Composite Structures 117 (2014) 362–372

Contents lists available at ScienceDirect

Composite Structures

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

Study on vibration damping of composite sandwich cylindrical shell with pyramidal truss-like cores

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ARTICLE INFO

Article history:
Available online 15 July 2014

Keywords:
Cylindrical shell
Sandwich
Composite
Damping
Natural frequency

ABSTRACT

The vibration and damping characteristics of free–free composite sandwich cylindrical shell with pyramidal truss-like cores have been conducted using the Rayleigh–Ritz model and finite element method. The predictions for the modal properties of composite sandwich cylindrical shell with pyramidal truss-like cores showed good agreement with the experimental tests. The influences of fiber ply angles on the natural frequency and damping loss factor were investigated. Three types of such composite sandwich cylindrical shells were manufactured using a hot press molding method and the relevant modal characteristics of various sandwich cylindrical shells could be obtained by modal tests. It can be found that modal strain energy approach was effective to estimate the structural damping loss factors and the variation of damping for each vibration modes could be explained suitably through the contributions of each strain energy components. Results showed that the structural damping loss factors not only depended on inherent material damping, but also relied on the vibration modes. The natural frequencies of composite sandwich cylindrical shell increased with the increasing of the ply angle of the inner and outer curve face sheets, whereas the damping loss factors of present shells did not increase monotonically.

1. Introduction

Sandwich cylindrical shell structures including metal alloys and composites are being increasingly applied to many spacecraft, automobile and construction industries due to their lightweight and highly load carrying capacities. Furthermore, the use of cellular cores for panels and shells not only can further reduce the structural weight, but also potentially possess superior heat dissipation, vibration control and energy dissipation characteristics [1–5]. Some mechanical properties such as compression, bending, impacting and vibration [6–12] have been reported by many scientists. Such cylindrical shell structures may be subjected to external dynamic loads that cause resonance responses, decline of carrying capacities or even destruction. Additionally, the vibrations can cause undesirable noise that can be detected through sonar and put mechanical devices in danger in the case of military vehicles, such as submarines. To date, rare investigations of free vibration analysis, much less the damping characteristics of composite sandwich structures with lattice truss cores are reported. Therefore, it is of considerable importance to investigate and predict the vibration and damping performances of sandwich cylindrical shell structures.

Some typical theories about sandwich plate and shell can be used to analyze the vibration damping properties of sandwich structures [13–25]. For the free vibration problems in the dynamics of composite multilayered shells, it is currently popular to conduct with an energy formulation and then apply Hamilton' principle for different boundary conditions using an approximate solution of the Rayleigh–Ritz method [18–20], and based on that, Maheri and Adams [18] predicted the vibration and damping properties of composite honeycomb sandwich panels using the Reissner–Mindlin first-order shear deformation plate theory combined with Rayleigh–Ritz method. The estimated results were shown good agreement with the results obtained by experiment and finite element method which based on the modal strain energy approach [21–24]. The finite element models based on modal strain energy approach is an efficient method for predict the modal damping loss factors for the three layered laminated composite with and without a viscoelastic core. However, to the author's knowledge, this method has been very scarcely used to investigate the damping characteristics of the composite cylindrical shell and no report for damping analysis of composite sandwich cylindrical shells with lattice truss core could be found. Hence, one of the major purposes of this paper is to apply the

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http://dx.doi.org/10.1016/j.compstruct.2014.06.042

modal strain energy method in the damping analysis and to inspect the suitability of the method for such type of present structures. The vibration and damping analysis for three types of composite sandwich cylindrical shell with pyramidal truss-like cores in a free–free configuration will be conducted. Firstly, a Rayleigh–Ritz vibration model based on the Reissner–Mindlin first-order shear deformation plate theory will be developed to predict the modal characteristics of such sandwich cylindrical shells with free ends. Then, three types of composite sandwich cylindrical shells with pyramidal truss-like core will be fabricated using a hot press molding method. Then, modal tests will be conducted to study the vibration and damping characteristics of such sandwich cylindrical shells. Next, a finite element model based on the modal strain energy approach will be proposed to estimate the structural damping loss factors. The results of analytical and finite element models will be compared to the experimental results and the influences of fiber ply angles on the natural frequency and damping loss factor will also be studied and the conclusion will be made finally.

2. Theoretical formulation

2.1. Assumptions and preliminary definitions

The composite cylindrical sandwich shell with free–free boundary conditions consists of two composite laminated face sheets and a series of pyramidal truss-like cores. Based on the Reissner–Mindlin first-order shear deformation plate theory, some following basic assumptions are necessary to establish to simplify the equations and calculations.

(1) The vibration behaviors are based on linear elastic small deformation analysis.
(2) The shell middle surface normals remain straight and generally no longer perpendicular to the mid-plane after deformation.
(3) For the thin outer and inner face sheets, only the in-plane deformation is considered, for the discrete pyramidal truss-like cores, only out-plane deformation is considered.
(4) Perfect combination is assumed to the outer face sheets, inner face sheets and the pyramidal truss-like cores. There are no defects between each laminates.

