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# MULTIFUNCTIONAL AND MULTIPHYSICS MATERIALS AS LOAD-BEARING STRUCTURAL COMPONENTS

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## ABSTRACT

Multifunctional and multiphysics cellular solids are introduced in this paper as load-bearing structural components. Cellular solids offer a robust low-mass alternative for applications requiring lightweight and stiff components. The unique properties of cellular solids are achieved through cell geometry, connectivity, relative density, and properties of constituent materials. Inspired by biological systems, smart cellular solids can integrate low-mass, sensing/actuating, and self-healing properties into structural components. Discrete fabrication, by integrating patches of smart/active materials onto cellular solids, and continuous fabrication, using additive manufacturing, are two fabrication techniques for the manufacturing of multifunctional cellular solids. We propose a multiscale methodology for the analysis and design of smart cellular structures on the basis of homogenization, structural hierarchy, multiphysics simulation, and multi-objective optimization. It is shown that relative density, cell microarchitechture, cell topology, and volume fraction play a considerable role on the characteristics of multifunctional materials. At last, the potential application of smart cellular solids in civil and building construction industry are reviewed. The paper sheds lights on the emergence of multifunctional and multiphysics materials in industrial sectors and introduces the effect of tailoring the architecture of smart cellular solids in multiple scales on tuning and optimizing the structural functionality.

Keywords: Additive manufacturing, Cellular solids, Multifunctional material, Multiphysics simulation, Structural engineering.

## 1. INTRODUCTION

Remarkable amount of energy and material is wasted in industrial sectors, from building and transportation to automotive and aerospace. The culprits are not only the construction and manufacturing process or inefficient thermodynamic cycles of operating systems, but also the lack of existence of reliable lightweight materials with low energy consumption and multiple functionalities. Inspired by nature and biological systems, where load-carrying, sensing, actuating, and self-healing properties are all integrated, advanced multifunctional and multiphysics materials can be designed and synthesized as a promising alternative to reduce both energy and material waste. Multifunctional and multiphysics materials can not only serve as load-bearing structural materials, but also as self-powered vibration and thermal insulators. These types of advanced materials can be utilized for electric power generation via embedding fuel-cells, photovoltaic cells, and piezoelectric materials into porous composite materials (Akbarzadeh 2013, Akbarzadeh et al, 2014, Guo et al. 2015, Lee et al. 2014).

Smart materials with multifunctional capabilities, energy harvesting abilities, and a low level of external energy consumption are recently being developed, in the form of piezoelectric and multiferroic materials, to provide intelligent self-powered sensors and actuators (Akbarzadeh et al. 2014). At the same time, cellular solids with distinctive physical properties offer a robust low-mass alternative for applications requiring lightweight and stiff components (Wadley et al. 2003). Man-made metamaterials fashioned by repeating unit cells have recently enabled designers and engineers to achieve unprecedented physical properties, like negative stiffness, phononic band gaps, and negative index of refraction (Lee et al. 2012). Opposed to conventional composite materials, metamaterials gain their extreme properties from their underlying microarchitecture and not only from the material composition. On the other hand, nature reveals incredible innovation in the design of biological systems that can inspire designers to integrate multiple functionalities into a single structure/material. In this attempt, multifunctional materials have recently been synthetized to integrate load-carrying, sensing, actuating, and self-healing properties into a single material.

In this article, we highlight the prospect of practical applications of advanced cellular-based multifunctional and multiphysics metamaterials. Specific attention is devoted to load-bearing multifunctional materials in construction and steel/composite structure sectors. We present a straightforward multiphysics approach for the analysis, design, and manufacturing of multifunctional cellular solids not only as load-bearing structural materials but also as thermal and vibration insulators and self-powered sustainable energy harvesters. As a case study, a functionally graded load-bearing beam made of multifunctional cellular solids is considered. It is found that how the tailoring of microarchitecture can effectively optimize the structural performance of multifunctional materials, while reducing the weight of structure.

