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Hybrid carbon fiber composite lattice truss structures

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ABSTRACT

Carbon fiber reinforced polymer (CFRP) composite sandwich panels with hybrid foam filled CFRP pyramidal lattice cores have been assembled from linear carbon fiber braids and Divinycell H250 polymer foam trapezoids. These have been stitched to 3D woven carbon fiber face sheets and infused with an epoxy resin using a vacuum assisted resin transfer molding process. Sandwich panels with carbon fiber composite truss volumes of 1.5–17.5% of the core volume have been fabricated, and the through-thickness compressive strength and modulus measured, and compared with micromechanical models that establish the relationships between the mechanical properties of the core, its topology and the mechanical properties of the truss and foam. The through thickness modulus and strength of the hybrid cores is found to increase with increasing truss core volume fraction. However, the lattice strength saturates at high CFRP truss volume fraction as the proportion of the truss material contained in the nodes increases. The use of linear carbon fiber braids is shown to facilitate the simpler fabrication of hybrid CFRP structures compared to previously described approaches. Their specific strength, moduli and energy absorption is found to be comparable to those made by alternative approaches.

1. Introduction

Ultra-light sandwich panel structures with high structural efficiency and impact energy absorption capacity are attracting significant research interest [1]. These structures utilize light, stiff, and strong face sheets [2], and stiff, and strong but compressible cellular cores made of metallic foams [3,4], honeycombs [5] including those fabricated from polymers such as Nomex [6], and lattice trusses from light metals such as aluminum [7–10] and titanium alloys [11,12]. The stiffness and strength of sandwich structures scale with the properties of the materials used to make them, the topology and density of the core [13] and the allocation of mass between the faces and the core. There is substantial interest in using lighter, stiffer and stronger materials to fabricate sandwich structures.

Sandwich panel structures fabricated from carbon fiber reinforced polymer (CFRP) have attracted substantial recent interest [14–18]. The lattice variants of such structures can be made by using hot press molding of pre-preg materials [14,15], or a snap fit method [17,18] while a slotting and adhesive bonding approach is used for honeycombs [16]. Under compression, these CFRP structures typically fail catastrophically, exhibiting little ability to support load after the initial strut failure. Furthermore, since the trusses are brittle, they absorb little energy during impacts, an area of application where polymer and metal foams perform very well [19,20].

Recently, a hybrid braided carbon truss/polymer foam core approach for fabricating CFRP pyramidal lattice structures has been explored [21]. In this approach, a braided carbon fiber net was combined with closed cell polymer foams to form a hybrid truss/foam core that was stitched to CFRP faces using Kevlar fiber to form a resin infused sandwich panel. The nodes of the braided net provided robust attachments to the faces of the panels, and no nodal failures were observed even under in-plane shear loading. The braided truss structure was resistant to delamination failure, and when combined with polymer foams, the hybrid core was shown to have to exhibit a robust mechanical response after truss failure, and high energy absorption efficiency [21]. However, the initially circular cross section trusses within hybrid cores made with weak (lowest density) foams were found to develop an elliptical cross-section due to compression of the polymer foam during autoclave consolidation, and this decreased the struts compressive strength (by decreasing the struts second moment of inertia and thus critical buckling strength). This effect could be avoided by the use of stronger, less compressible foams, but at the cost of increasing the density of the hybrid core. As the foam density was increased, the mechanical response of the trusses was substantially

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improved, but the hybrid became increasingly "foam-like". Since the CFRP truss has a higher specific strength than foams, a better balance of properties might be achieved by increasing the volume fraction of the core occupied by trusses, while using the lowest density foam whose compressive strength was sufficient to preserve the trusses cross sectional shape. However, the complexity of the braiding process used to make a carbon fiber net made it difficult to increase the truss volume fraction, and to therefore investigate the effect of changing the truss volume fraction on the properties of the hybrid core.

Here, we explore the use of a simpler linear carbon fiber braid approach to fabricate hybrid CFRP truss/foam core sandwich panels using a medium strength and density (Divinycell H250) foam, and investigate the effect of varying the CFRP truss volume fraction within the core. The truss relative density within the core unit cell could be easily changed by varying either the truss length *l*, or the diameter *d*, of the braid. It will be shown that the compressive strength and modulus of the hybrid cellular material increase with the CFRP truss volume fraction. However, the relationship between the hybrid core strength and the truss relative density eventually saturates at high core volume fraction because of the growing mass fraction of the CFRP allocated to the nodes. The energy absorbed per unit volume of this lower foam strength hybrid material is slightly less than that of the braided net structures of similar density where more of the core mass fraction was allocated to foam.

2. Panel design and fabrication

2.1. Hybrid design

The hybrid linear braid sandwich panel design is schematically illustrated in Fig. 1 and was similar to that fabricated using the braided net approach [21]. Briefly, linear carbon fiber braids of different diameters were fabricated from the same IM7 carbon fiber used in the braided net study. These were utilized along with a medium density closed cell PVC (Divinycell H250) polymer foam to form a hybrid CFRP/polymer foam structure. The linear braids formed the trusses within the core, and were stitched to 3-D woven face sheets using Kevlar thread. Divinycell foam has a density of 250 kg m^{-3} and a compressive strength of 6 MPa; sufficient to reduce truss flattening during the consolidation process and to support the trusses after their initial fracture during compressive testing. The trapezoidal cross section foam molds were created by milling the Divinycell foam. They contained semi-circular cross section, variable diameter grooves for placement of the trusses and control of the truss fiber volume fraction.

