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Bending analysis of sandwich plates with different face sheet materials and functionally graded soft core

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A B S T R A C T

This paper presents an investigation on the bending response of functionally graded material (FGM) sandwich plates under transverse distributed loadings. A new model of FGM sandwich plate is developed. The top face sheet and the bottom face sheet have different material properties. The material properties of the functionally graded soft core are assumed to be graded depending on the volume fractions of the constituents in the thickness direction. The governing equations are deduced based on the static equilibrium method. Containing only three unknowns, these equations are then solved via Navier approach. Benchmark comparisons of the new model solutions with the solutions of several other theories are conducted to verify the rationality and efficiency of the proposed method. The influences of volume fraction distribution, the thickness to side ratio and the layer thickness ratio on plate bending characteristics are studied in detail.

1. Introduction

Sandwich structures, due to their outstanding properties, such as high specific stiffness and strength as well as energy absorption capability, have been widely used in areas of aircraft, aerospace, naval/marine, construction, transportation, and wind energy systems [1–3]. However, the abrupt change in material properties across the interfaces between the face sheets and the core can result in large interlaminar stresses, often leading to delamination, which is a major problem in sandwich structures. One of solutions to this problem is to explore the functionally graded material (FGM) in sandwich design. FGMs are a class of advanced composite materials in which the material properties vary continuously and smoothly, thus eliminating the above mentioned abrupt changes in properties [4,5]. FGM sandwich structures can be divided into two types: type-A, sandwich plates with FGM face sheets and homogeneous core; type-B, sandwich plates with homogeneous face sheets and FGM core [6,7].

Heretofore, a number of studies have investigated the bending of FGM sandwich plates. Zenkour [8] presented a sinusoidal shear deformation theory to study the bending of a simply supported type-A FGM sandwich plate. Wang and Shen [9] carried out a nonlinear bending analysis of a type-A sandwich plate resting on elastic foundations by a two-step perturbation technique. Merdaci et al. [10] employed a four-variable refined plate theory [11–13] to investigate the bending behavior of type-A FGM sandwich plates. Thai et al. [14] presented analytical solutions for bending analysis of type-A FGM sandwich plates using a new first-order shear deformation theory (FSDT). Mahi et al. [15] developed a new hyperbolic shear deformation theory for the bending of type-A FGM sandwich plates. Bessaim et al. [16] extended a new higher-order shear and normal deformation theory [17–19] to the static analysis of type-A FGM sandwich plates. In their study, the number of unknown functions is five and the thickness stretching effect [20,21] is considered. Thai et al. [22] analyzed the bending of type-A FGM sandwich plates by using a new simple four-unknown shear and normal deformations theory. It is noted that all the above mentioned studies focus on type-A FGM sandwich plates.

For type-B FGM sandwich plates, Kashtalyan and co-workers [23,24] presented an investigation into the bending behavior of type-B sandwich plates based on a 3D elasticity solution. In their studies, the sandwich plate is assumed to be symmetric with respect to the mid-plane. Abdelaziz et al. [25] studied the bending response of two types of FGM sandwich plates using a four-variable refined plate theory. Based on the Reissner assumptions, Li et al. [26] studied the bending of simply supported type-B sandwich plates with functionally graded (FG) soft core and orthotropic face sheets subjected to transverse distributed loadings. In their study, both of the face sheets are assumed to be membranes made of the same materials. Ferreira et al. [27] analyzed the bending of a type-B FGM sandwich plate using a quasi-3D higher-order shear deformation theory (HSDT) and a meshless technique. Liu et al. [28] used a layerwise theory and a differential quadrature finite element method for the analysis of type-B FGM sandwich shells. Alibeigloo and Alizadeh [29] carried out a static analysis of type-B FGM

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sandwich plates based on the three dimensional theory of elasticity using state space differential quadrature method. Mantari and Granados [30] developed a new FSDT which contains only four unknowns to analyze the static behavior of type-B FGM sandwich plates. Nguyen et al. [31] investigated a rotation-free moving Kriging meshfree approach for two types of isotropic FGM sandwich plates based on a refined plate theory. In the above studies into bending of type-B sandwich structures apart from Ref. [26], the FGM core is considered as hard core.

In the structural design, the soft core is commonly employed because of its light weight, which is especially of vital importance in the field of aeronautics and astronautics [32,33]. In this paper, a new model for the bending analysis of FGM sandwich plates with FG soft core is developed based on the Hoff assumptions. In the model, the face sheets are considered as thin plates made of different materials and the mechanical properties of the soft core are assumed to be graded in the thickness direction in terms of the volume fractions of the constituents. The bending of simply supported sandwich plate subjected to transverse distributed loadings is analyzed. The governing equations are derived by static equilibrium method, and then solved via Navier solution. It is shown that the solution process only deals with solving three simultaneous differential equations for three unknown functions. Numerical examples are presented to verify the rationality of the proposed method. The influences of several parameters are discussed. This study is relevant to aerospace structures and wind turbine systems in which light weight and high bonding strength are required.

2. Theoretical formulation

Consider a sandwich plate composed of three layers as shown in Fig. 1. The Cartesian coordinate system xyz has the plane $z = 0$ coinciding with the mid-plane of the sandwich plate. The bottom skin is made of an isotropic metal material, while the top skin is made of an isotropic ceramic material. The Young's modulus of the FGM core follows an arbitrary function $E_c(z)$ through the thickness, and the Poisson's ratio μ is assumed to be constant.

