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Thermo-elastic analysis of functionally graded circular plates resting on a gradient hybrid foundation

A. Behravan Rad

Department of Mechanical Engineering, Karaj Branch, Islamic Azad University, Karaj, Iran
Chassis and Power Train Division, Engineering Department, ZAMYAD Company (Saipa Group), Comm. Vehicles Mfg. Co. Km 15, Old Karaj Rd., Tehran, Iran

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ABSTRACT

In this paper an attempt is made to investigate the thermo-elastic behavior of functionally graded (FG) circular plates embedded on gradient hybrid foundation and subjected to non-uniform asymmetric mechanical and uniform thermal loads. The supporting medium is modeled as the Horvath–Colasanti type foundation with variable coefficients in the radial and circumferential directions. The thermal environment is assumed to be uniform over the bottom and top surfaces of the plate and varies along the thickness direction only. The governing state equations are extracted in terms of displacements and temperature based on 3D theory of thermo-elasticity, and assuming the material properties of the plate except the Poisson's ratio vary continuously throughout the thickness direction according to an exponential function. These equations are solved using a semi-analytical method and some numerical results are displayed to clarify the effects of material heterogeneity indices, foundation stiffness coefficients, foundation gradient indices, loads ratio and temperature difference between the upper and lower surfaces of the plate on displacement and stress fields. The results are reported for the first time and the new results can be used as a benchmark for researchers to validate their numerical and analytical methods in the future.

1. Introduction

Recently, a new class of materials known as functionally graded materials (FGMs) has been introduced in the literature. FGMs have received considerable attention by researchers in recent years because those novel thermo-mechanical properties enable them to be widely used in many scientific and engineering disciplines, such as aerospace, vehicles, mechanical, optics, electronics, nuclear and biomedical engineering. Rectangular and circular plates made of FGMs resting on elastic foundations often find various applications in engineering fields. Practical applications may be found in the power transmission systems, photographic facilities, support tables, driven plates of a friction clutch, biological organs resting on artificial organs and Nano-structures embedded in an elastic matrix or resting on an elastomeric substrate.

The bending, vibration, stability and buckling responses of plates to mechanical and thermal loads, with/without considering the interaction between structure–foundation have been studied by many scientists and numerous papers have been published.

Some researchers have investigated thermo-elastic behavior of the functionally graded rectangular/circular plates employing the plate theories. For example, the transient nonlinear thermo-elastic behavior of a ceramic/metal FG

