Coss&Vita

ArchiMatHOS

UP-COMECH2021

e-Workshop on design and analysis of non-classical architectured materials

April 8-9, 2021

Mechanical architectured materials are designed to feature extreme or non-classical properties such as negative Poisson's ratio or strain floppy modes. These emergent properties may require generalized continua such as strain-gradient or micromorphic continua in order to accurately bring-out the effective mechanical behavior.

The present e-workshop provides an update on these topics, awaiting the next regular workshop which will be hopefully held in Alghero on 23-28 May 2022.

A particular attention is paid to non-classical up-scaling methods, new topology optimization techniques, experimental characterization of the non-classical properties and the computational techniques required by generalized continua.

Topics

- Up-scaling methods for non-classical continua in mechanics
- Fabrication and testing of non-classical continua
- Topology optimization of Metamaterials
- Computational and numerical aspects

The e-Workshop is organised by IRP Coss&Vita (CNRS) and M&MoCS (Universita dell'Aquila) and supported by ArchiMatHOS (Agence Nationale de la Recherche, grant ANR-17-CE08-0039).

Organizers

- Boris Desmorat (Institut D'Alembert, Sorbonne Université)
- Arthur Lebée (Laboratoire Navier, École des Ponts - ParisTech, France)
- Pierre Seppecher (Imath, Toulon university, France)
- Emilio Turco (University of Sassari, Italy)

Up Comech – e-workshop – 8,9 April 2021 – Abstracts

Torsion in strain and stress gradient elasticity
Application to the finite element analysis of stress gradient media

Samuel Forest
Centre des Matériaux, MINES ParisTech, CNRS UMR 7633, BP 87, 91003 Evry, France
samuel.forest[at]mines-paristech.fr

Tobias Kaiser
Institute of Mechanics, TU Dortmund University,
Leonhard-Euler-Str. 5, D-44227 Dortmund, Germany

We report on the solution of the torsion problem for circular cylindrical bars according to the strain and stress gradient linear elasticity theories. The strain gradient solution is known but deserves attention due to the particular way size effects are induced in the theory. The solution is compared to the Cosserat solution for completeness. The stress gradient solution is new and was reported recently [1]. The stress gradient continuum theory was developed in the last ten years [2]. Finite deformation and elastoplasticity constitutive frameworks were newly developed for this continuum [3]. However the present contribution concentrates on the linear elastic case and shows that the stress gradient theory predicts the opposite trend to the strain gradient model in terms of size effects.

This solution is then used to validate a finite element implementation of the stress gradient theory [1]. The implementation relies on a reformulation of the governing set of partial differential equations in terms of one primary tensor-valued field variable of third order, the so-called generalised displacement field, following [4]. Whereas the volumetric part of the generalised displacement field is closely related to the classic displacement field, the deviatoric part can be interpreted in terms of micro-displacements. The associated weak formulation moreover stipulates boundary conditions in terms of the normal projection of the generalised displacement field or of the (complete) stress tensor. A detailed study of representative boundary value problems of stress gradient elasticity shows the applicability of the proposed formulation. In particular, the finite element implementation is validated based on the analytical solutions for a cylindrical bar under tension and torsion derived by means of Bessel functions. In both tension and torsion cases, a *"smaller is softer"* size effect is evidenced in striking contrast to the corresponding strain gradient elasticity solutions.

References

[1] T. Kaiser, S. Forest and A. Menzel, *A finite element implementation of the stress gradient theory*, Meccanica, 2020. doi:10.1007/s11012-014-01266-3

[2] S. Forest and K. Sab, *Finite deformation second order micromorphic theory and its relations to strain and stress gradient models*, Mathematics and Mechanics of Solids, vol. 17, pp. 1429-1449, 2020. doi:10.1177/1081286517720844

[3] S. Forest, *Continuum thermomechanics of nonlinear micromorphic, strain and stress gradient media*, Philosophical Transactions A, vol 378, p. 20190169, 2020. 10.1098/rsta.2019.0169

[4] K. Sab, F. Legoll and S. Forest, *Stress Gradient Elasticity Theory: Existence and Uniqueness of Solution,* Journal of Elasticity, vol. 123, pp. 179-201, 2016. doi:10.1007/s10659-015-9554-1

Modelling of elastic networks with rigid junctions using micropolar elasticity

Victor A. Eremeyev

DICAAR, University of Cagliari, Italy

Faculty of Civil and Environmental Engineering, Gdańsk University of Technology, Gdańsk, Poland

For two- and three-dimensional elastic structures made of families of flexible elastic fibers undergoing finite deformations we propose homogenized models within the micropolar elasticity. Here we restrict ourselves to networks with rigid connections between fibers. In other words we assume that the fibers keep their orthogonality during deformation. Starting from a fiber as the basic structured element modelled through the Cosserat curve beam model, we get 2D and 3D semi-discrete models. These models consist of systems of ordinary differential equations describing statics of a collection of fibers with certain geometrical constraints. Using a specific homogenization technique we introduce two- and three-dimensional equivalent continuum models which correspond to the six-parametric shell model and the micropolar continuum, respectively. We call two models equivalent if their approximations coincide to each other up to certain accuracy. The two- and three-dimensional constitutive equations of the networks are derived and discussed within the micropolar continua theory. The recent analysis of static deformations in [1] was extended to dynamics considering a kinetic energy density. It is shown that the rotatory inertia of joints may play an important role for oscillations and wave propagations.

Keywords: elastic network; micropolar elasticity; homogenization

1. Eremeyev, V.A., 2019. Two-and three-dimensional elastic networks with rigid junctions: modeling within the theory of micropolar shells and solids. *Acta Mechanica*, 230(11) 3875-3887.

On periodic homogenization of highly contrasted elastic structures

Lukáš Jakabčin[1,2] & Pierre Seppecher[1]

Abstract

While homogenization of periodic linear elastic structures is now a well-known procedure when the stiffness of the material varies inside fixed bounds, no homogenization formula is known which enables to compute the effective properties of highly contrasted structures. Examples have been given in which the effective energy involves the strain-gradient but no general formula provides this strain-gradient dependence. Some formulas have been proposed which involve such terms and provide a small correction to the classical effective energy still when the stiffness of the material varies inside fixed bounds. The goal of this paper is to check the applicability of these formulas for highly contrasted structures. To that aim we focus on structures whose limit energy is already known and we compare the energies given by (i) the convergence results, (ii) the corrective formulas and (iii) by a direct numerical simulation of the complete structure.

[1]Institut de Mathématiques de Toulon, Université de Toulon, BP 20132, 83957 La Garde Cedex, France.

[2]Laboratoire de Mécanique et d'Acoustique, Université d'Aix-Marseille, Technopôle Château-Gombert, 4, impasse Nicola Tesla, CS 40006, 13453 MARSEILLE Cedex 13, France.

Email: jakabcin@lma.cnrs-mrs.fr, seppecher@imath.fr.

Asymptotic homogenization and parameter determination in metamaterials

Bilen Emek Abali

Uppsala University, Department of Materials Science and Engineering, Uppsala, Sweden

The possibility in additive manufacturing is called “infill ratio,” which is exploited to reduce the weight of the structure. A periodic lattice substructure is introduced for this purpose. We know that such a substructure causes a deviation from the linear elasticity and strain gradient elasticity is used to characterize the material response. Additional parameters emerge in the strain gradient theory and determination of these parameters is challenging. Based on asymptotic homogenization [1] a new formalism is applied in [2]. This procedure computes all effective material parameters in metamaterials by using a representative volume element incorporating the substructure. The computational procedure by means of finite element method (FEM) is developed with the aid of open-source packages. A brief explanation of the formalism, verification of the procedure, and examples will be given in this talk.

