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3D printed hierarchical honeycombs with shape integrity under large compressive deformations

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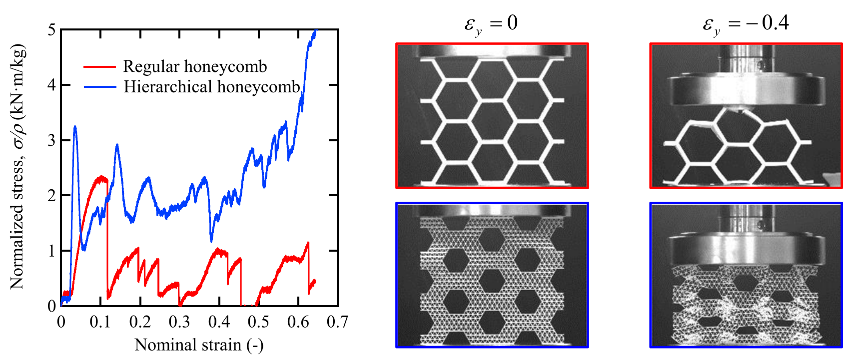
HIGHLIGHTS

- A new class of hierarchical honeycombs was designed and fabricated using 3D printing technique.
- The hierarchical honeycomb exhibits a progressive failure mode under uniaxial compression.
- Compared with regular honeycombs, improved stiffness and energy absorption have been achieved simultaneously.
- High energy dissipation at large imposed strains (up to 60%) have also been observed under cyclic loading.

GRAPHICAL ABSTRACT



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ABSTRACT

We describe the in-plane compressive performance of a new type of hierarchical cellular structure created by replacing cell walls in regular honeycombs with triangular lattice configurations. The fabrication of this relatively complex material architecture with size features spanning from micrometer to centimeter is facilitated by the availability of commercial 3D printers. We apply to these hierarchical honeycombs a thermal treatment that facilitates the shape preservation and structural integrity of the structures under large compressive loading. The proposed hierarchical honeycombs exhibit a progressive failure mode, along with improved stiffness and energy absorption under uniaxial compression. High energy dissipation and shape integrity at large imposed strains (up to 60%) have also been observed in these hierarchical honeycombs under cyclic loading. Experimental and numerical studies suggest that these anomalous mechanical behaviors are attributed to the introduction of a structural hierarchy, intrinsically controlled by the cell wall slenderness of the triangular lattice and by the shape memory effect induced by the thermal and mechanical compressive treatment.

1. Introduction

Recent advances in the defense, aerospace, automotive, semiconductor, and energy industries have triggered a tremendous demand for high-performance materials with lightweight and enhanced mechanical properties. A typical example of this quest is the research and

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development activity in the aerospace field, for which structural components with a combination of lightweight, high stiffness, energy absorption, and fracture toughness for extreme loading conditions are continuously sought after [1,2]. On a smaller scale, electrodes for lithium-ion batteries in energy applications require porous structures that exhibit considerable damage tolerance to improve the battery safety and operational life [3,4]. Compared with bulk materials, cellular structures and lattice solids can be designed to possess all these desired properties. In this regard, natural materials such as bone [5–7] and wood [8–11] have offered inspiration to design lightweight materials with remarkable mechanical properties. One of the reasons behind the presence of unusual deformation mechanisms in these biological structural materials is because of their hierarchical cellular configuration at multiscale [12–16]. Several efforts have been devoted to synthesize open or closed foams with similar cellular structures [17–19]. Yet, specific properties such as stiffness, strength, and energy absorption are still limited by the random and stochastic microstructure of these porous materials, which result in structural defects, inhomogeneity, and local stress concentration. In addition, the stiffness of cellular structures is typically characterized by the bending deformation of their ribs, which indicates that the effective mechanical properties decrease dramatically with the decrease of relative density (cube of the relative density) [20].

Structural topologies have a significant impact on the mechanical behavior of cellular structures, and in that sense, efforts have been devoted to designing deterministic materials for new mechanical functionalities. For example, ultralight metallic micro-lattice materials that exhibit excellent energy dissipation and recoverability have been designed and fabricated [21]. Their unusual mechanical properties and recoverability are attributed to their rationally designed hierarchical structure, which ranges from the nano to the millimeter scale. Ultralow density lattice metamaterials with similar structural features have also been introduced [22–28]. Localized fracture around the nodes of these micro-lattice materials, however, arises during the fabrication and the uniaxial compression. To circumvent this problem a new type of low-density cellular structure (shelluar) has been developed [29–31]. In contrast to the sharp shape changes around the nodes of a classical cellular topology, the shelluar configuration has a three-dimensionally continuous smooth surface that could carry the load and distribute the stress uniformly. Although this new configuration allows reaching an ultralow density range, stiffness, and strength are still low compared to other micro-lattice materials. It is worth pointing out that, besides the rationally designed architectures, these unusual properties are enabled by using state-of-the-art fabrication techniques such as two-photon lithography [22] and projection micro-stereolithography [23]. More recently, a new type of mechanical metamaterial with a combination of cubic and octet foams has shown the possibility to reach the theoretical upper bounds for isotropic elasticity and strain energy storage [32]. This remarkable feature is attributed to the specific topology that allows for a better load transfer between neighboring members. Moreover, this relatively simple design can be fabricated by using widely available 3D printers with a broad range of material selections.

