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Compressive efficiency of stretch–stretch-hybrid hierarchical composite lattice cores

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ABSTRACT

Composite lattice cores featuring structural hierarchy were developed to achieve greater buckling resistance. The stretch–stretch-hybrid hierarchical lattice cores were fabricated with a two-step approach by assembling composite pyramidal lattice (CPL) sandwiches into macroscopic truss configurations. Analysis and experiments were performed to determine the out-of-plane compressive strength. Hierarchical CPL cores were evaluated based on their failure mechanism maps, and the structural efficiency was affected by the ratio of strut length at different scales (e.g. L/l_1). With the specific limited L/l_1, the optimized hierarchical CPL core was almost 5 times stronger than lower-order CPL cores with rectangular trusses (at relative density 0.01). The fully optimized hierarchical CPL cores can be as efficient as optimized CPL cores with hollow trusses. Effects of topologies at two different length scales on the performance of hierarchical structures were also assessed.

1. Introduction

Lattice materials are widely regarded as efficient, stretch-dominated structures well-suited for multifunctional applications, and can be produced from metals, polymers, or composites [1–3]. Metallic lattice structures have been produced with a variety of topologies such as tetrahedral [4], pyramidal [5] and Kagome [6]. Composite lattices can also be produced in various configurations, and exhibit specific properties superior to their metallic counterparts, allowing designers to fill gaps in the material property space. Because of the intrinsic hierarchical nature of composites on small length scales (10–20 μm) [7], composite lattices are assumed as hierarchical structures that can be analyzed from the materials level up to the structural level [8]. In weight-sensitive designs, ultralightweight composite lattices are susceptible to buckling, which can limit their eligibility for certain applications.

Through design of the truss members, several composite truss structures have been explored, including a hollow composite pyramidal lattice (CPL) core [9], a hybrid truss CPL concept [10] and CPL cores with foam sandwich struts [11]. To produce hollow CPL cores, a thermal expansion molding technique was developed [9]. In that work, the out-of-plane compressive strength of a hollow CPL core was reportedly twice that of solid truss counterparts at ultra-low densities, where Euler buckling controls failure . The specific strength of the hollow CPL can surpass that of hollow metallic microlattices, reportedly the world's lightest structures [12].

Structural hierarchy is generally observed in natural materials (e.g., wood and bone [13,14]) and often employed in engineering structures to increase buckling strength. For engineering cellular materials, several hierarchical structures have also been developed, including a self-similar hierarchical corrugated sandwich core [15], a corrugated sandwich core with foam sandwich struts [16], and a hierarchical honeycomb core [17]. The self-similar hierarchical corrugated core is reportedly 10 times stronger than that of the lower-order corrugated core of equivalent relative density [15]. However, it is generally difficult and costly to fabricate hierarchical structures directly, especially with periodic cellular materials, due to the different length scales that must be controlled and assembled simultaneously.

The scope of the present study is to increase the buckling resistance and the specific compressive strength of traditional lattice structures by employing structural hierarchy. Extended hierarchical constructions based on carbon fiber reinforced composite lattice cores are developed using a two-step fabrication approach. Specially, a protocol is outlined to evaluate efficiencies of these complex structures based on the flowchart presented in Fig. 1. By following the protocol, both analysis and experiments are carried out, and the newly developed structures are compared with competing constructions. Effects of topology or shape variation at

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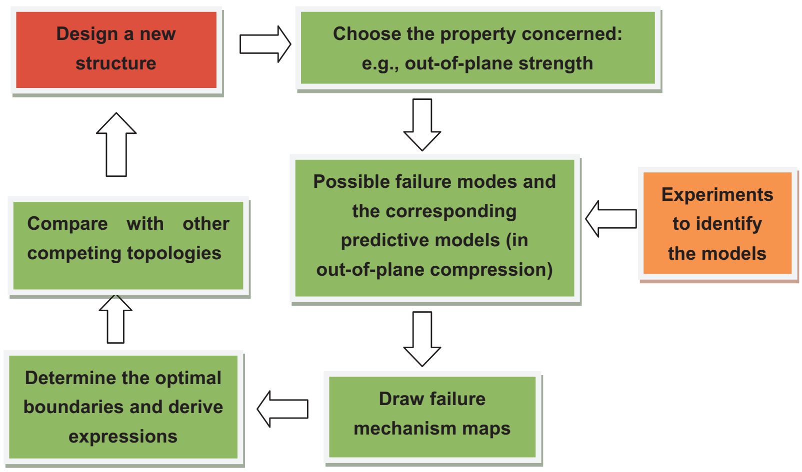

Fig. 1. A protocol guiding structural design.

different length scales on the structural performance are also assessed and discussed.