## 2. MULTIFUCNTIONAL CELLULAR SOLIDS

Conventional design concepts for structural components focus on inhibiting static and fatigue failure as well as excessive deflection under multiphysics load. As a result, stiff and high-mass materials with a single functionality are typically employed for the material selection of structural design. Concerning the limitation on material and energy resources, the environmental impact of using mineral/natural resources, and the large amount of material waste during construction and manufacturing, innovation in design concepts and construction materials is inevitable to lessen the negative impacts on our economy and environment. Advanced lightweight active materials, like multifunctional cellular solids, are one of the evolving materials to lighten structural components and to integrate multiple functionalities into one single material. As shown in Fig. 1, heavy, stiff, and expensive steels, concretes, and timbers can be replaced by advanced multifunctional materials for design of structural components in dams, offshore structures, and bridges. Among the advanced materials, one can refer to functionally graded cellular materials (FGCM), shellular and cellular materials, graphene and carbon nanotubes, mechanical metamaterials, multifunctional polymers, piezoelectric films, foldable origami/kirigami-like structures (Akbarzadeh et al. 2014, Han et al. 2015, Rodriguez-Perez et al. 2013, Rafsanjani et al. 2015, Lee et al. 2014, Park et al. 2014, Filipov et al. 2015, Overvelde et al. 2016).

To fabricate lightweight structures, porous materials are one of the most promising alternatives. For example, the core of lightweight sandwich panels can be made of either foams, e.g. polyurethane foams, or periodic cellular solids (lattices), e.g. corrugated metals. The porous materials are preferred to their solid counterparts because of their low mass, ability to satisfy multifunctional requirements, low thermal expansion, reasonable electrical conductivity and flow permeability, and thermal and acoustic isolation capabilities. The properties of cellular materials are controlled by the geometry of the unit cell, in particular their topology, nodal connectivity, and relative density. While there are many studies on the multiphysics responses of cellular materials, the research on multifunctional cellular solids is very recent due to the complexity of manufacturing of multifunctional cellular solids. Recent advances in fast prototyping and material science enable us to ponder about the fabrication and design of cellular solids made of smart and multiferroic particles with multifunctional capabilities.

Analysis and design of multifunctional cellular solids need a complex multiscale analysis via the detailed finite element analysis and/or molecular dynamics simulation. To avoid the intricate procedure, homogenization theory can be used to determine effective properties of multifunctional cellular solids (Hollister et al. 1992). Via homogenization, multifunctional composites with complex microarchitecture and material composition are replaced by homogenous materials with effective multiphysics properties. The concept of homogenization in a sandwich tube with a cellular core has schematically been illustrated in Fig. 2 (Akbarzadeh et al. 2014). Among homogenization techniques, e.g. micropolar theory, standard mechanics, and asymptotic homogenization, we introduce standard mechanics homogenization for the analysis of architectured multifunctional materials.

