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Technical Report

Mechanical behavior of carbon fiber reinforced polymer composite sandwich panels with 2-D lattice truss cores

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ABSTRACT

Composite sandwich structures with lattice truss cores are attracting more and more attention due to their superior specific strength/stiffness and multi-functional applications. In the present study, the carbon fiber reinforced polymer (CFRP) composite sandwich panels with 2-D lattice truss core are manufactured based on the hot-pressing method using unidirectional carbon/epoxy prepregs. The facesheets are interconnected with lattice truss members by means of that both ends of the lattice truss members are embedded into the facesheets, without the bonding procedure commonly adopted by sandwich panels. The mechanical properties of the 2-D lattice truss sandwich panels are investigated under out-of-plane compression, shear and three-point bending tests. Delamination of the facesheets is observed in shear and bending tests while node failure mode does not occur. The tests demonstrate that delamination of the facesheet is the primary failure mode of this sandwich structure other than the debonding between the facesheets and core for conventional sandwiches.

1. Introduction

Sandwich structures consisting of low density core and solid face sheets are widely used in naval and aeronautical applications due to their high stiffness/strength-to-weight ratio [1]. The conventional cores are honeycombs [2,3] and foams [4,5]. These sandwich panels have superior mechanical properties to their solid plate counterpart; however, these closed-cell configurations limit their multi-functional applications [6,7]. Recently, lattice truss cores have begun to be explored as a candidate core material because of their superior specific strength/stiffness and the large interconnected void space. The stiffness and strength of lattice materials scale linearly with the relative density $\bar{\rho}$, which results that the lattice materials, at low relative densities, can therefore be more than an order of magnitude stronger and stiffer than equivalent mass per unit volume foams made from the same parent material. In order to explore the mechanical properties of lattices, the corresponding techniques to manufacture such sandwich structures have rapidly expanded during the past years. The investment casting, metal weaving and perforated wrought mental sheet folding methods have emerged to fabricate metal lattice structures [8–10]. For the design calculations, the mechanism maps based on beam theory have been given by Desphande and Fleck [11]. Wicks and Hutchinson have optimally designed such panels subject to prescribed combinations of bending and transverse shear loads [12]. Besides, the quasi-static /dynamic mechanical response of the lattice sandwich structures has been investigated by numerous scholars [13–15]. The measurements have shown that the lattice sandwich structures have desirable mechanical properties such as specific strength/stiffness and impact energy absorption. In addition, such materials are also expected to find applications in lightweight, compact structural heat exchangers [16]. Their open-cell configuration allows heat exchange along the panel core, making them as attractive candidates for development of multi-function systems. Moreover, the Kagome core sandwich structures have been investigated as shape morphing structure by Symons et al. [17,18]. As we know, the behavior of sandwich structures primarily depends on the topology and the parent material. The optimized lattice topology and superior parent material properties can be combined to create new engineering materials, which expand the material property space. In view of this, the CFRP which can provide high uniaxial specific strength is used as the parent material of the lattice core sandwich structures.

Fan et al. [19,20] have manufactured a carbon fiber-reinforced three-dimensional lattice core sandwich panel using an intertwining method. Finnegan et al. [21] manufactured CFRP pyramidal truss cores by slot-fitting method. In order to improve the shear performance of pyramidal lattice core sandwich structure, Yuguo Sun and Liang Gao presented an improved pyramidal lattice truss core sandwich structure by introducing a series of parallel

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distributed cross-bars to core members [22]. Compared with 3-D lattice sandwich structures, the preparation process of 2-D lattice sandwich structures is easier [23]. In contrast, the longitudinal shear performance of 2-D lattice sandwich structures is better, which may be used under shear loading in one direction. Thus, the aim of the present work is to develop a new method to manufacture the composite 2-D lattice sandwich structures. In addition, the mechanical properties of 2-D lattice truss core sandwich panels are tested under the out-of-plane compression, shear and three-point bending loadings. Finally, the failure mechanism and mechanical properties of the new structure are also discussed.

2. Fabrication

The unit cell of 2-D lattice truss core is shown in Fig. 1. The relative density of the 2-D lattice truss cores depends on the diameter of the truss member d, inclination angle ω, length l of truss member, width b of the unit cell, and the distance t between the adjacent truss members, which is as following

$$\bar{\rho} = \frac{\pi d^2}{4b \sin\omega(l\cos\omega + t)} \tag{1}$$

The geometrical parameters are taken as $d = 3$ mm, $l = 17$ mm, $b = 20$ mm, $t = 3$ mm, and $\omega = 45°$ in the present study, so the relative density of the truss core, $\bar{\rho}$, is 3.33%.