2. Illustration and analysis of a hierarchical CPL core construction

A schematic illustrating the procedure used to build hierarchical periodic structures is shown in Fig. 2a. A hierarchical pyramidal lattice core was assembled from hollow CPL sandwiches. Ignoring the hierarchy of the parent materials (fiber composites), the hierarchical structures developed here can be considered to be of order 2. The macroscopic core is a pyramidal lattice core with rectangular struts, while the individual rectangular struts are mesoscopic sandwich beams with hollow CPL truss cores. The relative density $\bar{\rho}'$ of the hierarchical CPL core, can be expressed as

$$\bar{\rho}' = \frac{2(2Lwt_f + \bar{\rho}_h Lwl_1 \sin\omega)}{L\sin\omega'[L\cos\omega' + w + (2t_f + l_1\sin\omega)/\sin\omega']^2} \tag{1}$$

where geometrical dimensions of the sandwich strut L, w, t_f, ω' and those of lattice strut of the hollow CPL core l_1, d_o, d_i, ω are defined in Fig. 2a, and $\bar{\rho}_h$ represents the relative density of the hollow CPL cores in the sandwich strut. Note that in this expression, the

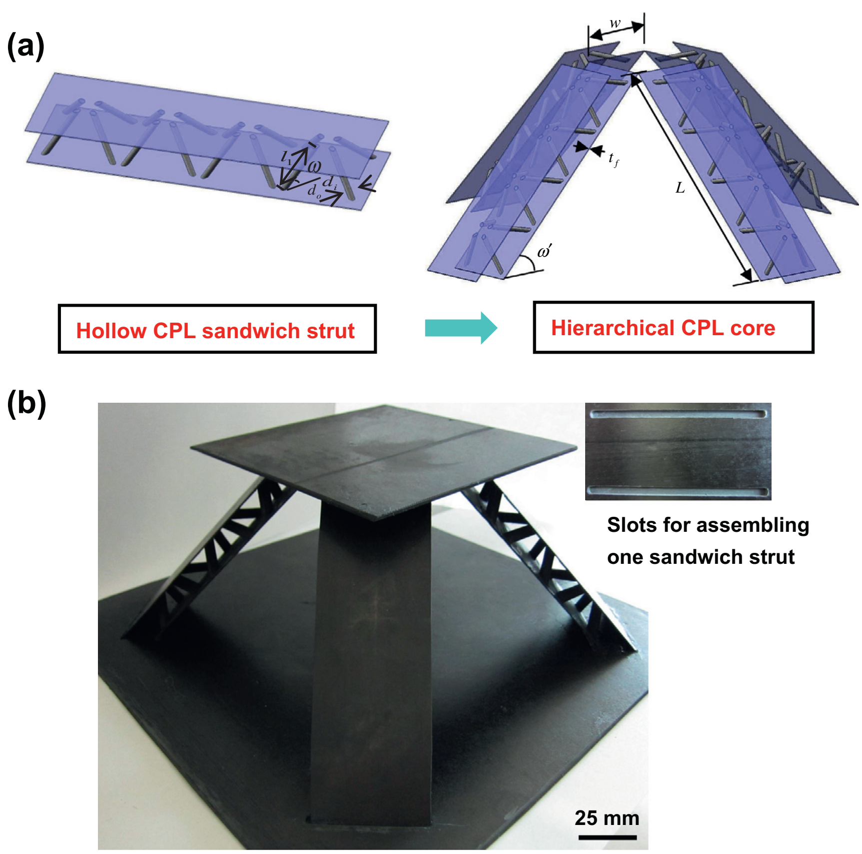

Fig. 2. (a) Illustration for building hierarchical periodic structures: from composite pyramidal lattice (CPL) core sandwich to hierarchical CPL core and (b) prototypical hierarchical CPL core sandwich structure.