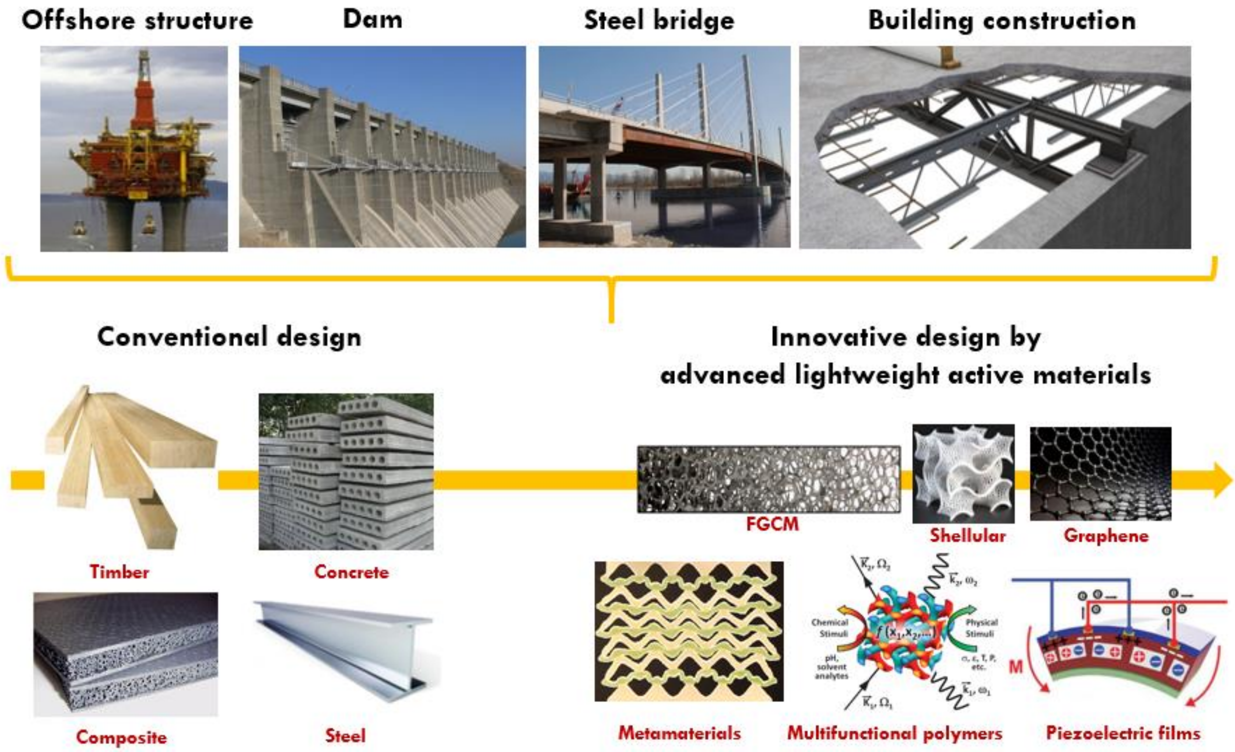


Fig. 1: Innovative design in building construction and structural design by the application of advanced lightweight active materials, e.g. FGCM, shellular materials, graphene and carbon nanotubes, metamaterials, multifunctional polymers, and piezoelectric films (Akbarzadeh et al. 2014, Han et al. 2015, Rodriguez-Perez et al. 2013, Rafsanjani et al. 2015, Lee et al. 2014, Park et al. 2014).

Standard mechanics homogenization can be applied to each unit cell of cellular-based multifunctional composites to obtain effective multiphysics properties. For example, the effective stiffness tensor of a representative volume element is expressed as:

[1] $$\overline{C}_{ijkl} = \frac{1}{V_{RVE}} \int C_{ijmn} \, M_{mnkl} \, dV_{RVE}$$

where $C_{ijkl}$ $(i, j, k, l = 1, 2, 3)$ is stiffness tensors, $V_{RVE}$ is the volume of a representative volume element (RVE), and $M_{ijkl}$ represents local structural tensor. In Eq. (1), overbar stands for the effective properties. Using the homogenization approach, effective multiphysics properties can be expressed in terms of cell topology, material composition of multifunctional materials, and relative density $\rho_r = \overline{\rho} / \rho_s$, in which the subscript "*s*" represents solid materials. This approach enables us to come up with design charts of multiphysics properties of multifunctional cellular solids to reach optimum lightweight structures with low energy and materials consumption.

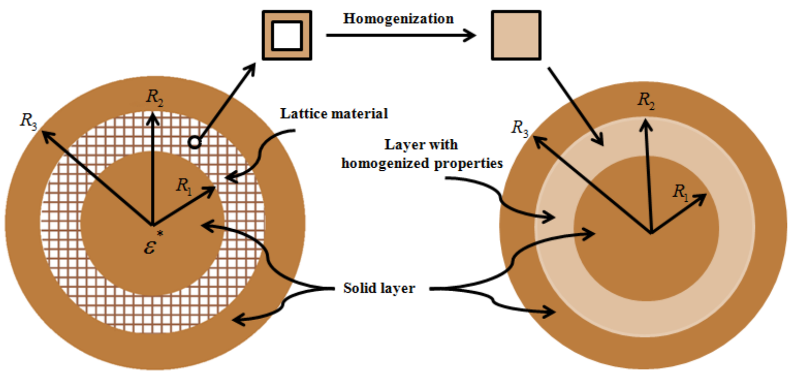


Fig. 2: Schematic figure on the concept of homogenization for the multiscale analysis of structures made of solid/cellular-based multifunctional composites (Akbarzadeh et al. 2014).

