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Fabrication and testing of composite orthogrid sandwich cylinder

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ABSTRACT

To get a strong, stiff and weight efficient cylindrical shell, a carbon fiber reinforced orthogrid-core sandwich cylinder was designed and fabricated. The core is made up of orthogonal grids and manufactured by interlocking method. The sandwich cylinder is fabricated by filament winding method. Free vibration test combining with theoretical analysis and numerical simulation was carried out to reveal the vibration responses and estimate the modulus of the wound laminate. Uniaxial compression test was performed to reveal the strength and failure mode. Without end flanges, laminate delamination at the end controls the peak load. Delamination of skins induces interfacial debonding and dimpling of inner skin finally. An engineering method based on the average strain at the peak load is proposed to predict the load capacity of the cylinder. Compared with stiffened cylinder, the orthogrid sandwich cylinder is stiffer and stronger. Meanwhile, its making process is simplified and the mechanical ability is comparable with other lattice-core sandwich cylinders.

1. Introduction

Carbon fiber reinforced lattice truss composite structures are weight efficient for its high specific stiffness and strength [1,2]. These structures, including Octet truss [1], lattice block [3], tetrahedral truss [4], pyramidal truss [1,5], Kagome lattice [5], hierarchical lattice [6], woven lattice [7], IsoTruss® [8,9] and Isogrid [10–12], have the potential to enhance innumerable applications in aerospace structures. By comparision, lattice-core sandwich cylinder (LSC) [13–16] is more weight efficient than thin-walled solid cylinder and stiffened cylinder under uniaxial compression instances for spacecraft and rocket barrels. Fan et al. [13] manufactured a carbon fiber reinforced composite (CFRC) LSC, which is four times stiffer and stronger than grid stiffened cylinder (GSC) [17]. Li et al. [18] manufactured a corrugated lattice truss sandwich cylinder and the cylinder is also stiffer and stronger than referenced grid stiffened cylinder. Zhang et al. [19] pointed out that LSC of the same weight and dimension, compared with GSC, is always much stiffer, so that LSC has greater fundamental frequency and could be designed even lighter in most astronautic applications to satisfy the first order frequency requirement [20]. Isogrid is usually adopted as the core layer to make the sandwich cylinder through filament winding method based on metallic or silicon rubber mould.

In this paper, an orthogrid LSC was designed and manufactured. To simplify the fabrication, interlocking method was applied to make the orthogrid. Compression behaviors and free vibration responses of the cylinder were revealed by experiments.

2. Orthogrid sandwich cylinder structure

2.1. Orthogrid sandwich cylinder

The sandwich cylinder has two cylindrical face sheets and an orthogrid structure performing as the core, as shown in Fig. 1(a). The orthogrid cylinder has two stacks of parallel ribs, as shown in Fig. 1(b). One stack is straight along the height of the cylinder. The other stack is circular around the circumferential direction, as shown in Fig. 1(c). Relative density of the lattice truss structure, ρ^*, is given by

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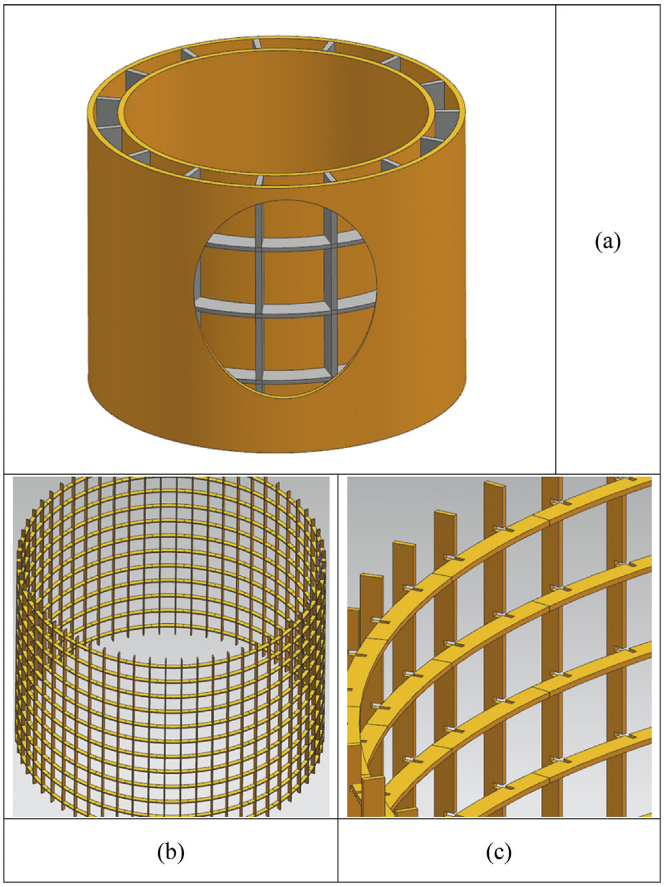

Fig. 1. Orthogrid structure: (a) Sketch map of the orthogrid sandwich cylinder; (b) orthogrid cylinder and (c) interlocking method of orthogrid.

$$\rho^* = \frac{4t_c d - t_c^2}{2d^2}, \tag{1}$$

where d and t_c denote the cell dimension and the thickness of the orthogrid strut.

