Editorial for the Special Issue on "Architectured Materials Mechanics"

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Architectured materials and mechanical metamaterials are an emerging and exciting class of materials with the promise of advantageous performance and multifunctional properties. These materials are characterized by specific and periodic structural features which are larger than what is typically considered a microstructural length scale (such as a grain size) but smaller than the size of the final component made of the architectured material. This class of materials includes but is not limited to lattice materials and cellular material systems, dense material systems composed of building blocks of well-defined size and shape.

We recently organized an IUTAM symposium dedicated to "Architectured Material Mechanics" in Chicago, Illinois (USA), September 17 - 19, 2018. This event provided a review of the state of the art and a platform for discussions on the future of the science and engineering of architectured materials. It covered the mechanics, design, fabrication and mechanical performance of all categories of architectured materials including lattice materials, metamaterials, multilayered system and topologically interlocked materials. The 89 researchers who attended the symposium came from 18 countries: Austria, Canada, China, Denmark, France, Germany, Israel, Poland, Argentina, China, Korea, Switzerland, The Netherlands, Spain, Sweden, Switzerland, United Arab Emirates, United States. A wide range of disciplines was represented including Physics, Architecture, Computer Science, Materials, Civil, Materials and Mechanical Engineering. The symposium also demonstrated the enthusiasm of young researchers active in research on this topic as 32 participants were either graduate students or post-doctoral researchers. Abstracts of all conference contributions are available at [1].

This special issue of the *Journal of Applied Mechanics* provides expanded contributions of the three original conference themes: (1) Design, optimization and fabrication, (2) Bioinspiration, strength and toughness, (3) Heterogeneity, instability, shape transformation and dynamical behavior.

(1) Design, optimization and fabrication: Sessions on this theme included discussion on topics of topology optimization, periodic truss structures, origami materials, active architecture materials, knit-process materials, macro-micro-and nanoscale concepts, and on material assembly concepts. In this special issue, Tessmann and Rossi contrast features of monolithic and segmented architecture material systems and structures, and demonstrate the vast design space envisioned for material systems by assembly of unit building blocks. Along similar lines, Frederickson describes the specific work of the architect Ernest Irving Freese and underpins his tile structures with computational geometry. Both contributions challenge researchers in the field to expand their views on possible material systems configurations. Kontsos et al. and Picu et al. [2] demonstrate material architecture in fibrous materials. Kontsos et al. demonstrate the material property of knit-process derived material systems. The underlying manufacturing processes allows for the

realization of a various periodic material architectures and mechanical response features. Picu et al. [2] on the other hand discuss fiber materials with random space associated with Voronoi construction principles. This contribution indicates opportunities to tune a linear vs. nonlinear material response. Dirrenberger et al. consider periodic lattice structures and systematically explore a parametric geometry space, thereby deriving architecture-property relationships for auxetic response. Finally, Reasa and Lakes present a design of a lattice material with chiral elements, with uncommon properties in terms of twist-compression coupling and size effects.

(2) Bioinspiration, strength and toughness: Sessions on this theme focused on achieving novel material configurations such as nacre architecture, interlocked geometries, auxetics, and lattice configurations, all with exceptional toughness and new underlying mechanics principles. Speakers discussed applications in biomedical devices and in material systems for impact protection. In this special issue several papers show how material architecture provides new opportunities to achieve increased strength and toughness. Barthelat et al. and Siegmund et al. demonstrate how tessellated material systems (also found in many biological systems) can produce remarkable mechanical performance. In these materials the interaction of individual building blocks together with the respective contact and interface interactions leads to the overall material system response. Barthelat et al. [8] used a computational mechanics approach to capture the increase in strength and toughness achievable for tessellated material assemblies under in-plane loading. Siegmund et al. [9] derived closed form expressions for plate-like material systems based on geometrically interlocked building blocks. Kolednik et al. show how soft interlayers with regular spacing can increase toughness by way of a material homogeneities effect. Mohr et al. provide a study on the relationship between stiffness and strength and the cellular structure of honeycomb-like materials and compare the classical hexagon and triangular lattices to a class of lattices architectures with chiral character. These authors demonstrate how the added architecture feature of chirality allows to not only tailor stiffness and strength but also the Poisson's ratio.

