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Postbuckling of nanotube-reinforced composite cylindrical panels resting on elastic foundations subjected to lateral pressure in thermal environments

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Modeling and analysis for the postbuckling of carbon nanotube-reinforced composite (CNTRC) cylindrical panels resting on elastic foundations subjected to lateral pressure in thermal environments are presented. Various profiles of single walled carbon nanotubes (SWCNTs) which are assumed to be uniformly distributed (UD) or functionally graded (FG) distribution along the thickness are taken into consideration. The temperature dependent material properties of FG-CNTRC panels are estimated through a micromechanical model. The formulations are developed based on a higher order shear deformation theory. To capture the large deflections, geometrical nonlinearity in von Kármán sense is taken into account. The panel-foundation interaction and thermal effects are also included. The initial deflections caused by lateral pressure and thermal bending stresses are both taken into account. The governing equations are first deduced to a boundary layer type that includes nonlinear prebuckling deformations and initial geometric imperfections of the panel. These equations are then solved by means of a singular perturbation technique along with a two-step perturbation approach. The influences of CNT volume fraction, temperature variation, panel geometric parameters as well as foundation stiffness on the postbuckling behavior of FG-CNTRC cylindrical panels are investigated.

1. Introduction

Carbon nanotubes (CNTs) are known as an excellent candidate to reinforce the composites due to their exceptional mechanical, thermal and electrical properties [1]. When a carbon nanotube is introduced into a polymer matrix, it markedly improves the mechanical property of the resulting nanocomposite such as tensile strength and stiffness while, it keeps the weight of the composite low about three to five times lighter than metal materials [2,3]. It was the designing of CNTs to be aligned uniaxially in an axial direction that led to a new class of composite materials called the carbon nanotube-reinforced composites (CNTRCs). The major difference between the conventional carbon fiber-reinforced composites and the carbon nanotube-reinforced composites lies in that the former can contain very high percentage of the carbon fibers (usually over 60% by volume), while the latter only has a low percentage of CNTs (about 2–5% by weight) [4–7]. This is due to the fact that the more CNT volume fraction in CNTRCs can actually lead to the deterioration of their mechanical properties [8]. In order to effectively make use of the low percentage of CNTs in the composites, Shen [9] proposed to apply the functionally graded (FG) concept to CNTRCs so that CNTs can be concentrated at certain locations to increase the mechanical/thermal behaviors of the resulting CNTRC structures. The concept of functionally graded nanocomposites was implemented in laboratory as reported in a recent publication [10] in which a functionally graded CNT reinforced aluminum matrix composite was fabricated by a powder metallurgy route.

To further explore FG-CNTRC ability in enhancing mechanical behaviors of structures, Shen and his co-authors studies FG-CNTRC beams [11], plates [12,13] and shells [14–17] against compressive and thermal postbuckling. Following this trend, many other researchers have also conducted extensive researches in this area [18–27]. The buckling and postbuckling studies on CNTRC cylindrical panels, however, are relative less frequent. Zhang et al. [28] studied the large deflection of FG-CNTRC cylindrical panels subjected to lateral uniform pressure and/or point load using the element-free kp-Ritz method. In their analysis, the material properties of FG-CNTRCs are assumed to be graded in the thickness direction and are estimated through an equivalent continuum model based on the Eshelby–Mori–Tanaka approach. Liew et al. [29] carried out studies on the compressive postbuckling of

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FG-CNTRC cylindrical panels subjected to axial compression by employing the element-free kp-Ritz method based on the first order shear deformation shell theory. More recently, based on a higher-order shear deformation shell theory Shen and Xiang [30–32] studied the nonlinear bending and compressive and thermal postbuckling of FG-CNTRC cylindrical panels resting on elastic foundations in thermal environments. It is noted that for all the aforementioned studies [28–32], only Shen and Xiang [30–32] took consideration of the effective material properties of CNTRCs being temperature-dependent. To the best of the author's knowledge, there is no literature covering the nonlinear response of CNTRC cylindrical panels subjected to lateral pressure resting on elastic foundations in thermal environments.

