Cauchy stresses. These stresses are work-conjugated to strains, and they have non-singular values in SGET solutions for the problems with cracks and sharp notches. We confirm our suggestion based on the full-field finite element (FE) simulations and provide examples of identification of the length scale parameters of SGET for the known experimental data with pre-cracked brittle and quasi-brittle materials [1]. We show that SGET solutions allow to capture the size effects for the cracks of different length that are well-known in fracture mechanics. Previously similar results were obtained only within approximate analytical and numerical methods [2, 3]. Based on the performed analysis we show that the identified length scale parameters allow us to predict the failure loads for the experimental samples with different type of cracks by using the maximum principal Cauchy stress criterion. In the experiments with a mixed-mode fracture of the quasi-brittle material (PMMA with inclined cracks), we found that there may arise a transition between the failure determined by the maximum principal stress criterion and the criterion related to the second invariant of the Cauchy stress tensor that can be explained by the change of the stress state triaxiality.

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*Speaker

Exceptional impact strength of sandwich beams with pantographic-type metamaterials in the core

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In the present work we propose to use the pantographic mechanical metamaterials as the cores of sandwich structures. We evaluated numerically and experimentally the mechanical performance of 3d-printed polyamide sandwich beams with such cores. Four variants of sandwich beams are considered, which differ in the type of connections between the elements in the lattice structure of the core (Fig. 1). We consider the pantographic-type lattices formed by the two families of inclined beams placed with small offset and connected by stiff joints (variant 1), by hinges (variant 2) and made without joints (variant 3). The fourth type of the core has the standard plane geometry formed by the intersected beams lying in the same plane (variant 4). Experimental tests were performed for the localized indentation loading according to the three-point bending scheme with small span-to-thickness ratio. From the experiments we found that the plane geometry of variant 4 has the highest rigidity and the highest load bearing capacity in the static tests. However, other three variants of the pantographic-type cores (1–3) demonstrate the better performance under the impact loading. The impact strength of such structures is in 3.5–5 times higher than those one of variant 4 with almost the same mass per unit length. This result is validated by using numerical simulations and explained by the decrease of the stress con- centration and the stress state triaxiality and also by the delocalization effects that arise in the pantographic-type cores [1].

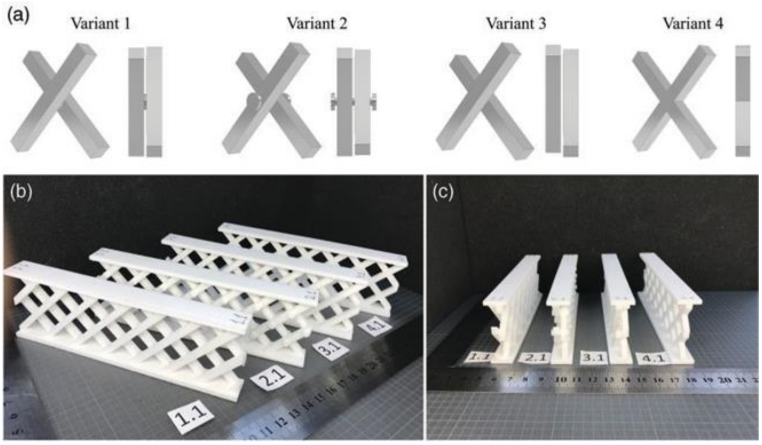

Figure 1. Variants of connections between the beams in the lattice cores (a) and 3d printed samples of sandwich beams (b, c)

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Homogenized Elastic Model for In-Plane Analysis of Masonry Walls Retrofitted by Steel Fiber Reinforced Mortar Coating

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Unreinforced Masonry has been one of the most used construction materials worldwide and is still in use in many parts of Europe. However, it is well known that the low tensile resistance makes these structures vulnerable to both in plane and out of plane seismic actions. For this reason, many research studies are devoted to develop and improve retrofitting tech- niques for enhancing the seismic behavior of masonry buildings. Among these, an innovative retrofitting technology consists of steel fiber reinforced mortar (SFRM). The literature about this topic regards mainly experimental tests (see [1-2]). On the contrary, the modelling of SFRM and of its interaction with masonry structures is rather lacking. In this work, a homogenization procedure (inspired by [3]) is used to derive simple closed- form expressions for ”equivalent” linear elastic constants of masonry walls retrofitted by SFRM, solicited in their plane. The method mainly consists of modeling the behavior of an elementary cell using suitable designed assemblies of in-parallel springs. Thereafter, an equivalent homogenized orthotropic material is defined, the elementary cell of which has the same stiffness as the assembly. The stresses of the masonry and SFRM components are also evaluated analytically once the average stress acting on the homogeneous medium is deter- mined. The accuracy of the theoretical results is assessed by means of comparisons with finite element (FE). Finally, static and dynamic FE analyses are carried out on sample retrofitted masonry walls, with the aim of comparing the non-homogeneous and homogeneous models. The latter is found to describe both the local and global behavior of masonry walls to a satisfactory extent.

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