Architected Materials

Introduction

Architected material (or architectured material) is a class of materials that show new and/or customized behaviors by the interplay between material properties and geometry[1,2,3]. There have been active studies in this area with the progress of computational modeling that can predict the behaviors of materials and structures and advanced manufacturing methods such as 3D printing that can spatially control material constituents. There were related articles in the journal club in the past including "Negative Poisson's Ratio Materials" (April 2010, Katia Bertoldi), "Harnessing Instabilities in Response to Stimuli" (November 2012, Xuanhe Zhao), "Metamaterials Inspired by Concepts for Elastic Wave Energy Harvesting" (December 2012, Massimo Ruzzene), "Mechanical Metamaterials" (April 2013, Jongmin Shim) and "Nano-architected Nanolattice Structures" (November 2013, Lucas Meza, Lauren Montemayor, Julia Greer). Since then, there were many exciting development in the field in terms of investigating design principles, developing new fabrication approaches, and exploring new properties and applications. So, it is good time to summarize recent findings in the field and explore future opportunities. The article is not intended as a comprehensive review of the field due to limited space. Rather, it is intended as a living document that can facilitate the discussion among researchers in the field and a broad iMechanica community so that one can add thoughts and references about this growing field. After introduction, some of the recent examples in architected materials will be described followed by current challenges in the field and potential future directions as a starting point for further discussion.

Recent progress in architected materials

Since 2014, there have been exciting new studies in the field that significantly expanded available property spaces (or filled "white spaces" in Ashby plot) as well as introduced new properties not available before. Figure 1 shows some of the examples of the recent developments. Based on rational design of architecture followed by high resolution 3D printing, Zheng *et al*. reported ultralight and ultrastiff materials (Figs. 1A-B) with the minimum density of 0.87 kg/m^3 (c.f. density of water ~1000 kg/m^3) and the modulus of ~ 1 MPa[4]. The architected material has 0.025% relative density (i.e. 99.75% air), but it has substantial load bearing capability. In the same year, Meza *et al*. reported 3D ceramic lattices (Figs. 1C-D) with high specific stiffness and shape recovery after large deformation. While ceramics tend to undergo plastic deformation or fracture under large deformation, the reported architected ceramic lattices could recover their original shapes after compressions in excess of 50% strain[5]. Since then, there have been many studies that expanded available material property spaces. However, there was no geometry or architecture that achieved a theoretical upper bound of material properties such as isotropic elastic stiffness. The recent study by Berger *et al*. addressed this challenge by reporting architected materials (Figs. 1E-F) with isotropic elastic stiffness at the theoretical limit of Hashin–Shtrikman upper bounds[6]. Beyond expanding available property spaces, there have been also works to generate new properties or behaviors that are not observed in bulk forms.

