International Journal of Solids and Structures 132–133 (2018) 171–187

Contents lists available at ScienceDirect

International Journal of Solids and Structures

journal homepage: www.elsevier.com/locate/ijsolstr

Mechanical properties and failure mechanisms of sandwich panels with ultra-lightweight three-dimensional hierarchical lattice cores

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ARTICLE INFO

Article history:
Received 2 April 2017
Revised 30 August 2017
Available online 21 September 2017

Keywords:
Lattice core
Hierarchical structure
Sandwich panel
Mechanical properties
Failure mechanism map

ABSTRACT

Mechanical properties and failure mechanisms of sandwich panels with “corrugated-pyramidal” hierarchical lattice cores were investigated through analytical modeling and detailed numerical simulations. This included studying the behavior of hierarchical lattice core material under compression and shearing, as well as investigating the mechanical performance of sandwich panels subjected to in-plane compression and three-point bending. Failure maps were constructed for the hierarchical lattice cores, as well as sandwich panels with hierarchical lattice cores by deriving analytical closed-form expressions for strength for all possible failure modes under each loading. 3D printed samples were manufactured and tested under out-of-plane compression in order to provide limited experimental validation of the study. Our study provides insights into the role of structural hierarchy in tuning the mechanical behavior of sandwich structures, and new opportunities for designing ultra-lightweight lattice cores with optimal performance.

1. Introduction

Unique mechanical properties, as well as multifunctional advantages offered by lattice materials with open-cell configurations make them an attractive choice for designing and constructing lightweight multifunctional structures (Roper, 2011; Barnett et al., 2001; Evans, 2001; Ashby, 2001; Wei et al., 2016; Zok et al., 2016). In this context, numerical simulations and theoretical studies have been previously employed to investigate the effects of geometry, mass density, and structural defects on mechanical properties (Ajdari et al., 2008) and deformation (Liao et al., 2014; Wang et al., 2013) of two-dimensional periodic lattice materials. The effects of temperature on the mechanical properties of composite sandwich structures also have been studied through experiments (Liu et al., 2014, 2015). Currently, various types of three-dimensional periodic truss sandwich structures with high specific strength and high specific stiffness have emerged and their superior mechanical properties have been broadly recognized (Vaziri and Xue, 2007; Ajdari et al., 2011; Lim and Kang, 2006; Liu et al., 2007; Dong et al., 2015; Schaedler et al., 2011). Introducing hierarchy in the structural organization of lattice materials can potentially improve their mechanical and multifunctional properties (Han et al., 2015; Xiong et al., 2015; Mousanezhad et al., 2015, 2016). Lakes (1993) is amongst the pioneers in investigating the role of structural hierarchy in the mechanical properties of natural and man-made materials. Taking wood (Deshpande et al., 2006) and bone (Weaver et al., 2007) as examples of biological materials with hierarchical architecture, their internal microstructure is composed of tiny truss-like elements contributing to their enhanced energy absorption and anti-vibration characteristics. Even at nanoscales, it has been shown that carbon nanotube ropes with hierarchical helical structures exhibit superior properties such as larger failure strain, easily tunable elastic properties, and higher energy storage ability compared to bundles of straight nanotubes (Zhao et al., 2014). Therefore, integrating the concept of structural hierarchy with man-made lattice structures has a potential of improve their mechanical performance.

In this context, structural hierarchy has been recently integrated into honeycomb structures to broaden the achievable range of elastic and plastic responses (Ajdari et al., 2012; Mousanezhad et al., 2016; Haghpanah et al., 2013, 2014; Oftadeh et al., 2014a,b). The results show that honeycombs with 1st and 2nd orders of hierarchy are capable of attaining specific Young’s modulus as much as 2 and 3.5 times that of a regular honeycomb with the same mass (Ajdari et al., 2012), and can further be increased at higher levels of hierarchy (Oftadeh et al., 2014a,b). Recently, structural hierarchy has been shown to induce the unusual “auxetic” property (i.e.,

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https://doi.org/10.1016/j.ijsolstr.2017.09.024
0020-7683/

negative Poisson's ratio) in honeycombs (Mousanezhad et al., 2015), and enhance the phononic properties of these materials (Mousanezhad et al., 2016).

In another set of studies, analytical, numerical, and experimental investigations are carried out to study the mechanical performance of hierarchical corrugated composite sandwich cores under out-of-plane compressive and in-plane shearing loads (Kazemahvazi et al., 2009; Kazemahvazi and Dan, 2009). Again, structural hierarchy has been shown to increase the effective compressive strength up to seven times greater than those of non-hierarchical structures with the same mass at small relative densities. Although introducing hierarchy increases manufacturing complexity (compared with 1st order lattice structures), it is also shown to have significant potential in improving the structural performance of cellular materials (Ajdari et al., 2012; Kazemahvazi et al., 2009; Oftadeh et al., 2014a,b).

Under dynamic loading, hierarchical periodic truss sandwich structures exhibit enhanced anti-crushing behavior and higher specific energy absorption (Zhang et al., 2013; Fan et al., 2014; Qiao and Chen, 2016; Sun et al., 2016a,b). Yang et al. (2016) introduce a novel hybrid foam-core/solid-shell structure that inherits the advantages of their constituent components (i.e., conventional foam and solid-shell structure), in both strength and deformation, and can obtain high energy absorption capability. Inspired by a luffa sponge hierarchical bio-cellular topology, An and Fan (2016) propose a hierarchical aluminum foam cylinder, reinforced by stiff thin-walled carbon fiber reinforced plastic (CFRP) tubes, and show that the interaction between the CFRP tubes and aluminum foam results in an increase in the specific energy absorption of the hierarchical cylinder.