(3) Heterogeneity, instability, shape transformation and dynamical behavior: The symposium sessions in this theme focused on topics of wave propagation and band gaps, phase transformation and instabilities, on active material concepts and the issue of non-reciprocity in architecture materials. Pasini and co-workers show how material architecture and hierarchy can be used to amplify local thermal expansion and generate large, anisotropic change of shape. Zavattieri and colleagues explore the mechanics of phase transforming cellular materials (PXCMs) based on chiral architectures, using tape springs as the base material. They show how the interplay of the base elements (tape springs) and the architecture can lead to superior energy dissipation. Coulais and colleagues explore another route for energy dissipation, where the intrinsic viscoelasticity of 3D printed rubbers can be harnessed through snapping mechanisms to generate high damping for vibration and impact applications. Vibrations and stress can also be manipulated with architecture as demonstrated in the paper by Matlack and colleagues. In particular, they show how signal attenuation near band gaps can be tuned with the lattice architecture of the material. Finally, the dynamic response of architectured materials can also be controlled with phenomena involving multiple physics as demonstrated by Rudykh and co-workers who study wave band gaps appearing in magnetoactive laminates.

The field of architectured materials and metamaterial is a fast evolving and exciting area of research, and we hope that this special issue will give you a good overview of the recent

accomplishments and potential for type of material. We also hope that you enjoy reading this special issue, as much as enjoyed putting it together.

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References

[1] Proceedings of the IUTAM Symposium Architectured Materials Mechanics, T. Siegmund & F. Barthelat (Eds.)*, September 17-19, 2018* , Chicago, IL: Purdue University Libraries Scholarly Publishing Services, 2018. https://docs.lib.purdue.edu/iutam.
[2] S. Deogekar, Z. Yan and R.C. Picu: "Random fiber networks with superior properties through network topology control", *J. Appl. Mech* 86(8), 081010 (Jun 4, 2019)

Appendix
Symposium program

Oral Presentations

Focus 1: Design, optimization and fabrication

1. Yves Brechet: Architectured Materials: 15 Years of Progress, and Emerging Challenges
2. Ole Sigmund, Jeroen Groen: Extremal Material and Structure Design by Topology Optimization
3. Heinrich M. Jaeger, Kieran A. Murphy, Leah K. Roth: Architectured Particulate Materials
4. Frank Zok, Matthew R. Begley, Ryan M. Latture: Design and Performance of Periodic Trusses
5. Julian J. Rimoli, Hossein Salahshoor, Raj Kumar Pal: Topology Matters: Expanding the Design Space of Lightweight Mechanical Metamaterials
6. Rafael Estevez, Alexis Faure, Georgios Michailidis, Charles Dapogny, Grégoire Allaire: Shape and Topology Optimization of Architectured Materials: From the Design to Real Structures
7. Antonios Kontsos: The Behavior of Knitted Textiles through the Lens of Architectured Material Mechanics
8. Greg N. Frederickson: Hidden in Plane Sight: the Extraordinary Vision of Ernest Irving Freese
9. Julia R. Greer, Lucas Meza, Arturo Mateos, Carlos Portela, Dennis Kochmann, Yong-Wei Zhang: Mechanics of Three-Dimensional Nano-Architected Meta-Materials
10. Yonggang Huang: Mechanics-guided Deterministic 3D Assembly
11. SungWoo Nam: Mechanical Instability-driven Architecturing of Atomically-thin Materials
12. Jie Yin: Kirigami-based Mechanical Metamaterials
13. Andres F. Arrieta, Jakob Faber, Katherine S. Riley, André R. Studart: Extending Origami: Crease Pre-stressing for Functional Adaptation
14. A. Mocci, D. Codony, A. Abdollahi, I. Arias: Flexoelectricity-based Electromechanical Metamaterials
15. Kunal Masania, André Stuart: 3D Printing of Biologically-inspired Materials

Focus 2: Bioinspiration, strength and toughness

1. Zdeněk P. Bažant, Wen Luo: Fishnet Statistics for Failure Probability of Nacreous Staggered Laminar Materials
2. Francois Barthelat: Exploring Material Property Space Using Bioinspiration and Architecture
3. H. Daniel Wagner, Israel Greenfeld, Wenyong Zhang, XiaoMeng Sui: Intermittent Interfaces: Bioinspired Strategies Towards Material Resilience
4. Iwona Jasiuk, Fereshteh A. Sabet, Christopher Kozuch, Diab Abueidda, Frances Su, Joanna McKittrick: Bioinspired Architectured Materials with Interpenetrating Phases
5. Sung Hoon Kang, Galip Ozan Erol, Emilio Bachtiar, Azra Horowitz: Architected Cardiovascular Implants for Accommodating Growth
6. Nan Hu, Hanqing Zhang, Daobo Zhang, Peng Feng, Amal Jerald Joseph M, Davut B. Gul: Tunable Failure in Non-periodic Architected Materials Inspired by Physarum Polycephalum Growth
7. Stavros Gaitanaros: Random Foams: Instabilities, Fracture and Shocks
8. Oliver Tessmann, Andrea Rossi: Parametric and Combinatorial Topological Interlocking Assemblies
9. Thomas Siegmund: Topologically Interlocked Material Systems: From a Material Design Concept to Properties
10. Catalin R. Picu, Anirban Pal: Interlocked Fragmented Continua: A Stochastic Metamaterial
11. Thomas Tancogne-Dejean, Marianna Diamantopoulou, Colin Bonatti, Maysam Gorji, Dirk Mohr: Plastic Anisotropy of Elastically-isotropic Beam, Shell and Plate Networks: Theory and Experiments
12. Tiantian Li, Lifeng Wang: Exploiting Auxetics to Design Composite Materials with Enhanced Mechanical Performance
13. Frédéric Albertini, Justin Dirrenberger, Andrey Molotnikov, Cyrille Sollogoub: Mechanical Behaviour of Architectured Auxetic Hybrid Lattice Structures

