Mechanical properties and failure modes of carbon fiber composite pyramidal lattice structures

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Summary This paper presents a novel and efficient methods for high rate fabrication of low density carbon fiber sandwich panel cores based on laser beam cutting (LBC). The mechanical response of the truss cores to out-of-plane compression and shear were measured and the resulting failure modes were modeled analytically. Shear strength was improved by eliminating core-to-face-sheet bond failures. The investigated sandwich-panel cores appear to be promising candidates for low-weight systems and multifunctional applications.

Introduction

Fiber reinforced plastic (FRP) composite cellular structures provide a unique opportunity to develop lightweight multifunctional structural systems due to their unique structural and thermal properties. FRP cores with lattice truss topologies are competitive with closed cell structures (e.g. honeycombs) and are generally superior to stochastic foams. The effort to fabricate composite sandwich panels with low density lattice core construction has led to development of several manufacturing techniques including hot press molding [1, 2], electro-discharge machining [3], and water-jet cutting [4]. Two key challenges that limit the application of composite sandwich panels are the slow and costly processes associated with the current manufacturing techniques which cannot be used in large scale industry, and the low quality of the core to face sheet bonding, which is generally the 'weakest link' of the panels.

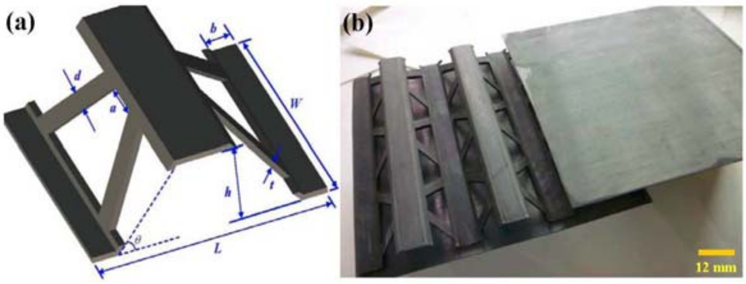

Fig. 1 (a) Sketch of the unit cell of pyramidal truss-like core. (b) Photograph of a carbon fiber composite oblique pyramidal truss-like core sandwich structure. The core relative density is 4.99%.

Fabrication method

Here, we introduce a novel and practical method to fabricate composite sandwich panels with lattice cores that effectively addresses both challenges discussed above. The method is based on perforating carbon fiber corrugated core with large, flat upper and lower bonding surfaces using a laser beam. This method results in composite sandwich panels with lattice cores with strut morphologies and with a high node-to-face sheet bond strength. A key advantage of this method is the high rate of cutting and manufacturing, which provides an economic way to manufacture all-composite sandwich panels. As an example, a pyramidal lattice core with 3×3 unit cell can be cut in 1/2 hour, compared to hot press molding method and electro-discharge machining, which require 4 hours and 8 hours, respectively, for manufacturing same-size specimens.

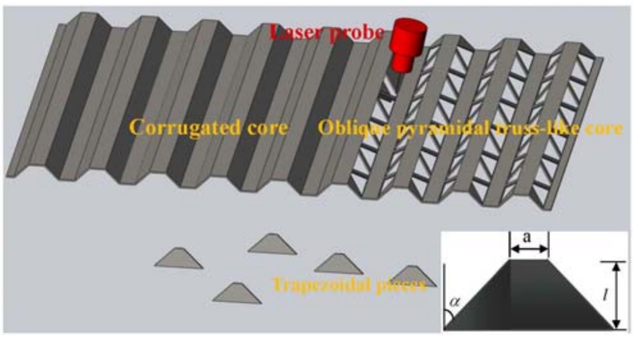

Fig. 2 Schematic of the manufacturing process of the pyramidal truss-like core using laser beam cutting method, the dimensions of removed pieces are also included in the figure.

Beam models for compressive and shear responses

The process results in a sandwich panel in which the sheet-to-core adhesive area is enlarged to improve the node-face sheet interface strength. The unit cells of each pyramidal truss cores have been shown in Fig. 1a and Fig. 2. The relative densities (i.e., volume fraction) of near-pyramidal, cut-from-corrugated truss core in oblique configurations, denoted by , are given by:

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$$\bar{\rho} = \frac{2tW[h/\sin\theta - l - t\tan(\theta/2)] + 4tbW + 4tdl/\cos\alpha}{WL(h+t)} \qquad (1)$$

where b, d, h, t and θ are geometrical parameters shown in Fig 1a and Fig 2.

