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Interlocked hierarchical lattice materials reinforced by woven textile sandwich composites

Hualin Fan [a,b,*], Fangfang Sun [a], Lin Yang [a], Fengnian Jin [b], Dajuan Zhao [c]

[a] College of Mechanics and Materials, Hohai University, Nanjing 210098, China
[b] State Key Laboratory for Disaster Prevention & Mitigation of Explosion & Impact, PLA University of Science & Technology, Nanjing 210007, China
[c] Nanjing Fiberglass Research & Design Institute, Nanjing 210012, China

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ABSTRACT

Hierarchical structures are predicted to have ultra-light weight and superior mechanical properties, including excellent weight efficiency and anti-buckling capability. Adopting interlocking method, a new hierarchical lattice truss material reinforced by woven textile sandwich composite was designed, manufactured and tested. With sandwich walls, the hierarchical lattice material is ultra-light and renders high weight efficiency. A plastic model was suggested based on tested failure maps to reveal the plastic deformation of the hierarchical material. Mass efficiency and specific energy absorption of the hierarchical lattice truss material were analyzed and compared with typical metallic lattice truss materials. The glass fiber reinforced hierarchical lattice truss material has been proved to be a potential light weight-efficient structure.

1. Introduction

Deformation and strength of lightweight structures usually depend on the performance of their cell walls. Hierarchical structure [1,2] constructed by hollow struts or sandwich walls, is an efficient way to enhance the weight efficiency [3], the mechanical property [1,2,4–6] and the energy absorption [7,8] of light-weight porous materials. Hierarchy into structures has been credited with improving elastic properties and damage tolerance [9]. Due to the enlarged bending stiffness of the sandwich wall, strength and energy absorption of the hierarchical structure can be greatly enhanced. Bhat et al. [1] manufactured hierarchical honeycomb sandwich panels having a compressive strength about six times greater than the equal mass honeycomb sandwich panel. Lakes [2] constructed hierarchical honeycomb whose plastic strength was a factor of 3.8 times stronger than the ordinary one of the same density. Kooistra and Côté et al. [4,5] made hierarchical core sandwich panels. We have also published papers on hierarchical honeycombs [7,8], which have priority in the energy absorption. With hierarchical structure, Schaedler et al. [10] even made an ultra-light microlattice having a rather small relative density of 0.0001. Yin et al. [11] reported a stretch–bend-hybrid hierarchical composite pyramidal lattice structure. Chen and Pugno [12] discussed in-plane elastic properties of hierarchical nano-honeycombs. Yi and Chen [13] analyzed the impact response of sandwich beams with hierarchical cellular cores.

This work presents a preliminary experimental study on the mechanical behavior of an interlocked hierarchical lattice truss material.

2. Hierarchical structures and manufactures

2.1. Hierarchical structures

In this paper, two-order hierarchical lattice truss (HLT) materials were designed and made. The structure of the HLT is shown in Figs. 1 and 2. The 1st order structure is a square lattice truss (LT) panel with a thickens, H. Distance between neighboring ribs is $L/2$. The thickness of the rib is t. Ribs of the lattice are made of integrated woven lattice sandwich panels, the 2nd order structure. Glass fiber reinforced plastic (GFRP) integrated woven lattice sandwich composites (IWLSCs) composed of woven skins and 8-shape piles in the core are lightweight structures with high debonding resistance [14–16]. Compression strength of the skin of the woven sandwich varies from 10.5 MPa to 34.2 MPa. The equivalent strength of the woven sandwich is smaller than 5 MPa, rather smaller than the carbon fiber reinforced laminate adopted by Kazemahvazi et al. [6].

Hierarchical structure will make the lattice structure further lighter. The relative density of the HLT is determined by the product of

* Corresponding author.
E-mail address: fhl02@mails.tsinghua.edu.cn (H. Fan).

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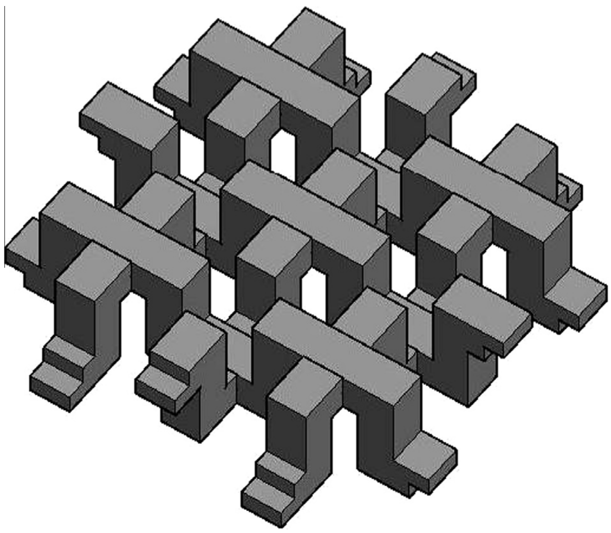

Fig. 1. Structure of the hierarchical lattice truss material.