## 3. MULTIPHYSICS SIMULATION OF MULTIFUNCTIONAL MATERIALS

Multiphysics simulation is the modelling of interaction among physical fields acting simultaneously. Multiphysics interaction is typically described by a set of partial differential equations, which are often strongly coupled (Akbarzadeh et al. 2014). The coupling in multiphysics simulation of multifunctional materials can often span multiple length scales, from nanoscale (Chen et al. 2015) to macroscale (McDowell et al. 2008). Multifunctional materials are fabricated by the composition of multiferroic materials and semiconductors with metallic and non-metallic components; for example, one can recall natural (wood, bone, and liquid crystals) or synthetic (piezoelectric, piezomagnetic, and polyelectrolyte gels) smart materials (Altay et al. 2008). The coupled multiphysics interaction in multifunctional materials may involve elastic, electric, magnetic, thermal, hygroscopic, chemical, and optical fields.

A critical step in the application of multifunctional materials, as structural components, is multiphysics simulation. Beside the application of multifunctional materials as load-carrying structural elements, they have found applications in structural health monitoring to avoid catastrophic failure and in energy harvesting to produce green energy. Although recent decades have seen the emergence of a great deal of research in multiphysics simulation and thermomechanical analysis of cellular-based multifunctional materials, multiphysics simulation of multifunctional materials should be yet explored. Akbarzadeh and Chen have recently developed a state-of-the-art linear multiphysics model for uncoupled interaction among mechanical, hygrothermal, and electromagnetic fields in composite materials. The model is called uncoupled hygrothermomagnetoelectroelasticity (Akbarzadeh et al. 2014). To be able to conduct a fully coupled hygrothermomagnetoelectroelastic analysis, we propose here a coupled hygrothermomagnetoelectroelasticity theory, which can be extended for cellular-based multifunctional materials using the homogenization techniques, introduced in Section 2.

Constitutive equations for a coupled hygrothermomagnetoelectroelasticity analysis are introduced as (Akbarzadeh 2013):

[2a] $$\sigma_{ij} = C_{ijkl}\varepsilon_{kl} - e_{kij}E_k - d_{kij}H_k - \beta_{ij}\theta - \xi_{ij}m$$

[2b] $$D_i = e_{ijk}\varepsilon_{jk} + \in_{ij} E_j + g_{ij}H_j + \gamma_i\theta + \chi_i m$$

[2c] $$B_i = d_{ijk}\varepsilon_{jk} + g_{ij}E_j + \mu_{ij}H_j + \tau_i\theta + \upsilon_i m$$

[2d] $$q_i = k^M_{ijkl}\varepsilon_{kl,j} - k^E_{ijk}E_{k,j} - k^B_{ijk}H_{k,j} - k^T_{ij}\vartheta_{,j} - k^H_{ij}m_{,j}$$

[2e] $$p_i = \zeta^M_{ijkl}\varepsilon_{kl,j} - \zeta^E_{ijk}E_{k,j} - \zeta^B_{ijk}H_{k,j} - \zeta^T_{ij}\vartheta_{,j} - \zeta^H_{ij}m_{,j} \qquad (i,j,k,l = 1,2,3)$$

where $\sigma_{ij}$, $D_i$, $B_i$, $\varepsilon_{ij}$, $E_i$, $H_i$, $\theta$, and $m$ are stress tensor, electric displacement vector, magnetic induction vector, strain tensor, electric field vector, magnetic field vector, temperature change, and moisture concentration change, respectively. In addition, $C_{ijkl}$, $e_{ijk}$, $d_{ijk}$, $\in_{ij}$, $g_{ij}$, $\mu_{ij}$, $\beta_{ij}$, $\xi_{ij}$, $\gamma_i$, $\chi_i$, $\tau_i$, and $\upsilon_i$ are, respectively, elastic, piezoelectric, piezomagnetic, dielectric, electromagnetic, magnetic permeability, thermal stress, and hygroscopic stress coefficient tensors and pyroelectric, hygroelectric, pyromagnetic, and hygromagnetic coefficient vectors.