Focus 3: Heterogeneity, instability, shape transformation and dynamical behavior

1. Rod Lakes: Extreme Classical and Nonclassical Physical Properties in Heterogeneous Materials
2. Otmar Kolednik, Roland Kasberger, Masoud Sistaninia: Design of Damage-tolerant and Fracture-resistant Materials by Utilizing the Material Inhomogeneity Effect
3. Gerold A. Schneider, Berta Domènech, Diletta Giuntini, Büsra Bor: Organically Linked Nanoparticles as Building Blocks for Architectured Materials
4. C. Ayas, W.E.D Nelissen, C. Tekoglu: 2D Lattice Materials for Low Energy Actuation
5. Corentin Coulais: Non-reciprocity in Mechanical Metamaterials
6. Amr Farag, Hang Xu, Damiano Pasini: Thermally Actuated Planar Lattices with High Fractal Stiffness
7. Yanyu Chen: 3D Printed Hierarchical Honeycombs with Shape Integrity under Large Compressive Deformations
8. Katia Bertoldi: Architected Materials: From Reconfigurability to Nonlinear Waves
9. Pablo D. Zavattieri, Yunlan Zhang, Miriam Velay, David Restrepo, Nilesh D. Mankame: Architecting Stress- and Temperature-Induced Phase Transformation
10. Stephan Rudykh, Viacheslav Slesarenko, Pavel Galich, Jian Li: Micromechanics and Instabilities of Soft Architectured Composite Materials

11. Kathryn H. Matlack, Ignacio Arretche: Dynamic and Mechanical Properties of Lattice-Resonator Meta-Structures
12. G.L. Huang: Wave Propagation in Modulated Phononic Crystals and Metamaterials
13. Kuo-Chih Chuang, Xiang Fang, Zhiwen Yuan: Forming Flexural Band Gaps of Phononic Crystal Beams Based on Concentrated Masses
14. A. Srikantha Phani: Vibroacoustic Response of Lattices: Opportunities and Challenges
15. Jaejong Park, Alok Sutradhar: Design of Tunable Architectured Metamaterials for Biomedical Applications

Poster Contributions

1. Bill Arrighi, Jun Kudo, Dan Tortorelli, Seth Watts, Dan White: Three-Dimensional Multiscale Design Using Neural Net Surrogate Models of Lattice Material Response
2. Kieran A. Murphy, Heinrich M. Jaeger: Designed to Fail: Granular Plasticity and Particle Shape
3. Vince Vernacchio, Thomas Siegmund: Lattice Structures and Strength Optimization
4. Diab W. Abueidda, Iwona Jasiuk, Nahil A. Sobh: Acoustic Band Gaps, Sound Attenuation, and Elastic Stiffness of PMMA Cellular Materials Based on Triply Periodic Minimal Surfaces
5. Sree Kalyan Patiballa, Girish Krishnan: Conceptual Design of Spatial Auxetic Microstructures
6. MS. Hosseini, S.N. Garner, S. E. Naleway, J.M. McKittrick, P.D. Zavattieri: Role of Architecture in Controlling Crack Propagation Direction Bio-Inspired From Boxfish Scute
7. Will Langford, Neil Gershenfeld: Discretely Assembled Compliant Mechanisms
8. Susanta Ghosh, Mark Coldran, Praveen Bulusu, Upendra Yadav, Trisha Sain: Mechanics of Micro-Architectured Glass: Inverse Identification of Interface Properties and a Novel Analytical Model
9. Thomas Tancogne-Dejean,and Dirk Mohr: BCC Metamaterials Composed of Tapered Beams: Stiffness and Energy Absorption
10. Aman Thakkar, Nilesh Mankame, Pablo Zavattieri, Andres F. Arrieta: Energy Harvesting in Phase Transforming Materials
11. H. Cui, M.R. O'Masta V.S. Deshpande, Xiaoyu (Rayne) Zheng: Fracture Toughness of Hierarchical, Low Density Architected Metamaterials
12. Yunlan Zhang, Kristiaan Hector, Mirian Velay-Lizancos, David Restrepo, Nilesh D. Mankame, Pablo Zavattieri: Mechanics of Energy Absorbing Phase Transforming Cellular Materials
13. Di Wang, Alireza Zaheri, Benjamin Russell, Pablo Zavattieri, Horacio Espinosa: Fiber Reorientation Behavior of Bioinspired Bouligand Architectures with Functional Graded Fiber Orientation
14. Myungwon Hwang, Andres F. Arrieta: Input-Independent Response-Invariant Wave Propagation in Bistable Lattices with Elastic Interactions
15. Carlos M. Portela, Dennis M. Kochmann, Julia R. Greer: Controlling the Effect of Nodes on the Mechanical Response of Lattice Architectures
16. Muhammed Imam, Trisha Sain, Julien Meaud: Computational Design of Architectured Materials with Hierarchical Interlocking for Improved Multifunctional Properties
17. Andres Bejarano, Christoph Hoffmann: Topological Interlocking Cylinder Configurations: A Geometric Approach

