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Macroscopic response of carbon-fiber pyramidal truss core panel taking account of local defect

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ABSTRACT

In present paper, the macroscopic responses of carbon-fiber pyramidal truss core panel subject to uniaxial compressive loading are investigated through experimental, theoretical and finite element analysis (FEA) methods, taking account of local defect. The local defect is introduced in the form of missing strut for the unit cell. A theoretical model is proposed to predict the effect of defect on the compressive stiffness and ultimate strength of pyramidal truss core sandwich panel. To study the buckling and crushing behavior, a progressive damage model based on the Hashin failure criteria is implemented in ABAQUS software by means of a user subroutine VUMAT. The sensitivity of sandwich panel to the percentage of missing struts, defect type, and defect spatial configuration are respectively discussed. Comparing with the open-cell foam and honeycombs, the pyramidal truss has better defect tolerant than bending dominated construction. Moreover, the effects of defect type and defect spatial configuration on the strength of pyramidal truss panel are significant under the same percentage of missing struts. The numerical results reveal that the discrepancy can be up to 14% and 29%, respectively. The local defect should be considered in the design and application of pyramidal truss structure.

1. Introduction

Pyramidal truss structure has gained increasing attention in recent years due to their remarkable specific strength and stiffness as well as potential multifunctional advantages [1–6]. In fact, it retains an open-cell construction and has lower density and higher porosity in contrast with the convenient lightweight construction. Several manufacturing processes have been developed to fabricate the truss core with metal or fiber material, such as investment cast method [7–9], deformation forming method [10,11], hot press molding method [6,12], and slot-fitting method [13,14]. The macroscopic effective stiffness and strength have been systematically investigated by theoretical, numerical and experimental methods. However, various types of defects [15–23], such as missing strut, stochastic dispersion of node and non-periodic microstructure, can be originated in the manufacture or practical applications. The lightweight truss construction composites are sensitive to local defects, thus the unexpected defects will result in crucial influence on the mechanical performance of lattice materials.

For the honeycombs construction, Silva and Gibson [15], Guo and Gibson [20], and Wang and McDowell [21] investigated the effect of missing cell walls on the elastic buckling strength, plastic collapse strength and initial yield strength, using the finite element method (FEM). In the aspect of lattice truss, Wallach and Gibson [16] analyzed early the effect of removing truss core members on the effective modulus of octet-truss core structure using FEM. Their results revealed that the lattice truss construction was more tolerant to this type defect than convention foam. The compressive modulus and strength of structure decreased linearly with the fraction of ligaments removed. Hyun et al. [22] investigated the effect of geometry imperfections and material property imperfections on the macroscopic response of wire-woven bulk Kagome truss core through FEM and experimental tests. The periodic boundary conditions were applied on the unit cell to avoid the

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boundary effect. The defect interaction and reinforcement for the Kagome truss construction were discussed by Zhu et al. [23] through theoretical and FEM. An analytical model was proposed to predict the interaction of two defects in lattice materials based on a single defect model.

It should be noted that, for the pyramidal truss structure, the published studies on the effect of local defect are less by far. Biagi and Bart-Smith [17] investigated the effect of unbound nodes between the truss cores and face sheets on the compressive and shear performance through FEM, experimental and theoretical methods. They discussed the influences of percentage of unbound nodes and spatial configuration, and obtained the upper and lower limit on stiffness and strength. A three-dimensional model of a 9-cell core used for small scale simulation was created in Abaqus software, and meshed using continuum element. Recently, the effects of missing unit cell on the natural frequencies and the corresponding vibration modes of pyramidal truss core sandwich panel were studied by Lou et al. [12] through FEM. In fact, the missing strut of unit cell will lead to the degradation of stiffness and strength, thereby affecting the overall performance of construction. In our previous paper [24], a theoretical model was proposed, considering the strut bending and shear behavior, to describe the effect of missing struts on the overall stiffness and strength of pyramidal truss core sandwich panel. However, the influences of defect type and defect spatial configuration were neglected.

It can be found that, from the above mentioned publication, the finite element method has been widely used to evaluate the effect of defect on the macroscopic performance of lattice truss composite. The buckling and crushing behavior of lattice truss can be obtained by implementing various failure criteria. Actually, due to the discrepancy of boundary condition and manufacturing quality, the construction can exhibit different failure modes during the loading process. Xiong et al. [6] involved the failure behavior in pyramidal truss sandwich panel subject to edge compressive by experimental tests, and listed as three different failure modes, such as face sheet wrinkling, macro-buckling, and strut crushing.