References

[1] H. Yang, B. E. Abali, D. Timofeev, and W. H. Müller. Determination of metamaterial parameters by means of a homogenization approach based on asymptotic analysis. *Continuum Mechanics and Thermodynamics*, 32:1251–1270, 2020.

[2] B. E. Abali and E. Barchiesi. Additive manufacturing introduced substructure and computational determination of metamaterials parameters by means of the asymptotic homogenization. *Continuum Mechanics and Thermodynamics*, (1–17):1–20, 2020.

Discrete modeling of lattice materials with auxetic properties

Dr. Igor Berinskii,
School of Mechanical Engineering, Tel Aviv University

Elastic properties of two-dimensional cellular lattice materials are studied using a discrete model. The model is based on a representation of the lattice as a set of interacting nodes. A potential of interaction between the nodes is calibrated such that to simulate elastic linking. The analytical homogenization based on Cauchy-Born rule allowed determining the elastic properties of the effective continuum corresponding to the specific lattice. On the other hand, the same properties are found from the numerical simulations based on particle dynamics. It is shown that both ways lead to the same values of elastic constants.
Possible generalizations of the model to the three-dimensional case, large strains and fracture in lattice are discussed.

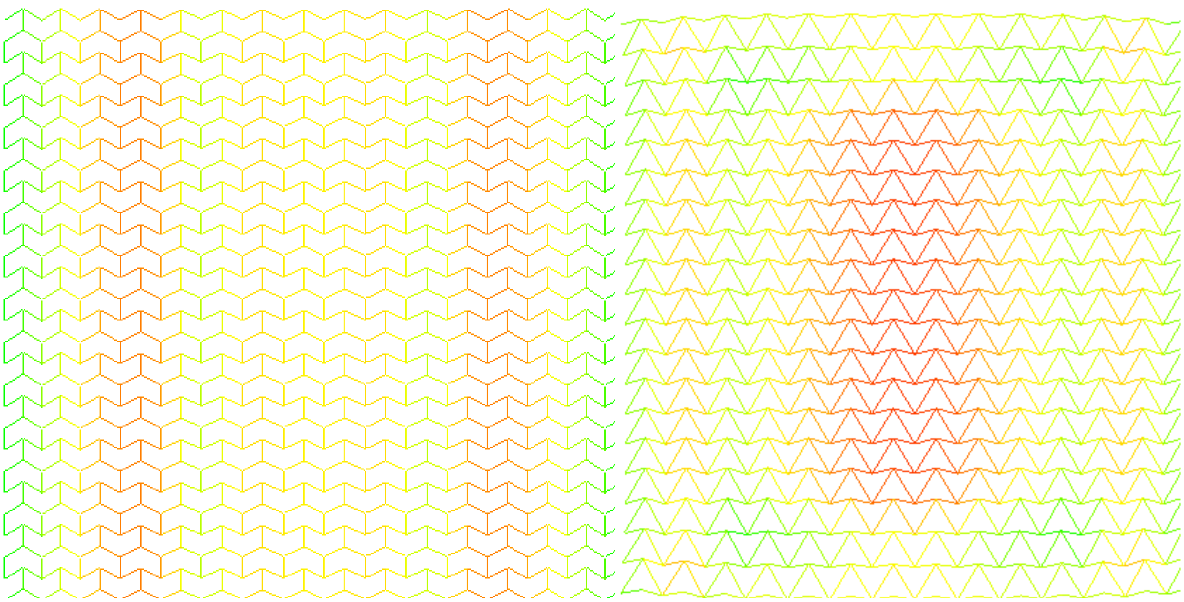


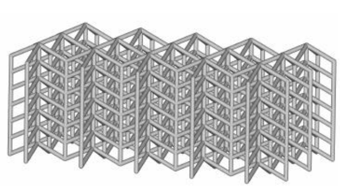
Fig. Examples of dynamic simulation of auxetic lattices using discrete modeling

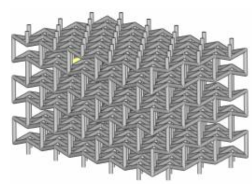
Simulation of the effective behavior of periodic auxetic structures

J. Orlik, G. Griso, L. Khilkova, H. Andrae, D. Neusius, Ch. Eberl, F. Wenz

Abstract

Based on asymptotic analysis results [1], [2], we classify some thin periodic unstable and auxetic structures and propose macroscopic models together with computational algorithms for their macroscopic behavior. Auxiliary problems on the periodicity cell are reduced to one-dimensional tensile and bending problems, systems of ODEs, which can be solved by one-dimensional finite element method. The limiting energy, which can be derived for a certain range of applied loadings, is convex. The admissible set of applied axial and nodal forces, and moments will be discussed for stable and unstable structures. For a certain class of structures, which are macroscopically stable for tension in some directions, the periodicity constraints provide some restrictions on rotations. Since, the effective elasticity tensor is computed from auxiliary cell-problems with 6 degrees of freedom, which additionally are decomposed for tension along "long" lines and inextensional displacements and rotations, the effective elasticity tensor is positive definite, even in the unstable directions. After "locking" under uni-directional loading, the structure becomes stable for the loading in this direction and the effective coefficient becomes higher (a kind of face transition). Models and theoretical results are illustrated by numerical examples in the talk.





[1] Griso, G., Khilkova, L., Orlik, J., Sivak, O.: Asymptotic Behavior of Stable Structures Made of Beams. J. Elast, Volume 143, Issue 2, pp. 239–299 (2021). https://doi.org/10.1007/s10659-021-09816-w

[2] Griso, G., Khilkova, L., Orlik, J., Sivak, O.: Asymptotic Behavior of Unstable Structures Made of Beams, in preparation

Higher-order homogenization of a continuous microstructure that leads to significant elasto-static strain-gradient effects

B. Durand, A. Lebée, P. Seppecher, K. Sab

Laboratoire Navier (UMR 8205), École des Ponts ParisTech, Université Gustave Eiffel, CNRS, Marne-la-Vallée, France
Institut de Mathématiques de Toulon, Université de Toulon, Toulon, France

Abstract —

The aim of this work is to investigate the elasto-static behavior of an architectured material featuring significant strain-gradient effects and denoted pantographic material. It is made of voids and a single and continuous linear elastic material allowing simple fabrication. The pattern consists of triangles connected by thin junctions and arranged so that two floppy strain modes are present. A homogenization scheme based on the two-scale asymptotic expansion is suggested, taking as a strating point the consistent variational derivation of higher-gradient theories suggested by Smyshlyaev and Cherednichenko [2000]. Only the significant strain-gradient contributions are kept in the homogenized energy by means of an adequate projection. The predictions from the homogenization scheme are validated against a full-scale simulation and yield very good L^2 error estimates whereas the classical first-gradient homogenization fails. Furthermore, the relative position of the unit-cell of the full scale computation does not have a significant influence on the quality of the prediction.

Keywords — Strain gradient continuum, Higher-order homogenization, Metamaterial, Compliant mechanism

References

V. P. Smyshlyaev and K. D. Cherednichenko. On rigorous derivation of strain gradient effects in the overall behaviour of periodic heterogeneous media. *Journal of the Mechanics and Physics of Solids*, 48(6):1325–1357, June 2000. ISSN 0022-5096. doi: 10.1016/S0022-5096(99)00090-3.

