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A finite element formulation for thermally induced vibrations of functionally graded material sandwich plates and shell panels

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ABSTRACT

A finite element formulation based on a higher-order layerwise theory is presented for the first time to investigate thermally induced vibrations of functionally graded material (FGM) sandwich plates and shell panels. The properties of FGM sandwich are assumed to be position and temperature dependent. The upper and lower layers of the sandwich panel are considered to be made of pure ceramic and metal, respectively and the elastic properties of FGM core are varied according to a power-law function. The top surface is exposed to a thermal shock and the bottom surface of the panel is either kept at a reference temperature or thermally insulated. The one-dimensional transient heat conduction equation is solved using a central difference scheme in conjunction with the Crank-Nicolson method. A higher-order layerwise theory is used for FGM sandwich panels, in which a higher-order displacement field for the FGM core and a first-order displacement field for the facesheets are assumed. The governing equations are solved using Newmark average acceleration method. It is shown that the proposed layerwise finite element formulation is simple and can easily be applied to investigate FGM sandwich plates and shell panels subjected to rapid heating.

1. Introduction

A typical sandwich structure consists of one or more layers of high-strength and high-stiffness facesheets (or skin) bonded to flexible core. Functionally graded materials are often used in high temperature applications such as nuclear, space and many other applications. Introduction of an FGM core along with ceramic and metal facesheets reduces deformations in sandwich structures. The elastic properties of the FGM sandwich panel vary continuously across the thickness of the panel. Since functionally graded sandwich panels are employed in high temperature applications, understanding thermally induced vibrations in such panels is essential for its application in high temperature structures.

The phenomenon of thermal induced vibrations was first reported by Boley [1] for a thin Euler-Bernoulli rectangular beam subjected to a sudden heat flux at the top surface while the bottom surface was thermally insulated. Kraus [2] examined the response of simply supported non-shallow spherical shells exposed to a rapid heat flux on one surface and the other surface, thermally insulated. Lu and Sun [3] studied the response of truncated thin conical shell subjected to rapid heating. Stroud and Mayers [4] analyzed displacement and stress histories of dynamic thermoelastic response of rapidly heated plate elements. Boley [5] presented a simple approximation for maximum dynamic deflection to static deflection ratio of heated beams and plates and studied the effect of damping, axial and in-plane loads. Jadeja and Loo [6] investigated thermally induced vibration of a rectangular plate with one edge fixed and other three edges having simply supported boundary conditions. Nakajo and Hayashi [7] investigated thermally induced vibrations of simply supported and clamped circular plates using an analytical method, finite element method (FEM) and also through experiments. Huang and Tauchert [8] examined the dynamic response of doubly curved, cross-ply laminated panels subjected to rapid heating. Chen et al. [9] presented dynamic structural response of thin walled configurations with arbitrary open cross sections under the influence of rapid heating by considering bending and torsional coupling effects. Khdeir [10] proposed an exact analytical solution for the dynamic response of cross-ply shallow shells with two parallel edges simply supported and remaining two edges clamped. Park and Banerjee [11] carried out two and three dimensional transient uncoupled thermoelastic analyses for an isotropic material by particular integral formulation. Akour and Nayfeh [12] studied thermally induced transverse displacement of unidirectional, cross-ply and anti-symmetric

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angle-ply composite plates. Kumar et al. [13] presented a finite element model for the active control of thermally induced vibration of laminated composite shells with piezoelectric sensors and actuators. Hong [14] investigated the rapid uniform heat induced vibration of two-layer cross-ply laminated shell using a generalized differential quadrature (GDQ) method.

Considering the importance of FGM structures, some researchers took up studies on FGM plate and shells subjected to thermal shock. Tanigawa et al. [15] solved one-dimensional transient heat conduction problem of a plate made of nonhomogeneous materials and considering temperature dependent material properties. Santos et al. [16] presented a semi-analytical axisymmetric finite element model using the three-dimensional linear elasticity theory for thermoelastic analysis of functionally graded cylindrical shells subjected to transient thermal shock loading. Kar and Kanoria [17] investigated the thermoelastic stresses, displacement and temperature distribution in a functionally graded orthotropic hollow sphere due to sudden temperature change. The thermal and mechanical properties of FGM were assumed to vary as the power of radial co-ordinate variable. Yun et al. [18] obtained analytical solutions for the temperature field by using Laplace transform and Dirac function and obtained the thermal stress response for a thick walled cylinder. Zhou et al. [19] presented a generalized coupled thermoelasticity based formulation to study the transient thermoelastic response of functionally graded rectangular plates. Akbarzadeh and Chen [20] analyzed transient heat conduction in functionally graded (FG) hollow cylinders and spheres by using non-Fourier heat conduction theories. Wang [21] proposed an analytical approach for transient thermal analysis in functionally graded hollow cylinder based on the laminate approximate theory. Dai and Rao [22] investigated nonlinear dynamic behavior of a long hollow FGM cylinder having temperature-dependent elastic properties subjected to a thermal shock. Jiang and Dai [23] obtained analytical solutions for three-dimensional steady and transient heat conduction problems of a double-layer plate with a local heat source. Zhang et al. [24] presented a transient thermal stresses of a functionally graded (FG) cylindrical shell subjected to a thermal shock using differential quadrature. Dai et al. [25] investigated thermoviscoelastic dynamic behavior of double-layered hollow cylinder made of a viscoelastic and homogenous layers subjected to a thermal shock. Zhang et al. [26] used differential quadrature method to solve transient displacements of FGM cylindrical shell under dynamic thermal loading. Kiani and Eslami [27], Ghiasian et al. [28] and Alipour et al. [29] studied thermally induced vibrations and highlighted the importance of temperature dependent elastic properties on the thermal response of FGM beams and plates.

