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The influence of correlating material parameters of gradient foam core on free vibration of sandwich panel

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ABSTRACT

For the sandwich panel with mass density gradient (DG) foam core, the Young's modulus of the core varies with the mass density along the thickness direction. To characterize the correlative effect of Young's modulus and mass density of the DG closed-cell foam material, a simplified formula is presented. Subsequently, based on a high-order sandwich plate theory for sandwich panel with homogeneous core, a new gradient sandwich model is developed by introducing a gradient expression of material properties. Finite element (FE) simulation is carried out in order to verify this model. The results show that the proposed model can predict well the free vibration of composite sandwich panel with the gradient core. Finally, the correlating effects of material parameters of the DG foam core on the natural frequencies of sandwich panel are investigated. It is found that the natural frequencies of sandwich panels decrease as the gradient changes of the DG foam cores increase under the condition of that the core masses keep constant.

1. Introduction

The typical sandwich structure [1] is composed of two high-density and high-strength face sheets which are adhesively bonded to a thick core. The cores consist of homogeneous or functionally gradient materials (FGMs) while the anisotropic laminates are commonly adopted as face sheets. With the excellent mechanical properties, sandwich structures have a prospect of wide applications in many fields such as aerospace, marine and civil engineering [2–4].

Over the past few decades, FGMs have attracted many research interests. The FGMs can be divided into two types: I. FG composite material [5,6]; II. FG cellular material [7–9]. The mechanical properties of FG composite materials along thickness direction are achieved by changing the volume fractions of two or more constituent materials, which are generally ceramic and metal. When the vibration and buckling problems of sandwich plate and beam are investigated, the approximations used to model the variation of properties of FG composite materials are usually exponential law [5,10,11] and power law [12–15]. Only some of them are cited here. And each of the material parameters (such as Young's modulus, mass density) is independent in change form. For FG cellular material shown in Fig. 1, such as the DG foam material, it means that the pore structures are gradient from one surface of the material to the other resulting in varying material properties. According to the previous studies on the foam materials by Gibson et al. [16], the correlations of Young's modulus and mass density of the foam material are not mutual independence. Hence, the assumption of material properties in change form for FG composite materials may be not available for FG cellular material. Ashby [17] presented a correlating quadratic polynomial of Young's modulus and mass density for the metallic foam material based on the experimental data and previous studies. However, in their formula a coefficient will be chose by experience. Hence, it's essential to develop an available formula to characterize the correlation of Young's modulus and mass density for FG foam material.

To investigate the influence of material parameters of gradient foam core on the sandwich structures, some theoretical models are developed. Based on the high-order sandwich panel theory [18], Rahmani et al. [19] presented a high-order gradient model for sandwich structures with the FG foam core. In the model, the mass density of gradient foam core is a constant and the Young's modulus varies along the thickness direction. However, the nonlinear polynomial to describe the vertical deformation of the foam core is complex. Amirani et al. [20] employed the element free Galerkin method [21] to investigated the free vibration of sandwich

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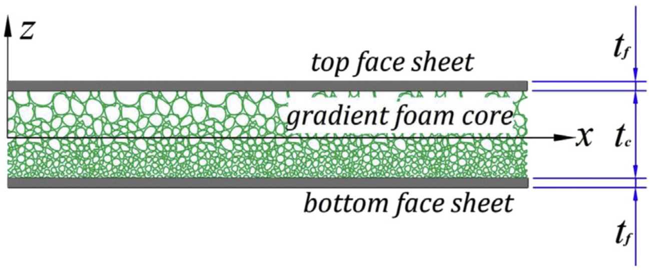

Fig. 1. Sandwich panel with the gradient foam core.

beams with gradient core. In this method, a special penalty method is needed to consider the effect of the material discontinuity between the face sheets and core. Sburlati [22] presented an analytical solution for the elastic bending response of the axisymmetric circular sandwich panels with gradient core in the framework of the elasticity theory. The Young's modulus of the core is assumed to be exponentially dependent on the transverse direction. The results reveal the graded cores can decrease the interface stresses. Neves et al. [23,24] analyzed the free vibration of sandwich plate/shell with gradient core using the Carrera Unified Formulation (CUF) [25,26] and meshless method [27]. In this model, the CUF method is employed to obtain the algebraic governing equations. And the meshless method is used to simplify the governing equations to obtain the vibration equation. The CUF has the advantage of being not restricted to polynomials which account for thickness-stretching effects of FG composite materials. However, the deficiency of this method is that it's difficult to solve the large number of related governing equations. Mashat et al. [28] have investigated free vibration of sandwich beams with gradient core based on the CUF and the FE method. And the natural frequencies are also compared with those calculated by several high order models and finite element method. Recently, Liu et al. [29] presented a refined high-order sandwich panel theory to investigate the free vibration analysis of sandwich plates with both functionally graded face sheets and functionally graded flexible core. In the model, the first order shear deformation theory is used for the face sheets and the a 3D-elasticity solution of weak core in high-order sandwich panel theory [18] is employed for the gradient core. The gradient effective material parameters (such as Young's modulus, mass density) are independent. And the fundamental frequency obtained from the present analytical method is compared with FE result.

