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Thermal buckling and postbuckling of functionally graded graphene-reinforced composite laminated plates resting on elastic foundations

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ABSTRACT

This paper presents the modeling and analysis for the thermal postbuckling of graphene-reinforced composite laminated plates resting on an elastic foundation and subjected to in-plane temperature variation. A micromechanical model is used to estimate the temperature-dependent material properties of the graphene-reinforced composites (GRCs). Piece-wise functionally graded (FG) GRC layers along the thickness direction of a plate is considered in this study. Employing the higher order shear deformation plate theory, the governing equations for FG-GRC plates are derived and the effects of plate-foundation interaction and temperature variation are included in the modeling. A two-step perturbation technique is applied to obtain the buckling temperature and the thermal postbuckling load-deflection curves for perfect and imperfect FG-GRC laminated plates. The results show that the buckling temperature as well as thermal postbuckling strength of the plates can be increased as a result of the functionally graded graphene reinforcement for the plates.

1. Introduction

Recently, a new member of advanced material family, graphene reinforced composites, has been synthesized [1–3]. Graphene is a two-dimensional nanomaterial consisted of a monolayer of sp^2-bond carbon atoms with atomic thickness arranged in a hexagonal pattern [4,5]. Due to graphene's extraordinarily high electrical and thermal conductivities, great mechanical strength, large specific surface area, and potentially low manufacturing cost [6–14], graphene sheets are considered as ideal material for composite reinforcements [15].

It is well known that unlike carbon fiber reinforced composites which contain a high proportion of carbon fibers (over 60% by volume), graphene reinforced composites can only take a low fraction of the carbon nano fillers (about 0.5–50% by weight) [16,17] as more carbon nano fillers can actually lead to the deterioration of the mechanical properties of the nanocomposites [18]. Rafiee et al. [19] studied the buckling of graphene/epoxy composite beams experimentally and observed that the buckling load of a nanocomposite beam with only 0.1% graphene by weight can be increased by up to 52% when compared to the pure epoxy beam. The buckling behavior of graphene/epoxy composite plates under uniaxial compression was investigated by Parashar and Mertiny [20] using the finite element method. Their study showed that with 6% graphene volume fraction the buckling capacity of the nanocomposite plate can be increased by 26%. Another study on the free vibration of graphene/epoxy composite plates was carried out by Chandra et al. [21] using the finite element method. Recently, Yang and his co-authors presented the nonlinear bending, compressed postbuckling and dynamic instability analyses of functionally graded polymer nanocomposite beams reinforced with graphene platelets based on the Timoshenko beam theory [22–24], and the linear free and forced vibrations of functionally graded polymer composite plates reinforced with graphene platelets [25]. In their analysis the graphene platelets are assumed to be uniformly dispersed and randomly oriented in the matrix and the weight fraction of graphene platelets is assumed to have a step variation in the thickness direction of the beam or plate. The equivalent isotropic Young's modulus of the nanocomposite is obtained by using the modified Halpin–Tsai model, and the material properties are assumed to be independent of temperature.

When graphene sheets are used as the reinforcing phase in a polymer nanocomposite, the distribution of graphene is either uniform or random in the nanocomposite. The mechanical, thermal, or physical properties in such nanocomposite do not vary spatially at the macroscopic level. As aforementioned that the amount of graphene in polymer nanocomposites is relatively low, the functionally graded (FG) material concept may be borrowed to change the spatial distribu-

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tion of graphene in the nanocomposites in order to achieve better mechanical properties of the graphene reinforced nanocomposite (GRC) structures. Shen [26] was the first researcher to propose the functionally graded carbon nanotube reinforced composites (FG-CNTRCs) with CNT being non-uniformly distributed along the thickness direction in the CNT reinforced nanocomposite structures. The mechanical behaviors of FG-CNTRC structures have since been thoroughly studied by many researchers in recent years. Shen and Zhang [27] studied the thermal buckling and postbuckling behavior of FG-CNTRC plates with mid-plane symmetric CNT distribution of reinforcements based on a higher order shear deformation plate theory. This is due to the fact that the bifurcation buckling does not exist due to the stretching-bending coupling effect for the simply supported functionally graded plates subjected to uniform or non-uniform temperature rise, like in the case of simply supported unsymmetric cross-ply laminated plates. Based on the first order shear deformation plate theory, the linear thermal buckling temperature and the thermal postbuckling equilibrium path of FG-CNTRC plates were performed by Mirzaei and Kiani [28] and Kiani [29] by using Chebyshev–Ritz method presented. Fan and Wang [30] studied the effect of matrix cracks on the thermal postbuckling and vibration of postbuckled hybrid laminated plates containing CNTRC layers resting on elastic foundations.