Solution of postbuckling behavior of the cylindrical panel subjected to lateral pressure is a more difficult task than the case of the same panel subjected to axial compression. This is because the cylindrical panel will firstly bend under lateral pressure before the buckling occurs. It has been reported that the postbuckling behaviors of plates [33], shells [34] and panels [35] are different. For example, the postbuckling equilibrium path of FGM cylindrical shells under external pressure is weakly hardening type [34], whereas the postbuckling equilibrium path of FGM cylindrical panels under lateral pressure is strongly hardening type [35,36] due to the edges restrained.

In the present work, we focus our attention on the postbuckling of CNTRC cylindrical panels resting on elastic foundations subjected to lateral pressure in thermal environments. The material properties of CNTRCs are assumed to be temperature-dependent. With CNTs assumed uniaxially aligned in axial direction and functionally graded in thickness direction of the panels, the effective material properties of CNTRC panels will be estimated through an extended rule of mixture micromechanical model. The formulations are derived in the framework of Reddy's higher order shear deformation theory and von Kármán strain–displacement relationships. The panel-foundation interaction and thermal effects are also included. The initial deflections caused by lateral pressure and thermal bending stresses are both taken into account. The governing equations are first deduced to a boundary layer type that includes nonlinear prebuckling deformations and initial geometric imperfections of the panel. These equations are then solved by means of a singular perturbation technique along with a two-step perturbation approach to determine the postbuckling equilibrium paths of CNTRC cylindrical panels.

2. Theoretical development

Consider a CNTRC cylindrical panel resting on an elastic foundation. As shown in Fig. 1, the radius of curvature, the total thickness of the panel, and the length in the X and Y directions of the panel are designated by R, h, a and b. The origin of coordinate system is located at the corner of the panel on the mid-plane. Parallel to the right-hand set of axes (X, Y, Z), in which X and Y are in the directions of the lines of curvature of the middle surface and Z is in the direction of the inward normal to the middle surface, panel displacements are designated by $\overline{U}, \overline{V}$ and $\overline{W}$. The foundation is assumed to be a compliant foundation of Pasternak-type, which means that no part of the panel lifts off the foundation in the large deflection region. The load–displacement relationship of the foundation is assumed to be $p_0 = \overline{K}_1\overline{W} - \overline{K}_2\nabla^2\overline{W}$, where p_0 is the force per unit area, $\overline{K}_1$ is the Winkler foundation stiffness and $\overline{K}_2$ is the shearing layer stiffness of the foundation, and $\nabla^2 = \partial^2/\partial X^2 + \partial^2/\partial Y^2$ is the Laplace operator. The panel is exposed to elevated temperature and is subjected to a transverse uniform pressure q. The CNTRC panel is made of a mixture of SWCNTs and the matrix which is assumed to be isotropic. The SWCNT

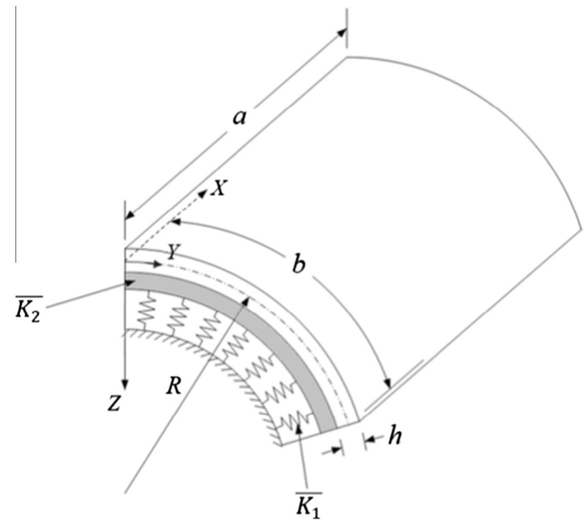

Fig. 1. Geometry and coordinate system of cylindrical panel on a Pasternak elastic foundation.

reinforcement is aligned in the X direction and is either uniformly distributed (UD) or functionally graded (FG) in the thickness direction of the panel.

