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Free vibration analysis of sandwich beams with honeycomb-corrugation hybrid cores

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ABSTRACT

The vibration performance of sandwich beams with honeycomb-corrugation hybrid cores was investigated in this paper. The method of homogenization was employed to obtain the equivalent macroscopic stiffness of honeycomb-corrugation hybrid cores. Finite element methods and modal analysis techniques have been used to predict their vibration characteristics (*i.e.* their natural frequencies and mode shapes). It is shown that in most cases the predictions by using the equivalent homogenization model (2D model) agree well with the experimental and three-dimensional finite element calculated results. For sandwich beams with corrugated cores, the filling honeycomb not only enhances their flexural rigidity and increases their natural frequency of higher orders, but also more or less eliminates the anisotropy of the structural stiffness and suppresses the local modes of vibration. In addition, considering mass efficiency, a dimensionless frequency parameter was proposed. It was found that the frequency parameter has different sensitivity to the geometry parameters, *i.e.* the slenderness ratio of corrugated member, the face sheet thickness ratio and the relative density of filling honeycomb.

1. Introduction

Due to their multi-functional characteristic, periodic cellular metal sandwich structural body comprising such as honeycomb or corrugated core have been being widely used in such engineering application fields as aerospace, high speed transportation, and submarine [1,2], which put forward the higher demand on physically limited space. However there is still a large amount of space in corrugated, honeycombed and pyramidal cores [3–5] at millimeter scale.

In order to improve their weight and space efficiency, many hybrid cores structures had been constructed to enhance mechanical properties of sandwich structures [6]. Originally filled polymer foams were applied to construct hybrid sandwich cores such as pin-reinforced foams [7–9], polymer foam-filled reinforced composite lattices [10,11], polymer foam-filled metallic corrugation [12–15] and polymer foam-filled honeycomb [16]. However the outcome was disappointing, as sandwiches with polymeric foam-filled cores only performed nearly as well as sandwiches of the same weight with unfilled cores. In recent years, metallic foams having higher strength than polymer foam have already been used as a filling material to form aluminum foam-filled metallic tubes [17] and metal foam-filled metallic corrugation [18–20]. It was surprising that metal foam filling could greatly increase the strength and energy absorption of sandwich structures. The completely different results were attributed to an underlying mechanism: the lateral support to the core member not by weakly but strongly filled foam, altering the deformation modes and considerably delaying core member buckling. However, the weight and space efficiency of new composite structures can still not be carried out adequately. The main reason is that filled foams in these structures have been enhanced next to nothing by such ordered porous materials as metallic corrugation. In order to improve structure efficiency in composite porous structures, new idea about honeycomb-filled corrugated core has been proposed [1,21], which significantly increases the weight and space efficiency of sandwich structures by mutual enhancement of corrugated member and filled honeycomb, *i.e.* the mutual constraint of corrugated member and honeycomb cell walls against buckling changes the deformation mode of structure.

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For large-scale sandwich structures with hybrid cores, it would be important to predict their natural frequencies. In recent years, homogenization equivalent methods have been widely used to obtain the equivalent model of some cellular structures [22–27]. Compared with tedious analytical methods and three dimensional detailed finite element methods (3D model) [22,23], the equivalent method can be used to improve the computational efficiency and further reduce the computational expense. Xia et al. [27] proposed such three equivalent methods as the honeycomb-plate theory, the sandwich theory and the equivalent-plate theory. It was shown that three equivalent methods were reliable and practical, and they can be used for predicting the natural frequencies of honeycomb-sandwich plates. Liu et al. [28,29] derived the effective stiffness matrix of corrugated and lattice truss cores. The equivalent models were used successfully for finite element analysis of characteristic modes. In comparison with the results obtained by three detailed finite element models, the equivalent approach can give acceptable predictions on dynamic behavior of sandwich panels. Yet until recently, Han et al. [15] studied the existing foam-filled corrugated hybrid cores, and obtained their equivalent elastic constants, and studied the vibration characteristics under thermal loading. However, newly honeycomb-corrugation hybrid cores for sandwich structures have rarely been investigated based upon the equivalent model. In this paper, based upon a micromechanics-based model, the effective elastic constants of honeycomb-corrugation hybrid core are derived by the homogenization method. The hybrid core is equivalent to a homogeneous medium used to constitute the equivalent model (2D model). In order to verify its accuracy, the three-dimensional finite element model (3D model) and experimental tests were carried out respectively to predict the vibration characteristics of sandwich structures with hybrid core under clamped-free boundary conditions. The influence of key geometrical parameters on their vibration performance is also explored.

2. Formulation of honeycomb-corrugation hybrid core homogenization

2.1. Homogenization

Based upon the micro-mechanical models with small elastic deformation, the honeycomb-corrugation hybrid cores are treated as homogeneous orthotropic materials as shown in Fig. 1. Geometric parameters of honeycomb-corrugation hybrid cores are: honeycomb cell length l_H, single wall thickness t_H, corrugated member length l_c, corrugation angle θ, the width of corrugation platform d, core height h_c, corrugated member thickness t_c, the sheet thickness t_f. ρ_s represents the density of the corrugated member and honeycomb material. Let E and v denote the Young's modulus and Poisson ratio.