A plate rests on an elastic foundation may be found in the applications of micro-electromechanical systems (MEMS) [31]. In the service life the plate may be subjected to mechanical or thermal loads and the plate may buckle and geometrical nonlinearity is induced. Recently, the postbuckling of FG-GRC laminated plates subjected to uniaxial compression and resting on elastic foundations in thermal environments was studied by Shen et al. [32]. The present work focuses attention on the thermal postbuckling analysis of GRC laminated plates through careful selection of material properties of graphene sheets and a novel reinforcing scheme. Like CNTRCs, GRCs usually have a lower graphene volume fraction. One of the problems is how to increase the buckling temperature and thermal postbuckling strength of GRC laminated plates under such a low graphene volume fraction. The temperature field considered is assumed to be a parabolic distribution over the plate surface and uniform through the plate thickness. The material properties of GRCs are estimated through a micromechanical model in which the graphene efficiency parameter is estimated by matching the elastic modulus of GRCs obtained from the MD simulation results with the numerical results predicted by the extended Halpin–Tsai model. A higher order shear deformation plate theory with a von Kármán-type of kinematic nonlinearity is employed to derive the governing equations and the thermal effect and foundation support are also considered. The four edges of the plate are simply supported with no in-plane displacements.

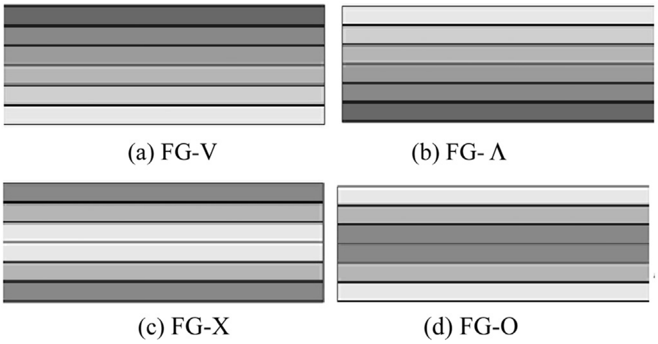
(a) FG-V
(b) FG-Λ
(c) FG-X
(d) FG-O

Fig. 1. Configurations of GRC laminates.

2. Multi-scale model for FG-GRC laminated plates

Here we consider a GRC laminated rectangular plate of length a, width b, and thickness h. The plate has N GRC plies and rests on an elastic foundation. Each GRC ply may have different value of graphene volume fraction. The graphene reinforcement distribution is functionally graded of piece-wise type in the thickness direction. As shown in Fig. 1, four types of FG material profile of GRCs, i.e. FG-V, FG-Λ, FG-X and FG-O may be considered. The reference coordinate system has its origin at the corner of the plate on the middle plane. The graphene reinforcement is either zigzag (refer to as 0-ply) or armchair (refer to as 90-ply). The Halpin–Tsai model [33] and the Voigt model (rule of mixture) [34] have been employed by researchers to estimate the mechanical properties of GRCs. However, these models can not be used directly to predict the effective material properties of GRCs [35,36] and modifications to the models are required. We employ the extended Halpin–Tsai model to estimate the effective material properties of the GRCs

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

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

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

in which a_G, b_G and h_G are the length, width and 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_{11}^G, E_{22}^G and G_{12}^G are the Young's moduli and shear modulus of the graphene sheet, E^m and G^m are corresponding properties for the matrix, V_G is the graphene volume fraction and $V_m = 1\text{-}V_G$ is the matrix volume fraction, respectively. The modification on the Halpin-Tsai model is introduced through the graphene efficiency parameters η_j $(j = 1,2,3)$ to consider the small scale effect and other effects on the material properties of GRCs. The values of η_j will be determined later by matching the elastic moduli of GRCs obtained from the MD simulation with the numerical results predicted by the extended Halpin–Tsai model.

According to the Schapery model [37], the thermal expansion coefficients in the longitudinal and transverse directions can be expressed 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 matrix. Since the material properties of both graphene sheet [38] and matrix [39] are functions of temperature T, the effective material properties of GRCs, such as the Young's modulus, shear modulus and thermal expansion coefficients, are also functions of temperature T. The Poisson's ratio depends weakly on temperature change and is expressed as

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

Let $\overline{U}$, $\overline{V}$ and $\overline{W}$ be the plate displacements parallel to a right-hand set of axes (X, Y, Z), where X is longitudinal and Z is perpendicular to the plate. $\overline{\Psi}_x$ and $\overline{\Psi}_y$ are the mid-plane rotations of the normals about the Y and X axes, respectively. The plate is assumed to be geometrically