To implement a multiphysics simulation for multifunctional materials, which are used as load-bearing structural components, each of the effective multiphysics coefficients defined in Eq. (2) needs to be determined for composite and cellular-based multifunctional materials. Upon the calculation of effective multiphysics properties by one of the homogenization techniques, effective multiphysics properties are introduced into the governing equations to predict the structural responses of multifunctional components subjected to alternative multiphysics loads. The classical multiphysics governing equations for a hygrothermomagnetoelectroelastic analysis include equation of motion, Maxwell's electromagnetic equation, energy conservation equation, and conservation law for the mass of moisture.

## 4. ADDITIVE MANUFACTURING AND 3DPRINTING OF MULTIFUNCTIONAL MATERIALS

Multifunctional materials have immense potential industrial applications not only as sensors/actuators but also as lightweight structural components. Tailoring the topology, material composition, and density of multifunctional materials provides a promising feature to optimize the multiphysics properties and to optimally satisfy design requirements of structural elements. Nonetheless, the most considerable challenge for promoting the application of advanced multifunctional materials in industrial sectors is their manufacturability and the experimental validation of numerical multiphysics simulation. Fortunately, advances in additive manufacturing and rapid prototyping have shed lights on the emergence of such advanced multifunctional materials and have enabled the fabrication of topologically optimized multifunctional and multiphysics materials with tailored architecture in multiple scales, from nanoscale to macroscale (Schaedler et al. 2011).

As shown in Fig. 3, rapid prototyping includes additive, subtractive, and additive/subtractive techniques. The recent considerable advances of additive manufacturing techniques have opened new horizons for the fabrication of a wide range of materials with an arbitrary multiscale structural morphology and architectural topology. Additive manufacturing, which often incorrectly referred as 3D printing, can fabricate plastic, rubber, metal, plaster, cement, sand, and even composites of multi-materials. Additive manufacturing enables fast and low-cost fabrication of free-form surfaces with small amounts of material waste. In recent years, researches are being conducted to explore the fabrication and printing of a full-scale building (Keating 2014, Perrot et al. 2015), manufacturing of structural porous biomaterials (Arabnejad et al. 2016), and fabrication of electrically conducting scaffold (Singh Talwar et al. 2014). At Advanced Multifunctional Multiphysics Materials Laboratory (AM$^3$L) of McGill University, we are currently investigating a series of additive manufacturing and 3D printing techniques to develop fully coupled cellular-based multifunctional materials responsive to multiple load cases while carrying mechanical loads.

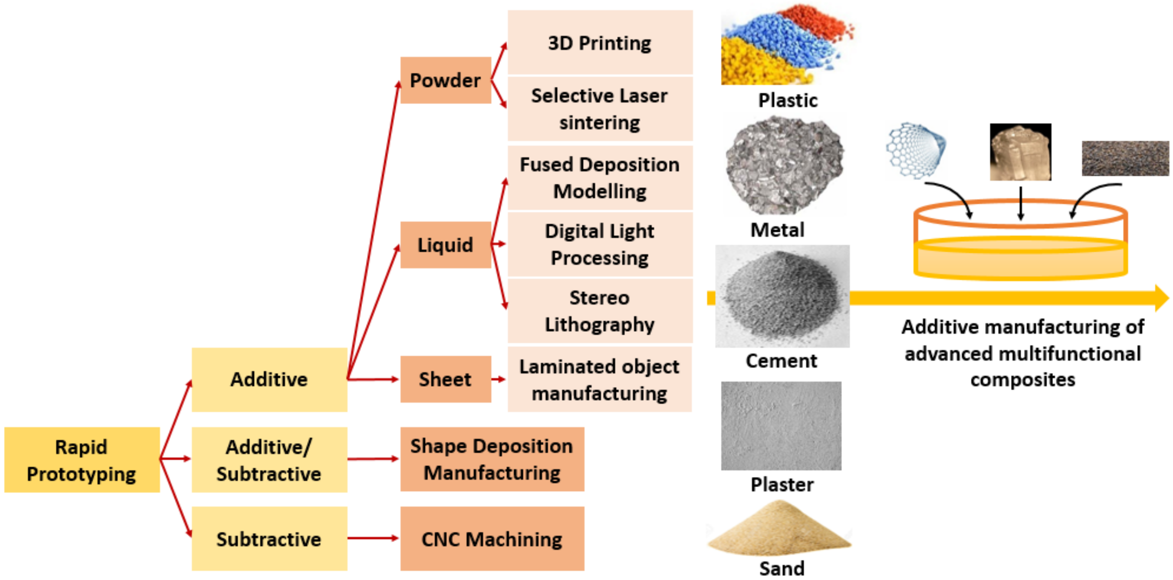

Fig. 3: Rapid prototyping and additive manufacturing for the fabrication of advanced multifunctional materials.