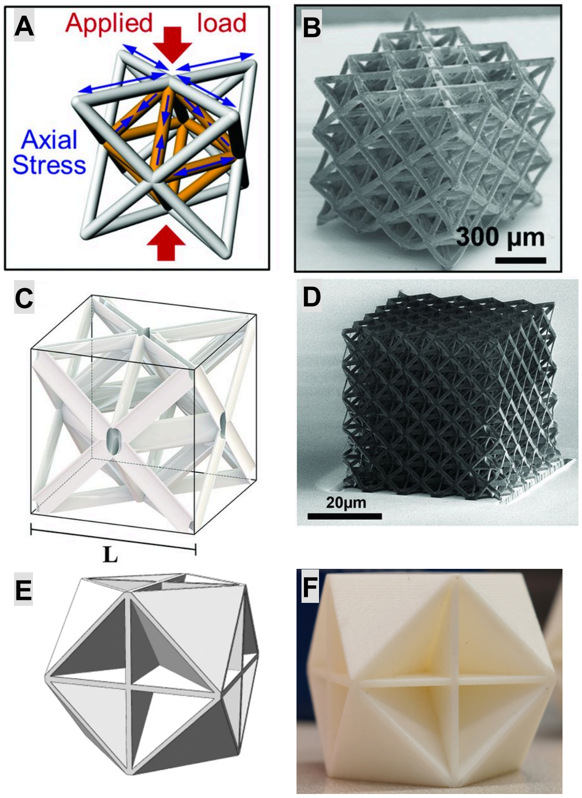

Fig. 1. (A) Mechanical response to compressive loading of a stretch-dominated octet-truss unit cell[4]. **(B)** Octet-truss unit cells packed into a cubic microlattice[4]. © 2014 American Association for the Advancement of Science. **(C)** Cutaway of hollow octet-truss unit cell[5]. **(D)** SEM image of alumina octet-truss nanolattice[5]. © 2014 American Association for the Advancement of Science. **(E)** A representative topology of cubic-octet foam (Isomax™)[6]. © 2017 Nature Publishing Group. **(F)** A 3D-printed model of the foam's cellular structure with isotropic elastic stiffness at theoretical limit. (Photo Credit: Sonia Fernandez)

In particular, there have been active studies that harness elastic deformation for novel reversible and/or tunable mechanical behaviors. For example, Shan *et al*. (Fig. 2A) and Frenzel *et al*. reported architected materials with reusable energy absorption by harnessing mechanical instability[7,8]. Restrepo *et al*. and Haghpanah *et al*. (Fig. 2B) reported shape reconfigurable materials with energy dissipation by elastic deformation[9,10]. Beyond quasi-static loading conditions, there were also studies reporting architected materials for dynamic loadings such as elastic wave propagation. Shan *et al*. reported an architected material (Fig. 2C) with tunable vibration propagation and absorption by triggering different mechanical instability-induced pattern formation[11]. Matlack *et al*. reported an architected material (Fig. 2D) with low frequency broad band vibration absorption[12]. Raney *et al*. reported stable propagation of mechanical signals in soft media (Fig. 2E) by storing elastic strain energy using mechanical instability[13].

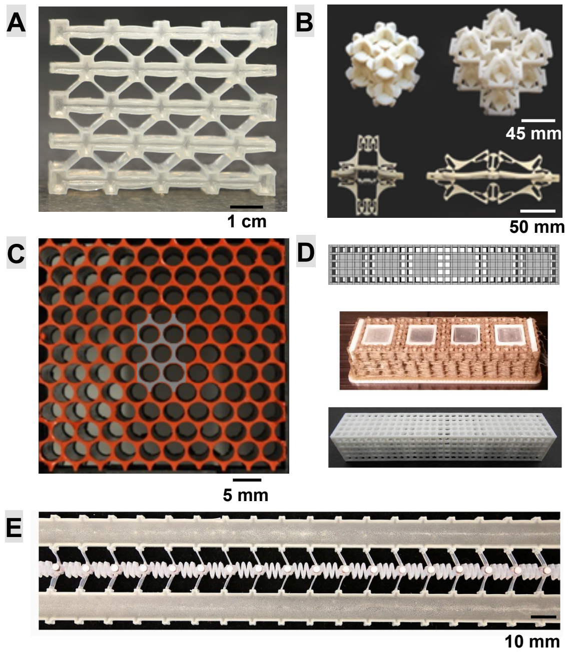

Fig. 2. (A) A photo of an architected material with reversible energy absorption[7]. © 2015 Wiley-VCH. **(B)** Images of multistable shape-reconfigurable architected materials[10]. © 2016 Wiley-VCH. **(C)** A photo of an architected material with tunable control of elastic wave propagation by harnessing multiple folding mechanisms in soft periodic structures[11]. © 2014 Wiley-VCH. **(D)** One-dimensional chain of mesoscale unit cells with periodicity in the *x* direction (Top). Photograph of a metastructure during 3D printing, with polycarbonate lattice (white), support material (brown), and embedded steel resonators (gray) (middle). Final 3D-printed metastructure with embedded resonators (bottom)[12]. © 2016 National Academy of Sciences. **(E)** A 1D series of bistable elements connected by soft coupling elements for stable propagation of mechanical signals in soft media using stored elastic energy[13]. © 2016 National Academy of Sciences.

Moreover, there have been also studies that reported architected materials with unusual or exotic properties such as negative effective swelling[14] (Fig. 3A), negative thermal expansion[15] (Fig. 3B) and static non-reciprocity[16] (Fig. 3C). These examples demonstrate the cases that the architected materials show in a way opposite properties of those of constituents and give us intriguing new opportunities for design of materials and structures.

