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Postbuckling of functionally graded graphene-reinforced composite laminated cylindrical shells subjected to external pressure in thermal environments

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ABSTRACT

The current investigation deals with the buckling and postbuckling behaviors of graphene-reinforced composite (GRC) laminated cylindrical shells subjected to lateral or hydrostatic pressure under thermal environmental conditions. The piece-wise GRC layers are arranged in a functionally graded (FG) pattern along the thickness direction of the shells. The temperature dependent material properties of GRCs are estimated by the extended Halpin–Tsai micromechanical model with graphene efficiency parameters being calibrated against the GRC material properties from a molecular dynamics simulation study. We employ the Reddy's higher order shear deformable shell theory in association with the von Kármán geometric nonlinearity to model the shell buckling problem under different thermal environmental conditions. The buckling pressure and the postbuckling equilibrium path for the perfect and geometrically imperfect GRC laminated cylindrical shells are obtained by applying a singular perturbation technique along with a two-step perturbation approach. We observe that the piece-wise functionally graded distribution of graphene reinforcement can increase the buckling pressure and the postbuckling strength of the GRC laminated cylindrical shells subjected to external pressure.

1. Introduction

The research on graphene reinforced composites (GRCs) has emerged as one of the hottest research topics in the materials engineering field in recent years. The graphene nano-fillers possess some of the most remarkable material properties such as the superior strength and lightweight, exceptional optical transparency and the best heat and electrical conductivities [1–9] which can be utilized to create high performing advanced nanocomposites for a wide range of applications. Recent researches [10–16] have demonstrated the achievement of such applications in MEMS/NEMS devices, energy storage and optical electronics etc.

Due to graphene dispersion issues and the limitation of the current manufacturing techniques [17], the weight percentage of graphene in nanocomposites is in general quite low when comparing with carbon fiber reinforced composites which can have more than 60% weight fraction of carbon fibers. Despite of the low graphene weight percentage in nanocomposites, it is still possible to achieve significant enhancement on the mechanical responses of graphene reinforced composite (GRC) structures [18–21]. Rafiee et al. [18] reported an increase by up to 52% of the buckling load for a graphene/epoxy beam with only 0.1% graphene weight fraction. Parashar and Mertiny [19] revealed that the buckling capacity of graphene/epoxy composite plates is improved by 26% with only 6% graphene volume fraction. Another study by Feng et al. [20] also demonstrated that the graphene/epoxy composite beams with 0.5% and 1.0% graphene weight fractions can decrease the deflection of the beams by 13.7% and 26.1%, respectively, when comparing to the beams made of pure epoxy. The fundamental vibration frequency of a graphene/epoxy plate with 1.2% graphene weight fraction is increased by about 160% as reported by Song et al. [21].

To better utilize the low percentage CNT content in composite structures, Shen [22] was the first to show that the concept of CNT and functionally graded (FG) material arrangement may be linked together with the introduction of a novel class of materials called functionally graded carbon nanotube reinforced composites (FG-CNTRC). In this type of composites volume fraction of CNT as reinforcement varies continuously from one surface of a structural element to another one. In

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the fundamental work of Shen [22] it was proved that FG-CNTRC plates can significantly increase the bending capacity of the plates comparing with the plates with uniform distribution of CNT reinforcement. Subsequently, Shen extended this pioneering research to the study on the postbuckling behaviors of FG-CNTRC cylindrical shells subjected to axial compression, external pressure, torsion and temperature rise [23–26]. On the other hand, the buckling analysis of FG-CNTRC cylindrical and conical shells was performed by Ansari et al. [27], Ansari and Torabi [28], and Duc et al. [29], respectively.

Shen [30,31] extended the concept of FGM to fiber reinforced composite structures with a piece-wise laminated type instead of a continuous type fiber reinforcement. This approach has recently been used to study the nonlinear vibration, nonlinear bending and postbuckling behaviors of plates with piece-wise functionally graded GRC laminated plies [32–35]. Unlike in [21,22], an FG-GRC laminated plate model is adopted in which the graphene sheets are assumed to be aligned and oriented in the matrix layer-by-layer. In the current investigation, the postbuckling behaviors of cylindrical shells consisting of uniformly distributed (UD) and piece-wise functionally graded (FG) GRC laminates will be studied. Unlike in the cases of FG ceramic-metal materials or FG-CNTRCs where the Mori-Tanaka model or the extended rule of mixture was adopted [36–41], in the current study the temperature dependent material properties of GRC laminates are determined by the extended Halpin-Tsai micromechanical model which contains the efficiency parameters. The Reddy's third order shear deformation shell theory and the von Kármán-type kinematic assumptions are applied to derive the governing equations for the postbuckling of GRC laminated cylindrical shells. The prebuckling deformations of the shell and the initial geometric imperfections are also taken into account. The governing equations are then solved by a singular perturbation technique in conjunction with a two-step perturbation approach to obtain the postbuckling equilibrium paths. The full nonlinear postbuckling responses of GRC laminated cylindrical shells subjected to external pressure at room and elevated temperatures are discussed in details.

