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Nonlinear thermomechanical deformation behaviour of P-FGM shallow spherical shell panel

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Abstract In the present article, the linear and the nonlinear deformation behaviour of functionally graded (FG) spherical shell panel are examined under thermomechanical load. The temperature-dependent effective material properties of FG shell panel are evaluated using Voigt's micro-mechanical rule in conjunction with power-law distribution. The nonlinear mathematical model of the FG shell panel is developed based on higher-order shear deformation theory and Green-Lagrange type geometrical nonlinearity. The desired nonlinear governing equation of the FG shell panel is computed using the variational principle. The model is discretised through suitable nonlinear finite element steps and solved using direct iterative method. The convergence and the validation behaviour of the present numerical model are performed to show the efficacy of the model. The effect of different parameters on the nonlinear deformation behaviour of FG spherical shell panel is highlighted by solving numerous examples.

1. Introduction

Functionally graded materials (FGMs) are the advanced class of composite while the constituents are graded in one or more direction with continuous variation to achieve the desired properties. The smooth grading of constituents result in better thermal properties, higher fracture toughness, improved residual stress distribution and the reduced stress intensity factors.[1] The above-discussed characteristics allow FGM structures to withstand large mechanical load under elevated thermal environment. Hence, the analysis of FGM structures through the mathematical model by taking one and all the complexities into the consideration are the major concern of the researchers. It is also true that experimental analysis of such complex problems is not only costly but also tough to achieve. Some of the important contributions on the linear and nonlinear deflection behaviour of FGM flat/curved panels under thermal and/or mechanical load are discussed in the following lines.

Nonlinear bending and the post-buckling responses of functionally graded (FG) plate are analysed by Yang and Shen,[2] using perturbation technique and 1-D differential quadrature approximation based on the classical plate theory (CPT) and von Karman nonlinear kinematics. In the continuation towards improvement, the static and dynamic behaviour of the FG flat/curved panel have been analysed

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using first-order shear deformation theory (FSDT).[3–5] Navazi and Haddadpour[6] reported exact solution of nonlinear bending responses of FG plate using the FSDT mid-plane kinematics and von Karman nonlinearity. In order to achieve the parabolic transverse shear through the thickness of the FG plate,[7] the mid-plane kinematics of the plate structure is evaluated using higher-order shear deformation theory (HSDT). Abdelaziz et al.[8] proposed new higher-order theory to obtain the bending response of FG sandwich rectangular plate. Upadhyay and Shukla[9] examined the nonlinear static and dynamic behaviour of FG skew plate using von Karman type nonlinear kinematics in the framework of the HSDT. Oktem et al.[10] examined the bending behaviour of flat and doubly curved FG panel in the framework of the HSDT mid-plane kinematics. Thai and Choi[11] developed a refined plate theory to analyse the static, vibration and buckling behaviour of FG plate resting on elastic foundation. Bourada et al.[12] developed a refined trigonometric higher-order beam theory to examine the vibration and the bending behaviour of FG beams. Yahia et al.[13] employed different higher-order shear deformation plate theories for wave propagation in FG plates. Meziane et al.[14] presented an efficient refined shear deformation theory to investigate the vibration and the buckling behaviour of exponentially graded sandwich plate resting on elastic foundation under different support conditions. Belabed et al.[15] employed an efficient and simple higher-order shear and normal deformation theory to study the bending and the free vibration behaviour of FGM plate. Draiche et al.[16] examine the free vibration behaviour of laminated plate with a localized patch mass using trigonometric four variable plate theory. Bousahla et al.[17] proposed a new trigonometric higher-order theory including the stretching effect to examine the static responses of FG plates. Hebali et al.[18] developed a new quasi-three-dimensional hyperbolic shear deformation theory to analyse the bending and the free vibration analysis of FG plates. Larbi et al.[19] developed an efficient shear deformation beam theory based on neutral surface position to examine the bending and the free vibration of FG beams. Few more layered/graded/sandwich type structures are analysed using higher-order shell theories for the computation of realistic responses.[20–23]

