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Thermo-elastic analysis of axially functionally graded rotating thick cylindrical pressure vessels with variable thickness under mechanical loading

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ABSTRACT

Using higher-order shear deformation theory (HSDT) and multi-layer method (MLM), a semi-analytical solution has been performed for the purpose of thermo-elastic analysis of functionally graded (FG) rotating thick cylindrical pressure vessels with variable thickness subjected to the temperature gradient and internal non-uniform pressure. Three different profiles (convex, linear and concave) are considered for the vessel with variable thickness. The material properties, except the Poisson's ratio, are assumed to vary with the power law function in the axial direction of the vessel. The governing equations, which are a system of differential equations with variable coefficients, have been solved with MLM. The effects of higher-order approximations on the radial and axial displacements, von Mises stress, and shear stress have been studied. Finally, some numerical results are presented to study the effects of mechanical and thermal loading, thickness profile type, and gradient index on the mechanical behavior of the cylindrical pressure vessel.

1. Introduction

Functionally graded material (FGM) is an inhomogeneous material with a gradually changing composition and structure of two materials with different properties (Zhou, Du, Song, Zhong, & Ge, 2007). FGMs have been analyzed in a variety of applications for the last three decades (Nejad & Fatehi, 2015; Birman, 2014). On other hand, thick shells involving cylindrical pressure vessels, in recent years, are widely used in space vehicles, aircrafts, nuclear power plants and many other engineering application (Nejad, Jabbari, & Ghannad, 2015a, 2015b, 2015c). A number of papers considering various aspects of cylindrical vessels have been investigated under various assumptions and conditions (Nejad & Kashkoli, 2014; Wu & Wang, 2015; Tokovyy & Ma, 2015).

Thermo-elastic analysis of thick cylinders is a topic which can be readily found in most standard elasticity books (Boresi & Paslay, 1965). Sherief and Anwar (1988) considered the problem of an infinitely long annular cylinder whose inner and outer surfaces are subjected to known surrounding temperatures and traction free. Through the application of a perturbation approach, Obata and Noda (1994) investigated the thermal stresses in a FGM hollow sphere and in a hollow circular cylinder. In other work, they presented the solution for thermal stresses of a thick hollow cylinder, under a two-dimensional transient temperature distribution, made of FGM (Obata & Noda, 1997). Reddy and Chin (1998) studied the dynamic thermo-elastic

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response of functionally graded (FG) cylinders and plates. Based on approximate solutions of temperatures and thermal stresses, the optimization of the material composition of an FGM hollow circular cylinders under thermal loading was discussed (Ootao, Tanigawa, & Nakamura 1999). Zimmerman and Lutz (1999) derived an exact solution for the problem of uniformly heating a cylinder whose elastic moduli and thermal expansion coefficient vary linearly with radius. Tarn (2001) studied the thermo-mechanical states in a class of FG cylinders under extension, torsion, shearing, pressuring, and temperature changes. Assuming that the material has a graded modulus of elasticity, while the Poisson‘s ratio is a constant, Tutuncu and Ozturk (2001) investigated the stress distribution in the axisymmetric structures. They obtained the closed-form solutions for stresses and displacements in FG cylindrical and spherical vessels under internal pressure. Jabbari, Sohrabpour, and Eslami (2002) performed a general analysis of one-dimensional steady-state thermal stresses in a hollow thick cylinder made of FGM. El-Naggar, Abd-Alla, Fahmy, and Ahmed (2002) investigated the radial deformation and the corresponding stresses in a non-homogeneous hollow elastic cylinder rotating about its axis with a constant angular velocity. Liew, Kitipornchai, Zhang, and Lim (2003) presented an analysis of the thermo-mechanical behavior of FG hollow circular cylinders. Shao (2005) presented the solutions of temperature, displacements, and thermal/mechanical stresses in a FG circular hollow cylinder by using a multi-layered approach based on the theory of laminated composites.