## 5. CASE STUDY: TAILORING PROPERTIES OF MULTIFUNCTIONAL MATERIALS AS LOAD-BEARING STRUCTURES

As a case study for the multiscale analysis of multifunctional structures, we consider a sandwich beam composed of a multifunctional cellular core. The lightweight sandwich beam can possess a variety of core cell topology and relative density. In the current study, we focus on mechanical responses of multifunctional sandwich beams made by cellular materials. Five alternative cell topologies are considered, including square, triangular, Kagome, and mixed triangular A and B. It is well-known that decreasing the density of beams (lightening structures) adversely decreases the in-plane stiffness, out-of plane stiffness, critical buckling load, and natural frequency (Akbarzadeh et al. 2016, 2014). Despite the trade-off effect of relative density of cellular-based multifunctional materials on weight and structural responses of beams, we show that functionally graded cellular multifunctional materials can be developed to optimize the structural performance of multifunctional beams.

Herein, we consider a functionally graded multifunctional beam, in which the relative density of cellular multifunctional materials varies gradually through the thickness of the beam. The beam is symmetric and relative density changes through the thickness (*z*-axis) of the beam with a total thickness of *h* according to the following power-law:

[3] $$\rho = \rho_m + (\rho_f - \rho_m)\left(\frac{2z}{h}\right)^n$$

where $\rho$ represents relative density and $n$ is the polynomial index of FGCM; subscripts "*m*" and "*f*" indicate the middle and the face of beam, respectively. To reach the optimal structural performance of the multifunctional beam, while reducing the structural weight, we search for FGCM index *n* which minimizes structural weight and maximizes first natural frequency $(\omega)$ and critical buckling load $(N_{cr})$. The multi-objective optimization problem is written in the following format and is solved using a non-dominated sorting genetic algorithm (NSGA-II) (Akbarzadeh et al, 2016):

[3] $$\min_n \left\{ \frac{weigth}{\omega(n)}, \frac{weight}{N_{cr}(n)} \right\}$$
$$s.t. \ \{0 \le n \le 2\}$$

The numerical results of implementing the optimization algorithm is shown in the form of Pareto fronts of optimal solutions in Fig. 4. As shown in this figure, the structural properties of sandwich beams are considerably affected by the cell topology of multifunctional materials. Although further failure analyses are needed to confirm the applicability of sandwich beam with square cell, our current analysis shows the efficiency of using square cell topology compared to other two-dimensional topologies to optimize the structural performance. Furthermore, it is seen that the trade-off multifunctional properties of load-bearing cellular beams can be optimized by selecting appropriate values for the variation of relative density through the beam thickness.