2. Multi-scale model for FG-GRC laminated cylindrical shells under external pressure

Consider a GRC laminated cylindrical shell which consists of N plies. Each ply is made of a mixture of graphene reinforcement and the polymer matrix. Each ply may have different value of graphene volume fraction. When volume fraction of graphene in plies is different, a piece-wise functionally graded (FG) GRC is achieved. The graphene reinforcement is either zigzag (refer to as 0-ply) or armchair (refer to as 90-ply). The shell has mean radius R, length L and thickness h and is in the (X, Y, Z) coordinates with the origin being at one end of the shell in the middle surface, X and Y being in the axial and circumferential directions of the shell and Z in the direction of the inward normal to the middle surface. The corresponding displacements of the shell along the X, Y and Z directions are denoted by $\overline{U}$, $\overline{V}$ and $\overline{W}$. It is presumed that each ply may have different value of graphene volume fraction. For nanocomposites, the micromechanical model, such as the Halpin-Tsai model should be modified. In the present study, the extended Halpin-Tsai model is used to estimate the Young's moduli and the shear modulus of the GRC layer as follows [32]

$$E_{11} = \eta_1 \frac{1 + 2(a_G/h_G)\gamma_{11}^G V_G}{1 - \gamma_{11}^G V_G} E^m \tag{1a}$$

$$E_{22} = \eta_2 \frac{1 + 2(b_G/h_G)\gamma_{22}^G V_G}{1 - \gamma_{22}^G V_G} E^m \tag{1b}$$

$$G_{12} = \eta_3 \frac{1}{1 - \gamma_{12}^G V_G} G^m \tag{1c}$$

in which a_G , b_G and h_G indicate, respectively, the length, width and the effective thickness of the graphene sheet, and

$$\gamma_{11}^G = \frac{E_{11}^G/E^m - 1}{E_{11}^G/E^m + 2a_G/h_G} \tag{2a}$$

$$\gamma_{22}^G = \frac{E_{22}^G/E^m - 1}{E_{22}^G/E^m + 2b_G/h_G} \tag{2b}$$

$$\gamma_{12}^G = \frac{G_{12}^G/G^m - 1}{G_{12}^G/G^m} \tag{2c}$$

where E^m and G^m are the Young's modulus and shear modulus of the matrix. E_{11}^G, E_{22}^G and G_{12}^G are the Young's moduli and shear modulus of the graphene sheet. V_G and V_m are the graphene and matrix volume fractions, respectively, which satisfy the condition $V_G + V_m = 1$. In order to account for the effects relating to the interaction and load transfer between the polymer matrix and the graphene, graphene efficiency parameters η_j (j=1,2,3) are introduced to the original Halpin-Tsai model as given in Eq. (1). The value of η_j are obtained through comparing the results from Eq. (1) against the ones from the MD simulations [42].

The temperature dependent material properties of the matrix and the graphene sheet [43,44] are considered in the current study. The thermal expansion coefficients in the longitudinal and transverse directions of the GRC layer are given by

$$\alpha_{11} = \frac{V_G E_{11}^G \alpha_{11}^G + V_m E^m \alpha^m}{V_G E_{11}^G + V_m E^m} \tag{3a}$$

$$\alpha_{22} = (1 + \nu_{12}^G) V_G \alpha_{22}^G + (1 + \nu^m) V_m \alpha^m - \nu_{12}\alpha_{11} \tag{3b}$$

where α_{11}^G, α_{22}^G and α^m are the thermal expansion coefficients, and ν_{12}^G and ν^m are the Poisson's ratios, respectively, of the graphene sheet and the matrix. The Poisson's ratio of GRCs depends weakly on temperature change and is expressed as

$$\nu_{12} = V_G \nu_{12}^G + V_m \nu^m \tag{4}$$

A geometrically imperfect GRC laminated cylindrical shell subjected to external pressure q in thermal environments is considered. Employing the Reddy's shear deformation shell theory [45] and taking in account of the von Kármán-type of kinematic nonlinearity, the governing differential equations for a GRC laminated cylindrical shell can be expressed as

$$\tilde{L}_{11}(\overline{W}) - \tilde{L}_{12}(\overline{\Psi}_x) - \tilde{L}_{13}(\overline{\Psi}_y) + \tilde{L}_{14}(\overline{F}) - \tilde{L}_{15}(\overline{N}^T) - \tilde{L}_{16}(\overline{M}^T) - \frac{1}{R}\overline{F}_{,XX} = \tilde{L}(\overline{W} + \overline{W}^*, \overline{F}) + q \tag{5}$$

$$\tilde{L}_{21}(\overline{F}) + \tilde{L}_{22}(\overline{\Psi}_x) + \tilde{L}_{23}(\overline{\Psi}_y) - \tilde{L}_{24}(\overline{W}) - \tilde{L}_{25}(\overline{N}^T) + \frac{1}{R}\overline{W}_{,XX} = -\frac{1}{2}\tilde{L}(\overline{W} + 2\overline{W}^*, \overline{W}) \tag{6}$$

$$\tilde{L}_{31}(\overline{W}) + \tilde{L}_{32}(\overline{\Psi}_x) - \tilde{L}_{33}(\overline{\Psi}_y) + \tilde{L}_{34}(\overline{F}) - \tilde{L}_{35}(\overline{N}^T) - \tilde{L}_{36}(\overline{S}^T) = 0 \tag{7}$$

$$\tilde{L}_{41}(\overline{W}) - \tilde{L}_{42}(\overline{\Psi}_x) + \tilde{L}_{43}(\overline{\Psi}_y) + \tilde{L}_{44}(\overline{F}) - \tilde{L}_{45}(\overline{N}^T) - \tilde{L}_{46}(\overline{S}^T) = 0 \tag{8}$$

where $\overline{W}^*$ is the initial geometric imperfection, $\overline{\Psi}_x$ and $\overline{\Psi}_y$ are the rotations of the normals to the middle surface with respect to the Y - and X – axes, and $\overline{F}$ 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. It is noted that the nonlinear operator $\tilde{L}(\ )$ in Eqs. (5) and (6) represents the geometric nonlinearity in the von Kármán sense, and the other linear operators $\tilde{L}_{ij}(\ )$ are defined in [46].

The thermal effects are also included in Eqs. (5)-(8), where the forces $\overline{N}^T$, moments $\overline{M}^T$ and higher order moments $\overline{P}^T$ due to elevated temperature can be obtained as