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Mechanical properties and failure behavior of the sandwich structures with carbon fiber-reinforced X-type lattice truss core

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ABSTRACT

As we known, composite sandwich structure with advantages of high specific strength/modulus, high temperature resistance, damping, etc., which is widely used in various fields. And there is more space in its core to supply for multi-functional filler, which provides the possibility for special engineering applications (such as heat insulation, wave absorption, etc.). In this paper, a new type of lightweight composite lattice structure (called X-type lattice structure) is proposed based on the stretching dominated idea of quadrilateral grid and lattice strut. The mechanical properties and failure behavior of X-type lattice structures are investigated based on theoretical and experimental methods. The experiment results show that the mechanical properties of the X-type lattice sandwich structure is more superior than those of other pyramidal lattice sandwich structures. In theoretical analysis, we found the fact that the shear equivalent stiffness of X-type lattice structure is independent of the loading direction, while the shear strength is related to the loading direction. Meanwhile, its minimum shear strength will be reached at the 0 degrees loading direction, and the maximum shear strength will be obtained when the loading direction is 45 degrees.

1. Introduction

With the development of human society, aeronautics and astronautics have been attracting much attention and the search for a lightweight, high modulus/strength material has been considered by many scientists [1,2]. Composite materials are able to combine the characteristic of the individual components to enhance their performance or extend their functionality. Compared with traditional materials, they are stronger, lighter, less expensive, high temperature resistance, or corrosion resistance. Meanwhile, with the exploration of structural forms, sandwich structure is considered as one of candidates used in aerospace and other transportation applications with relative low density and high mechanical performance [3–5].

After the concept of sandwich structure was proposed, the development of the core materials and structure had aroused wide attention of researchers, resulting in various kinds of sandwich structures. For the honeycomb structure subjected compressive load, the main deformation of structure is the cell wall bending, resulting in the performance of the material cannot be fully utilized [6,7]. In the view of this point, the lattice sandwich structure came into being. The most of lattice structure is stretching dominated structure with high specific strength and stiffness. For the bending dominated structure, the proportional relation of stiffness and strength to relative density can be expressed as: $E \propto \bar{\rho}^2, \sigma \propto \bar{\rho}^{3/2}$, but for stretching dominated structure, that can be found as follows: $E \propto \bar{\rho}, \sigma \propto \bar{\rho}$ [8]. In this case, the mechanical performance of lattice structure is better than that of the honeycomb bending dominated structures. Meanwhile, many benefits could be brought due to the open hole characteristic and relative larger porosity, including strong capacity, the heat transfer, energy absorption and braking functions, etc. The common lattice sandwich structures include pyramidal lattice structure [9], octet-truss lattice structure [10] and tetrahedral truss structure [11].

For the manufacturing of pyramidal composite sandwich structure, Finnegan et al. [12] proposed a embedded assembly technique. Van Lin et al. [13] successfully fabricated the carbon fiber lattice sandwich structure by three-dimensional braiding method. During the preparation of sandwich structures, the critical factor is the connection between the cores and the face sheets, which has been widely studied for many researchers. In order to solve this problem, Wang, et al. [14,15] manufactured the lattice truss cores and the facesheets in one process without bonding, which effectively improved the connection strength of the face and core.

For study on mechanical properties of lattice sandwich structures, Deshpande et al. [16] proposed the octet-truss lattice sandwich

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structure, which was fabricated based on the investment casting method. The experiment, theory and numerical simulation of such structure have been carried out. It is found that the octet-truss lattice sandwich structure is a stretching dominated structure, and its performance is better than that of metal foam. Kooistra et al. [17] used 6061 aluminums as the raw materials to fabricate the tetrahedron lattice sandwich structure successfully by the punching folding technology, and has carried on the compression experiment and the theory analysis of its mechanical properties. By comparison with corrugated plates, metal foams, and honeycombs, it is found that the strength of the lattice structures is higher than others, especially for such structures with the relative density. Lim et al. [18] investigated the mechanical properties of Kagome lattice structure and the tetrahedron lattice structure under flat compressive loading. For the failure modes, plastic yielding plays a dominant role in these two kinds of structures. Compared with the tetrahedron lattice structure, the Kagome structure has better energy absorption capability. Finnegan et al. [19] fabricated carbon fiber reinforced composite pyramidal lattice sandwich structure and investigated its failure model and mechanical property under compressive loading. Based on the analysis results, the composite lattice sandwich structure with relative low density has higher strength than that of metal lattice structure. The main failure modes of composite core under flat compression are buckling and fracture of core. The buckling failure mainly occurs at the low relative density structure that consists of the longer and thinner struts, while the fracturing failure dominated in the structure composed by shorter and thicker struts with large relative density.

The pyramidal lattice structure is one of the most representative of the lattice sandwich structures with high specific strength and stiffness, having attracted more scientists' attention. In this study, the design concept of the X-type lattice structure fabricated by the hot-press technique and interlocking method is derived from the pyramidal lattice structure, and aim to improve carrying capacity of the lattice structure. Under the condition that the mass and strut cross-sectional area of pyramidal lattice core and X-type lattice core are the same, the length of struts in X-type lattice core is reduced to half of that in the pyramidal lattice core, so that its slenderness ratio of the strut is also reduced by half. Thus, the load-carrying capacity of the lattice structure will be enhanced. The concept of this structure design and fabrication method has been detailed as following sections. The mechanical property and failure model was investigated by combination of theory model and experiment results. In the view of these failure model, the improved lattice structure has been proposed.