Instead of using the Reissner assumptions, the Hoff assumptions [34] are adopted in this paper and are given as follows:

(1) The face sheet is considered to be a thin plate.
(2) Since the Young's modulus of the core is relatively lower than those of faces, the stresses in the xy-plane in the core are assumed to be negligible, i.e. $\sigma_x^c = \sigma_y^c = \tau_{xy}^c = 0$.
(3) In the face sheets and the core, the z-direction normal stress and strain are so small that they are neglected.

2.1. Stress and displacement fields in the core

The equilibrium differential equations of the core are

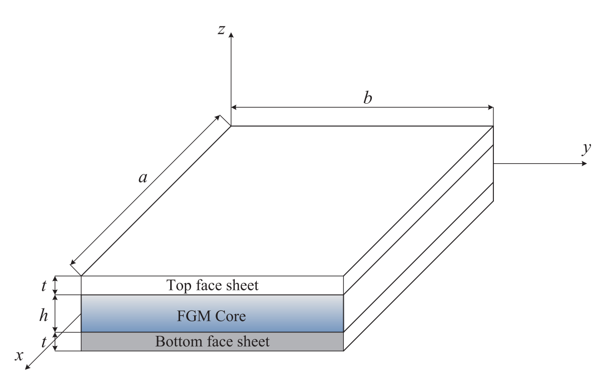

Fig. 1. Sandwich plate with FGM core and isotropic homogeneous face sheets.

$$
\begin{aligned}
&\frac{\partial \sigma_x^c}{\partial x} + \frac{\partial \tau_{yx}^c}{\partial y} + \frac{\partial \tau_{zx}^c}{\partial z} = 0\\
&\frac{\partial \sigma_y^c}{\partial y} + \frac{\partial \tau_{zy}^c}{\partial z} + \frac{\partial \tau_{xy}^c}{\partial x} = 0\\
&\frac{\partial \sigma_z^c}{\partial z} + \frac{\partial \tau_{xz}^c}{\partial x} + \frac{\partial \tau_{yz}^c}{\partial y} = 0
\end{aligned} \tag{1}
$$

where the body forces are neglected. By considering the assumptions (2) and (3), Eq. (1) can be simplified to be

$$
\begin{aligned}
&\frac{\partial \tau_{zx}^c}{\partial z} = 0\\
&\frac{\partial \tau_{zy}^c}{\partial z} = 0
\end{aligned} \tag{2}
$$

It can be deduced from Eq. (2) that the shear stresses τ_{zx}^c and τ_{zy}^c are uniform through the thickness of the core. Consequently, the shear stresses τ_{zx}^c and τ_{zy}^c can be expressed by the shear forces of the core Q_x^c and Q_y^c

$$
\tau_{xz}^c = \frac{Q_x^c}{h},\ \tau_{yz}^c = \frac{Q_y^c}{h} \tag{3}
$$

where h is the thickness of the core. According to the geometric equations and the linear elastic constitutive relations, the shear strains are as follows:

$$
\begin{aligned}
&\gamma_{xz}^c = \frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} = \frac{Q_x^c}{G_c(z)h}\\
&\gamma_{yz}^c = \frac{\partial w}{\partial y} + \frac{\partial v}{\partial z} = \frac{Q_y^c}{G_c(z)h}
\end{aligned} \tag{4}
$$

where u, v and are the displacement along x, y and z-axis, respectively. $G_c(z)$ is the shear modulus of the core, which is given by

$$
G_c(z) = \frac{E_c(z)}{2(1+\mu)} \tag{5}
$$

The displacements of the core are obtained by integrating Eq. (4) with respect to z

$$
\begin{aligned}
&u = \frac{2(1+\mu)Q_x^c}{h} J_0(z) - z\frac{\partial w}{\partial x}\\
&v = \frac{2(1+\mu)Q_y^c}{h} J_0(z) - z\frac{\partial w}{\partial y}
\end{aligned} \tag{6}
$$

where

$$
J_0(z) = \int \frac{1}{E_c(z)} \mathrm{d}z \tag{7}
$$

2.2. Displacement and stress fields in the face sheets

On the basis of assumption (1), the displacement field in the mid-plane of the face sheets can be written as

$$
\begin{aligned}
&u_{mid}^{\pm} = \frac{2(1+\mu)Q_x^c}{h} J_0\left(\pm\frac{h}{2}\right) \mp \frac{h+t}{2}\frac{\partial w}{\partial x}\\
&v_{mid}^{\pm} = \frac{2(1+\mu)Q_y^c}{h} J_0\left(\pm\frac{h}{2}\right) \mp \frac{h+t}{2}\frac{\partial w}{\partial y}
\end{aligned} \tag{8}
$$

where the superscripts (+) and (-) denote the top and bottom face sheets of the sandwich plate, respectively.

Then the displacement field in the face sheets can be expressed as

$$
\begin{aligned}
&u^{\pm} = \frac{2(1+\mu)Q_x^c}{h} J_0\left(\pm\frac{h}{2}\right) - z\frac{\partial w}{\partial x}\\
&v^{\pm} = \frac{2(1+\mu)Q_y^c}{h} J_0\left(\pm\frac{h}{2}\right) - z\frac{\partial w}{\partial y}
\end{aligned} \tag{9}
$$

Using constitutive equations, the stress field in the face sheets is