2.2. Core geometry

A unit cell of the most general pyramidal lattice with elliptical cross-section trusses, is shown in Fig. 2. The truss minor axis width (normal to the foam side surface) was defined as d_1 while its major axis length (parallel to the longitudinal axis of the mold) was d_2. The ellipticity ratio (d_1/d_2) was approximately 0.86 for all the samples. The angle of inclination of the trusses to the base of the unit cell, ω, determines the balance between out of plane compressive strength and in-plane shear resistance [22]. The structure investigated here used an angle of 45°. Preliminary trials indicated that simply folding a braid over the apex of a triangular foam mold led to dilation and ellipticity of the folded region, and resulted in low strength nodal failure of the braid during subsequent compression testing. This could be avoided by reducing the radius of curvature of the braid fold. The node at the truss/face sheet interface was therefore designed to have a width equal to twice the major axis diameter of the truss, and a length *b* that was set equal to 2 times the woven diameter of the braid *d* (see Table 1).

Four different linear braids were used to produce hybrid structures for this study. Their structure is illustrated, along with micrographs of the braids themselves, in Fig. 3a–d. The four braids were fabricated by 3Tex (Cary, North Carolina) using 8, 16, 32, or 64 tows of 12 k Hexcel IM7 carbon fiber, with a similar braiding angle of approximately 11°. The four linear braids have woven diameters of 2.7, 3.8, 5.2, and 7 mm, and repeat distances λ = 15, 25, 35, and 65 mm respectively. The linear braids had a fiber volume fraction of approximately 50%, and this volume fraction was maintained for all the experimental studies reported here. The geometry and properties of these linear braids are summarized in Table 1.

Linear braids with 8, 16, and 32 tows were used to prepare hybrid cores with truss relative densities of 1.5%, 2.7%, and 4% respectively with *l* fixed. The 64 tow braid was used to prepare cores with truss relative densities of 7%, 12.5%, and 17.5%, by changing the truss length *l*. The values of d_1 and d_2 for the oval truss were determined for each of the linear braids using X-ray computed tomography (X-CT) measurements of the completed,

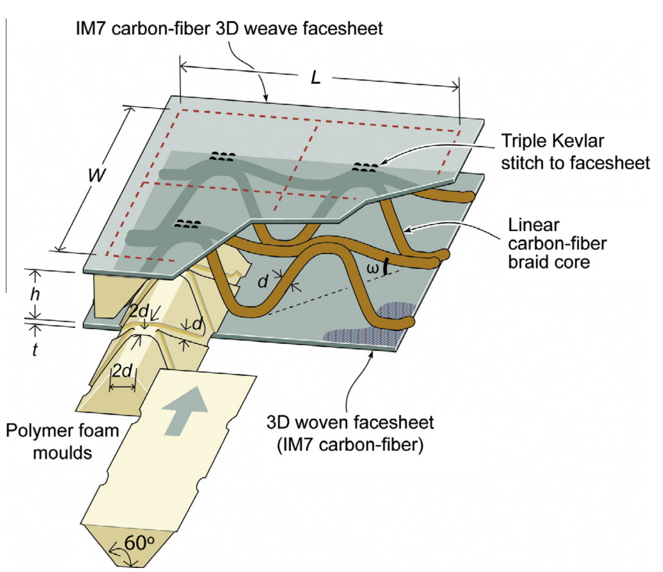

Fig. 1. Composite sandwich structure consisting of linear carbon fiber braids with polymer foam inserts configured as the core of a sandwich panel with 3D woven carbon fiber composite face sheets. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

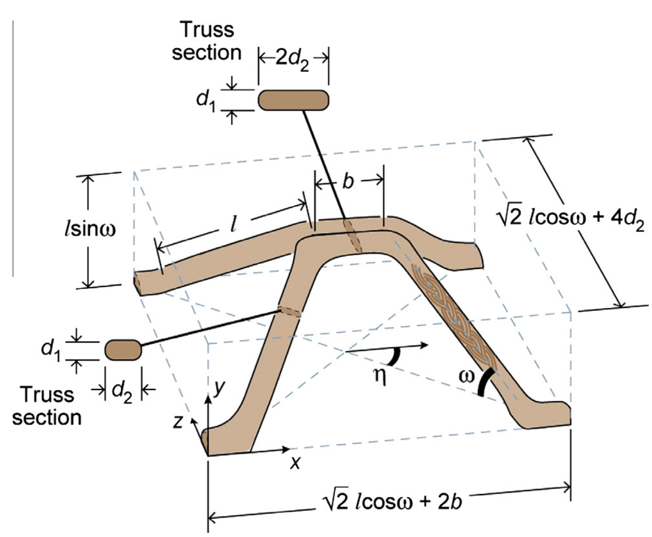

Fig. 2. Pyramidal CFRP unit cell with elliptical cross section trusses. Two linear braids are required to form each unit cell. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)