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Mechanical behavior of functionally graded sandwich plates on elastic foundation

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ABSTRACT

A new hyperbolic shear and normal deformation plate theory, presented in this paper, is used to study the static, free vibration and buckling analysis of the simply supported functionally graded sandwich plates on elastic foundation. This theory accounts for the realistic variations of the displacements through the thickness. In the analysis, two common types of FGM sandwich plates, namely, homogeneous face sheets with FGM core and FGM face sheets with homogeneous core are considered. The elastic foundation is described by the Pasternak model. The equations of motion are derived from Hamilton's principle. The closed form solutions are obtained by using Navier technique. Numerical results of present theory are compared with three-dimensional elasticity solutions and other higher-order theories reported in the literature. It can be concluded that the proposed theory is simple and efficient in predicting the mechanical behavior of functionally graded sandwich plates.

1. Introduction

Functionally graded material (FGM) is a type of heterogeneous composite material that exhibits a continuous variation of mechanical properties from one point to another. This material is produced by mixing two or more materials in a certain volume ratio. Material properties of FGM vary along the material size depending on a function. The concept of FGM was first considered in Japan in 1984 during a space plane project. Several studies have been performed to analyze the mechanical behavior of FG beams, plates and shells. Tornabene et al. [1] presented the dynamic analysis of doubly-curved shell structures using the generalized displacement field of the Carrera Unified Formulation (CUF), including the Zig-Zag (ZZ) effect given by the Murakami's function. Barretta and Luciano [2] proposed a new solution procedure, based on a correspondence principle between a linearly elastic, homogeneous and orthotropic Saint-Venant beam under torsion and an isotropic linearly viscoelastic and functionally graded Kirchhoff plate with no kinematic constraints on the boundary. Tornabene et al. [3] investigated recovery of through-the-thickness transverse normal and shear strains and stresses in statically deformed functionally graded (FG) doubly-curved sandwich shell structures and shells of revolution using the generalized zigzag displacement field and the Carrera Unified Formulation. Barretta et al. [4] founded new closed-form solutions of functionally graded beams undergoing nonuniform torsion by detecting axial distributions of longitudinal and shear moduli inducing an axially uniform warping field. Barretta et al. [5] analyzed the bending problem of functionally graded Bernoulli–Euler nanobeams starting from a nonlocal thermodynamic approach and proposed new nonlocal models. Barretta et al. [6] investigated the elastic equilibrium of two-phase random composite beams under torsion, with simply and multiply connected cross-sections. Barretta et al. [7] investigated the small-scale effects in nanorods with Young moduli which are functionally graded in the cross-section domain by nonlocal continuum mechanics. Barretta and Luciano [8] proposed an effective solution procedure, based on an analogy between functionally graded orthotropic Saint-Venant beams under torsion and inhomogeneous isotropic Kirchhoff plates, with no kinematic boundary constraints. Fantuzzi et al. [9] investigated the dynamic behavior of moderately thick FGM plates with geometric discontinuities and arbitrarily curved boundaries.

In many applications, the sandwich plate is a laminated construction, consists of two or more thin face sheets connected by one or more thick core in order to achieve superior properties such as light weight, high strength for noise, vibration, thermal isolation and long fatigue life, wear resistance. Although sandwich structures offer advantages to other types of structures, the sudden

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change in material properties across the bond between the face sheets and core cause delamination which is the most common type of damage for sandwich plates. To overcome this adverse feature, the functionally graded materials (FGMs) can be used. FG materials are a type of composite materials whose properties vary gradually and continuously from one surface to another. Because of the continuous change in material properties of a FGM, the interfaces between two materials disappear. Due to this feature, the FGMs have some advantages such as eliminating the material discontinuity and avoiding the delamination failure, reducing the stress levels and deflections. Combination of these characteristics attracts application of FGMs in sandwich structures.