A cycloidal metamaterial realized as a lattice shell of two families of curved Kirchhoff rods

I. Giorgio

March 6, 2021

Abstract

A nonlinear elastic model for nets made up of two families of curved fibers is proposed. The net is planar prior to the deformation, but the equilibrium configuration that minimizes the total potential energy can be a surface in the three-dimensional space. This elastic surface accounts for the stretching, bending, and torsion of the constituent fibers regarded as a continuous distribution of Kirchhoff rods. The fiber arrangement, namely a cycloidal orthogonal pattern, is examined to illustrate the predictive abilities of the model and assess the limit of applicability of it. A numerical micro-macro identification is performed with a model adopting a standard continuum deformable-body at the level of scale of the fibers. A few finite element simulations are carried out for comparison purposes in statics and dynamics, performing modal analysis.

Homogenization towards chiral Cosserat continua

H. Reda[b,c], S.E. Alavi[a,d], M. Nasimsobhan[d], J.F. Ganghoffer[a]

(a) LEM3. Université de Lorraine, CNRS. 7, rue Félix Savart, 57073, Metz, France
(b) Faculty of Engineering, Section III, Lebanese University, Campus Rafic Hariri, Beirut, Lebanon, (c) SDM Research Group, International University of Beirut BIU, Beirut, Lebanon

(d) Department of Mechanical Engineering, Amirkabir University of Technology (Tehran Polytechnic), 424 Hafez Ave., Tehran 15875, Iran

A homogenization methodology for the construction of effective Cosserat substitution media for heterogeneous materials is proposed, combining a variational principle in linear elasticity with the extended Hill-Mandel lemma accounting for the introduced generalized kinematics. The proposed method is general and can be applied to a wide class of architected materials and composites prone to such micropolar effects. The microscopic displacement field of the initially heterogeneous continuum splits into a homogeneous part polynomial in the generalized kinematic measures and a fluctuation involving localization operators. The tensors of effective micropolar moduli are formulated as integrals over a representative unit cell utilizing of the displacement localizators, solution of classical, and higher-order unit cell problems. The proposed method has the chief advantage of delivering size-independent higher-order effective moduli. Based on the developed homogenization method, the effective micropolar moduli of the tetrachiral lattice and composites made of a tetrachiral lattice reinforcement are computed to elaborate an enhanced Timoshenko microstructured beam model exhibiting couplings between different deformation modes induced by the response of its underlying tetrachiral microstructure.

Reference

H. Reda, S.E. Alavi, M. Nasimsobhan, J.F. Ganghoffer, 2021. Homogenization towards chiral Cosserat continua and applications to enhanced Timoshenko beam theories. Mechanics of Materials. In print.

Inverted and programmable Poynting effects in metamaterials

Ghorbani Aref [1], *Dykstra David* [2], *Coulais Corentin* [2], *Bonn Daniel* [2], *Van Der Linden Erik* [1], *Habibi Mehdi* [1]

Twisting a solid cylinder induces an elongation in the axial direction, which is called the Poynting effect. This phenomenon is a nonlinear elastic effect that appears due to the shear-induced positive normal force, which develops quadratically as a function of shear strain with a conventionally positive coefficient now call the Poynting modulus. Here, we also introduce the inverted Poynting effect as a novel concept, where a compression in the axial direction induces torsion. We designed a cylindrical metamaterial that exhibits both inverted and programmable Poynting effects. Our designed meta- cylinder shows three regimes of responses under compression: i) pre-buckling, ii) buckling, iii) self- contact. We discover that by applying compression, the cylinder induces nonlinear and linear torsions in the buckling and self-contact regimes, respectively. The induced torsion has a maximum at the top of the cylinder in torsion-free or at the middle in clamped compression. We also show that this meta- cylinder exhibits a highly programmable Poynting modulus. In the pre-buckling regime, despite the conventional solids, the Poynting modulus of the meta-cylinder is negative, causing a contraction under torsion. By applying a pre-compression, the Poynting modulus becomes zero in buckling and positive in self-contact regimes, with a maximum at the pre-compression that transition to the self- contact regime occurs. We show that we can program the sign of the Poynting modulus as well as its value up to one order of magnitude higher than the shear modulus. We reproduce the experimental results using a Hookean spring model and confirm the buckling and self-contact as design mechanisms to obtain inverted Poynting effect and program the Poynting and shear moduli. Our results provide a strategy to generate torsion/shear under compression and program the nonlinear elastic moduli in metamaterials, with potential applications in designing mechanical parts functioning under compression and torsion, such as a soft robotic arm.

[1] Wageningen University (Netherlands)

[2] University of Amsterdam (Netherlands)

EXPLICIT HARMONIC STRUCTURE OF BIDIMENSIONAL LINEAR STRAIN-GRADIENT ELASTICITY

N. AUFFRAY, MSME, Univ Gustave Eiffel, CNRS UMR 8208, F-77454 Marne-la-Vallée, France;

H. ABDOUL-ANZIZ, MSME, Univ Gustave Eiffel, UPEC, CNRS UMR 8208, F-77454 Marne-la-Vallée, France;

B. DESMORAT Institut d'Alembert, Sorbonne Université, CNRS UMR 7190, F-75252 Paris CEDEX 05, France;

In the perspective of homogenization theory, strain-gradient elasticity is a strategy to describe the overall behaviour of materials with coarse mesostructure. In this approach, the effect of the mesostructure is described by the use of three elasticity tensors whose orders vary from 4 to 6. Higher-order constitutive tensors make it possible to describe rich physical phenomena. However, these objects have intricate algebraic structures that prevent us from having a clear picture of their modeling capabilities. The harmonic decomposition is a fundamental tool to investigate the anisotropic properties of constitutive tensor spaces. For higher-order tensors (i.e. tensors of order n $\geq$3), their determination is generally a difficult task. In this paper, a novel procedure to obtain this decomposition is introduced. This method, which we have called the Clebsch-Gordan Harmonic Algorithm, allows one to obtain explicit harmonic decompositions satisfying good properties such as orthogonality and uniqueness. The elements of the decomposition also have a pre- cise geometrical meaning simplifying their physical interpretation. This new algorithm is here developed in the specific case of 2D space and applied to Mindlin's Strain-Gradient Elasticity. We provide, for the first time, the harmonic decompositions of the fifth- and sixth-order elasticity tensors involved in this constitutive law. The Clebsch-Gordan Harmonic Algorithm is not restricted to strain-gradient elasticity and may find interesting applications in different fields of mechanics which involve higher-order tensors.

Symmetry detection for architectured flexoelectric materials

H. Abdoul-Anziz[1], N. Auffray[1], B. Desmorat[2]

[1] MSME, Univ Gustave Eiffel, UPEC, CNRS UMR 8208, F-77454 Marne-la-Vallée, France
[2] Institut d'Alembert, Sorbonne Université, CNRS UMR 7190, F-75252 Paris CEDEX 05, France

March 15, 2021

Abstract

Flexoelectricity refers to the electromechanical coupling between strain gradient and electric polarization. This electromechanical effect has been identified in biological membranes [1], in 2D materials like graphene sheets [2]. Mathematically, the flexoelectricity effect is represented by a fourth-order tensor $\underset{\approx}{\mathrm{F}}$ which satisfies $F_{ijkl} = F_{jikl}$.