The relative density $\bar{\rho}$ of the honeycomb-corrugation hybrid core is:

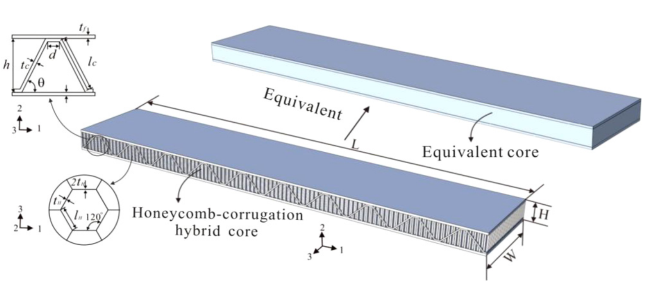

Fig. 1. Schematic diagram of sandwich beam with honeycomb-corrugation hybrid core transformed to equivalent one by homogenization method.

$$\bar{\rho} = \bar{\rho}_C + \bar{\rho}_H(1 - \bar{\rho}_C) \tag{1}$$

where $\bar{\rho}_H$ and $\bar{\rho}_C$ denote the relative density of the honeycomb and empty corrugation core, respectively, and λ is the volume fraction of hybrid core occupied by corrugation member, given by:

$$\bar{\rho}_H = \frac{8t_H}{3(\sqrt{3}l_H + 2t_H)} \cong \frac{8}{3\sqrt{3}}\frac{t_H}{l_H} \tag{2}$$

$$\bar{\rho}_C = \frac{t_c(d + l_c)}{(d + l_c\cos\alpha)(t_c + l_c\sin\theta)} \tag{3}$$

$$\lambda = \bar{\rho}_C \tag{4}$$

It is assumed that the corrugated members and the face sheets are welded together and no slip occurs when subjected to loading. Hence, the corrugated members are treated as Euler-Bernoulli beams with clamped support at both ends. It is further assumed that filling honeycomb and corrugated members keep close contact with each other during deformation. For small strain deformations, the deformation of the face sheets has negligible influence on the geometry of the unit cell.

The honeycomb-corrugation hybrid core may be analyzed at two different scales: (a) at the macro scale, the hybrid core is considered as a homogeneous continuum solid; (b) at the micro-scale, the corrugated members and filling honeycomb are separately considered. The derivation of micro-dium relies on the analysis of its representative volume element (RVE, or unit cell). The analysis parallels that of pin-reinforced foam cores [7] and foam-reinforced corrugated cores [15]. The macroscopic strain energy density of honeycomb-corrugation hybrid core may be written as:

$$U^* = U^C + U^H \tag{5}$$

$$U^C = \frac{1}{\Omega}\sum_{i=1}^{2}\left[\frac{1}{2}\left(\tilde{u}^{(i)} + 2\tilde{u}_p^{(i)}\right)^T\tilde{K}^{(i)}\tilde{u}^{(i)} - \tilde{g}_p^{(i)}\right] \tag{6}$$

$$U^H = (1-\lambda)\left(\frac{1}{2}C^H_{hjkl}E_{hj}E_{kl}\right) + \frac{1}{\Omega}\sum_{i=1}^{2}\tilde{g}_p^{(i)} \tag{7}$$

where U^C and U^H are the strain energy of the corrugated members and filling honeycomb, respectively. Ω denotes the volume of the unit cell. Superscript C and H represent the corrugation and the honeycomb, respectively.

2.2. Small strain kinematics

Consider the deformation of a unit cell comprising of a corrugated member surrounded by filling honeycomb and subjected to a $\bar{x} - \bar{z}$ plane macroscopic strain E as schematically shown in Fig. 2(a). The corrugated member in the $\bar{x} - \bar{z}$ plane can be treated as an Euler-Bernoulli beam of unit width, clamped at both ends. $\tilde{u}^{(i)}$ is the global nodal displacement vector for the ith inclined beam characterized by end nodes ζ and τ (Fig. 2(b)):

$$\tilde{\mathbf{u}}^{(i)} = \mathbf{T}^{\mathrm{T}}\tilde{\mathbf{u}}^{(i)e} \tag{8}$$

$$\tilde{\mathbf{u}}^{(i)e} = [w_\zeta,\ v_\zeta, \theta_\zeta, w_\tau,\ v_\tau, \theta_\tau]^{(i)\mathrm{T}} \tag{9}$$

where $\tilde{\mathbf{u}}^{(i)e}$ denotes the nodal displacement vector under local coordinates (x, z), $\mathbf{T}$ is the transformation matrix between local and global coordinates (see Appendix A), and e represents values in local coordinates. The global nodal displacement vector for the ith beam can be written as:

$$\bar{u}^{(i)} = [\Delta_1, \Delta_2, 0, 0, 0, 0]^{(i)\mathrm{T}} \tag{10}$$