An accurate method for conducting elastic analysis of thick-walled spherical pressure vessels subjected to internal pressure was devised by You, Zhang, and You (2005). Ruhi, Angoshtari, and Naghdabadi (2005) presented a semi-analytical thermoelasticity solution for thick-walled finite-length cylinders made of FGMs. Jabbari, Bahtui, and Eslami (2006) developed the analysis of axisymmetric mechanical and thermal stresses for a long hollow cylinder made of FGM, as functions of radial and longitudinal directions. Kordkheili and Naghdabadi (2007) presented an analytical thermoelasticity solution for hollow finite-length cylinders made of FGMs exposed to thermal loads, internal pressure and axial loadings. Assuming the different states of material properties including Poisson‘s ratio, modulus of elasticity, the yield strength, the coefficient of thermal expansion and the thermal conductivity, Argeso and Eraslan (2008) assessed the thermo-elastic response of cylinders and tubes. Eipakchi (2010) calculated the stresses and displacements of a pressure vessel with varying thickness under non-uniform internal pressure using higher-order shear deformation theory (HSDT). He found that the first-order shear deformation theory (FSDT) is sufficient for determining the displacements, but that for calculating the von Mises Stress it is necessary to use a higher-order approximation for the radial displacements. Based on FSDT and the virtual work principle, Nejad, Rahimi, and Ghannad (2009) obtained a complete and consistent 3-D set of field equations to characterize the behavior of FG thick shells of revolution with arbitrary curvature and variable thickness. Ozturk and Gulgec (2011) investigated elastic–plastic deformation of a solid cylinder with fixed ends, made of FGM with uniform internal heat generation, based on Tresca’s yield criterion and its associated flow rule, considering four of the material properties to vary radially according to a parabolic form.

In the recent years, Alashti and Khorsand (2012) carried out three-dimensional nonlinear thermo-elastic analysis of a FG cylindrical shell with piezoelectric layers under the effect of asymmetric thermo-electro-mechanical loads. Arefi and Rahimi (2012) obtained with the thermo elastic analysis of a clamped-clamped FG pressure vessel. Ootao and Ishihara (2012) concerned with the theoretical analysis of the FG magneto-electro-thermoelastic hollow cylinder due to uniform surface heating. Using the differential quadrature method, Alashti, Khorsand, and Tarahhomi (2013) carried out asymmetric deformation and stress analysis of a FG hollow cylindrical shell under thermo-mechanical loading. Bîrsan, Sadowski and Pietras (2013) studied the deformation of thermo-elastic multi-layered shells, using a Cosserat model. Aziz and Torabi (2013) derived analytical solutions for thermal stresses (radial, tangential, and axial) in a hollow cylinder with uniform internal heat generation for the thermal boundary condition of convective heating on the inside surface and convective cooling on the outside surface. Nejad, Jabbari and Ghannad (2014a, 2014b) derived an elastic solution for the purpose of determining displacements and stresses in a rotating thick cylindrical shell with variable thickness under uniform pressure where multi-layers method (MLM) has been used for solution. In their work, they converted a hollow cylinder with variable thickness into some disk layers and assumed the thickness to be constant in each disk. In other work, they derived an elastic solution for the purpose of determining displacements and stresses in a thick pressure vessel which MLM has been used for solution (Nejad et al., 2014a, 2014b). They obtained the MLM is very suitable for the purpose of calculation of radial stress, circumferential stress, shear stress and radial displacement, but it is not useful for axial stress and not useful at all for axial displacement. Ghannad and Gharooni (2012) presented an elastic analysis and a closed form analytical solution for rotating FG thick walled hollow cylindrical shells subjected to constant internal and/or external pressure. They observed that FSDT method has acceptable results, but the radial and von Mises stresses resulted from FSDT show a significant difference by the results calculated from HSDT and FEM solution.

Nejad and Kashkoli (2014) investigated time-dependent thermo-elastic creep response for isotropic rotating thick-walled cylindrical pressure vessels made of FGM, taking into account the creep behavior of the pressure vessels, as described in Norton’s model. Zenkour and Abbas (2014) discussed the problem of generalized thermoelasticity with one relaxation time for an infinite annular cylinder of temperature dependent physical properties. Dai and Dai (2014) presented an analytic study for thermo-elastic bending of a FGM cylindrical shell subjected to a uniform transverse mechanical load and non-uniform thermal loads. Akbarzadeh and Chen (2014) obtained analytical solutions for multi-physical responses of an FG, thermo-magneto-elastic, rotating hollow cylinder as well as a homogeneous orthotropic thermo-magneto-electro-elastic cylinder. Although the behavior of thick shells with radially gradient were studied in many papers, but researchers have less attention to this structures with axially gradient. This despite the fact that the axially gradient materials in some industrial parts, such as air-jet machining and sand-blasting process, can be used (Jianxin, Lili, & Mingwei,