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Compressive and shear characteristics of an octahedral stitched sandwich composite

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ABSTRACT

Octahedral composite sandwich panels were manufactured by integrating upper and lower skins with stitched core to overcome the weak interface between the core and skins of the sandwich structures. Quasi-static compression and shear tests were conducted to get stress–strain curves and to reveal the failure mechanisms of the structure. Dual peak stress was observed during the compression tests and each corresponding to the failure of a constituent layer. The compressive and shear strength was dominated by Euler buckling or fracture of the stitching yarns. To obtain a suitable baseline comparison, the mechanical properties were measured for aramid fiber reinforced honeycomb and aluminum honeycomb core panels. The octahedral stitched composite cores exhibited higher specific shear stiffness/strength and out-of-plane compressive strength than conventional sandwich cores, but showed lower compressive stiffness.

1. Introduction

Lightweight sandwich structures comprised of low-density cellular cores and solid face sheets are widely used in engineering applications. Among them, honeycomb, foam, truss core and corrugated core are the most widely used [1]. Lattice truss structures have been proposed as potential replacements for conventional foam core, because they provide comparable strength and stiffness levels. More importantly, they provide easy access to the core regions, which means that lattice cores can support additional functions, such as actuation and cooling. Many processes have been used to fabricate metallic lattice truss structures with a variety of topologies, such as pyramid, octet, and Kagome [2].

The mechanical properties of cellular structures depend on the intrinsic properties of the solids from which they are made (as well as the geometric arrangement of the components). Hence, stiffer, stronger materials are desirable for fabricating cellular structures with improved characteristics. Carbon fiber-reinforced composites, processing low density and high stiffness and strength, have been used to make truss cores for sandwich structures. Finnegan et al. [3] manufactured composite pyramidal truss core sandwich structures using a snap-fitted method. Fan et al. [4,5] reported a Kagome lattice composite composed of interlocked laminate ribs. Wang et al. [6,7] designed and manufactured composite columns reinforced foam core sandwich structures, whose vertical composite columns mechanically connect the top and bottom facesheets and are implanted in the foam core. Xiong et al. [8–11] introduced carbon fiber composite pyramidal truss cores fabricated by the molding hot-press method. Lee et al. [12] reported a new approach for fabricating truss cellular cores using pultruded unidirectional fiber-reinforced composite rods. Yin et al. [13] presented a hybrid truss construction concept that incorporates a second-phase core material into trusses of carbon fiber composite pyramidal lattice structures and fabricated carbon fiber–wood and carbon fiber–silicone rubber truss core structures. These research works have been very valuable in exploring further the lightweight sandwich structures. However, there is a problem of the relative low bonding strength and stiffness in the core–facings interfaces for the above mentioned truss core sandwich structures.

In order to overcome this shortcoming, the idea to add reinforcements in the transverse direction has been applied in the case of the sandwiches. Potluri et al. [14] highlighted that through-the-thickness properties are improved by stitching vertically. Moreover, Stanley and Adams [15] have compared the mechanical behavior of both vertical stitched and angled stitched sandwiches. Lascoup et al. [16,17] provides an improvement of the technology of through-the-thickness reinforcement of thermosetting composite sandwiches by the insertion of stitching yarns. They also studied the static and impact response of stitched

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sandwich composites. However, the stitching of sandwich structures received minimal attention, even if the mechanical improvement seems to be significant [18].

In this study, we designed and fabricated octahedral stitched composite sandwich structures. The upper and lower skins of the structures are integrated with the stitching yarns, thus preventing the weak interface between the core and skins. The compressive and shear responses of the stitched composite sandwich structures are investigated and compare its performance with other conventional lightweight structures.

2. Analytic solutions

In this section, the analytical models were presented for predicting the compressive and shear responses of the octahedral stitched core. Fig. 1 shows the configuration of the octahedral stitched structure.

2.1. Compressive characteristics of an octahedral stitched structure

Under out-of-plane compression, the four stitching yarns in a unit cell sustain identical force, as shown in Fig. 2(a). According to the symmetry of the microstructure, a force–displacement analysis can be conducted on a 1/2 unit cell, as shown in Fig. 2(b). In this study, the nominal stiffness and strength of the stitched core are analyzed through the deformation of a single stitching yarn, as shown in Fig. 3. A applied compressive loading F_z is imposed on the yarn of the stitched core in the through-thickness direction. Considering the stitching yarn is a beam. The force F_z that generates a displacement Δ_z at the node O (in the z-direction) will create a y-direction reactive force F_y, reactive moments M_1 and M_2 at the nodes O and B, respectively. F_a, F_s are the axial and shear forces in the stitching yarn OB. The relations between F_z, F_y and F_a, F_s are

$$F_a = F_z \sin\omega + F_y \cos\omega \tag{1}$$

$$F_s = -F_z \cos\omega + F_y \sin\omega \tag{2}$$

where ω is the inclination angle between the stitching yarns and the facesheets.