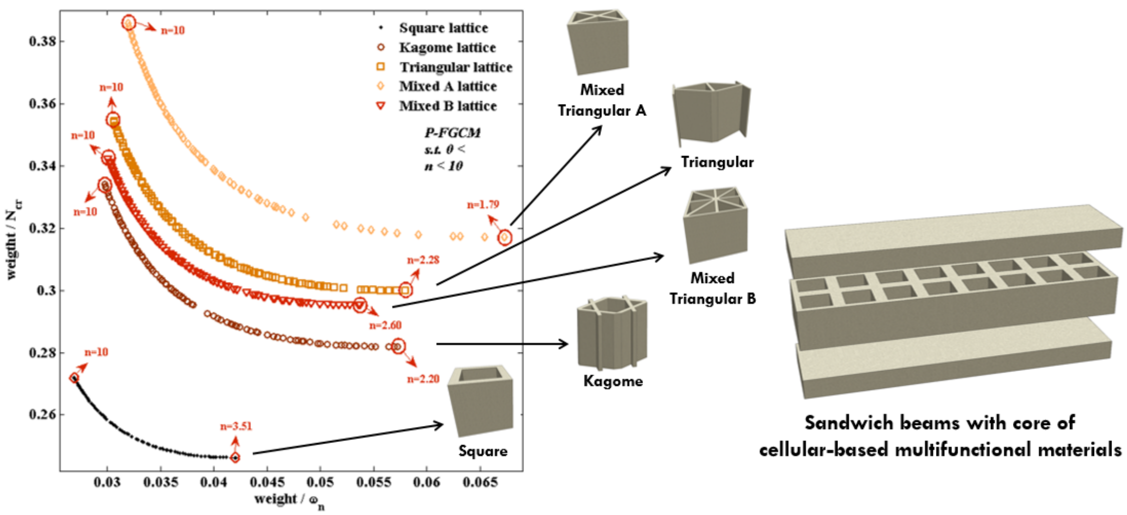


Fig. 4: Tailoring structural responses of load-bearing sandwich beams by alternating cell topology and relative density distribution through the beam thickness.

## 6. CONCLUSION

This paper has introduced a new type of multifunctional materials, called cellular-based multifunctional materials, as an alternative load-bearing material/structure for applications in building construction and steel/composite structural design beside those applications in automotive, aerospace, and medicine. A straightforward approach is presented for the analysis, design, and manufacturing using the multiphysics simulation, homogenization techniques, and additive manufacturing/3Dprinting. It is revealed that multifunctional structural members can be constructed by compounding metallic and non-metallic components with electromagnetic conductive materials for applications required high stiffness, low thermal conductivity, and a moderate range of electric conductivity. Cellular-based multifunctional materials enable designers not only to tailor material composition, relative density, and cell topology but also to tune the microstructural instability to reach unique extreme properties in multiphysical fields. As an example, it has been shown that tailoring the variation of relative density and even cell topology through the thickness of beam structures can lead to the design of lightweight structural elements with relatively high in-plane/out-of-plane stiffness, buckling load, and natural frequency. The successful development of these multifunctional materials enables the fabrication of lightweight, stiff, and sustainable structures with low construction costs in a reasonable timeframe.

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**REFERENCES**


Akbarzadeh, A.H. 2013. Multiphysical behaviour of functionally graded smart structures. Ph.D. thesis, University of New Brunswick.

Akbarzadeh, A.H., Arian Nik, M., and Pasini, D. 2016. Vibration Responses and Suppression of Variable Stiffness Laminates with Optimally Steered Fibers and Magnetostrictive Layers. *Composites Part B: Engineering*, 91: 315-326.

Akbarzadeh, A.H., Arian Nik, M., and Pasini, D, 2014. The Role of Shear Deformation in Laminated Plates with Curvilinear Fiber Paths and Embedded Defects, *Composites Structures*, 118: 217-227\].

Akbarzadeh, A.H., Chen, Z.T. 2013. Magnetoelectroelastic behavior of rotating cylinders resting on an elastic foundation under hygrothermal loading. *Smart Materials and Structures*, 21 (12): 125013-1-125013-17.

Akbarzadeh, A.H., Fu, J.W., Chen, Z.T., and Qian, L.F. 2014. Dynamic eigenstrain behavior of magnetoelastic functionally graded cellular cylinders. *Composite Structures*, 116 (1): 404-413.

Akbarzadeh, A.H. and Pasini, D. 2014. Multiphysics of multi-layered and functionally graded cylinders under prescribed hygrothermomagnetoelectromechanical loading. *ASME Journal of Applied Mechanics*, 81 (4): 041018.

Akbarzadeh, A.H. and Pasini, D. 2014. Phase-Lag Heat Conduction in Multilayered Cellular Media with Imperfect Bonds. *International Journal of Heat and Mass Transfer*, 75: 656-667.

Arabnejad, S., Johnston, R.B., Pura, J.A., Singh, B., Tanzer, M., and Pasini, D. 2016. High-strength porous biomaterials for bone replacement: A strategy to assess the interplay between cell morphology, mechanical properties, bone ingrowth and manufacturing constraints. *Acta Biomaterialia*, 30: 345–356.