As architectured materials often exhibit significant symmetries, designing an architectured flexoelectric solid material with a special symmetry is a challenge. We study the computational problem involved in detection or identification of the symmetries for bi-dimensional flexoelectric materials. A knowledge of the *harmonic decomposition* of the flexoelectric tensor $\underset{\approx}{\mathrm{F}}$ is indispensable for the detection of these symmetries. In this presentation, we will determine the different symmetry classes of 2D flexoelectric tensors. We will show that there are six symmetry classes. Using the *Clebsch-Gordan Harmonic Algorithm* (which will be presented by Nicolas Auffray), we will compute the explicit harmonic decomposition of the tensor $\underset{\approx}{\mathrm{F}}$. We will also give the link between the harmonic decomposition and the symmetry classes. Finally, we will provide the matrix representations of $\underset{\approx}{\mathrm{F}}$ and of the complete flexoelectric law for each symmetry class. These results will allow us to understand the nature of the different electromechanical couplings that took place in a flexoelectric material, such as the coupling between the stretch-gradient or the couple-stress and the electric polarization.

Keywords: flexoelectricity; strain gradient; symmetry classes

References

[1] Q. Deng, L. Liu, and P. Sharma. Flexoelectricity in soft materials and biological membranes. *Journal of the Mechanics and Physics of Solids*, 62:209–227, 2014.

[2] B. Javvaji, B. He, and X. Zhuang. The generation of piezoelectricity and flexoelectricity in graphene by breaking the materials symmetries. *Nanotechnology*, 29(22):225702, 2018.

3D printed shape-shifting panels from undulated ribbon lattice

Filippo Agnelli[1], Michele Tricarico[2], Andrei Constantinescu[1*]

[1]LMS, CNRS, Ecole polytechnique, Institut polytechnique de Paris, Palaiseau, France.
[2]MMC Laboratory, Department of Engineering Science, University of Oxford, United Kingdom

Materials that change their shape in response to external stimuli open up new prospects for efficient and versatile design and shaping of three-dimensional objects. Here, we present a novel class of micro-structures exhibiting an extension-bending coupling (EBC) effect, that can be harnessed as an elementary building block for shape-shifting panels. They are built with a single material as a network of undulated ribbons, parametrised using b-spline surfaces. The undulations feature an asymmetry along the height that is leveraged to obtain the EBC mechanism. The deformations mechanisms of both single and connected undulated ribbons are analysed using the finite element method to explain the main features of the EBC mechanism. While single undulated ribbons do not exhibit specific coupling mechanics, we demonstrate that their interconnection starts the mechanism.
For a particular micro-structure of the proposed class, the elastic response is investigated both under small strain assumption combining two-scale homogenization with Kirchhoff-Love plate theory, and at finite strains relying on numerical analysis. The range of achievable EBC ratio is then assessed with respect to the geometric parameters of the unit cell.
Patterned specimens are manufactured using a commercial FFF Ultimaker 3D printer and are mechanically tested at finite strain up to 20%. The displacement measured by point tracking match the predictions from the finite element simulations and indicate that the structure maintain its properties at finite strain. Moreover, a tensile test load with point-like boundary is proposed to highlight exceptional out of plane displacement.
The proposed ribbon based architectures can be combined with active materials for the actuation of shape shifting structures, like soft robots, control systems and power devices.

References

F. Agnelli, M. Tricarico, A. Constantinescu. Shape-shifting panel from 3D printed undulated ribbon lattice. *Extreme Mech. Lett.* 42, 101089, 2020.

[*] Corresponding author. E-mail: andrei.constantinescu@polytechnique.edu.

Data driven multi-scale topology optimization of compliant mechanisms

T. Djourachkovitch[1], N.Blal[1], N.Hamila[2], A.Gravouil[1]
[1] Univ Lyon, INSA-Lyon, CNRS UMR5259, LaMCoS, F-69621, France
[2] ENIB, UMR CNRS 6027, IRDL, F-29200, Brest, France

Topology optimization is a key issue to reduce structures weight while preserving suitable mechanical properties. This field received significant contributions in recent years. The recent advancement in additive manufacturing processes make using them in topology optimization a promising way in order to design more complex shapes. Going down into finest scales to design structures needs using very thin meshes that might become prohibitive in terms of computation cost. To overcome this issue, topology optimization processes based on multi-scale approaches seems to be an adequate strategy helping to split the reference problem into two separated sub problems (when scales separation assumption prevails). However, such approaches still imply a substantial computation effort since the overall number of design variables increases drastically.

In this work, we propose a multi-scale topology optimization design based on a data-assisted strategy. The final design is obtained coupling macro topology optimization results with micro topology optimization of associated micro-architectured materials for the finest scale. Firstly, the micro-architectured materials are constructed *a priori* and stored as materiel database. This database is then exploited during the optimization of the macro-scale.

The efficiency of this approach is compared to a standard multiscale topology optimization problem t highlight the advantages of the databased assisted strategy in terms of computational costs and attainability of the required micro-architectured materials.

Key-words : Database, Topology Optimization, Compliant Mechanisms, Inverse Homogenization, Micro-architectured materials

References :

[1] O.Sigmund,On the design of complian tmechanisms using topology optimization, *Journal of Structural Mechanics* 25 (4) (1997) 493–524.
[2] G.Allaire, F.Jouve, A-M.Toader. Structural optimization using sensitivity analysis and a level-set method. *Journal of Computational Physics*, 2004.
[3] A. Ferrer, J. Oliver, J. C. Cante, O. Lloberas-Valls, Vademecum-based approach to multi-scale topo- logical material design, A*dvanced Modeling and Simulation in Engineering Sciences* 3 (1) (2016) 23.
[4] T. Djourachkovitch, N. Blal, N. Hamila, and A. Gravouil. Multi-scale topological optimization of 3D printable structures using computational vademecums. International Conference on Simulation for Additive Manufacturing, sim-AM 2019.

Designing 3-D objects from planar pre-strained semiconductors

Alexandre Danescu[1] and Ioan R. Ionescu[2]

[1]University of Lyon, Institute of Nanotechnologies - INL, Ecole Centrale de Lyon, Ecully, France
[2]LSPM, University Sorbonne-Paris-Nord, Villetaneuse, France, and IMAR, Romanian Academy, Bucharest

Abstract

Very accurate control of thickness and composition in modern crystal growth technology allows fabrication of ultra-thin multi-layered materials with prescribed pre-stress. One of the most interesting properties of the pre-stressed materials is their ability to bend once detached from the substrate template used for the epitaxial growth. For practical reasons, in order to preserve the long range crystallographic structure of the materials involved in the process, the lattice misfit that controls the pre-strain between successive layers should be small. As a consequence, during the bending process of large areas the material undergo large displacements but small strains and the first attempts in this field lead to fabrication of large arrays of 3D resonators from strinaed films (rolls, curls, etc.) most of them obtained through the release of the prestresses in very simple geometries (see [1]).