2. Fabrication

The manufacture process of X-type lattice sandwich structure is as follows. Firstly, high-pressure water cutting machine was employed to cut out 2-D interlocking truss with required size from carbon laminate, and then they are interlocking into each other to complete the X-type lattice core. Secondly, the upper and lower panels with the thickness of 1 mm were fabricated by unidirectional carbon/epoxy prepreg (T700/12K, Beijing Institute of aeronautical materials, China). The properties of unidirectional carbon/epoxy laminates are detailed in Table 1. Finally, the panel and the X lattice core are bonded together by adhesive, then kept it in an oven at 120 °C for 2 h. The manufacturing process of the X-type lattice sandwich structure was illustrated in Fig. 1.

The unit cell geometry diagram of the X-type lattice core is shown in Fig. 2, and the relative density can be expressed in Eq. (1):

$$\bar{\rho}_1 = \frac{8lat + 4(2a + t_0)ta - 2at_0 t}{(2l\cos\omega + 2a + t_0 + \sqrt{2a})^2 H} \tag{1}$$

According to Deshpande [16], the calculation model of relative density can be approximately equivalent to the structure shown in Fig. 3. The relative density of X-type structure is calculated as:

Table 1
Mechanical properties of a unidirectional carbon fiber/epoxy laminate.

Property	Symbol	Value
Longitudinal stiffness	E_{11}	104 GPa
Transverse stiffness	E_{22}	7.58 GPa
Out-of-plane stiffness	E_{33}	7.58 GPa
Poisson's ratio	υ_{12},υ_{13}	0.3
Poisson's ratio	υ_{23}	0.3
Shear modulus	G_{12},G_{13}	3.44 GPa
Shear modulus	G_{23}	3.44 GPa
Longitudinal tensile strength	X_t	1880 MPa
Longitudinal compressive strength	X_c	760 MPa
Transverse tensile strength	Y_t	37 MPa
Transverse compressive strength	Y_c	188 MPa
Out-of-plane tensile strength	Z_t	37 MPa
Shear strength	S_{12},S_{13},S_{23}	103 MPa
Density	ρ	1543 kg/m^3

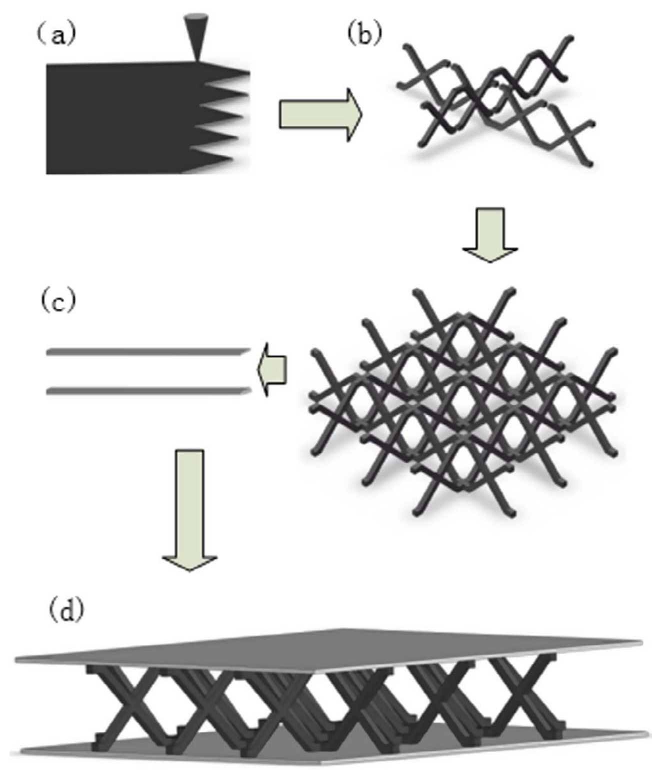

Fig. 1. Schematic of the manufacturing process of the X-type lattice sandwich structures.

$$\bar{\rho}_2 = \frac{1}{\cos^2\omega\sin\omega}\left(\frac{t}{l}\right)^2 \tag{2}$$

As a result of the cross caused by interlocking process affects the relative density of the structure and there is a certain distance between the two struts. Therefore, the coefficient of correction $\eta = \frac{2(t_0 + 2a)\,t - t^2}{(t_0 + 2a)^2}$ is introduced to correct the Eq. (2), which can be expressed:

$$\bar{\rho} = \frac{1}{\cos^2\omega\sin\omega}\left(\frac{t}{l}\right)^2 \eta \tag{3}$$

3. Experiment

3.1. Uniaxial compression test of single strut

The stiffness and strength of composite struts are investigated under axial compression along the fiber direction to determine the mechanical properties of the parent materials for the X-type lattice core. The