Composite Structures 100 (2013) 451–463

Contents lists available at SciVerse ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Response of sandwich structures with pyramidal truss cores under the compression and impact loading

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ARTICLE INFO

Article history:
Available online 30 January 2013

Keywords:
Truss core
Sandwich structure
Energy absorption
Impact

ABSTRACT

In this paper, the pyramidal truss core sandwich structures consisting of carbon fiber reinforced polymer (CFRP) facesheets and aluminum alloy cores were manufactured based on the slot-fitting method. This hybrid concept is to maximize the specific bending stiffness/strength as well as obtain excellent energy absorption ability. Quasi-static compression tests were conducted to get the stress–strain curves and to evaluate the energy absorption mechanism. Low velocity impact tests were carried out to investigate the damage resistance of such structures. The compressive measurements show that the low density aluminum alloy pyramidal truss cores have superior energy absorption ability compared with other lightweight lattice cores. In the impact tests, the failure of matrix cracking, fiber breakage, delamination of CFRP facesheets and buckling of truss members occurred and the extent of damage was significantly affected by the impact site. In addition to experimental testing, finite element models for compression and impact simulations have been developed using ABAQUS software. The numerical results were validated compared with the experimental tests.

1. Introduction

Sandwich constructions are composed of two thin but stiff skin layers separated by the lightweight core material. This allows for sandwich structures possessing a superior bending stiffness/strength to monolithic counterpart [1]. Therefore, sandwich structures are commonly employed in aerospace, marine and automotive industries where a lightweight material with high flexural stiffness and high strength to weight ratios is needed [2–6]. Among them, sandwich structures with honeycomb, foam or corrugated cores are most widely used. More recently, interest in the sandwich structures has concentrated on the lattice core sandwich structures because of their excellent specific strength and stiffness, especially the unique open cell architecture for multi-functionality [7–9]. A lot of effort was put into the manufacturing techniques. Investment casting of high fluidity non-ferrous casting alloys was initially adopted [10–12]. Later, sheet folding, waving and extrusion methods emerged to fabricate these metal lattices [13–15]. In addition, slot-fitting, intertwining and molding hot-press method were exploited to manufacture composite sandwich structures with lattice cores [16–20].

Although CFRP truss cores have higher specific stiffness and strength over metal lattice truss cores, their energy absorption was poor due to the premature brittle rupture or delamination of truss members [16,19]. In addition, the shaping of composite truss core topologies was rather complex compared with metal truss cores. In order to tackle some of the existing weakness of the lattice truss core sandwich structure, a hybrid sandwich structure has been developed by combining the advantages of CFRP and metal while avoiding some of their major disadvantages. The design concept is using CFRP laminate as the facesheets to maximize the specific bending stiffness/strength while introducing lightweight metal cores to obtain excellent energy absorption ability.

The focus of the present study is on the lattice sandwich structures consisting of CFRP facesheets and pyramidal truss cores made from aluminum alloy sheets. This material combination is analogous to the sandwich panels with aluminum honeycomb cores and polymer composite skins, commonly used in the aerospace industry. Here, a methodology is introduced to fabricate these lattice sandwich structures in Section 2. The flatwise compressive response of these pyramidal truss cores with three kinds of density is measured, and the details are provided in Section 3.2. As sandwich structures with thin CFRP skins are known to be susceptible to impact damage, so their behavior under impact should receive enough attention. Therefore, the evaluation of these lattice sandwich structures under low velocity impact is carried out in Section 3.3. In addition to experiments conducted, the three-dimensional finite element models are also developed to analyze the lattice sandwich structures under compression and impact loading. The comparisons between the numerical calculation and experimental measurement are discussed in Section 4.

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http://dx.doi.org/10.1016/j.compstruct.2013.01.012

2. Fabrication methodology

The pyramidal lattice truss cores were made from aluminum alloy sheets (2A12-T4, Harbin Dongqing Metals Manufacturing Co., China). Fig. 1 schematically shows the preparation process. First, continuous 2-D slot-fitting truss patterns were cut from the stacked aluminum alloy sheets using wire electro discharge machining. Then, these were cropped into the required dimension and slot-fitted into each other to build the pyramidal truss core topology. CFRP facesheets of thickness 1 mm made from unidirectional carbon/epoxy (T700/3234, Beijing Institute of Aeronautical Materials, China) pregs were finally bonded to the top and bottom faces of lattice cores using film adhesive (J-272, Heilongjiang Institute of Petrochemical, China). The detailed properties of unidirectional carbon/epoxy laminate are listed in Table 1.