Altay, G. and Dokmeci, M.C., 2008. Certain hygrothermopiezoelectric multi-field variational principles for smart elastic laminae. *Mechanics of Advanced Materials and Structures*, 15: 1-32.

Chen, L., Zhang, L., Kang, Q., Viswanathan, H.S., Yao, J., and Tao, W. 2015. Nanoscale simulation of shale transport properties using the lattice Boltzmann method: permeability and diffusivity. *Scientific Reports*, 5 (8089): 1-8.

Filipov, E.T., Tachi, T., and Paulino, G.H. 2015. Origami tubes assembled into stiff, yet reconfigurable structures and metamaterials. *Proceedings of the National Academy of Sciences*, 112 (40): 12321–12326.

Guo, S.Z., Yang, X., Heuzey, M.C., and Therriault, D, 2015. 3D printing of a multifunctional nanocomposite helical liquid sensor. *Nanoscale*, 7: 6451-6456.

Han, S.C., Lee, J.W., and Kang, K. 2015. A new type of low density material: shellular. *Advanced Materials*, 27: 5506-5511.

Hollister, S.J. and Kikuchi, N. 1992. A comparison of homogenization and standard mechanics analyses for periodic porous composites. *Computational Mechanics*, 10 (2): 73-95.

Keating, S. 2014. Beyond 3D printing: The new dimensions of additive fabrication, O'Reilly Media Publication, ISBN: 978-1-4493-7051-0.

Lee, J.H., Koh, C.Y., Singer, J.P., Jeon, S.J., Maldovan, M., Stein, O., and Thomas, E.L. 2014, $25^{th}$ anniversary article: ordered polymer structures for the engineering of photons and phonons. *Advanced Materials*, 26: 532-569.

Lee, J.H., Singer, J.P., and Thomas, E.L. 2012. Micro-/Nanostructured Mechanical Metamaterials. *Advanced Materials*. 24(36): 4782-4810.

McDowell, D.L. and Olson, G.B. 2008. Concurrent design of hierarchical materials and structures. *Scientific Modeling and Simulation*, 15 (1-3): 207-240.

Overvelde, J.T.B., De Jong, T.A., Shevchenko, Y., Becerra1, S.A., Whitesides, G.M., Weaver, J.C., Hoberman, C., and Bertoldi, K. 2016. A three-dimensional actuated origami-inspired transformable metamaterial with multiple degrees of freedom, *Nature Communication*. 7 (10929): 1-8.

Park, K., Son, J.H., Hwang, G.T., Jeong, C.K., Ryu, J., Koo, M., Choi, I, Lee, S.H., Byun, M., Wang, Z.L., and Lee, K.J. 2014. Highly-Efficient, Flexible Piezoelectric PZT Thin Film Nanogenerator on Plastic Substrates, *Advanced Materials*, 26: 2514:2520.

Perrot, A., Rangeard, D., and Pierre, A. 2015. Structural built-up of cement-based materials used for 3D-printing extrusion techniques, *Materials and Structures*, DOI 10.1617/s11527-015-0571-0.

Rafsanjani, A., Akbarzadeh, A.H., and Pasini, D. 2015. Snapping Mechanical Metamaterials under Tension. *Advanced Materials*, 27: 5931-5935.

Rodriguez-Perez, L., Angeles Herranz, M., and Martin, N. 2013. The chemistry of pristine graphene. *Chemical Communications*, 49: 3721-3735.

Schaedler, T.A., Jacobsen1, A.J., Torrents, A., Sorensen, A.E., Lian, J., Greer, J.L., Valdevit, L., and Carter, W.B. 2001. Ultralight metallic microlattices. *Science*, **334** (6058): 962-965.

Singh Talwar, B., Chizari, K., Guo, S., and Therriault, D. 2014. Investigation of carbon nanotubes mixing methods and functionalizations for electrically conductive polymer composites. *ASME International Mechanical Engineering Congress and Exposition*. IMECE2014-39970.

Wadley, H.N., Fleck, N.A., and Evans, A.G. 2003. Fabrication and structural performance of periodic cellular metal sandwich structures. *Composite Science and Technology*, 63(16): 2331-2343.