E-mail addresses: behravanrad@gmail.com, abehravanrad@aol.com

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rectangular plate was investigated by Praveen and Reddy [1] by applying the Von Karman plate theory and the finite element method. Reddy and Cheng [2] presented a three-dimensional analytical solution for the thermo-mechanical response of a simply supported FG rectangular plate by using an asymptotic expansion method. Vel and Batra [3] analyzed three-dimensional deformations of a simply supported FG rectangular plate under mechanical and thermal loads on its top and bottom surfaces by extending an analytical method. Shao et al. [4] analyzed thermo-mechanical behavior of functionally graded hollow circular cylinders under axisymmetric mechanical and transient thermal loads by employing the Laplace transform and the Galerkin technique in conjunction with series method to solve the governing differential equations. Brischetto et al. [5] derived thermo-elastic deformations of a simply supported FG rectangular plate by using the principle of virtual displacements. Matsunaga [6] applied the two-dimensional higher order shear deformation theory to describe the thermo-elastic behavior of a FG rectangular plate with simply supported edges and subjected to thermo-mechanical loads. Bodaghi and Saidi [7] presented an analytical solution based on the Reddy's higher-order shear deformation theory and energy method to investigate the thermo-elastic buckling behavior of FG thick rectangular plate. Kiani and Eslami [8] considered the buckling and post-buckling behavior of sandwich plates with FGM face sheets under uniform temperature rise loading and resting on a Pasternak type elastic foundation based on the first-order shear deformation plate theory by employing the single mode approach and Galerkin technique. Bouidjra et al. [9] presented the buckling behavior of FG rectangular plate under the various thermal loads based on a four-variable refined plate theory and noticed that this theory can predict accurately the critical temperatures of the plate relative to other plate theories. Khorshidvand et al. [10] studied the thermal buckling of FG circular plates integrated with piezoelectric layers under the uniform, linear and nonlinear temperature variation and constant voltage. They applied the energy method with the use of calculus of variations based on the classical plate theory to obtain the critical buckling temperature. Gomshei and Abbasi [11] developed a finite element formulation for analyzing the axisymmetric thermal buckling of variable thickness of FG annular plates subjected to arbitrary distribution thermal loads along the plate radial direction. Gaikwad [12] studied thermo elastic deformation of thin hollow circular disk due to the partially distributed and axisymmetric heat supply on the upper surface, and analyzed thermo-elastic deformations analytically based on Kirchhoff–Love's hypothesis and introduced an integral transforms method to analysis the temperature field. Bouderba et al. [13] analyzed thermo mechanical bending response of FG thick rectangular plates resting on Winkler–Pasternak elastic foundations by using four-variable refined plate theory. Kiani and Eslami [14] studied analytically the buckling of heated FG annular plates resting on a conventional Pasternak-type elastic foundation based on the classical plate theory under the effect of various thermal loads. Alipour and Shariyat [15] investigated the free vibration of FG annular sandwich plates resting on non-uniform Winkler-type elastic foundation based on a zigzag global–local plate theory. They solved resulting coupled differential equations by using a finite Taylor's transformation technique. Kiani and Eslami [16] studied analytically thermal buckling of transversely graded circular plate attached to a centric partial Winkler-type elastic foundation based on the classical plate theory and considering the distribution of thermo-mechanical properties of the plate across the thickness direction according to power law function. Abbasi et al. [17] analyzed the static behavior of FG circular plates by power law distribution of constituents and resting on Winkler-type elastic foundation by employing the differential transforms method to solve the governing differential equation obtained based on the classical plate theory.

Among the numerical methods that have been employed for solving the governing equations of the rectangular/circular plates, the finite element method, the differential quadrature rule and meshless local Petrov–Galerkin (MLPG) method have been considerable interests. Gunes and Reddy [18] studied the behavior of geometrically nonlinear FG circular plates under the effect of thermo-mechanical loads. They used Green–Lagrange strain tensor and finite element method to derive and solve the governing equations. Afsar and Go [19] applied the finite element method to analysis of thermo elastic field in a thin FG circular disk subjected to thermal load and an inertia force due to rotation of the disk. They considered the thermo-mechanical properties of the plate constituents graded in radial direction and formulated the governing equation of an axisymmetric problem based on the two dimensional thermo elastic theories. Pradhan and Murmu [20] analyzed thermo-mechanical vibration behavior of FG and FG sandwich beams resting on variable elastic foundations using differential quadrature (DQ) method. Safaeian et al. [21] applied the differential quadrature (DQ) method to present the effects of thermal environment and temperature dependence of the material properties on axisymmetric bending of FG circular and annular plates. Based on the Reissner–Mindlin theory, Sladek et al. [22–23] analyzed the thermo-elastic behavior of rectangular plate and shallow shells with FGM properties under stationary and thermal shock loads by means of meshless local Petrov–Galerkin (MLPG) method.

It is evident that results of the three-dimensional theory of elasticity are exact and more accurate than the plate theories, therefore some researchers reported the static, dynamic, vibration and thermo-elastic behavior of FG rectangular/circular plates based on 3D elasticity theory. Based on the state-space formalism, Wen et al. [24] presented a three dimensional solution for dynamic analysis of orthotropic functionally graded rectangular plate with simply supported edges under static and dynamic loads. Assuming the material properties to vary with an exponential law in transverse direction, Li et al. [25] investigated the axisymmetric thermo-elastic field in a FG circular plate under thermal load and they presented an analytical solution to solve the governing equations using direct displacement method. Nie and Zhong [26] analyzed the three-dimensional free and forced vibration of functionally graded circular plate with various boundary conditions based on three dimensional elasticity theory by using semi-analytical method (State space and one dimensional differential quadrature rule). Alibeigloo [27] carried out an exact solution for three dimensional thermo-elastic analysis of FG rectangular plate with simply supported edges and subjected to thermo-mechanical loads. Moreover, he [28] studied the thermo-elastic behavior of FG rectangular plate with simply supported edges and integrated with piezoelectric sensor and actuator layers under the effect