The geometry and global orthogonal curvilinear coordinate system (x, φ, z) having its origin in the middle surface of the composite cylindrical shell with pyramidal truss-like cores is shown in Fig. 1. x, φ, z are the axial, circumferential and normal coordinate, respectively. The local fiber-adapted 1, 2, 3 coordinate system can be transferred to the global coordinate system through the transformation matrices [25]. The length of shell, radius of mid-plane of cylindrical shell, thickness of the pyramidal truss-like core and face sheets are denoted as L, R, h and t, respectively (Fig. 1(a)), and as Fig. 1(b) shown, a, b, c, d, l, t, α and β are geometrical parameters of the pyramidal truss-like core. So the relative density of the core can be expressed as:

$$\bar{\rho}_c = \frac{\left[\frac{2ab}{\sin\alpha} + dl + \left(\frac{\pi R}{n} - \frac{h}{\tan\beta} - d\right)\left(c + \frac{2b}{\cos\alpha}\right)\right] Nt}{\pi R h l} \tag{1}$$

where N is the number of core construction unit cell in the circumferential direction.

According to the analytical prediction method of the effective shear stiffness for the lattice core [26], the transverse shear modulus of the pyramidal truss-like cores in x direction and y direction can be similarly derived as:

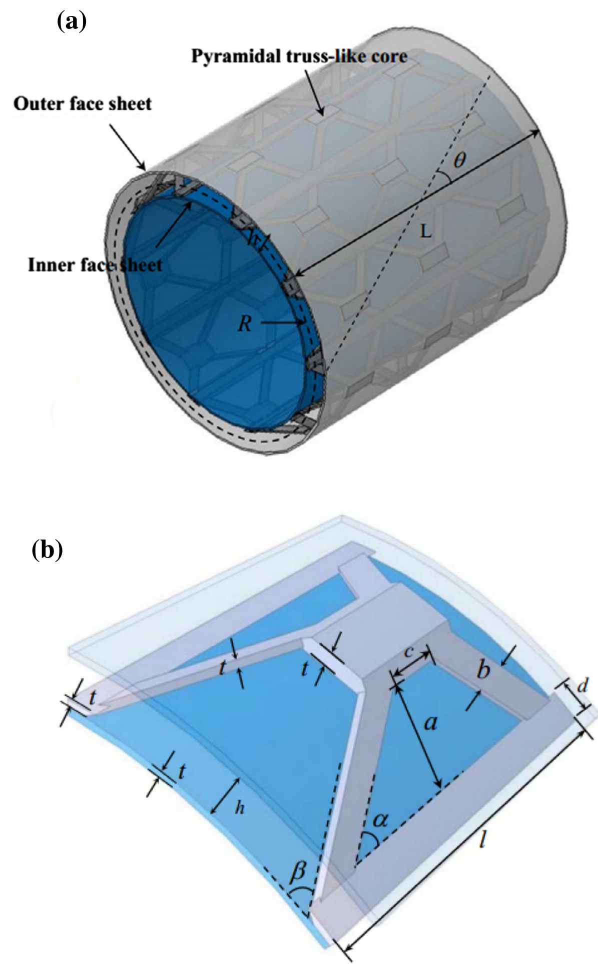

Fig. 1. (a) Diagrammatic drawing of composite sandwich cylindrical shell with pyramidal truss-like cores. (b) Unit cell of pyramidal truss-like core.

$$G_{13}^c = \frac{2E_s\sqrt{1-\sin^2\beta\cos^2\alpha}\cos^2\beta\cos^2\alpha}{\sin\alpha}\frac{nbt}{\pi Rl} \times \frac{h+t}{a}\left[\cos\beta + \frac{t^2(1-\cos^2\beta\cos^2\alpha)}{a^2\cos\beta} + \frac{b^2}{a^2\cos\beta}\right] \tag{2}$$

$$G_{23}^c = 2E_s\cos\beta\cos^3\alpha\frac{nbt}{\pi Rl} \times \frac{h+t}{a}\left[\cos\beta + \frac{t^2(1-\cos^2\alpha\cos^2\beta)}{a^2\cos\beta} + \frac{b^2}{a^2\cos\beta}\right] \tag{3}$$

where E_s denotes the apparent elastic modulus of individual trusses.

2.2. Determination of eigenfrequencies

The analysis of the eigenfrequencies of composite cylindrical shell with pyramidal truss-like cores was based on the minimum total potential energy principle and solved through the Rayleigh–Ritz energy minimization method. Firstly, the displacement field (u, v, w) can be expressed as:

$$\begin{aligned} u(x,\varphi,z) &= u_0(x,\varphi) + z\phi_x(x,\varphi) \\ v(x,\varphi,z) &= v_0(x,\varphi) + z\phi_\varphi(x,\varphi) \\ w(x,\varphi,z) &= w_0(x,\varphi) \end{aligned} \tag{4}$$

where u_0, v_0, w_0 are the mid-plane displacements in axial, circumferential and normal directions, respectively. ϕ_x and ϕ_φ are the total rotations of the normal associated with the transverse shear deformations.