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A nanolattice-plate hybrid structure to achieve a nearly linear relation between stiffness/strength and density

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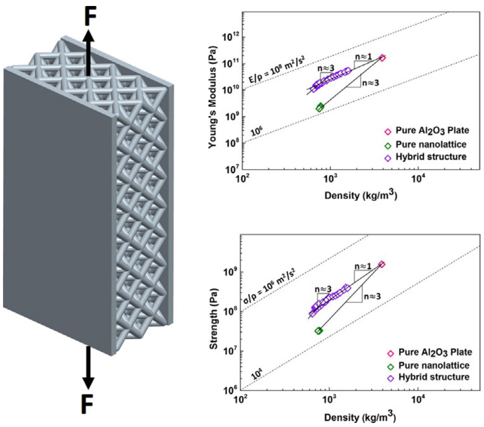
HIGHLIGHTS

- Hybrid structures consisting of a space-filling three-dimensional octet-truss alumina nanolattice and stretching-dominant plates are proposed in this study.
- The structures are found to exhibit a nearly linear scaling of stiffness and strength with density when the hybrid structures fail via intrinsic material failure mechanism.
- The stiffness, failure strength and failure mode of these hybrid structures can be tuned by changing their geometrical parameters.
- This structure thus provide a much larger design space in terms of stiffness, strength and density than that of pure nanolattice structures.

GRAPHICAL ABSTRACT



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ABSTRACT

A great deal of effort has been made on the design and fabrication of materials or structures that simultaneously possess ultra-high stiffness, ultra-high strength, and yet ultra-low density. Here, using finite element simulations, we design hybrid structures comprising a space-filling nanolattice and stretching-dominated plates and study how the stiffness, failure strength and failure mode of such hybrid structures depend on the geometrical parameters of the nanolattice. It is found that the stiffness, failure strength and failure mode of these hybrid structures can be tuned by changing the geometrical parameters. In particular, we show that a nearly linear scaling can be achieved between the stiffness/failure strength and the density if intrinsic material failure occurs. Hence, such hybrid structures are able to expand the design space of ultra-light and strong materials for wide structural applications.

1. Introduction

Design and fabrication of materials or structures that simultaneously possess ultra-high stiffness, ultra-high strength, and ultra-low density has attracted a great deal of attention due to their potential applications in acoustic insulation, vibration-damping, shock energy absorption,

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thermal insulation, and also weight reduction in transport, construction and aerospace structures [1–9]. Many monolithic materials that exhibit an ultra-high strength and stiffness are not suitable for many important applications due to their high density [10–13]. It is well-known that the mechanical response of a material is closely correlated with its internal architecture and density. In general, the strength and stiffness of materials decrease rapidly with decreasing their density.

Many natural materials with cellular structures, such as trabecular bone [14], plant parenchyma [15], and sponge [16], are found to simultaneously exhibit high stiffness, high strength and high toughness and yet low density. Inspired by these natural cellular structures, and made available by recent advances in fabrication of metamaterials with complicated geometries, various lightweight cellular materials have been designed and fabricated to achieve outstanding specific stiffness and strength (that is, high stiffness vs density ratio and high failure strength vs density ratio). Recently, a new class of metamaterials in the form of microlattices and nanolattices has been designed, fabricated and tested [17–19]. For example, Zheng et al. [20] fabricated microscale cellular materials and found that these materials are able to maintain a nearly constant stiffness per unit mass density even at an ultra-low density. Meza et al. [21] designed and created three-dimensional (3D) hierarchical nanolattices consisting of multiple self-similar unit cells spanning length scales over four orders of magnitude in fractal-like geometries, and showed that these nanolattices exhibit a unique combination of ultra-lightweight, deformation recoverability, and a near-linear scaling of stiffness and strength with density. Bauer et al. [22] created ultra-strong glassy carbon nanolattices with single strut length shorter than 1 μm and diameter as small as 200 nm, and found that their material strengths can be up to 3 GPa, and their strength-to-density ratio can be six times higher than those of previously reported microlattices [23,24]. Berger et al. [25] studied mechanical metamaterials with relatively simple cubic + octet foam geometry, and found that the resulting low-density metamaterials have many advantageous mechanical properties, arising from the ordered hierarchical structure. These studies have shown that structures with microlattice or nanolattice are of fascinating mechanical properties, and promising for many novel applications [26–31].

Previous studies have shown that the elastic stiffness and failure strength of a cellular material follow power laws with its density [32,33]. The power law exponents are closely related to the architecture and deformation mode of the materials. For pure stretching deformation, the exponent is 1; while for a pure bending deformation, the exponent is 3. In general, for a mixed mode, the exponent is in between 1 and 3 [34]. Hence how to design a cellular structure with stretching dominance is of great importance to achieve a metamaterial with high stiffness vs density and strength vs density ratios.