18. Miroslawa El Fray, Rahul Sahay, XiaoMeng Sui, H. Daniel Wagner: Architectured Helically Coiled Structures Through Novel Electro-writing Technique
19. Hang Xu, Amr Farag, Damiano Pasini: Routes to Program Thermal Expansion in Three-dimensional Lattices Built from Tetrahedral Building Blocks
20. Pu Zhang: Symmetry of Phonon Modes for Periodic Structures with Glide Symmetry
21. Baig Al-Muhit, Florence Sanchez: Mechanical Properties of Nanolaminate Tobermorite-9Å/Graphene Composite
22. Lichen Fang, Jing Li, Zeyu Zhu, Santiago Orrego, Sung Hoon Kang: Piezoelectric Polymer Thin Films with Architected Cuts
23. Haodong Du, Liang Zhang, Bo Peng, Wenbin Yu: Constitutive Modelling of Cosserat Metamaterials
24. Xiao Shan, Lu Liu, Ahmad Rafsanjani, Damiano Pasini: Durable Bistable Auxetics Made of Rigid Solids
25. Mohammad Mirkhalaf, Tao Zhou, Florent Hannard, Francois Barthelat: Strong and Tough Ceramics Using Architecture and Topological Interlocking
26. Qianli Chen, Ahmed Elbanna: Emergent Wave Phenomena in Coupled Elastic Bars: From Extreme Attenuation to Realization of Elastodynamic Switches
27. J. William Pro, Najmul Abid, Ali Shafiei, Francois Barthelat: Discrete Element Models of Architectured Biological and Bio-inspired Composites
28. Marianna Diamantopoulou, Colin Bonatti, Dirk Mohr: Periodic Ceramic-Polymer Shell-Network of High Specific Stiffness
29. Mirit Sharabi, H. Daniel Wagner: Bio-mimetics of Structural Micro-mechanisms in Soft Composite Materials
30. Howon Lee, Chen Yang, Manish Boorugu: Lightweight Microlattice with Tunable Mechanical Properties Using 3D Printed Shape Memory Polymer
31. Michael Jandron, David Henann: A Numerical Simulation Capability for Electroelastic Wave Propagation in Dielectric Elastomer Composites: Application to Tunable Soft Phononic Crystals
32. Ye-eun Na, Dahye Shin, Kisun Kim, Seokwoo Jeon, Dongchan Jang: Emergence of New Density-Strength Scaling Law in 3D Hollow Ceramic Nano-Architectures
33. Andrew Williams, Thomas Siegmund: Tesselations and Percolations in Topologically Interlocked Stereotomic Material Systems
34. Colin Bonatti, Dirk Mohr: Mechanical Response of Three Cubic Shell-based Metamaterials
35. Amrita Kataruka, Shelby B. Hutchens: Analysis of Plant-inspired, Osmosis-mediated Structures
36. Vanessa Restrepo, Miriam Velay, Pablo Zavattieri: Structural Interfaces Bioinspired by Natural Adhesives: New Self-healing Material with High Energy Dissipation
37. Catalin R. Picu: Architected Fibrous Networks with Highly Tuneable Properties
38. Christine E. Gregg, Benjamin Jenett, Kenneth C. Cheung Assembled Composite Lattice Structures: Towards Ideal Performance in Large-Scale Applications
39. Le Cao: Multiscale Method in Lattice Structures Stability Analysis with Topology Optimization
40. Caglar Oskay, Ruize Hu: Multiscale Simulation Framework for Transient Wave Propagation in Viscoelastic Composites

41. Davis J. McGregor, Sameh Tawfick, William P. King: Mechanical Properties of Hexagonal Lattice Structures Fabricated Using Continuous Liquid Interface Production Additive Manufacturing
42. Josh Pribe, Thomas Siegmund: Architecture and Internal Material Length Scale: Fatigue Crack Growth Across Weak Interfaces
43. Kamran Khan: Architected Active Metamaterials