Based on Reddy's higher order shear deformation theory [37] with a von Kármán-type of kinematic nonlinearity and including panel-foundation interaction and thermal effects, the governing equations for a FG-CNTRC cylindrical panel can be derived and can be expressed by

$$\widetilde{L}_{11}(\overline{W}) - \widetilde{L}_{12}(\overline{\Psi}_x) - \widetilde{L}_{13}(\overline{\Psi}_y) + \widetilde{L}_{14}(\overline{F}) - \widetilde{L}_{15}(\overline{N}^T) - \widetilde{L}_{16}(\overline{M}^T) - \frac{1}{R}\overline{F}_{,YY} + \overline{K}_1\overline{W} - \overline{K}_2\nabla^2\overline{W} = \widetilde{L}(\overline{W} + \overline{W}^*, \overline{F}) + q \tag{1}$$

$$\widetilde{L}_{21}(\overline{F}) + \widetilde{L}_{22}(\overline{\Psi}_x) + \widetilde{L}_{23}(\overline{\Psi}_y) - \widetilde{L}_{24}(\overline{W}) - \widetilde{L}_{25}(\overline{N}^T) + \frac{1}{R}\overline{W}_{,XX} = -\frac{1}{2}\widetilde{L}(\overline{W} + 2\overline{W}^*, \overline{W}) \tag{2}$$

$$\widetilde{L}_{31}(\overline{W}) + \widetilde{L}_{32}(\overline{\Psi}_x) - \widetilde{L}_{33}(\overline{\Psi}_y) + \widetilde{L}_{34}(\overline{F}) - \widetilde{L}_{35}(\overline{N}^T) - \widetilde{L}_{36}(\overline{S}^T) = 0 \tag{3}$$

$$\widetilde{L}_{41}(\overline{W}) - \widetilde{L}_{42}(\overline{\Psi}_x) + \widetilde{L}_{43}(\overline{\Psi}_y) + \widetilde{L}_{44}(\overline{F}) - \widetilde{L}_{45}(\overline{N}^T) - \widetilde{L}_{46}(\overline{S}^T) = 0 \tag{4}$$

where $\overline{\Psi}_x$ and $\overline{\Psi}_y$ are the rotations of the normals to the middle surface with respect to the Y- and X-axes, $\overline{F}$ is the stress function defined by $\overline{N}_x = \overline{F}_{,YY}, \overline{N}_y = \overline{F}_{,XX}$ and $\overline{N}_{xy} = -\overline{F}_{,XY}$, where a comma denotes partial differentiation with respect to the corresponding coordinates.

In Eqs. (1)–(4), the linear operators $\widetilde{L}_{ij}(\ )$ are defined as in Shen [14] and the geometric nonlinearity in the von Kármán sense is given in terms of $\widetilde{L}(\ )$ which can be expressed by

$$\widetilde{L}(\ ) = \frac{\partial^2}{\partial X^2}\frac{\partial^2}{\partial Y^2} - 2\frac{\partial^2}{\partial X\partial Y}\frac{\partial^2}{\partial X\partial Y} + \frac{\partial^2}{\partial Y^2}\frac{\partial^2}{\partial X^2} \tag{5}$$

It is noted that the governing Eqs. (1)–(4) for a CNTRC cylindrical panel are identical to those of unsymmetric cross-ply laminated cylindrical panels. It is well known that the postbuckling and the large deflection are two different nonlinear problems. In the former the lateral pressure is an unknown and we seek for the postbuckling load–deflection curves, whereas in the latter the lateral pressure is prescribed and we seek for the bending load–deflection curves, as reported in Shen and Xiang [30].