It is well known that the FG structures are well suited to elevated thermal environment and very few numerical and/or analytical thermoelastic analysis of FG flat/curved panels are reported in the open literature. Woo and Meguid[24] studied the nonlinear bending of flat and spherical FG panel under combined thermo-mechanical loading based on the CPT kinematics and von Karman nonlinearity. The linear and nonlinear static responses are computed for FG shell panel subjected to thermomechanical loading in the framework of Sander's FSDT kinematics with the advent of mesh-free kp-Ritz method.[25,26] The analytical/numerical nonlinear solutions for FG plate under combined thermomechanical load have been investigated using HSDT kinematics with von Karman nonlinearity.[27–29] Wattanasakulpong et al.[30] employed an improved HSDT mid-plane kinematics to examine the free and forced vibration behaviour of FG plate under thermal environment. The nonlinear flexural and stability responses of FG spherical shell panels under thermomechanical load are solved analytically.[31,32] Na and Kim[33] investigated the nonlinear bending responses of FG plate under different thermal environment using 3D finite element method (FEM). Zidi et al.[34] employed a four variable refined plate theory to study the bending of FGM plate resting on elastic foundation and subjected to hygro-thermo-mechanical load. Tounsi et al.[35] proposed a refined trigonometric shear deformation theory with the transverse shear deformation effect for bending analysis of FG sandwich plates under thermomechanical load. Bouderba et al.[36] presented the thermomechanical bending of FG plates resting on Winkler–Pasternak elastic foundations using the refined trigonometric shear deformation theory. Khalfi et al.[37] examined thermal buckling of solar FG plate resting on two-parameter Pasternak's foundations using a refined and simple shear deformation theory. Attia et al.[38] employed different refined plate theories to examine the vibration behaviour of temperature-dependent FG plates. Hamidi et al.[39] studied the bending analysis of FG sandwich plates subjected to thermomechanical loading using a sinusoidal plate theory. Houari et al.[40] developed a new higher-order shear and normal deformation theory to examine the bending behaviour of FGM sandwich plates under thermomechanical load.

It is clear from the above review that the studies related to the nonlinear bending analysis of the FG flat/curved panel are very few in numbers. We note that most studies are presented on the linear flexural analysis without considering the temperature effect. Based on the authors' knowledge, no study has been reported yet in open literature on the nonlinear bending analysis of power-law based FGM (P-FGM) spherical shell panel by considering Green-Lagrange type geometrical nonlinearity and the HSDT mid-plane kinematics with/without temperature-dependent material properties. In addition to the above, all the nonlinear higher-order terms are included in the present mathematical formulation to compute the exact flexural responses. Hence, in this present work, authors' aim to develop a general nonlinear mathematical model of P-FGM shallow shell panel with temperature-dependent properties of each constituent (ceramic and metal) in the framework of the HSDT mid-plane kinematics and Green-Lagrange type full nonlinearity. In this study, the P-FGM shell panel properties are computed using Voigt's micromechanical model and the desired nonlinear governing equation is developed through variational approach. The domain has been discretised using suitable finite element steps and a direct iterative method is introduced to compute the desired nonlinear solution. Wide varieties of numerical examples are exemplified to highlight the effect of different geometrical and material parameters on the linear and nonlinear thermomechanical responses of the P-FGM shallow spherical shell panel.

2. Mathematical formulations

2.1. Kinematic model for shallow spherical shell panel

For the analysis purpose, a shallow spherical shell panel with a rectangular base ($a \times b$) is developed mathematically in Cartesian coordinates (x–y–z) as shown in Fig. 1. Here, h is the total panel thickness and, R_x and R_y are the radii of curvature of mid-plane along x- and y- axis, respectively. The displacement field of the present P-FGM spherical shell panel is defined in the HSDT mid-plane kinematics[41] as