The many advantages of sandwich structures attract the engineers to use them in nearly all phases of structure work from roof and wall panels to the thermal isolation of the buildings, from space craft to marine vessels. The significant increase in the use of sandwich structures requires the development of rigorous mathematical models to predict their response under any given set of conditions. For this purpose, several refined theories have been proposed by various authors. Zenkour [10] presented a two-dimensional theory for bending analysis of simply supported FG ceramic–metal sandwich plates. The field equations are derived for FG sandwich plates whose deformations are governed by either the shear deformation theories or the classical theory. Zenkour [11] used the sinusoidal shear deformation plate theory, presented in the first part of his paper, to study the buckling and free vibration of the simply supported FG sandwich plate. Effects of rotatory inertia are considered. The critical buckling load and the vibration natural frequency are investigated. Li et al. [12] studied the free vibration of FGM sandwich rectangular plates with simply supported and clamped edges based on the three-dimensional linear theory of elasticity. The three displacements of the plates are expanded by a series of Chebyshev polynomials multiplied by appropriate functions to satisfy the essential boundary conditions. The natural frequencies are obtained by Ritz method. Brischetto [13] analyzed the bending response of several sandwich plates with a FG core, using advanced equivalent single layer and layerwise models with linear to fourth-order expansion in the thickness direction. The FG properties of the core have been approximated by means of Legendre polynomials. Zenkour and Alghamdi [14] studied the bending response of sandwich plates subjected to thermo-mechanical loads. Field equations for FG sandwich plates whose deformations are governed by either the shear deformation theories or the classical theory are derived. Displacement functions that identically satisfy boundary conditions are used to reduce the governing equations to a set of coupled ordinary differential equations with variable coefficients. Exact solutions for FGM sandwich plates are presented. El Meiche et al. [15] presented a new hyperbolic shear deformation theory taking into account transverse shear deformation effects for the buckling and free vibration analysis of thick FG sandwich plates. Abdelaziz et al. [16] introduced a new displacement based high-order shear deformation theory for the static response of FG sandwich plate. Hadji et al. [17] used a four-variable refined plate theory for the free vibration analysis of FGM sandwich rectangular plates. Merdaci et al. [18] developed two refined displacement models for a bending analysis of FG sandwich plates. Xiang et al. [19] developed a n-order model for FG and composite sandwich plate. This model uses the n-order polynomial term to represent the displacement field. Carrera et al. [20] evaluated the effect of thickness stretching in plate/shell structures made by materials which are FG in the thickness directions. That is done by removing or retaining the transverse normal strain in the kinematics assumptions of various refined plate/shell theories. Variable plate/shell models are implemented according to Carrera's Unified Formulation. Zenkour and Shoby [21] presented the static response of simply supported FGM viscoelastic sandwich plates subjected to transverse uniform loads. The FG sandwich plates are considered to be resting on Pasternak's elastic foundations. The sandwich plate is assumed to consist of a fully elastic core sandwiched by elastic-viscoelastic FGM layers. Neves et al. [22] proposed a variation of Murakami's Zig-Zag theory for the analysis of FG sandwich plates. The new theory includes a hyperbolic sine term for the in-plane displacements expansion and accounts for through-the-thickness deformation, by considering a quadratic evolution of the transverse displacement with the thickness coordinate. Natarajan and Ganapathi [23] investigated the bending and the free flexural vibration behavior of sandwich FGM plates using QUAD-8 shear flexible element developed based on higher order structural theory. The governing equations obtained are solved for static analysis considering two types of sandwich FGM plates. Viola et al. [24] investigated the static analysis of doubly-curved laminated composite shells and panels. A theoretical formulation of 2D higher order shear deformation theory has been developed. Tornabene and Reddy [25] focused on the static analysis of functionally graded (FGM) and laminated doubly-curved shells and panels resting on nonlinear and linear elastic foundations using the Generalized Differential Quadrature (GDQ) method. Viola et al. [26] proposed a 2D higher-order shear deformation theory of moderately thick laminated doubly-curved shells and panels by using differential geometry to define the arbitrary shape of the middle surface of shells and panels with different curvatures. Tornabene et al. [27] proposed a general formulation of a 2D higher-order equivalent single layer theory for free vibrations of thin and thick doubly-curved laminated composite shells and panels with different curvatures. Neves et al. [28] derived a higher-order shear deformation theory for modeling FG plates accounting for extensibility in the thickness direction. The explicit governing equations and boundary conditions are obtained using the principle of virtual displacements under Carrera's Unified Formulation. The static and eigen problems are solved by collocation with radial basis functions. Zenkour [29] presented a refined trigonometric higher-order plate theory for bending analysis of simply supported FG ceramic–metal sandwich plates. The effects of transverse shear strains as well as the transverse normal strain are taken into account. Kamarian et al. [30] focused on the free vibration characteristics of FG sandwich rectangular plates resting on Pasternak foundations using the three-dimensional elasticity theory. Xiang et al. [31] used the meshless global collocation method based on the thin plate spline radial basis function and nth-order shear deformation theory to analyze the free vibration of sandwich plate with FG face and homogeneous core. Bessaim et al. [32] developed a new higher-order shear and normal deformation theory for the bending and free vibration analysis of sandwich plates with FG isotropic face sheets. Tornabene et al. [33] presented the static and dynamic analyses of laminated doubly-curved shells and panels of revolution resting on the Winkler–Pasternak elastic foundation using the generalized differential quadrature (GDQ) method. The analyses have been worked out considering the first-order shear deformation theory (FSDT). Sayyad and Ghugal [34] developed a sinusoidal shear and normal deformation theory taking into account effects of transverse shear as well as transverse normal for the analytical solution of the bidirectional bending analysis of isotropic, transversely isotropic, laminated composite and sandwich rectangular plates. Nguyen et al. [35] proposed a new inverse trigonometric shear deformation theory for the static, buckling and free vibration analyses of isotropic and FG sandwich plates. It accounts for inverse trigonometric distribution of transverse shear stress and satisfies the traction free boundary conditions. Thai et al. [36] presented a generalized shear deformation theory for static, dynamic and buckling analysis of FGM sandwich