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Thermoelastic analysis of functionally graded doubly curved shell panels using nonlinear finite element method

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ABSTRACT

In this article, large amplitude flexural behaviour of functionally graded doubly curved shell panel is investigated numerically under the thermomechanical load. The nonlinear mathematical model of doubly curved shell panel is developed first time based on higher-order shear deformation theory and Green–Lagrange geometrical nonlinearity. In order to achieve the exact flexure of the structure, all the nonlinear higher order terms are included in the mathematical model. The effective material properties of functionally graded material (metal/ceramic) have been obtained based on Voigt's micromechanical model. The continuous gradation of metal and ceramic is achieved through the power-law distribution. The governing equation of the panel structure is obtained using the variational principle and a direct iterative method is employed to compute the desired responses numerically. The convergence behaviour of the proposed numerical analysis has been checked and validated through different comparisons to that available literature. Wide variety of examples is solved to reveal the effect of different geometrical parameters, material properties, constraint conditions and thermal and/or mechanical loads on the linear and nonlinear flexural behaviour of functionally graded curved panels.

1. Introduction

The concept of functionally graded material (FGM) was first conceptualised in Japan during a space project [1] programme. FGMs are the advanced form of composites which exhibit an inhomogeneous character specially designed for high-temperature applications such as aircraft engines, rocket heat shields, thermal barrier coatings, heat exchanger tubes, etc. Hence, the analysis and modelling of FGM made components are now being highlighted by many researchers to overcome the design/manufacturing difficulties. In general, FGM comprises of metal and ceramic in which ceramic offers high heat-resistant and anti-oxidant properties on the high-temperature side and toughened and strengthened by the metallic composition on low-temperature side. These tailor-made properties of FGM are achieved by changing the material composition gradually from metal to ceramic which results in reduction or elimination of residual stresses. Some of the recent reviews on the vibration, bending and the solution techniques of functionally graded (FG) structures are presented in details [2–5]. Now, to define the objective of the present work some of the earlier and recent important contributions are discussed in the following lines.

Yang and Shen [6] investigated the nonlinear bending and the post-buckling behaviour of FG plate through perturbation technique and one-dimensional differential quadrature approximation using classical plate theory (CPT) and von-Karman nonlinear kinematics. Kiani et al. [7] solved analytically the static and dynamic responses of FG doubly curved panels using modified Sander's shell kinematics in the framework of the first order shear deformation theory (FSDT). Navazi and Haddadpour [8] reported exact solution of nonlinear bending responses of shear deformable FG plate. The mathematical model has been developed using the FSDT kinematics and von-Karman nonlinearity. Dai et al. [9] investigated the static and dynamic behaviour of FG plate using mesh free radial point interpolation method in the framework of FSDT mid-plane kinematics. Thai and Choi [10] developed a simple FSDT kinematic model to analyse the bending and the vibration behaviour of FG plates. In order to overcome the lacuna of the FSDT the vibration and bending responses are again analysed using a new higher-order shear deformation theory (HSDT) by Thai and Kim [11]. Upadhyay and Shukla [12] investigated the nonlinear static and dynamic responses of FG skew flat panel using the HSDT mid-plane kinematics and von Karman nonlinearity. Talha and Singh [13] reported the free vibration and linear static responses of shear

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deformable FG flat panels using the HSDT type mid-plane kinematics. Mantari et al. [14] examined the bending responses of FG plate in the framework of the HSDT type mid-plane kinematics to achieve the exact flexure of the structural deformation. Oktem et al. [15] investigated bending behaviour of flat and doubly curved FG shell panels using the modified higher-order theory. Neves et al. [16,17] examined the static and the free vibration behaviour of FG plate through a collocation method in conjunction with radial basis functions using two different plate kinematics (hyperbolic sine shear deformation theory and hybrid quasi-3D sinusoidal shear deformation theory). Santos et al. [18] presented the bending and vibration responses of FG cylindrical panel using semi-analytical axisymmetric finite element (FE) model based on the 3D linear elastic theory.