The moment equilibrium on the x–z plane about the origin gives

$$M_1 + M_2 = F_z c \cos\omega - F_y c \sin\omega \tag{3}$$

where c denotes the half length of a stitching yarn, ω is the inclination angle between the stitching yarns and the facesheets.

Δ_y, Δ'_y are the y-direction deflection and the slope of the stitching yarn OB at the node O due to the external loading. Considering the boundary conditions at the node O ($\Delta_y = 0$, $\Delta'_y = 0$), yields two equations as

$$\frac{(F_y\cos\omega + F_z\sin\omega)c\cos\omega}{E_sA} - \left[\frac{(F_z\cos\omega - F_y\sin\omega)c}{3E_sI} - \frac{M_1}{2E_sI}\right]c^2\sin\omega = 0 \tag{4}$$

$$\frac{M_1 c}{E_sI} - \frac{(F_z\cos\omega - F_y\sin\omega)c^2}{2E_sI} = 0 \tag{5}$$

where A, I, E_s is the cross section area, the moment of inertia and the Young's modulus of the stitching yarn, respectively.

From Eqs. (3)–(5), all the forces and moments can be expressed as functions of the applied loading F_z

$$F_y = \frac{(c^2A - 12I)\sin\omega\cos\omega}{c^2A\sin^2\omega + 12I\cos^2\omega}F_z \tag{6}$$

$$M_1 = \frac{6Ic\cos\omega}{c^2A\sin^2\omega + 12I\cos^2\omega}F_z \tag{7}$$

The displacement at the top of the stitching yarn in z-direction Δ_z is given by

$$\Delta_z = \frac{(F_z\sin\omega + F_y\cos\omega)c\sin\omega}{E_sA} + \frac{(F_z\cos\omega - F_y\sin\omega)c^3\cos\omega}{3E_sI} - \frac{M_1c^2\cos\omega}{2E_sI} \tag{8}$$

Therefore, the equivalent Young's modulus of an octahedral stitched core is

$$E_z = \frac{\sigma}{\varepsilon} = \frac{4F_zc\sin\omega}{\Delta_zA_1} = \frac{\sin\omega\,\pi d^2(4c^2\sin^2\omega + 3d^2\cos^2\omega)}{8c^4\cos^2\omega}E_s \tag{9}$$

where $A_1 = 2c^2\cos^2\omega$ is the effective area of a stitched sandwich structure.

The peak compressive strength of a stitched sandwich structure σ_{pk} is dependent on the initial failure mode of the stitching yarns. Two competing mechanisms that will ultimately determine σ_{pk} include buckling and fracture of the yarns.

Before considering each of these failure modes, in turn, we derive expressions relating the failure strength of the octahedral core to the compressive failure strength σ_c of a single stitching yarn. The ratio of the compressive load F_z and axial force F_a is given from Eqs. (1) and (6) as

$$F_z = \frac{c^2A\sin^2\omega + 12I\cos^2\omega}{c^2A\sin\omega}F_a \tag{10}$$

Then the peak compressive strength σ_{pk} is determined from Eq. (10)

$$\sigma_{pk} = \frac{4(c^2A\sin^2\omega + 12I\cos^2\omega)}{c^2A_1\sin\omega}\sigma_c = \frac{\pi d^2(4c^2\sin^2\omega + 3d^2\cos^2\omega)}{8c^4\sin\omega\cos^2\omega}\sigma_c \tag{11}$$

(i) Euler buckling of stitching yarns:

The Euler buckling strength for a built-in Euler column subjected to axial load can be estimated from

$$\sigma_c = \frac{\pi^2d^2E_s}{4c^2} \tag{12}$$

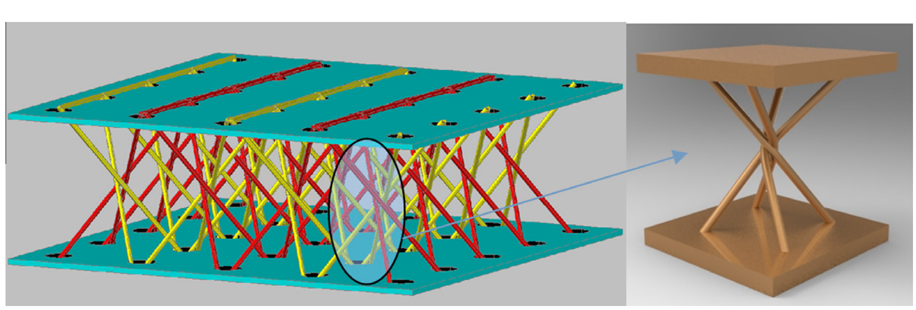

Fig. 1. Schematic illustrations of the octahedral stitched sandwich structure.