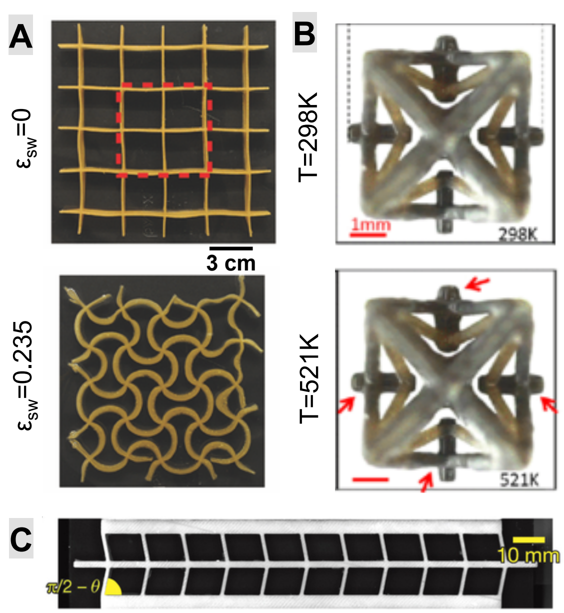

Fig. 3. (A) Experimental snapshots of an architected material with effective negative swelling during the swelling process. The dashed red square indicates the cells that are used to calculate ε_{sw} (strain by swelling)[14]. © 2016 Wiley-VCH. **(B)** Experimental sequences of a unit cell with increasing temperature that show negative thermal expansion behaviors. The red arrows indicate the inward bending of the reinforced PEGDA beams[15]. © 2016 American Physical Society. **(C)** A 3D printed architected material with static non-reciprocity[16]. © 2017 Nature Publishing Group.

Challenges & perspectives

While there have been many exciting progress in architected materials, there are also challenges such as inverse design capability and fabrication of hierarchical architectures across different length scales. To design architected materials, unit cell-based parametric approaches are most common methods. Other methods include combinatorial approach (Fig. 4B)[17] and searching mechanical analogues of physical principles as the case of the architected materials with static non-reciprocity[16]. However, there are challenges of guiding the inverse design of architecture for desired applications based on these approaches. In this sense, recent developments in topology optimization (Fig. 4A)[3] provide design algorithms for architected materials with desired properties with consideration of other conditions such as manufacturing constraints and tolerance, making them suitable as guidance for fabricating architected materials. Nevertheless, there are also challenges in this approach such as considering instability in the optimization algorithms for rational design of tunable architectures with changing properties. To the best of my knowledge, currently, there is no algorithm or tool that provides us inverse design capability of architected materials with nonlinear behaviors of materials and/or structures.

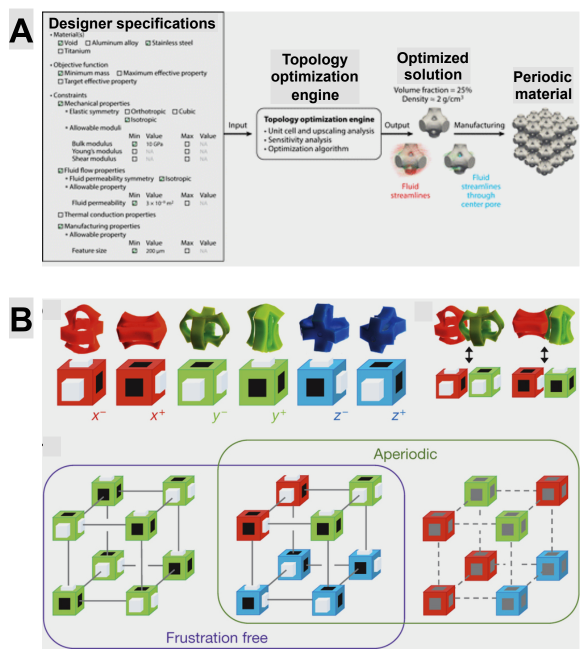

Fig. 4. (A) An example of the topology optimization design framework for architected materials. The optimized unit cell architecture is then repeated in all directions and manufactured to form the bulk material[3]. © 2016 Annual Reviews. **(B)** (1st Row) (Left) Bricks (top) and their schematic representation (bottom), with the color indicating orientation, and black dents and white protrusions representing deformations. (Right) Two examples where appropriately polarized, adjacent bricks fit together. (2nd Row) Periodic (left), complex (middle) and frustrated (right) $2 \times 2 \times 2$ stackings—for the frustrated stacking, no consistent brick configurations exist (grey/dashed). Schematic symbols are separated from one another for ease of visualization[17]. © 2016 Nature Publishing Group.