In order to eliminate the concentration of local stress around the nodes, rounding was adopted at ends of truss members. Apart from that, bulky nodes were designed to ensure adequate attachment between the facesheets and cores. The unit cell geometry of pyramidal lattice truss core is shown in Fig. 2. The relative density $\bar{\rho}$ of the pyramidal truss core is written as follows:

$$\bar{\rho} = \frac{4btl + 4[(h_a + h_b)ct - cth_a]}{ha^2} \tag{1}$$

The corresponding parameters of the three kinds of cores (A, B and C) investigated in this paper are listed in Table 2. The corresponding specimens with the core A, B and C are symbolized with specimen A, B and C.

3. Mechanical testing

3.1. Properties of the aluminum alloy material

In order to characterize the mechanical properties of these lattice core sandwich structures, tensile specimens of dog-bone geometry were cut from the aluminum alloy sheets (2A12-T4).

Table 1
Material properties of the unidirectional carbon/epoxy (T700/3234) laminate.

Symbol	Value	Property
E_{11}	123 GPa	Longitudinal stiffness
E_{22}	8.4 GPa	Transverse stiffness
E_{33}	8.4 GPa	Out-of-plane stiffness
υ_{12}, υ_{13}	0.32	Poisson's ratio
υ_{23}	0.3	Poisson's ratio
G_{12}, G_{13}	4 GPa	Shear modulus
G_{23}	3 GPa	Shear modulus
X_t	2100 MPa	Longitudinal tensile strength
X_c	800 MPa	Longitudinal compressive strength
Y_t	25 MPa	Transverse tensile strength
Y_c	120 MPa	Transverse compressive strength
Z_t	50 MPa	Out-of-plane tensile strength
S_{12}, S_{23}, S_{13}	40 MPa	Shear strength
ρ	1560 kg/m^3	Density

The tensile uniaxial response of the aluminum alloy sheets at an applied strain rate of 10^{-3} is plotted using axes of true stress and logarithmic strain, as shown in Fig. 3. The material properties of aluminum alloy sheets (2A12-T4) are listed in Table 3.

3.2. Flatwise compression tests of the aluminum alloy lattice cores

Based on the ASTM C365/C365M-05 [21], the flatwise compression tests of these pyramidal lattice cores comprising 3×3 cells were conducted on a screw-driven test machine Instron 5569 with the displacement rate of 0.50 mm/min. The representative compressive responses of the specimen A, B and C are given in Fig. 4. All the lattice cores exhibit a similar compressive stress–strain response. After some initial bedding-in, there is a regime of linear elastic loading. Following the linear region, all the cores show an initial peak compressive strength followed by "softening" due to the inelastic buckling of the core members. Subsequently, the cores exhibit a long stress plateau region until densification where the cores display greatly increased load resistance. Comparing the

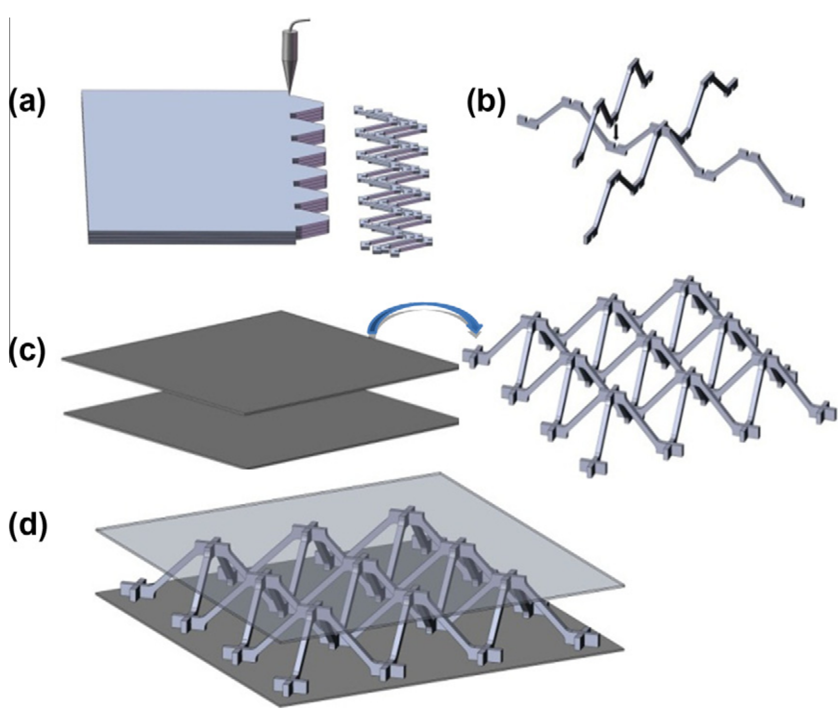

Fig. 1. Schematic of the manufacturing process of the aluminium alloy pyramidal core sandwich structures. (a) Cut continuous 2-D snap-fit truss patterns; (b) assemble the lattice core; (c) bond the lattice cores with facesheets; and (d) the fabricated sandwich structure with pyramidal lattice core.