Strut bending and axial deformation are evaluated in compressive and shear load conditions. Euler buckling (subscript E) and compressive crushing (subscript C) are the major strut failure modes.

$$E_z = 4E_s \sin\theta\cos^2\alpha \frac{dt}{WL}\frac{h+t}{l}[\sin\theta\cos\alpha + \frac{t^2\cos\alpha(1-\sin^2\theta\cos^2\alpha)}{l^2\sin\theta}] \qquad \text{Compressive stiffness (2)}$$

$$\sigma_{zE} = \frac{\pi^2}{3}\frac{t^2}{l\sin\theta(h+t)}E_z \qquad \sigma_{zC} = \frac{E_z}{E_s}\frac{l}{h+t}\frac{1}{\sin\theta\cos^2\alpha}\sigma_C \qquad \text{Compressive strength (3)}$$

$$G_x = 4E_s\cos\theta\cos^3\alpha\frac{dt}{WL}\frac{h+t}{l}[\cos\theta + \frac{t^2(1-\cos^2\alpha\cos^2\theta)}{l^2\cos\theta} + \frac{d^2}{l^2\cos\theta}] \qquad \text{Shear stiffness (4)}$$

$$\tau_{xE} = \frac{\pi^2}{3\cos\theta}\frac{t^2}{l(h+t)}G_x \qquad \tau_{xC} = \frac{G_x}{E_s}\frac{1}{\cos\theta\cos^2\alpha}\frac{l}{h+t}\sigma_c \qquad \text{Shear strength (5)}$$

Experiments and results

The compressive and shear properties of pyramidal truss-like structures were strongly dependent on material properties and dimensions. We carried out uniaxial compression and shear tests using a screw-driven testing machine (INSTRON 5569) following ASTM C365 and C273.

In all compressive loading, the adhesive core-to-sheet bond is in compression (except perhaps in bonds close to the panel edges), and therefore is not expected to fail. Indeed, no bond failures were observed. Carbon fiber composite pyramidal truss cores made by the hot press method and by the snap-assembly method suffer from core-to-sheet bond failure under out-of-plane compressive and shear loading. These failures are initiated at defects or in the small face sheet-to-truss core bonding area under shear loading. The fabrication method described above yields carbon fiber composite sandwich panels in which the truss core - face sheet adhesion area has been increased, so as to transfer much greater forces from the face sheets to the truss cores. As shown in Fig. 3, compared with carbon fiber composite pyramidal truss cores fabricated by other methods, oblique struts structures can increase the upper limit of shear strength for the higher relative densities ($\bar{\rho} \geq 4.5\%$).

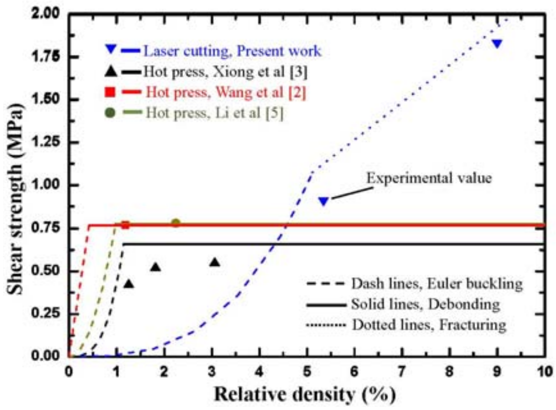

Fig. 3 Comparison of the Shear strength for different carbon fiber composite pyramidal truss cores made by other method subjected to shear loading. Here, we show the Euler buckling by dashed line, bonding failure by solid line and strut fracture by dotted lines. Wang et al [2] and Li et al [5] provided only one experimental data. In both cases the shear strength was governed by bonding failure.

Conclusion

We have demonstrated that laser cut cores can substantially increase the upper limit of shear strength for higher relative density pyramidal truss core. The present method can be used to fabricate carbon fiber composite pyramidal truss-like structures for lightweight and multifunctional applications.

Acknowledgment

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