In order to extend this process to a larger class of three-dimensional objetcs we have investigated in [2] the interplay between the design degrees of freedom, *i.e.* the pre-strain and the planar design, and the geometry of the relaxed configuration, a problem that falls outside the framework of direct methods in elasticity. The resulting equations for efforts moments of a rather general kinematic assumption (a perturbation of Love-Kirchhoff type superposed on a plate-to-shell theory) for materials with a weak material transversal heterogeneity provide the supplementary equations to compute the in-plane pre-strain/stress. We showed that, in agreement with previous experimental evidence, small regions relax toward spherical caps and large areas toward cylindrical shapes[1]. The former case, shows that the class of mid-surface small strain (or isometric) transformations is to narrow to include the experimental evidence. We extend here the class of geometries presented in [2] to include plate-strips (or plate-ribbons) described by two small parameters: the ratio between the film thickness and the Eulerian curvature $\delta = h/\kappa$ and the ratio between the lateral extent (width) and the characteristic length of the planar design, i.e. $\eta = d/L$. Our results, provide sufficient conditions to cover completely or partially some classical surfaces (the cylinder, the sphere and the torus) and put forward the role of the geodesic curvature for the geometry of the planar design.

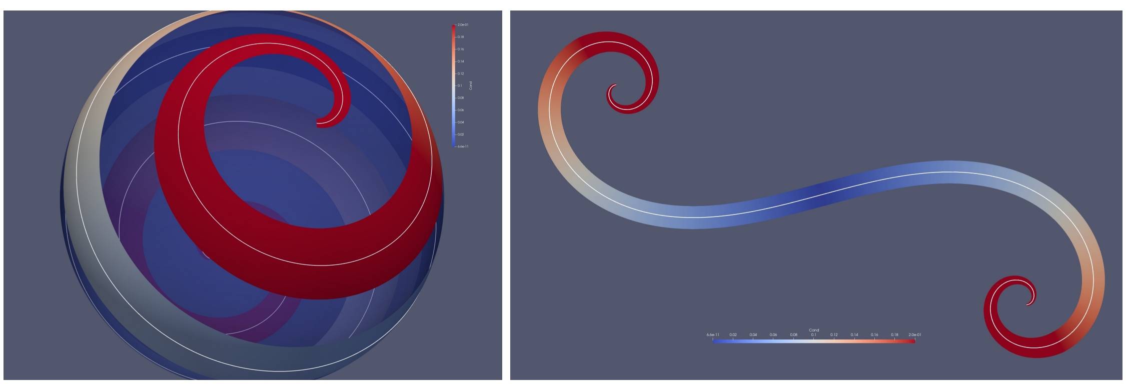


Figure 1: A spherical ribbon and the corresponding planar design to obtain it.

References

[1] V.Y. Prinz *et al*, Terahertz metamaterials and systems based on rolled-up 3D elements: designs, technological approaches, and properties, *Scientific reports*, 7(1), 1-15 2017.

[2] A. Danescu, I.R. Ionescu, Shell design from planar pre-stressed structures, *Math. Mec. Solids*, 25(6), 2127-2134, 2020.

[3] M. de Benito Delgado, B. Schmidt, Energy minimising configurations of pre-strained multilayers, *J. Elast.* 140, 303-335, 2020.

[1]A result predicited also by a recent theoretical model in [3]

Non-intrusive and multiscale uncertainty propagation and parametric/topological optimization for problems with microstructured material

Chenchen Chu, Nawfal Blal, David Dureisseix, Béatrice Faverjon

Univ Lyon, INSA Lyon, CNRS, LaMCoS, UMR5259, F-69621 Villeurbanne, France

Abstract. Materials with engineered micro-structures are still an emerging topic, since they can be optimized for given functionalities, and therefore may exhibit higher performances when compared to standard bulk materials, [2, 6].

When used not for mass production, but tuned for on-demand applications, their manufacturing involves prototyping rather than mass-production flows. For instance, 3D printing is one possible candidate, when the micro-structure has not a too small scale length, [7]. As a counterpart, there are some uncertainties involved, due to a not-so-well controlled production flow, that should be taken into account for the overall design problem.

We also address herein non-conventional cases where transient thermal evolutions leads to a so-called macroscopic memory effect (a non local-in-time model), when microsctructure phases exhibit a large contrast in thermal conductivity [3, 5], figure 1.

Concerning optimization of these materials and structures for thermomechanical evolutions, topology optimization is of interest at macroscale [4], while for ensuring manufacturability, parametric optimization is preferred at the microstructure scale.

In this work, we promote non-intrusive strategies, such as probabilistic collocation method [8], and genetic algorithms for optimization [10]. Since the direct problem is untractable, upscaling techniques are used, herein pseudo-periodic homogenization; concerning design parameter descriptions, we rely on a level-set discretization [1, 9] on a dedicated mesh.

Keywords. Homogenization; Architectured material; Polynomial Chaos Expansion; Surrogate modeling; Thermomechanical problems

Acknowledgments

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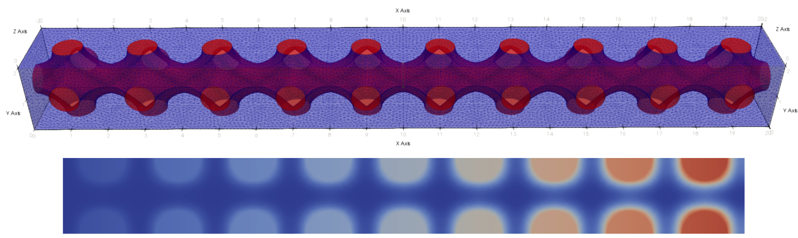

Figure 1: A test case of a 3D structure with a 2-phase microstructure, and a temperature field solution for a large contrast of phase conductivities

References

[1] G. Allaire, F. de Gournay, F. Jouve, and A.-M. Toader. Structural optimization using topological and shape sensitivity via a level set method. *Control and Cybernetics*, 34(1):59–80, 2005.

[2] M. F. Ashby and Y. J. M. Bréchet. Designing hybrid materials. *Acta Materialia*, 51(19):5801–5821, 2003.

[3] J.-L. Auriault. Upscaling heterogeneous media by asymptotic expansions. *Journal of Engineering Mechanics*, 128(8):817–822, 2002.

[4] T. Djourachkovitch, N. Blal, N. Hamila, and A. Gravouil. Multi-scale topological optimization of 3D printable structures using computational vademecums. In *Proceedings of the International Conference on Simulation for Additive Manufacturing, sim-AM 2019*, 2021.

[5] D. Dureisseix, P. Royer, and B. Faverjon. Numerization of a memory effect for a homogenized composite material with a large contrast in the phase thermal conductivities. *International Journal of Heat and Mass Transfer*, 90:140–148, 2015.

[6] N. A. Fleck, V. S. Deshpande, and M. F. Ashby. Micro-architectured materials: past, present and future. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, pages 4662495–2516, 2010.

[7] N. Hopkinson, R. J. M. Hague, and P. M. Dickens., editors. *Rapid Manufacturing: An Industrial Revolution for the Digital Age*. John Wiley & Sons, Ltd, 2006.

[8] S. Huang, S. Mahadevan, and R. Rebba. Collocation-based stochastic finite element analysis for random field problems. *Probabilistic Engineering Mechanics*, 22(2):194–205, apr 2007.

[9] S. Kambampati, C. Jauregui, K. Museth, and H. A. Kim. Large-scale level set topology optimization for elasticity and heat conduction. *Structural and Multidisciplinary Optimization*, 61(1):19–38, 2019.

[10] K. Tai and T. H. Chee. Design of structures and compliant mechanisms by evolutionary optimization of morphological representations of topology. *Journal of Mechanical Design*, 122(4):560–566, sep 1998.