In terms of fabrication, there are still limitations in terms of available materials and fabrication approaches for different length scales. Most of fabrication approaches are effective for particular class of materials and/or length scales. There is no single tool that can allow us to fabricate arbitrary 3D structures made of any material from sub micro to macro scale hierarchically. The recent demonstration of fabricating multiscale materials (Fig. 5A)[18] using a single fabrication tool provides a potential fabrication path to connect different length scales. We can also expand the design space of architected materials by using various stimuli-responsive materials including shape memory materials and gels.

Beyond controlling external geometry, one can further expand the design space and the resulting performance space of architected materials by coupling geometry with printing path[19] or microstructures in addition to materials properties. Recent progress in 3D printing provides such opportunities by enabling microstructure control within the printed geometry (Figs. 5B-C)[20,21]. The additional control of microstructures can allow us to have architected materials with different responses based on microstructures while they have the same geometries and material compositions.

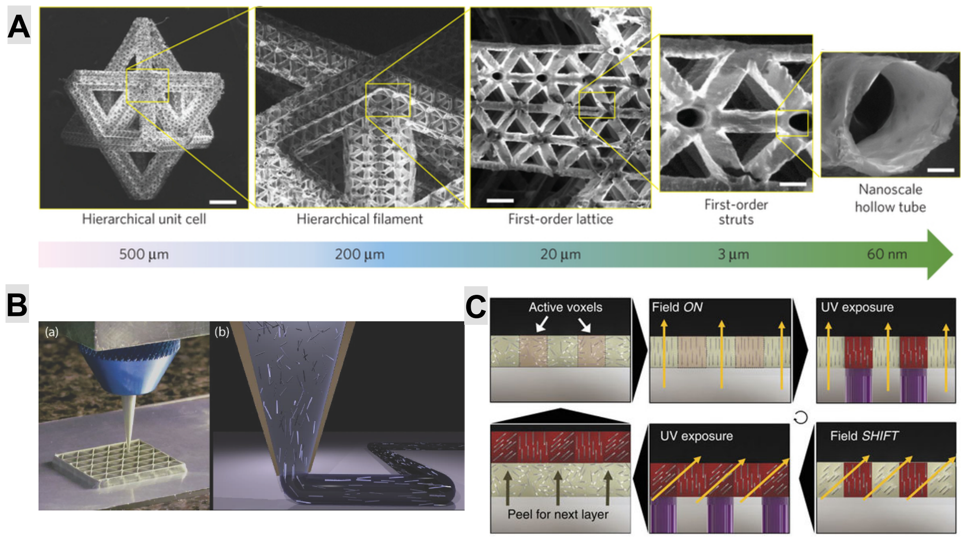

Fig. 5. (A) Scanning electron micrographs showing cross-section breakdown of structural hierarchy of the multiscale architected material shown down to tens of nanometers in wall thickness[18]. © 2016 Nature Publishing Group. **(B)** (Left) Optical image of 3D printing of a triangular honeycomb composite. (Right) Schematic illustration of the progressive alignment of high aspect ratio fillers within the nozzle during composite ink deposition[20]. © 2014 Wiley-VCH. **(C)** Schematics showing the 3D magnetic printing process systematically aligns and selectively polymerizes groupings of voxels programmed to have specific reinforcement orientation within each layer of printed material based upon a shifting field[21]. © 2015 Nature Publishing Group.

As a closing remark, architected material is an exciting field that opens new opportunities by coupling various disciplines including mechanics, materials science/engineering, physics, chemistry, and biology. It is also a field that needs further studies in many areas including analytical and numerical modeling as well as advanced fabrication methods with expanded palettes of materials, length scales, and microstructures. Beyond scientific community, industries are also active in this field for applications such as aerospace, automotive and sportswear. Architected material is a field that researchers across disciplines and sectors can work together to bring new understanding of behaviors of materials and structures and open new opportunities for materials and structures with tailored and/or intriguing characteristics.

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