According to the literature (summarized above), studies on the mechanical properties of hierarchical lattice core constructions have been limited to out-of-plane compression and shear loading, and analytical modeling of these structures under lateral compressive and three-point bending loads has not yet been explored. Here, we investigate the mechanical performance of the "corrugated-pyramidal" lattice truss structures under out-of-plane and transverse compression, shear, and three-point bending. To this end, we first introduce the geometry of these hierarchical structures which are based on pyramidal lattice structures introduced earlier by Wu et al. (2016). Based on the recently established terminology and taxonomy for periodic truss structures (Zok et al., 2016), our geometry is classified as "compound cubic truss". Next, we derive closed-form expressions for the structural strength associated with different possible failure modes, and construct failure maps for sandwich panels with hierarchical lattice core construction. The effects of structural hierarchy are highlighted by comparing the results with those of non-hierarchical counterparts (of same mass).

2. Geometry of hierarchical lattice core

The original non-hierarchical structure is composed of the 1st order "corrugated-pyramidal" truss core sandwiched between the 1st order face sheets, while the 2nd order structure is achieved by replacing each 1st order truss element with the 2nd order face sheets and a 2nd order corrugated pyramidal truss core, Fig. 1. Here, for the sake of brevity, the 1st and 2nd order lattice cores are referred to as core I and II, respectively. Fig. 1 shows a schematic diagram of geometrical characteristics of the unit cells of the original and 2nd order structures, where b and b_f are the width of the 1st and 2nd order face sheets, and t_f and t_c are face sheet and strut thickness of the 2nd order structure in core II, respectively. In addition, l and l_c are the strut length of core I and core II, respectively, and ω and ω_c are the angles which core I and II struts make with their corresponding face sheets, respectively. Finally, α, and β are the angles which core I makes with axis 1 and axis 2. The relative density, ρ, defined as the ratio of the density of the "corrugated-pyramidal" core ρ_c to that of the parent carbon fiber composite, ρ_{cf}, is calculated by

$$\bar{\rho} = \frac{2A_a\left(2t_f\cos\omega + t_c\right)}{l^2 l_c \cos^3\omega \sin^2\omega}, \tag{1}$$

where $A_a = b_f(l_c \sin\omega_c + t_f)$ denotes the cross-sectional area of the 1st order lattice core.

3. Out-of-plane compression of lattice core

3.1. Stiffness

With reference to the method presented by Chen et al. (2012), the equivalent out-of-plane compressive stiffness of the "corrugated-pyramidal" 2nd order lattice truss, normalized by the Young's modulus of the parent material, is (see Appendix for details)

$$\frac{\bar{E}}{E} = \frac{2\xi_\omega A_{\mathrm{I}} \sin^2\omega}{l^2\cos^2\omega}, \tag{2}$$

where ξ_ω is a non-dimensional parameter, and its corresponding expression is

$$\xi_\omega = \sin\omega + \frac{12(EI)_{\mathrm{I}}\cos^2\omega}{(EA)_{\mathrm{I}} l^2 \sin\omega}. \tag{3}$$

In Eq. (3), $(EA)_{\mathrm{I}}$ and $(EI)_{\mathrm{I}}$ are equivalent compressive stiffness and flexural rigidity of core I, respectively, which can be obtained using the following equations.

$$(EA)_{\mathrm{I}} = 2Eb_f t_f + Eb_f \frac{t_c^3}{l_c^2}\sin^2\omega_c\cos\omega_c + Eb_f t_c \cos^3\omega_c, \tag{4}$$

$$(EI)_{\mathrm{I}} = \frac{1}{6}Eb_f t_f^3 + \frac{1}{2}\left(l_c\sin\omega_c + t_f\right)^2 Eb_f t_f + \frac{1}{4}\sin^2\omega_c\cos^3\omega_c l_c^2 Eb_f t_c + \frac{1}{12}\mathrm{f}(\omega_c)Eb_f t_c^3, \tag{5}$$

where $\mathrm{f}(\omega_c) = \cos\omega_c + 3\sin^2\omega_c\cos\omega_c - 3\sin^2\omega_c\cos^3\omega_c$.

To validate these analytical expressions, finite element (FE) based numerical simulations were conducted using commercial software ABAQUS 6.13-2 (SIMULIA, Providence, RI). Six different types of structures with various relative densities and geometrical characteristics were considered for numerical simulations, Table 1. The parent material was assumed to be a carbon fiber-reinforced composite with effective compressive stiffness and strength of 100 GPa and 850 MPa, and Poisson's ratio of 0.3.

We performed FE analysis for the lattice core unit cell, shown in Fig. 1. In the simulations, rigid face sheets were tied to the lattice core structure at the interface nodes. While the bottom face sheet was fixed, a compressive displacement was then applied to the top face sheet to simulate core crushing. The models were meshed using three-dimensional 8-node linear brick elements with reduced integration (i.e., C3D8R element in ABAQUS), and a mesh sensitivity analysis was performed to guarantee that the results were not mesh-dependent. Static-general solver of ABAQUS was used to simulate the response of structures under compressive loads.

Fig. 2 plots the normalized equivalent out-of-plane compressive stiffness of the 1st and 2nd order lattice trusses as a function of the relative density. The dashed and solid lines show the analytical expression presented by Eq. (2), respectively, while the markers denote the FE results for the 1st and 2nd order structures. An excellent agreement is observed between the analytical and FE results. The results presented in Fig. 2 shows that the equivalent out-of-plane compressive stiffness of the "corrugated-pyramidal"