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Short communication

Multi-failure theory of composite orthogrid sandwich cylinder

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Under uniaxial compression, carbon fiber reinforced composite (CFRC) orthogrid sandwich cylinder has four potential failure modes, including global buckling, monocell buckling, rib buckling and material failure. The smearing method was applied to predict the equivalent stiffness and calculate the stresses of the skins and the orthogrid, providing fundaments to build the failure criteria. Theoretical models were established to reveal the failure modes and predict the ultimate load of the compressed orthogrid cylinder by the way of failure maps, providing a feasible way to optimally design CFRC anisogrid cylinder.
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1. Introduction

Recently, composite lattice structures gained more and more attentions for its weight efficiency [1–3]. Among them, CFRC anisogrid structures [4–9] have been applied in rockets, satellites, and airplanes. Usually the structural concept considered for a spacecraft body structure is an anisogrid stiffened laminate configuration [4]. Fan et al. [10–16] developed CFRC anisogrid lattice-core sandwich shells and found the sandwich style endows the cylinder greater stiffness and strength compared with stiffened cylinder [4] through restricting rib buckling [10]. Hu et al. [17] designed and fabricated corrugated lattice truss composite sandwich pane. The lattice core is made up of orthogonal corrugated lattice trusses and this structure was applied to construct CFRC lattice truss sandwich cylinder by Li et al. [17]. Yang et al. [18] developed all-composite corrugated sandwich cylindrical shells.

Under uniaxial compression, CFRC anisogrid-core sandwich cylinder usually has four potential failure modes, including global buckling, facesheet monocell buckling, rib buckling and material failure [10,19]. A smearing method was proposed to predict the equivalent stiffness of the Isogrid sandwich structure [10,19]. Fan et al. [10] and Sun et al. [19] build multi-failure criteria of CFRC Isogrid sandwich cylinder.

In this short communication, a smearing method and multi-failure criteria were developed to analyze the mechanical behaviors of CFRC orthogrid sandwich cylinder.

2. Orthogrid sandwich cylinder

A new type of CFRC orthogrid sandwich cylinder was fabricated by interlocking and filament winding technique [20], as shown in Fig. 1. The diameter of the cylinder, D, is 625 mm. The height, H, is 392.7 mm [21]. The thickness of the skin is 1.0 mm. The thickness of the core layer, c, is 8 mm. The thickness and the width of the orthogrid rib are 2.0 mm and 8.0 m. T700/epoxy-resin CFRC was used to make the cylinder by hot-pressing and filament winding. Through uniaxial compression test, the failure load is 302.75 kN. At the top end of the cylinder, the facesheet failed at laminate delamination, and then induced debonding and wrinkling in post-failure stage. In the test, material failure controls the ultimate load of the cylinder.

3. Equivalent theory

According to the conversion relationship between axial force and deformation in all directions and the stress and strain of the equivalent homogeneous element, the representative element of rectangular orthogrid structure can be equivalent to element of continuum, as shown in Fig. 2. The equivalent elastic modulus, E, of the orthogrid is given by

$$E = \frac{E_{r1} t_r}{h}, \tag{1}$$

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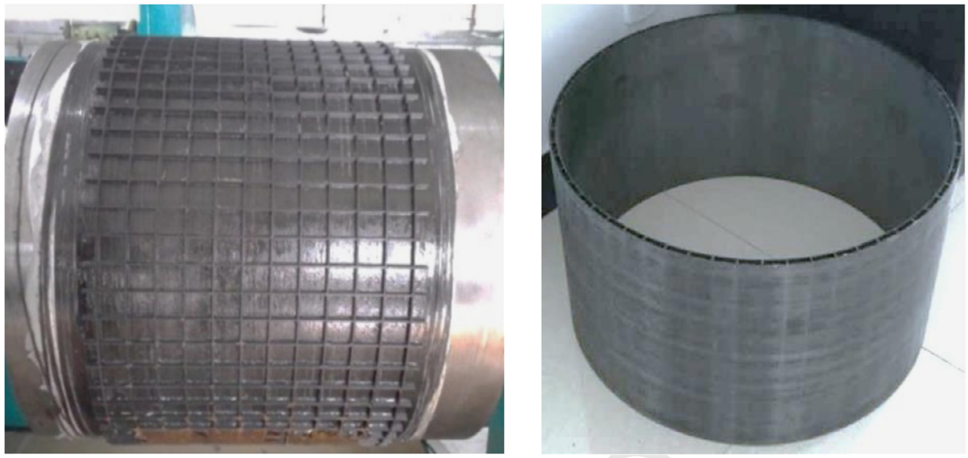

Fig. 1. Orthogrid-core sandwich cylinder [20].