In this work we design and fabricate a new type of hierarchically structured honeycomb with overall part size at centimeter scale, using a commercially available 3D printer. Our purposes here are two-folds. On one hand, we aim to explore the unusual properties of hierarchical honeycombs at large deformations. We also aim to demonstrate the potential of using the commercial 3D printer to facilitate the mass production of materials with complex architectures by applying a post-processing technique to preserve the shape and structural integrity of the printed structures. Honeycomb topologies have been the main topic of an extensive body of research due to their lightweight, novel thermomechanical properties, and energy absorption capability [33–38]. Their mainly bending-dominated mechanical behavior along the in-plane directions poses, however, a great limitation to potential applications. Structural hierarchy has been recently used as a new design strategy to explore improved mechanical and other unusual physical properties in honeycombs. Structural hierarchy is ubiquitous in both architecture designs and nature; typical examples range from the Eiffel Tower to hierarchically architected biological materials with multiple length scales [39–41]. Inspired by these designs researchers have introduced structural hierarchy into conventional honeycombs materials [42–47]. By replacing the cell walls of regular honeycombs with Kagome and triangular lattices it is theoretically possible to increase the stiffness of hierarchical honeycombs by about two orders of magnitude, compared to regular honeycombs [48,49]. In addition, recent studies have also shown that it is possible to control wave propagation by harnessing the multiscale characteristic of hierarchical honeycombs [49–51]. Quite remarkably, the introduction of a structural hierarchy into regular honeycombs results in significant energy absorption under crushing loading conditions [52–54]. Though analytical and numerical approaches have been developed to understand the mechanical response of these hierarchical honeycombs, the mechanical behaviors and associated mechanisms under large deformation are still elusive.

We report in this paper how designed hierarchical honeycombs with particular post-processing techniques may exhibit improved stiffness and energy absorption under uniaxial compression, as well as energy dissipation and shape preservation under cyclic loading. A combination of qualitative and quantitative analysis is performed to reveal the underlying mechanisms responsible for the mechanical behaviors of the hierarchical honeycombs under large deformations. The fabrication of the hierarchically structured cellular solids with features ranging from micrometer to centimeter is made possible by recent advances in additive manufacturing, which allows for fabricating complex topologies with fine features quickly, inexpensively and at a relatively large scale.

2. Materials and methods

2.1. Characterization of the hierarchical honeycombs

The hierarchical honeycomb topology described in this work is made by replacing the cell walls of regular honeycombs with triangular lattices (Fig. 1(a)–(d)). Two geometric parameters are defined to characterize the hierarchical honeycombs: the hierarchical length ratio $\gamma = l_t/l$ and the number of triangular lattices away from the central axis, N. We indicate by l and l_t the lengths of cell walls of the regular honeycomb and the triangular lattice, respectively. The length and thickness of the triangular lattices are determined by a mass equivalence between the regular honeycombs and the hierarchical honeycombs. As a result, the thickness and length of the triangular lattice can be calculated as:

$$\frac{t_t}{l_t} = \frac{1}{\sqrt{3}}\left(1 - \sqrt{1 - \frac{4\sqrt{3}}{3R\gamma^2}\left[\frac{t}{l} - \frac{1}{2\sqrt{3}}\left(\frac{t}{l}\right)^2\right]}\right) \tag{1}$$

where t and t_t are the cell wall thickness of the regular honeycomb and the triangular lattice, respectively. The parameter R stands for the number of triangular lattices, and it is determined by γ and N.

In view of the resolution of the 3D printer and the size of the compression platen, here we choose $\gamma = 1/5$, $N = 2$, and $l = 3$ cm and each sample consists of 2×3 representative volume elements. As a result, the dimensions of the prototypes are 180 mm × 157 mm (Fig. 1(e)–(f)). The relative density of the regular and hierarchical honeycombs can be controlled by tailoring the thickness of the cell wall.

2.2. Sample fabrication

All samples used in the study have been printed by using an Objet Connex260 multi-material 3D printer (Stratasys). VeroWhite (a glassy polymer) is the constitutive material used for the 3D printing, the mechanical properties of which are shown in Fig. S1. It should be pointed