Here, we designed hybrid structures consisting of a space-filling octahedral truss alumina nanolattice and stretching-dominated solid plates. Using finite element (FE) analysis, we obtained the stiffness, failure strength and failure mode of these hybrid structures under uniaxial tensile loading. By comparing their stiffness and strength with those of pure alumina nanolattice and pure alumina solid plate, we found that these hybrid structures show interesting scaling relations between the stiffness/strength and density. In particular, we found that such a combination of space-filling nanolattice and stretching-dominated solid sheets is able to achieve a nearly linear scaling relation of material strength and stiffness with density if intrinsic material failure occurs.

2. Structure model, material model, boundary and loading conditions

Fig. 1 shows the CAD design of the hybrid structure (Fig. 1A) comprising a space-filling octahedral truss alumina (Al_2O_3) nanolattice sandwiched between two alumina plates, and the definitions of the geometrical parameters are also given. The unit cell (Fig. 1B) of the nanolattice consists of hollow tubes (Fig. 1C). We chose the octahedral truss nanolattice because of its high predicted fracture toughness [35]. In connecting the nanolattice to the plates, we have made a cut to the nanolattice at a distance of tube wall thickness t from the outmost boundary of the nanolattice to create cross sections (see the shaded areas in Fig. 1D). These shaded areas are then bonded to the surfaces of the plates to form the connections.

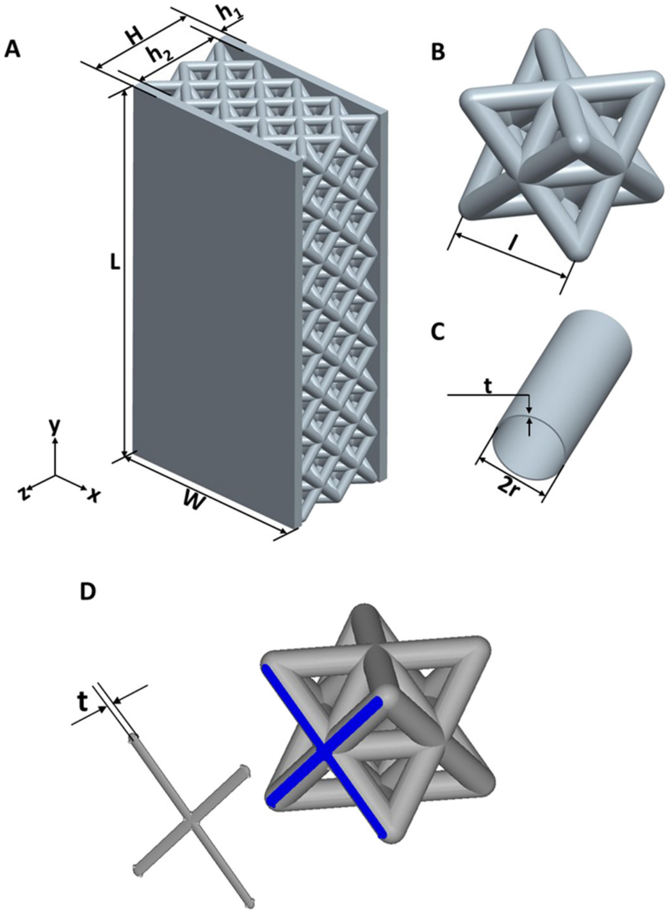

Fig. 1. (A) The CAD design and geometry of the hybrid structure comprising a space-filling octahedral truss alumina nanolattice sandwiched between two alumina plates. (B) The unit cell comprising hollow tubes and exhibiting a cubic symmetry with a nodal connectivity of 12. (C) The hollow tube. (D) Illustration of the connections between the nanolattice and the plate.

In the simulations, the length of the hybrid structure is kept at $L = 151.04$ μm, the width of the hybrid structure at $W = 75.52$ μm, the plate thickness at $h_1 = 1$ μm and the radius of the tube at $r = 491$ nm. The length of unit cell l is changed from 2.36 μm to 37.76 μm and the tube wall thickness t from 1 nm to 120 nm. As a result, the lattice structure thickness h_2 is changed from 4.72 μm to 37.76 μm, depending on the unit cell length and the number of cell layer n along the thickness of the hybrid structure. The thickness of the hybrid structure is $H = 2 \times h_1 + h_2$, which is changed from 6.72 μm to 39.76 μm, again depending on the unit cell length and the number of cell layer n along the thickness of the hybrid structure. During uniaxial tensile loading, the bottom surface of the hybrid structure is fixed along Y direction and the middle point of the bottom surface is fixed along X, Y, and Z directions, a loading velocity of $v = 500$ mm/s along Y direction is prescribed at the top surface of the structure (Fig. 1A), while other boundary surfaces are traction-free. Considering the physical instability arising from material failure and numerical efficiency, we adopted explicit dynamics procedure to model the quasi-static uniaxial tension loading. To do so, a velocity-controlled loading condition was applied to model these structures. To ensure a quasi-static response, the energy balance of the modeling system was constantly monitored such that the kinetic energy