2.2. Mechanical behaviors

Stress matrix of the laminated skin, $\boldsymbol{\sigma}$, is given by

$$\boldsymbol{\sigma} = \mathbf{C}\boldsymbol{\varepsilon}, \tag{2}$$

where $\boldsymbol{\sigma} = \begin{bmatrix} \sigma_x & \sigma_y & \sigma_{xy} \end{bmatrix}^{\mathrm{T}}$ and strain matrix $\boldsymbol{\varepsilon} = \begin{bmatrix} \varepsilon_x & \varepsilon_y & \varepsilon_{xy} \end{bmatrix}^{\mathrm{T}}$. Superscript $^{\mathrm{T}}$ denotes the transpose of a matrix. Neglecting the transverse modulus of unidirectional monolayer, the stiffness matrix $\mathbf{C}$ of the laminate is simplified and given by

$$\mathbf{C} = \frac{1}{N}\begin{bmatrix} \sum E_1 \cos^4\theta_i & \sum E_1 \cos^2\theta_i \sin^2\theta_i & \sum E_1 \cos^3\theta_i \sin\theta_i \\ \sum E_1 \cos^2\theta_i \sin^2\theta_i & \sum E_1 \sin^4\theta_i & \sum E_1 \cos\theta_i \sin^3\theta_i \\ \sum E_1 \cos^3\theta_i \sin\theta_i & \sum E_1 \cos\theta_i \sin^3\theta_i & \sum E_1 \cos^2\theta_i \sin^2\theta_i \end{bmatrix}, \tag{3}$$

where θ_i is the angle of the layup to the circumferential direction (x-axis) of the cylinder. E_1 is the axial modulus of unidirectional laminate. N is the layer number. Bending rigidity of the sandwich wall of the cylinder, $\mathbf{D}$, is given by

$$\mathbf{D} = \left(\frac{t_f c^2}{2}\right)\mathbf{C}, \tag{4}$$

where t_f is the thickness of the skin and c is the core layer thickness.

According to the bending stiffness, the natural frequency of free-vibrational cylinder, f_{n-1}, and the 1st order, f_1, are given by Ref. [21].

$$f_{n-1} = \frac{1}{2\pi}\sqrt{\frac{E}{\rho}\frac{t^2}{12r^4}\frac{n^2\left(1-n^2\right)^2}{1+n^2}}, \tag{5}$$

and

$$f_1 = \frac{1}{2\pi}\sqrt{\frac{E}{\rho}\frac{t^2}{r^4}\frac{3}{5}} = \sqrt{\frac{D}{M}\frac{H}{\pi r^3}\frac{18}{5}} \tag{6}$$

for $n = 2$, respectively, where E and D denote the modulus and bending rigidity of the cylindrical wall. r, t and H denote the radius, wall thickness and height of the cylinder. ρ and M denote the density and mass of the cylinder. For LSC

$$f_{n-1} = \frac{1}{2}\sqrt{\frac{E_f H}{M}\frac{t_f c^2}{\pi r^3}\frac{n^2\left(1-n^2\right)^2}{1+n^2}}, \tag{7}$$

and

$$f_1 = 3\sqrt{\frac{H}{5}\frac{E_f}{M}\frac{t_f c^2}{\pi r^3}}, \tag{8}$$

where E_f is the modulus of the quasi-isotropic skin and calculated through Eq. (8) when the 1st order natural frequency is measured by free vibration test.

The load capacity of the cylinder, N_{cr}, can be determined by a simple equation as

$$N_{cr} = 2\pi r\left[2t_f\frac{E_f}{1-\nu^2} + c\frac{\rho^*}{4}E_s\right]\varepsilon_{cr} \approx 4\pi r t_f E_f \varepsilon_{cr}, \tag{9}$$

where E_s is the modulus of the orthogrid rib. Usually $\varepsilon_{cr} \approx 3 \times 10^3 \sim 4 \times 10^3$ με from previous experiments [13,18]. Eq. (9) helps us estimate the strength of LSC.

3. Fabrication

To design the orthogrid sandwich cylinder, GSC of Kim [17] and LSC published by Li et al. [13] were selected as the referenced cylinders. These cylinders have identical dimensions and close masses. As listed in Table 1, the diameter of the cylinder ($2r$) is 625 mm. The length of the cylinder is 392.7 mm, a little longer than the referenced cylinders. Skin thickness of the cylinder is 1.0 mm. Thickness

Table 1
Designed dimensions of the cylinder.

Dimensions	Values
Outer diameter, $2r$	625 mm
Cylindrical height, H	392.7 mm
Skin thickness, t_f	1 mm
Rib thickness, t_c	2 mm
Orthogrid thickness, c	8 mm
Circumferential cell number	30
Longitudinal cell number	6
cell dimension, d	65.45 mm
Orthogrid relative density, ρ^*	0.1271