In this paper, based on the sandwich plate theory for homogeneous core [30], a new model for the sandwich panel with gradient foam core is developed to investigate the correlating effect of material properties of the gradient foam core on free vibration of sandwich panel. Firstly, Kirchhoff-Love model is used for the face sheets, and the first and second order expansions of the transverse and tangential displacements for the gradient foam core. Secondly, the governing equations of composite sandwich panel with gradient foam core are derived by Hamilton's principle. Thirdly, the Extended Galerkin's Method is adopted to simplify the governing equations and the vibration equation is obtained. Subsequently, a quartic polynomial to characterize the correlating effect of Young's modulus and mass density for the DG closed-cell foam is incorporated into the present gradient model. Finite element (FE) simulation [31] is carried out in order to verify this model. Finally, the correlating effects of material properties of the DG foam core on the natural frequencies of sandwich panel are investigated.

2. Gradient sandwich panel model

2.1. Displacements of the sandwich panel

The sandwich structures such as the leading edges of the swing on the plane or the submarine hull of large aspect ratio are widely used. Hence, sandwich structures can be idealized as a 2D (two dimension) plane-strain problem. The composite sandwich panel with gradient foam core is shown in Fig. 1. In the sketch, t_f, t_c are the thickness of face sheet and gradient foam core, respectively. The length of sandwich panel is l. The material properties of the gradient foam core only vary along the thickness direction.

In order to derive vibration equation of the sandwich panel with gradient foam core, the following assumptions are made: (1) the face sheets are composed of orthotropic material in which the principle material direction is parallel to the x axis; (2) the gradient core is made of flexible material and it is capable of carrying the transverse normal and shear stresses; (3) the face sheets are considered to be incompressible in the transverse direction because of the large tangential stiffness. The Kirchhoff-Love theory is used for the face sheets.

For the sandwich panel, ν_1^i and $\nu_3^i (i = t, c, b)$ represent the displacements in x and z directions, respectively; Superscripts t, c and b represent top face sheet, gradient foam core and bottom face sheet, respectively. The displacements in x and z directions of the top face sheet are governed by:

$$\begin{cases} \nu_1^t = u_1^t(x,t) - \left(z - \dfrac{t_c + t_f}{2}\right) \dfrac{\partial u_3^t(x,t)}{\partial x} \\ \nu_3^t = u_3^t(x,t) \end{cases} \tag{1}$$

where $u_1^t(x,t)$ and $u_3^t(x,t)$ are the mid-surface displacements in x and z direction of the top face sheet, respectively. The variable t signifies the time.

The displacements in x and z directions of the bottom face sheet are calculated by:

$$\begin{cases} \nu_1^b = u_1^b(x,t) - \left(z + \dfrac{t_c + t_f}{2}\right) \dfrac{\partial u_3^b(x,t)}{\partial x} \\ \nu_3^b = u_3^b(x,t) \end{cases} \tag{2}$$

where $u_1^b(x,t)$ and $u_3^b(x,t)$ are the mid-surface displacements in x and z direction of the bottom face sheet, respectively.

The displacements of the core [30] are written as:

$$\begin{cases} \nu_1^c = u_1^a(x,t) - \dfrac{t_f}{2}\dfrac{\partial u_3^d(x,t)}{\partial x} + \dfrac{2z}{t_c}u_1^d(x,t) + \dfrac{t_f z}{t_c}\dfrac{\partial u_3^a(x,t)}{\partial x} + \left[\dfrac{4z^2}{(t_c)^2} - 1\right]\varphi_1^c(x,t) \\ \nu_3^c = u_3^a(x,t) + \dfrac{2z}{t_c}u_3^d(x,t) \end{cases} \tag{3}$$

where $\varphi_1^c(x,t)$ is an additional warping function describing the