In addition to the above, the linear and/or nonlinear bending behaviour of FG flat/curved panels under thermoelastic loading have also been reported in past using various shear deformation theories. Woo and Meguid [19] investigated large deflection responses of FG flat and spherical shell panel under thermo-mechanical loading based on the CPT kinematics and von-Karman type geometrical nonlinearity. Zhao et al. [20] studied the static and the free vibration responses of FG shell based on Sander's FSDT kinematics and solved using element-free kp-Ritz method under thermal environment. Zhao and Liew [21] reported the nonlinear responses of FG cylindrical shell panels under mechanical and thermal loading using the modified Sander's shell theory and the element-free kp-Ritz method. Reddy [22] presented Navier's solutions in conjunction with finite element method (FEM) to analyse the linear and the nonlinear responses of FG plate under the thermo-mechanical load. The mathematical model of FG flat panel has been developed using the FSDT and the HSDT type mid-plane kinematics and von-Karman nonlinearity. Shen [23] presented analytical solutions of the nonlinear thermo-mechanical bending responses of FG plate in the framework of the HSDT plate kinematics. Yang and Shen [24] investigated nonlinear thermoelastic bending responses of FG plate under different support conditions using the HSDT mid-plane kinematics and von-Karman nonlinearity. Bich and Tung [25] solved analytically the nonlinear axisymmetric responses of FG spherical shell panel under uniform external pressure including temperature effect. Bich et al. [26] reported analytical solutions of the nonlinear static and the dynamic buckling responses of FG shallow spherical shells by taking the combined effect of the pressure and the temperature. Zenkour and Sobhy [27] developed a mathematical model of simply-supported FG plate resting on Pasternak's elastic foundation using the sinusoidal shear deformation plate theory to analyse thermoelastic bending response. Qian et al. [28] reported thermoelastic deformation behaviour of thick simply-supported FG plate using a mesh-less local Petrov–Galerkin method. Na and Kim [29] employed a 3D FEM to examine the nonlinear bending behaviour of FG plate under the thermo-mechanical load.

A significant number of work has already been reported in open literature to examine the mechanical responses (static, dynamic and stability behaviour) of flat/curved and isotropic/orthotropic/laminated composites/FG structures under combined thermo-mechanical load using higher order mid-plane kinematics by considering C^0 type FE model to avoid the mathematical complexities [30–41].

It is clear from the above review that, the nonlinear bending behaviour of FG doubly curved shell panels in the framework of the FSDT/HSDT and the geometrical nonlinearity under thermoelastic load are very limited. Based on the authors' knowledge, no work has been reported yet on the nonlinear thermoelastic behaviour of FG single/doubly (cylindrical, hyperbolic and elliptical) curved shell panels in the framework of the HSDT mid-plane kinematics and Green–Lagrange type geometrical nonlinearity. Hence, the present study aims to develop a general nonlinear mathematical model for single/doubly curved FG shell panel in the framework of the HSDT and Green–Lagrange nonlinear kinematics first time to analyse the nonlinear bending responses under thermomechanical load. The effective FG material properties are introduced through Voigt's micromechanical model and graded from top to bottom via a power-law distribution. In addition to this, all the nonlinear higher order terms are incorporated in the present formulation to count the exact flexure of the FG curved panels due to the large deformation. The desired governing equation of the FG curved panel is obtained through the variational principle and discretised using a nine noded isoparametric Lagrangian element with nine degrees of freedom per node. The desired flexural responses are computed using a direct iterative method. The convergence behaviour of the present numerical results have been checked and validated by comparing the responses to those available published literature. Finally, the effects of different parameters (thickness ratios, curvature ratios, power-law indices, aspect ratios and support conditions) on the linear and the nonlinear bending responses of different FG curved panels are discussed in details.

2. Effective material properties of FGM

The present FGM panels are assumed to be varying continuously from metal (at bottom surface) to ceramic (at the top surface) along the thickness direction according to the power-law distribution [42]. The volume fractions of ceramic constituent as per the power-law distribution in any metal-ceramic graded material can be written as:

$$V_{f_c} = \left(\frac{2z+h}{2h}\right)^n \tag{1}$$

where, n $(0 \leqslant n < \infty)$ is the power-law index and it defines the material variation profile to generate infinite number of composition distributions in between the metal-ceramic phase. Similarly, z is any arbitrary point in the transverse direction whereas, h represents the total thickness of the assumed panel. The effect of power-law indices on the volume fractions of the ceramic and metal along with their thickness direction are plotted in Figs. 1 and 2. The

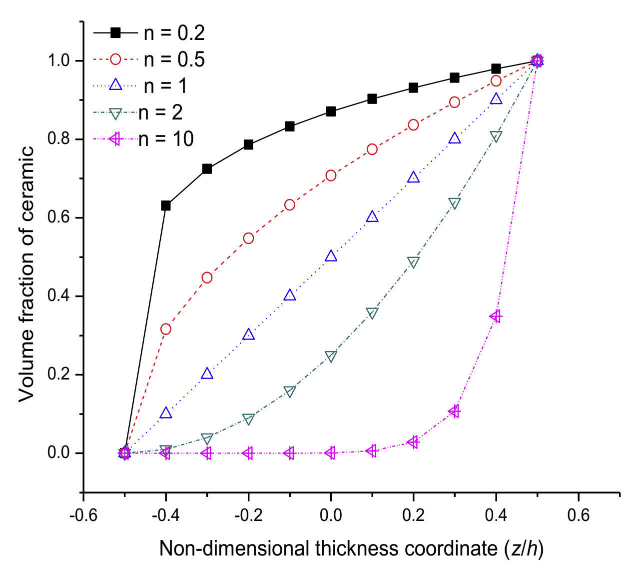

Fig. 1. Effect of power-law index on volume fraction of ceramic along thickness direction.