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Shear response of carbon fiber composite octet-truss lattice structures

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ABSTRACT

Ultralight three dimensional space filling octet-truss lattice structures have been fabricated from carbon fiber reinforced polymer (CFRP) laminates using a mechanical snap-fitting and adhesive bonding technique. The lattice structures moduli and strengths have been measured during (001) in-plane shear as a function of the lattice relative density ($\bar{\rho}$). Their strength was determined by the activation of two strut failure modes: elastic buckling of the struts governed the response when $\bar{\rho} < 5\%$, while delamination failure controlled the strength for $16\% > \bar{\rho} > 5\%$. The measured shear strengths are shown to be well predicted by micromechanics models based on the elastic buckling and delamination failure of the struts. Snap-fit CFRP octet-truss lattice structures with densities of 24–230 kg m^{-3} are found to have mechanical properties superior to polymer and metal foams, and are competitive with Balsa wood and recently reported Ti–6Al–4V octet-truss lattices. They provide new opportunities for ultra-lightweight multi-axially loaded structures.

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1. Introduction

Cellular lattice structures have attracted considerable interest for the cores of lightweight sandwich panels [1–3]. In this approach, two thin face sheets made from materials with high specific stiffness and strength are widely separated by a low density lattice core [4–6]. The mechanical performance of a sandwich panel is governed by its geometry (face sheet thickness and core height) and by the mechanical properties of its faces and core with the latter governed by the core topology and properties of the materials used to make it. In addition to their significant bend resistance, some sandwich panel structures also provide substantial out of plane compressive strength [7–15], and have attracted interest for mitigating the effects of impulsively applied loads [16–21].

Lattice topology core structures with pyramidal and tetrahedral cell topologies [3] have been developed to promote truss deformation in a stretch dominated manner [22], whereupon the stiffness and strength scale linearly with relative density, $\bar{\rho}$, of the lattice structure (the density of the lattice structure divided by that of the material from which it was made) [4,5,23]. The use of high specific stiffness carbon fiber reinforced polymer (CFRP) laminates to make sandwich panel structures using single layer pyramidal lattice has been explored recently [11–14,24]. These studies indicate their mechanical properties are competitive with existing materials and topologies. However, as the thickness of a core is increased to improve the bending resistance of a sandwich panel, the distance of nodal connections between the core and the faces (which scale with depth for single unit cell thick cores) also increases [9,18,25,26]. This then increases the susceptibility of the panel to face sheet wrinkling [27,28] and nodal failure [28] during panel bending. Furthermore, as the relative density of such a lattice is decreased to enable more of the panel mass to be allocated to faces, the trusses become more slender resulting in failure by elastic buckling [29,30]. These considerations have led to an interest in the multilayer lattice structures whose cell size can be defined independently of the sandwich core thickness.

The octet-truss [31] lattice structure, Fig. 1 with face-centered cubic symmetry, provides a method for filling 3-D space with a structurally efficient truss structure of arbitrary cell size. The joint connectivity of the octet truss is 12, and the trusses of this spatially periodic material deform by local stretching for all macroscopic loading states [32]. The effective mechanical properties of the stretch-dominated octet-truss lattice have been analyzed using a micromechanics approach [32], and shown to have an almost isotropic yield surface. When made from high specific strength materials, the octet-truss lattice is a highly weight efficient, multiaxial stress supporting structure. Lightweight aluminum alloy structures have been made by an investment casting [32] and by additive manufacturing methods [33–35]. Wrought titanium alloy octet-truss lattices have also been recently fabricated [36] via a combined snap-fit and brazing approach, and offer potential for elevated temperature aerospace applications.

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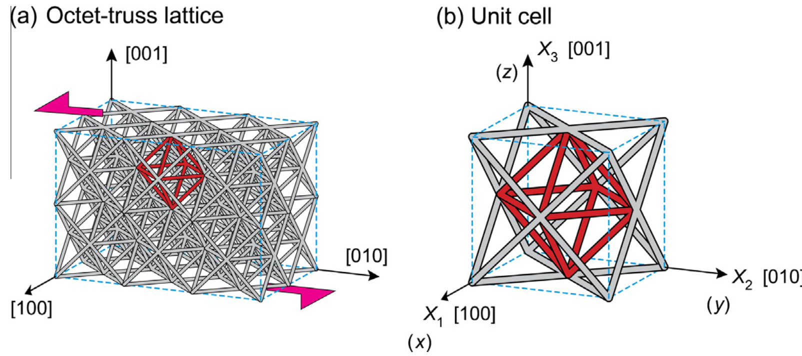