The present work involves the effect of local defect on macroscopic response of carbon-fiber pyramidal truss core sandwich panel subject to uniaxial compressive. The defect is introduced in the form of missing strut for the individual cell. A theoretical model is proposed to predict the overall stiffness and ultimate strength. A three-dimensional finite element model containing 4-cell is created according to experimental tests. The strut buckling and collapse behavior are simulated based on the Hashin failure criteria which is implemented in the ABAQUS software by means of a user subroutine VUMAT. The effects of the percentage of missing strut, defect type, and defect spatial configuration are respectively discussed.

2. Experiments details

2.1. Materials and manufacturing

In present paper, unidirectional carbon fiber cloth (T300) was used to fabricate the face sheets and pyramidal lattice truss core, and the polymer used as matrix was Unsaturated Polyester Resin 189. The face sheets were firstly manufactured using hot press molding method. 32-ply carbon fiber cloth was stacked in the sequence of [0°/90°], and the thickness of each cloth was 0.125 mm. The pressure was set as 0.6 MPa, and kept for half an hour at 140 °C. The truss core was fabricated through expendable pattern casting process, and the diameter of lattice strut was 4 mm. It should be mentioned that the fiber in strut is unidirectional along the axial direction. Finally, the face sheets and truss core were cemented together using the strong adhesive which was provided by CHN carbon fiber technology Co. Ltd, China.

As shown in Fig. 1, three types of compressive samples containing 4-cell were cut from the pyramidal truss core sandwich panel, including the perfect cell (Fig. 1b), missing two-strut (Fig. 1c) and missing four-strut (Fig. 1d). The shape dimension of sample was listed in Table 1, and the specific structures of three sample types were shown schematically in Fig. 2. As seen, the solid circles denote the top nodes bound with upper face sheet, and the hollow circles are the base nodes bound with lower face sheet. Solid lines represent the carbon fiber strut connecting two nodes, and the dash lines represent the struts have been removed.

2.2. Compressive tests

To evaluate the effect of defect on the macroscopic mechanical performance of pyramidal truss core panel, uniaxial compressive tests were conducted using Instron-3382 servo-electric testing machine at the ambient temperature following the ASTM C365 standard, and three samples per type. The loading speed was set as 0.5 mm/min. In fact, the three types were corresponding to the percentage of missing strut 0.00%, 12.5%, and 25.00%.

3. Theoretical model

A theoretical model has been proposed in our previous paper [24], based on the general elastic theory, to predict the effect of missing strut percentage on the overall stiffness and strength of truss core panel. Moreover, the bending and shear effects of strut were considered in contrast with traditional theoretical models. This was necessary to obtain accurate stiffness, especially for the lower relative density of truss core.

The compressive stiffness of pyramidal truss core with perfect unit cell was expressed as

$$E_{zz}^{(0)} = E_s\bar{\rho}\sin^4\omega + \frac{1}{\frac{4}{3}l^2 + 2(1+v)} E_s\sin^2\omega\cos^2\omega \tag{1}$$

where E_s was the compressive stiffness of strut material. $\bar{\rho}$ was lattice relative density, ω was the angle between the truss members and face sheet, and l were the length of strut. v was the Poisson's ratio. Note that, the mark '(0)' denoted the unit cell was perfect in present study. '(1)' and '(2)' represented the unit cell missing one-strut and two-struts, respectively.

According to the geometrical relation, the compressive stiffness of truss core with defects can be obtained as

$$E_{zz}^{(1)} = \frac{3E_{zz}^{(0)}}{4}, \quad E_{zz}^{(2)} = \frac{E_{zz}^{(0)}}{2}. \tag{2}$$

For the ultimate strength of pyramidal truss core, it should be divided into two cases. One was the strut buckling failure. According to the Euler buckling formulation, the ultimate strength can be expressed as

$$\sigma_u^{(0)} = \frac{\pi^2 d^2 E_s}{4l^2}\bar{\rho} \tag{3}$$

Here, d was the diameter of strut. When the main failure mode was strut crushing, it would be expressed as

$$\sigma_u^{(0)} = \bar{\rho}\alpha\sigma_{cr}\sin^2\omega \tag{4}$$

where σ_{cr} was the ultimate compressive strength of strut material and α was a material constant depending on the manufacturing quality which can be obtained through the uniaxial compressive tests. For the truss core with defects, the ultimate compressive strength can be derived similar as Eq. (2) which can expressed as