EXPERIMENTAL CHARACTERIZATION OF ARCHITECTURED MATERIALS' EFFECTIVE MECHANICAL BEHAVIOR

Maxence Wangermez[1,2], Martin Poncelet[1] and Nicolas Auffray[2]

[1]Univ. Paris-Saclay, ENS Paris-Saclay, CNRS, LMT - Laboratoire de Mécanique et Technologie
91190, Gif-sur-Yvette, France.
Email: maxence.wangermez@ens-paris-saclay.fr, martin.poncelet@ens-paris-saclay.fr

[2]Univ. Gustave Eiffel, CNRS, MSME UMR 8208,
F-77454 Marne-la-Vallée, France.
Email: nicolas.auffray@univ-eiffel.fr

Keywords: Architected Materials, Experimental Homogenization, Effective Behaviour, Kinematic Uniform Boundary Conditions

ABSTRACT

In the last few years, advanced industries have been focusing on architected materials and 3D printing technologies. Indeed, architected materials allow to design interesting effective mechanical properties from microstructures thus reducing for example the mass of structures while increasing their performances.

Until a few years ago, 3D printing techniques were only used to make prototypes or rough parts. Slowly, the introduction of these new technologies in manufactured products is made possible by a growing theoretical and technical maturity. One of the major directions of research in architected materials lies in the modeling of their mechanical behavior and remains a challenging topic.

Because of the multi-scale nature of these materials, the associated numerical models are highly complex. Thus, Direct Numerical Simulations (DNS) of complete structures at mesoscopic scale are still not actually handled. To overcome this difficulty, many calculation methods have been developed according to the scale of interest such as FE2 ([1], [2]), HDPM ([3]–[5]), Variational MultiScale Method ([6], [7]), M.I.E.L ([8], [9]), filtering methods ([10], [11]), multi-scale BDD methods ([12]–[14]).

Yet, in most cases, the numerical models used in these simulations are based on perfect CAD geometries. It is therefore natural to ask the question of the accuracy of the results according to the deviation from the nominal dimensions or from the health materials. Recent developments have focused on the digitalization of actual mesostructures in order to introduce them into multi-scale computations ([15]–[17]). These methods require expensive equipment since they are based on Computed Tomography (CT scans).

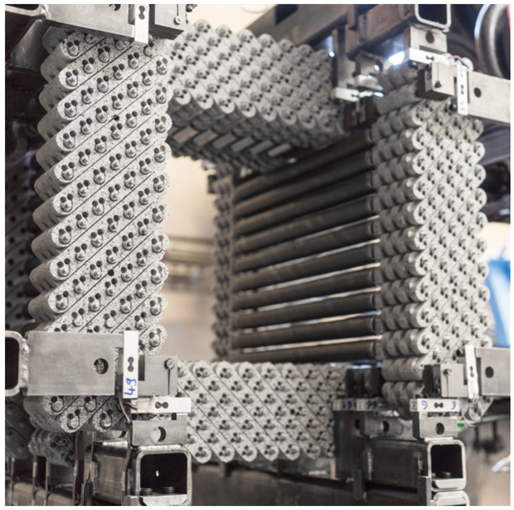

Figure 1: KUBC testing machine.

In order to prevent the necessity of handling complex numerical models, one way is to operate on real microstructures. The objective of this work is to develop an experimental device and an associated methodology to measure the effective mechanical behavior of architected materials directly from a specimen without using numerical models (Figure 1). The concept of the proposed experimental device, initiated by the work of [18], is based on an arrangement of pantographic structures which allows to perform first-order kinematic homogenization tests (KUBC) on plate structures of size 300 × 300 mm^2. The homogenized behavior is easily measured by the dedicated device of the machine composed of strain gauges but an extra full-field measurement of the architected material during its loading can be easily performed by Digital Image Correlation (DIC).

In addition to the macroscopic components of the first-order elasticity tensor, some components from generalized continua can be measured. Moreover, the device allows to measure directly the invariants of the elasticity tensor of a structure. Perspectives around problems of fatigue or dynamic pre-stressed solicitations could be considered.

REFERENCES

[1] F. Feyel, “Multiscale FE2 elastoviscoplastic analysis of composite structures,” *Comput. Mater. Sci.*, vol. 16, no. 1, pp. 344–354, Dec. 1999, doi: 10.1016/S0927-0256(99)00077-4.

[2] F. Feyel and J.-L. Chaboche, “FE2 multiscale approach for modelling the elastoviscoplastic behaviour of long fibre SiC/Ti composite materials,” *Comput. Methods Appl. Mech. Eng.*, vol. 183, no. 3, pp. 309–330, Mar. 2000, doi: 10.1016/S0045-7825(99)00224-8.

[3] J. T. Oden, K. Vemaganti, and N. Moës, “Hierarchical modeling of heterogeneous solids,” *Comput. Methods Appl. Mech. Eng.*, vol. 172, no. 1, pp. 3–25, Apr. 1999, doi: 10.1016/S0045-7825(98)00224-2.

[4] J. T. Oden and T. I. Zohdi, “Analysis and adaptive modeling of highly heterogeneous elastic structures,” *Comput. Methods Appl. Mech. Eng.*,

vol. 148, no. 3, pp. 367–391, Sep. 1997, doi: 10.1016/S0045-7825(97)00032-7.

[5] T. I. Zohdi, J. T. Oden, and G. J. Rodin, "Hierarchical modeling of heterogeneous bodies," *Comput. Methods Appl. Mech. Eng.*, vol. 138, no. 1, pp. 273–298, Dec. 1996, doi: 10.1016/S0045-7825(96)01106-1.

[6] T. J. R. Hughes, "Multiscale phenomena: Green's functions, the Dirichlet-to-Neumann formulation, subgrid scale models, bubbles and the origins of stabilized methods," *Comput. Methods Appl. Mech. Eng.*, vol. 127, no. 1, pp. 387–401, Nov. 1995, doi: 10.1016/0045-7825(95)00844-9.

[7] T. J. R. Hughes, G. R. Feijóo, L. Mazzei, and J.-B. Quincy, "The variational multiscale method—a paradigm for computational mechanics," *Comput. Methods Appl. Mech. Eng.*, vol. 166, no. 1, pp. 3–24, Nov. 1998, doi: 10.1016/S0045-7825(98)00079-6.

[8] A. Ibrahimbegović and D. Markovič, "Strong coupling methods in multi-phase and multi-scale modeling of inelastic behavior of heterogeneous structures," *Comput. Methods Appl. Mech. Eng.*, vol. 192, no. 28, pp. 3089–3107, Jul. 2003, doi: 10.1016/S0045-7825(03)00342-6.

[9] D. Markovič and A. Ibrahimbegović, "On micro–macro interface conditions for micro scale based FEM for inelastic behavior of heterogeneous materials," *Comput. Methods Appl. Mech. Eng.*, vol. 193, no. 48, pp. 5503–5523, Dec. 2004, doi: 10.1016/j.cma.2003.12.072.

[10] J. Yvonnet and G. Bonnet, "A consistent nonlocal scheme based on filters for the homogenization of heterogeneous linear materials with non-separated scales," *Int. J. Solids Struct.*, vol. 51, no. 1, pp. 196–209, Jan. 2014, doi: 10.1016/j.ijsolstr.2013.09.023.

[11] J. Yvonnet and G. Bonnet, "Nonlocal/coarse graining homogenization of linear elastic media with non-separated scales using least-square polynomial filters," *Int. J. Multiscale Comput. Eng.*, vol. 12, no. 5, pp. 375–395, Jan. 2014, doi: 10.1615/IntJMultCompEng.2014010414.