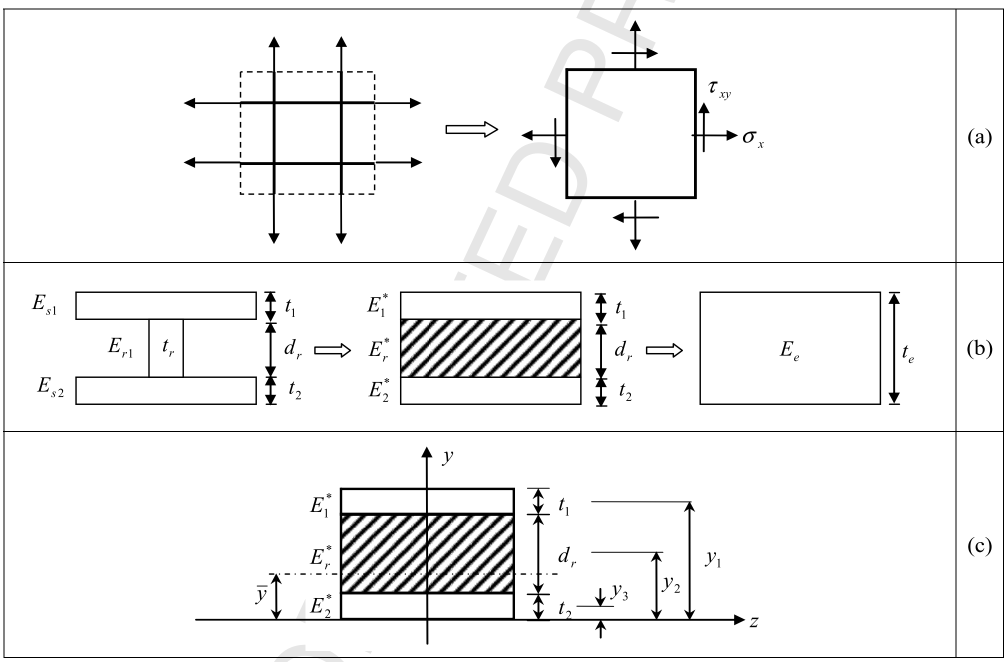

Fig. 2. Equivalent process of (a) the orthogrid and (b) the orthogrid-core sandwich and (c) central coordinate of sandwich structure.

where E_{r1} is the elastic modulus of the orthogrid rib. t_r and h are the thickness of the rib and the length of the unit orthogrid cell. It puts forward that the orthogrid is equivalent to homogeneous structure firstly, then, according to the principle of equivalence that tensile stiffness and bending stiffness are invariable, the sandwich structure is equivalent to a homogeneous panel or shell structure, which has equivalent elastic modulus, E_e, and equivalent thickness, t_e. For the convenience of calculation, it is necessary to define the parameters as follows: E_{s1} and E_{s2} are elastic modulus of external and inner quasi-isotropic skin; t_1 and t_2 are thickness of outer and inner skin; d_r is the thickness of the orthogrid layer; E_1^* and E_2^* are elastic modulus of two skins of sandwich and E_r^* is elastic modulus of sandwich core, as shown in Fig. 2. Defining the relative density of the orthogrid, $\rho^* = 2t_r/h$; the effective thickness of the orthogrid panel, $b = t_r E_{r1}/E_{s1}$; the thickness ratio of the inner and the external skin, $\lambda = t_2/t_1$; the ratio of the height of orthogrid and the thickness of external skin, $\delta = d_r/t_1$; the ratio of elastic modulus of the orthogrid and the external skin, $\eta = E_{r1}/E_{s1}$; the ratio of elastic modulus of inner and external skin, $\xi = E_{s2}/E_{s1}$, the in-plane effective elastic modulus of the orthogrid is $E_r^* = \rho^* E_{r1}/2 = E_{r1}t_r/h$; the ratio of the equivalent tensile stiffness of the core layer and the external skin is $\alpha = \rho^*\eta\delta/2$; the ratio of the equivalent tensile stiffness of the inner and the external skins is $\mu = \lambda\xi$.

In smearing, the orthogrid-core sandwich turns to homogeneous solid shell with equivalent extensile and bending stiffness, as shown in Fig. 2. Since the skin itself is homogeneous, so that $E_1^* = E_{s1}$, $E_2^* = E_{s2}$ and $E_2^* = E_{s2}$. The equivalent extensile stiffness, K_e, is

$$K_e = \left(E_1^* t_1 + E_r^* d_r + E_2^* t_2\right)/\left(1 - \nu^2\right). \tag{2}$$

The equivalent bending stiffness, D_e, is given by:

$$D_e = \frac{E_1^* t_1^3}{12(1-\nu^2)} + E_1^* t_1 (y_1 - \bar{y})^2 + \frac{E_r^* d_r^3}{12(1-\nu^2)} + E_r^* d_r (y_2 - \bar{y})^2 + \frac{E_2^* t_2^3}{12(1-\nu^2)} + E_2^* t_2 (y_3 - \bar{y})^2, \tag{3}$$

where $\bar{y}$ is the location of the neutral axis of the sandwich structure and calculated by

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