Fig. 1. (a) An octet-truss lattice constructed by the 3D translation of the unit cell shown in (b). The unit cell of the octet-truss lattice is composed of a (red) center octahedral unit and 8 (gray) edge tetrahedral cells. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Carbon fiber composites (CFRP) have a higher specific strength and stiffness than aluminum and titanium alloys, and are therefore a promising material for making stiff and potentially strong cellular structures for ambient temperature, lightweight applications. The application of a simple "snap-fit" assembly method [10] for fabricating and joining the pyramidal trusses and intermediate faces of an octet-truss cellular material made from CFRP laminates has been recent described [14]. The compressive responses of the octet-truss lattice in both its [001] and [100] directions were characterized as a function of the lattice relative density. However, sandwich panels are most widely used in situations where they are subjected to significant bending; a loading mode in which the shear response of the core governs the panel's mechanical response [1,2]. Here, the in-plane shear of snap-fit CFRP octet-truss lattices has been experimentally investigated as a function of the lattice relative density and their stiffness and strength compared to micromechanical predictions.

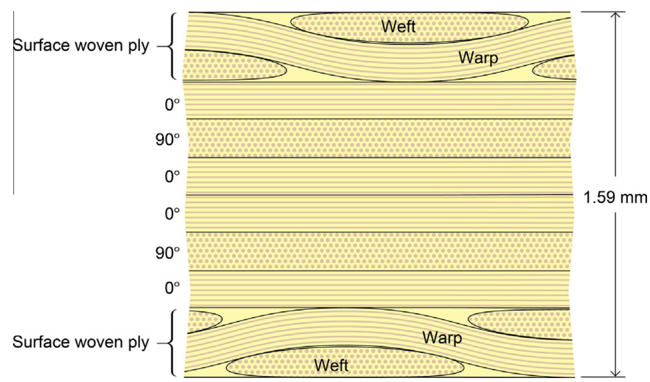

Fig. 2. Schematic illustration of the internal structure of the as-received CFRP laminate used to make the lattice. The laminate comprised 2 surface plies made from plain weave fabrics that sandwich 6 unidirectional plies of the same thickness arranged as a [0/90/0]s layup. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. CFRP lattice fabrication

2.1. Composite laminate materials

CFRP laminates with a 0/90 architecture were procured from McMaster-Carr and used to make the octet-truss lattice structures using a snap-fit method. The laminate sheets had a thickness $t = 1.59$ mm and had a 55% by volume carbon fibers. The carbon fibers have a Young's modulus of 228 GPa (33 Msi) and were dispersed in a vinyl ester matrix. The density of the laminate material was 1440 kg/m^3. The laminate was comprised of 8 plies: the 2 surface plies were made from plain weave fabrics while the 6 unidirectional interior plies of the same thickness were laid up in a [0/90/0]s arrangement, Fig. 2. The plain weave fabric layers contained fibers oriented along the two in-plane axes, and once cured could support flexural and tensile loads applied on multiple axes [20]. The woven laminates are also less sensitive to local damage compared with unidirectional laminates, and reduced the susceptibility to delamination during cutting operations [20]. Laminate sheets with woven plies on the outer surfaces were thus selected for the present study based upon this manufacturing constraint: the need to minimize the risk of delamination failures during fabrication and assembly of the lattice structures. Octet-truss lattices made from laminates with quasi-isotropic stacking sequence would be very interesting and a ripe area for future studies as it simplifies analysis of the laminate responses.

Experimental [11,12,15] and more fundamental studies [37–40] have shown that the compressive strengths of woven laminates are lower than unidirectional laminates due to fiber waviness. It is noted that the as-received laminate sheets contained two plain weave fabrics, four 0° unidirectional plies and two 90° unidirectional plies. Such a microstructure indicates that the as-received laminate sheets will be orthotropic rather than the transversely isotropic material often encountered in the simpler 0/90 balanced laminates.

The composite laminate materials were tested in uniaxial compression along the two unidirectional fiber directions in order to determine the longitudinal and transverse compressive and tensile moduli and strengths of the parent material used to manufacture the octet-truss lattices. A nominal applied strain rate of 10^{-4} s^{-1} was employed in these tests. Unclamped compression tests were conducted with stocky (to prevent elastic buckling) dog-bone shaped laminate specimens [14] compressed between two flat, parallel and rigid platens with no end clamping. Celanese compression (CLC) tests were also conducted in which the longitudinal splitting and delamination can be suppressed. The mechanical properties of the as-received CFRP laminate along both the longitudinal and transverse directions are summarized in Table 1. The laminate exhibited a substantial amount scattering in compressive strength; this well-known phenomenon [41] has been attributed to the complex distribution of damage zones (induced by internal flaws or stress concentrations) which create instabilities that prematurely trigger kink band formation.

The laminate compressive strengths differ in different loading conditions due to different failure mechanisms: in CLC compression, failure was controlled by plastic fiber micro-buckling, whereas the failure was dominated by delamination in unclamped compression, as observed optically (Fig. 3(a) and (b)) and confirmed by μ-XCT analysis (Fig. 3(c) and (d)). The damage modes

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