[12] C. Farhat and F.-X. Roux, "A method of finite element tearing and interconnecting and its parallel solution algorithm," *Int. J. Numer. Methods Eng.*, vol. 32, no. 6, pp. 1205–1227, 1991, doi: 10.1002/nme.1620320604.

[13] J. Mandel, "Balancing domain decomposition," *Commun. Numer. Methods Eng.*, vol. 9, no. 3, pp. 233–241, 1993, doi: 10.1002/cnm.1640090307.

[14] P. Ladevèze, "Une nouvelle méthode pour l'analyse des structures massives," *Note Tech. Aerosp. STS*, vol. 3, p. 45, 1990.

[15] J. Bénézech and G. Couégnat, "Variational segmentation of textile composite preforms from X-ray computed tomography," *Compos. Struct.*, vol. 230, Dec. 2019, doi: 10.1016/j.compstruct.2019.111496.

[16] A. Mendoza, J. Schneider, E. Parra, E. Obert, and S. Roux, "Differentiating 3D textile composites: A novel field of application for Digital Volume Correlation," *Compos. Struct.*, vol. 208, pp. 735–743, Jan. 2019, doi: 10.1016/j.compstruct.2018.10.008.

[17] M. Wangermez, O. Allix, P.-A. Guidault, O. Ciobanu, and C. Rey, "Interface coupling method for the global–local analysis of heterogeneous models: A second-order homogenization-based strategy," *Comput. Methods Appl. Mech. Eng.*, vol. 365, p. 113032, Jun. 2020, doi: 10.1016/j.cma.2020.113032.

[18] T. Dassonville, M. Poncelet, and N. Auffray, "Toward a homogenizing machine," *Int. J. Solids Struct.*, vol. 191–192, pp. 534–549, May 2020, doi: 10.1016/j.ijsolstr.2019.12.018.

Numerical analysis of softening materials: some often overlooked aspects

Emilio Barchiesi (1,2), Salvatore Sessa (3), Luca Placidi (2,4)

Techniques ranging from high-resolution electron to atomic-force microscopy enable the examination of very low scales and provide an unprecedented possibility to link the micro-structure with the macroscopic properties of materials. Regrettably, while the significance of micro-scale softening mechanisms in influencing macro-scale material behaviours is nowadays largely recognized in continuum damage mechanics and many efforts are being spent to forge the link between micro and macro, micro-scale damage modelling is often addressed numerically too naively. The talk will highlight some topical aspects that have been up to now overlooked or dealt with too superficially by comparing the performances of different numerical algorithms in solving KARUSH-KUHN-TUCKER conditions for a simple softening spring. It is concluded that even such a primitive model might require numerical analysis to face unexpected challenges.

(1) École Nationale d'Ingénieurs de Brest, 760 ENIB, UMR CNRS 6027, IRDL, F-29200 Brest (France).

(2) International Research Center on Mathematics and Mechanics of Complex Systems. Università degli Studi dell'Aquila. Via Giovanni Gronchi 18 - Zona industriale di Pile, 67100 L'Aquila (Italy).

(3) University of Naples Federico II, via Claudio 21, Napoli (Italy).

(4) International Telematic University UNINETTUNO. Faculty of Engineering. Corso Vittorio Emanuele II 39, 00186 Roma (Italy).

One-dimensional chiral granular metamaterials: micropolar model development and predictions

Anil Misra[1],*, Nima Nejadsadeghi[2]
[1] Civil, Environmental and Architectural Engineering Department, the University of Kansas, amisra@ku.edu
[2] Mechanical Engineering Department, the University of Kansas, nima.nejadsadeghi@ku.edu

The significance of chirality lies in its wide range of applications in diverse branches of science, and hence, understanding the mechanisms leading to chirality deems necessary. The literature on lattice chirality offers comprehensive studies on the chiral properties of particular pre-designed microstructural units using novel experimental and numerical schemes. However, to further enhance the understanding on mechanical chirality, a general analysis in determining the effect of different factors contributing to chirality proves essential. This presentation focuses upon chiral granular (meta-) materials and investigates the role of different micro-level deformation mechanisms on the macroscopic chiral behavior of the system by incorporating the coupling between the deformation mechanisms in different axes and rotations. To this end, a granular micromechanics based micropolar model is obtained through Hamilton's principle to describe chirality in a one-dimensional chiral granular string in a two-dimensional deformation plane. The model is shown to reduce to Timoshenko beam model if particular inter-granular mechanisms vanish. Moreover, predictions of the behavior of chiral granular strings in tension is parametrically investigated.

Investigating the domain of validity of one-dimensional micropolar chiral granular model through parametric experimentation

Nima Nejadsadeghi[1,*], Francois Hild[2], Anil Misra[3]
[1] Mechanical Engineering Department, the University of Kansas, USA, nima.nejadsadeghi@ku.edu
[2] Université Paris-Saclay, ENS Paris-Saclay, CNRS, LMT - Laboratoire de Mécanique et Technologie, France, Francois.HILD@ens-paris-saclay.fr
[3] Civil, Environmental and Architectural Engineering Department, the University of Kansas, USA amisra@ku.edu

The significance of chirality lies in its wide range of applications in diverse branches of science, and hence, understanding the mechanisms leading to chirality deems necessary. Recently, a granular micromechanics based micropolar model was developed to describe the mechanical behavior of one-dimensional chiral granular (meta-) materials in a two-dimensional deformation plane, incorporating the coupling between the deformation mechanisms in different axes and rotations. In this presentation, the domain of validity of the proposed model is investigated through parametric experimentation. To this end, a particular chiral granular string composed of 11 grains is considered. Each grain is interacting with its neighboring grains through some form of mechanism that induces chirality. The granular string is varied in two geometrical parameters describing the interaction between the two grains, hence providing parametric spaces with respect to the considered geometrical parameters. The granular strings are fabricated using a Formlabs Form 3 printer in Durable resin, and undergo tensile experiments in an ElectroForce 3200, TA Instruments, uniaxial testing machine. The surface of granular strings is sprayed in black to obtain a speckle pattern. A DSLR camera is used to obtain images from the experiment, which are analyzed using Digital Image Correlation (DIC) in three different scales. The DIC results are used to investigate the range of applicability of the model to predict the behavior of granular strings by comparing the predicted displacement and rotation fields by the model and the experimental results.

Identification, based on granular micromechanics, of elastic isotropic strain gradient stiffness matrices for geometrically nonlinear deformations

Emilio Barchiesi [1], *Anil Misra* [2], *Luca Placidi* [3], *Emilio Turco* [4]

Although the primacy (and utility) of higher-gradient theories are being increasingly accepted, estimates of second gradient elastic parameters are not widely available. In this talk, we present such estimates for a second-gradient continuum. These estimates are obtained in the framework of finite deformations using granular micromechanics assumptions for materials that have granular textures at some 'microscopic' scale. The presented approach utilizes Piola's ansatz for discrete-continuum identification. As a fundamental quantity of this approach, an objective relative displacement between grain-pairs is obtained and deformation energy of grain-pair is defined in terms of this measure. Expressions for elastic constants of a macroscopically linear second gradient continuum are obtained in terms of the micro-scale grain-pair parameters. Finally, the main results is that the same coefficients, both in the 2D and in the 3D cases, have been identified in terms of Young's modulus, of Poisson's ratio and of a microstructural length.

References:

Anil Misra and Ching S Chang. Effective elastic moduli of heterogeneous granular solids. International Journal of Solids and Structures, 30(18):2547. 2566, 1993.