The composite sandwich panels with 2-D lattice truss cores are manufactured based on the hot-pressing method. In order to configure the lattice core topology, many cuboid flat steel plates with semicircular grooves on the side face are used as molds, as shown in Fig. 2. In the manufacturing process, the molds are assembled after the surface is cleaned with acetone and coated with the mold release agent. Carbon fiber prepregs are cut to the required size, and then rolled into rods as truss members with fibers along the direction of truss members, whose radius coincides with that of the semicircular grooves on the side face of molds. Then, the composite rods are inserted into the holes of the assembled mold with about 0.5 cm outside the molds, as depicted in Fig. 3. After that, the unidirectional carbon/epoxy (T700/TDE85) prepregs are layered on the top surface of molds to configure the facesheets, with the stacking sequence $[0^0/45^0/-45^0/0^0]_s$, and both ends of truss members are dispersed and gradually embedded into the eight layers of facesheets. The preforms are then cured at 170 °C under pressure of 0.7 MPa for 3 h on the hot press. Finally, removing the molds and cutting out the panels to the required dimensions, we get the corresponding samples, as shown in Fig. 4.

3. Experiments

3.1. Out-of-plane compression of 2-D truss core sandwich panels

Compression tests are performed with panels of 73 × 60 × 15 mm to determine their compressive stiffness and strength in the out-of-plane direction in accordance with ASTM: C365/C365 M-11a A screw driven testing machine (Instron 5569) is used to test samples at a rate of 0.5 mm/min. At least three tests are conducted to confirm the repeatability of the measurements.

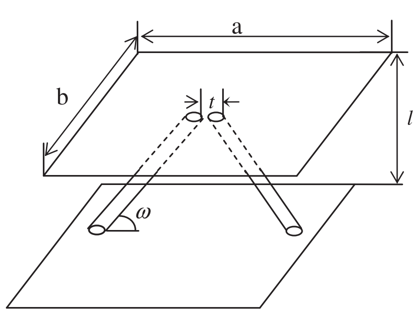

Fig. 1. Schematic of 2-D lattice truss core unit cell.

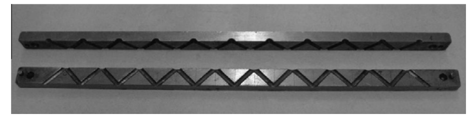

Fig. 2. Photograph of the molds.

3.2. Shear behavior of 2-D truss core sandwich panels

As we know, sandwich structures are usually used in situations where they are subjected to significant bending loads. The applied bending moment is balanced by the bending stress in the facesheets. On the other hand, the traverse shear load is supported mainly by the core. Typically, cores are the weakest part of sandwich structures. Based on the work done by Deshpande and Fleck [11], we know that this 2-D lattice is anisotropic in bending and shearing loads. Along the orthogonal direction, the shear/bending strength must be much smaller. Thus, the core should be optimally designed to select the appropriate orientation to achieve a high load carrying capacity, and the case that the core along the orthogonal direction bears the load is not desirable. Therefore, it is instructive to explore the properties of this core along the wave direction. In this case, the shear or bending tests for this sandwich structure is also along this direction.

Shear tests are performed in accordance with ASTM: C273/C273 M-11. The test fixture used to obtain shear stress/strain of the core is shown in Fig. 5. The specimens are rigidly bonded to steel plates by adhesive, and the dimensions of the specimens are 150 × 60 × 15 mm.

3.3. Bending behavior of 2-D truss core sandwich panels

Three-point bending tests are conducted using the Instron 5569 universal testing machine according to ASTM C393/C393 M-11e1 The specimens with the dimension of 200 × 60 × 15 mm, and the distance between the supports is 180 mm, as shown in Fig. 6. The column radius of the support and loading pins is 10 mm.

4. Results

The typical compressive stress–strain response is shown in Fig. 7. Following an initial linear response, the compressive stress approaches the peak value. After that, the zigzag fluctuation appears due to the splitting occurring at the ends of truss members, and then the load suddenly decreases because of the buckling of the fibers, as shown in Fig. 8. Based on the compressive stress–strain curve, the compressive strength and the Young's modulus, 2.64 and 210.2 MPa, respectively, are obtained for such sandwich structure. Considering the composite density of 1560 kg/m^3, the specific strength (compressive strength/ density) of this 2-D lattice truss core is 51.28 × 10^3 N m/kg, which is compared well with other lightweight cores [24].

The shear stress–strain response is shown in Fig. 9. During the initial stage of loading, the response is fairly linear. Thus, based on this linear stage, we can obtain the shear modulus of 94.8 MPa. Thereafter, a small fluctuation emerges when the shear stress approaches 1.1 MPa while the load continues to increase as the shear stress arrives at the maximum value, 1.38 MPa. In the tests, delamination of facesheets is observed which is due to the defects such as fiber tangle or voids generated when the truss members are embedded into the facesheets, as shown in Fig. 10.