Higher-order shear deformation theories (HSDT) are considered to accurately predict the static and dynamic behavior of plate and shell panels. In the HSDT, the displacement fields are considered to have cubic variation and the transverse shear strains to have parabolic variation across the thickness of the panel, eliminating the use of shear correction factor. Many of these theories considered the displacement field according to the Taylor series expansion and are based on the model proposed by Lo et al. [30]. Also, higher-order theories proposed by Reddy [31] and Reddy and Liu [32] for analysis of laminated plate and shells are propular. However, Reddy's third-order theories required C^1 continuity and to overcome this requirement, Kant and Pandya [33] presented a C^0 continuous higher-order finite element formulation for static analysis of laminated and sandwich plates. Though the HSDT based equivalent single layer theories give accurate results for laminated panels, the use of layerwise theory is mandatory for analysis of sandwich structures [34].

From the detailed review of literature, the authors found that thermally induced vibration of laminated structures are investigated in detail. But, research focus on thermally induced vibration of FGM panels is limited and not in proportion with the significance of the usage of FGM in high temperature applications. Moreover, to the best of authors' knowledge, studies on FGM sandwich plate and shell panels subjected to thermal shock are not available in the literature. Therefore, in the present work, a finite element formulation is proposed for investigating thermally induced vibrations of FGM sandwich panels using a higher-order layerwise theory. This theory is an extension of the authors' earlier theory on plates [35]. The top layer of the three-layered sandwich panel is considered to be made of ceramic, whereas the bottom surface is made of pure metal. The core of the FGM sandwich is composed of ceramic and metal and has elastic properties graded along the thickness direction according to a power-law function. The properties of FGM core are also assumed to be temperature dependent. In order to study the thermally induced vibration of the FGM panel, the ceramic (top) surface of the panel is subjected to a thermal shock and the metal (bottom) surface is kept at a reference temperature or thermally insulated. The one-dimensional transient heat conduction equation is solved using central difference scheme in conjunction with the Crank-Nicolson method. A higher-order displacement fields for the core and first-order displacement field for both top and bottom facesheet are assumed in the proposed layerwise theory. Conditions are imposed at the layer interface to satisfy the interlaminar displacement continuity. An eight-noded isoparametric element is used in the finite element formulation and the governing equations are solved using Newmark average acceleration method. First, the authors' results are validated with those available in the literature for thermal induced vibration of isotropic and single layered FGM plates. Next, a parametric study is conducted to examine the effects of varying volume fraction index (n), core to facesheet thickness ratio, radius of curvature and boundary conditions on the dynamic response of FGM sandwich panels subjected to thermal shock. This study shows that the layerwise finite element formulation presented here is simple and can be easily applied for wide range of geometries and boundary conditions.

2. Mathematical formulation

2.1. FGM sandwich shell configuration and material properties

Consider a three layered shell made of functionally graded sandwich material. The top (layer 3) and bottom (layer 1) facesheets of the sandwich are made of ceramic and metal, respectively and the core (layer 2) is made of FGM (Fig. 1). The radii of curvature of the shell panel along x and y directions are R_x and R_y, respectively. The projection of the shell on x-y plane is a rectangle of dimensions a and b. Functionally graded materials are primarily used in high temperature applications and their elastic properties such as Young's modulus E, Poisson's ratio ν, coefficient of thermal

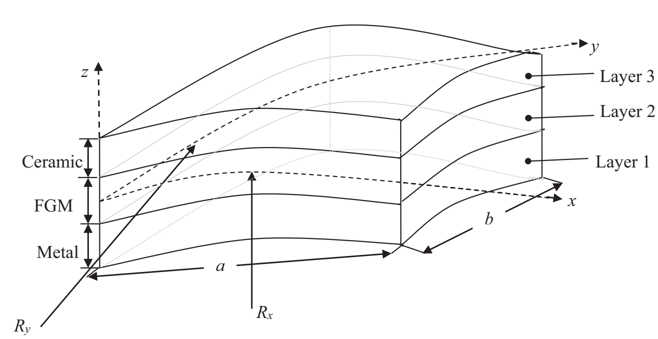

Fig. 1. Sandwich shell with FGM core and homogenous facesheets.