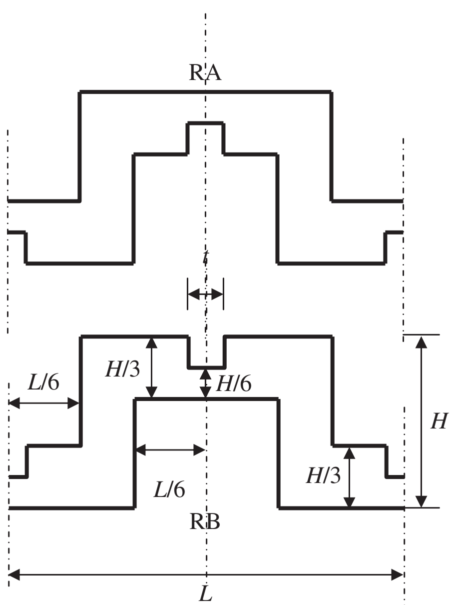

Fig. 2. Interlocked ribs of the hierarchical lattice truss material.

$$\rho^* = \rho_1^* \rho_2^*, \tag{1}$$

where

$$\rho_1^* = \rho_{1r}^* \rho_{1l}^* = \frac{20}{9}\frac{t}{L}\left(1 - \frac{3}{5}\frac{t}{L}\right), \tag{2}$$

with

$$\rho_{1r}^* = \frac{5}{9} - \frac{t}{3L}, \tag{3}$$

and

$$\rho_{1l}^* = \frac{4t}{L}, \tag{4}$$

where ρ^*, ρ_1^* and ρ_2^* denote the relative density of the HLT, the LT and the IWLSC, respectively.

Structural model of the HLT is shown in Fig. 3(a). The equivalent strength, σ_{eff}, and equivalent stiffness, E_{eff}, of the HLT are given by

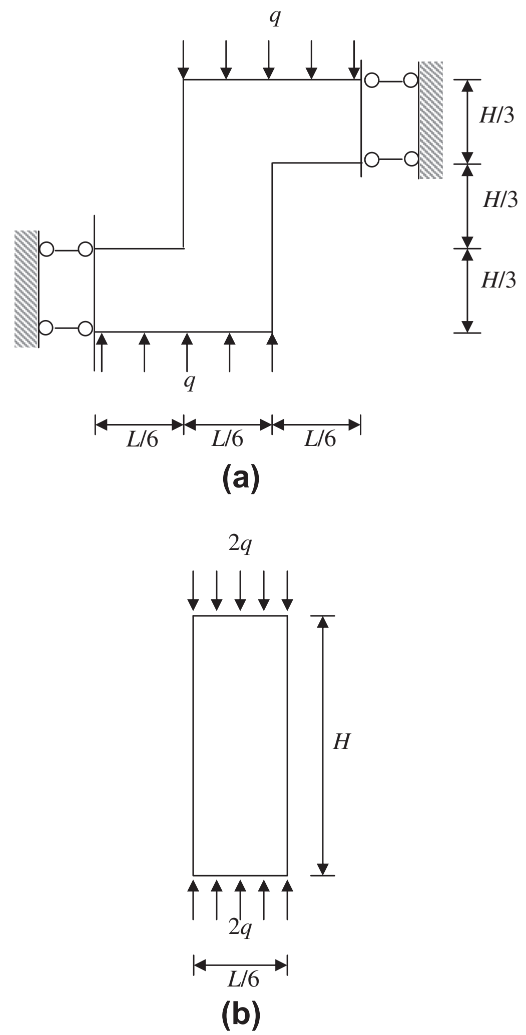

Fig. 3. (a) Structural model of the rib and (b) the corresponding simplified model.

$$\frac{E_{eff}}{E_{rib}} = \rho_{1l}^* = 4\frac{t}{L}, \tag{5}$$

and

$$\frac{\sigma_{eff}}{\sigma_{rib}} = \rho_{1l}^* = 4\frac{t}{L}, \tag{6}$$

where σ_{rib} and E_{rib} denote the strength and stiffness of the slotted ribs, respectively. A simplified model was suggested to consider the influence of the slots, as shown in Fig. 3(b), where the load was assumed to be loaded on the central vertical pile. Properties of slotted ribs are estimated by reduction coefficient γ_1 defined as

$$\frac{E_{rib}}{E_s} = \gamma_1 \tag{7}$$

for the stiffness and reduction coefficient γ_2 defined as

$$\frac{\sigma_{rib}}{\sigma_s} = \gamma_2 \tag{8}$$

for the strength of the slotted ribs, respectively, where σ_s and E_s denote the strength and stiffness of the intact IWLSC panel, respectively. Suggested by the simplified model in Fig. 3(b), the reduction coefficients are given by

$$\gamma_1 = \gamma_2 = 1/3. \tag{9}$$

The simplified prediction is consistent with the simulation of the finite element method (FEM), as suggested by Fig. 4(a). In simulation,