Emilio Barchiesi, Anil Misra, Luca Placidi, Emilio Turco. Granular micromechanics-based elastic identification of isotropic strain gradient stiffness matrices for geometrically nonlinear deformations. Submitted to ZAMM

Dmitry Timofeev, Emilio Barchiesi, Anil Misra, Placidi L (in press).

Hemivariational continuum approach for granular solids with damage- induced anisotropy evolution. MATHEMATICS AND MECHANICS OF SOLIDS, ISSN: 1081-2865, doi: 10.1177/1081286520968149

Valerii Maksimov, Emilio Barchiesi, Luca Placidi, Anil Misra, Dmitry Timofeev. Size effects in strain gradient granular solids with damage- induced anisotropy evolution. Submitted to JRNEMENG.

Luca Placidi, Emilio Barchiesi, Anil Misra, Dmitry Timofeev. Micromechanics-based elasto-plastic-damage energy formulation for strain gradient solids with granular microstructure. Submitted to CMAT.

[1] International Research Center for the Mathematics & Mechanics of Complex Systems and University of Sassari (Italy)

[2] University of Kansas (United States)

[3] Università telematica internazionale Uninettuno (Roma, Italy)

[4] University of Sassari (Italy)

Topological sensitivity of second order homogenized tensors in elasticity and applications

V. CALISTI[1]*, A. LEBÉE*[2]*, A.A. NOVOTNY* [3]*, AND J. SOKOLOWSKI* [4]

The shape and topology optimization of microstructures can be performed using the topological derivative method. In this lecture, we recall the context of homogenized linear elasticity for periodic materials, resulting in "second gradi- ent media". First and second order homogenized elasticity tensors are formally defined, from the two-scale asymptotic expansion method and the expression of the strain energy average on the unit cell. Then the topological derivatives of those tensors are evaluated in the framework of periodic Sobolev spaces, introducing appropriate adjoint problems. The expression of the topological derivative is explicitly given, with the use of corresponding adjoint states, and of polarization tensors. Finally the optimization scheme is presented, using the singular domain perturbations in order to find a descent direction.

[1]Institut Élie Cartan de Lorraine, UMR 7502, Université de Lorraine, B.P. 70239, 54506 Vandoeuvre-lès-Nancy Cedex, France, email address: valentin.calisti@univ-lorraine.fr.

[2]Laboratoire Navier, UMR 8205, École des Ponts ParisTech, Université Gustave Eiffel, CNRS, Champs-sur-Marne, France, email address: arthur.lebee@enpc.fr

[3]Laboratorio National de Computação Cientifica LNCC/MCT, Coordenação de Métodos Matemáticos e Computacionais, Av. Getúlio Vargas 333, 25651-075 Petrópolis - RJ, Brasil, email address: novotny@lncc.br.

[4]Systems Research Institute of the Polish Academy of Sciences, ul. Newelska 6, 01-447 Warszawa, Poland and Department of Scientific Computing, Informatics Center, Federal University of Paraba, Brazil, and Institut Élie Cartan de Lorraine, UMR 7502, Université de Lorraine, B.P. 70239, 54506 Vandoeuvre-lès-Nancy Cedex, France, email address: jan.sokolowski@univ-lorraine.fr.

Investigation and design of 3D architected materials with tunable properties

Fengwen Wang*, Morten Nørgaard Andersen, Ole Sigmund

Dept. of Mechanical Engineering, Technical University of Denmark, 2800 Kgs. Lyngby, Denmark
** Corresponding author: fwan@mek.dtu.dk*

Abstract

Material stiffness and strength are fundamental properties for determining material load-bearing capability. Stiffness accounts for the material's ability to resist deformation, while strength measures material ultimate load-carrying capacity. The quest for optimal stiff and strong material is complex. Many studies have been devoted to exploring materials with optimal stiffness by carefully tailoring material geometries [1]. Based on the small deformation theory, material stiffness and yield strength are evaluated using the homogenization method. Buckling strength under a given macroscopic stress state is estimated using linear buckling analysis with Bloch-Floquet boundary conditions to capture local and global buckling modes. Due to computational cost, material buckling strength investigation and optimization have been mainly focused on 2D materials [2]. In this study, we systematically investigate the performance of a set of reference material microstructures included in Ref [1] and propose two-term interpolation schemes for effective material properties accurate for up to moderate volume fractions, including material stiffness, yield, and buckling strength [3]. We further design 3D architected materials with tunable stiffness and buckling response using topology optimization methods [4]. The optimization problem is formulated to maximize the weighted stiffness and buckling response. A class of 3D isotropic materials is designed to achieve tunable stiffness and buckling response by assigning different weight factors for stiffness and buckling strength under uniaxial compression. Moreover, inspired by the topology optimized material configurations, a subsequent feature-based shape optimization approach is employed to simplify material geometries. In the feature-based approach, material architectures are parametrized using several hollow and one solid super-ellipsoids. Compared to stiffness-optimal closed-cell plate material, the material class reduces Young's modulus to a range from 79% to 58% and improves the uniaxial buckling strength to a range from 180% to 767%. Both topology and shape optimized results demonstrate that material buckling strength can be significantly enhanced by enlarging member bending stiffness via allowing curved plates and member thickening.

Keywords: 3D architected material; buckling strength; stiffness; property interpolation; optimization

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References

[1] Berger, J. B., Wadley H. N. G., and McMeeking R. M., (2017), Mechanical metamaterials at the theoretical limit of isotropic elastic stiffness. Nature 543(7646), 533-537.

[2] Thomsen, C.R., Wang, F. & Sigmund, O., (2018) Buckling strength topology optimization of 2D periodic materials based on linearized bifurcation analysis. Computer Methods in Applied Mechanics and Engineering, 339, 115-136.

[3] Andersen, M. N., Wang, F., & Sigmund O, (2021), On the competition for ultimately stiff and strong architected materials. Materials & Design 198: 109356.

[4] Wang, F., & Sigmund, O. (2020). Extreme 3D architected isotropic materials with tunable stiffness and buckling strength. arXiv preprint arXiv:2012.01359.

Polarization and soft modes in Kagome lattices

Hussein Nassar,* Hui Chen, Guoliang Huang

Department of Mechanical and Aerospace Engineering, University of Missouri, Columbia

(*speaker, nassarh@missouri.edu)

Isostatic lattices are mechanical trusses where the number of degrees of freedom locally matches that of elastic constraints. Lacking any redundancy in their connectivity, isostatic lattices tend to exhibit a number of soft modes, or mechanisms, such that the lattice deforms at little energy cost. Recently, in the context of "topological mechanics", it was discovered that certain geometric distortions trigger in isostatic lattices a migration of soft modes from one side of the lattice to the opposite side [1]. Thus, the deserted side stiffens, the other softens, and the lattice becomes elastically polarized. In this talk, we report on an effective medium theory which faithfully accounts for the distortion-induced migration of soft modes as well as the resulting polarized elastic behavior in the fairly generic case of the Kagome lattice [2]. The effective theory is of the generalized, enriched, type and has one extra degree of freedom per periodic soft mode. The accuracy of the theory is demonstrated through various analytical and numerical computations.

REFERENCES

[1] C. L. Kane, T. C. Lubensky, Nat. Phys., 10, 39-45 (2014).
[2] H. Nassar, H. Chen, G.L. Huang, JMPS, 144, 104107 (2020).