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Coupled thermoelastic analysis of an FG multilayer graphene platelets-reinforced nanocomposite cylinder using meshless GFD method: A modified micromechanical model

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ABSTRACT

The coupled thermoelasticity analysis based on the Green–Naghdi theory with energy dissipation is carried out to assess the thermoelastic wave propagations in an FG multilayer graphene platelets-reinforced nanocomposite cylinder. The cylinder is assumed to be made of multi-layers (sub-cylinders), and each layer is reinforced by a uniform distribution of graphene platelets (GPLs). A modified micromechanical model is used to calculate the thermal and mechanical properties considering nonlinear grading patterns of the GPLs along the radial direction of the cylinder. Using a proper arrangement of the layers, the nonlinear grading patterns of the GPLs are created along the radial direction of the whole cylinder. To solve the obtained governing partial differential equations (PDEs), the meshless generalized finite-difference (GFD) method and the Newmark method are employed. The inner surface of the cylinder is excited by three types of the thermal shock loading including the suddenly temperature increase described by the Heaviside step function, as well as sinusoidal and ramp pulses. The effects of the key parameters such as the weight fraction of the GPLs and volume fraction index on the thermoelastic wave propagations and dynamic behaviors of the field variables are studied in details. Also, the effects of the key parameters on the thermoelastic damping in the temperature field are illustrated using the presented modified micromechanical model. The accuracy and stability of the presented meshless method and the numerical results are verified by the published reference data.

1. Introduction

Reinforced composite structures are widely applied in engineering and industries. Because of the excellent thermal and mechanical properties of the graphene platelets (GPLs), the GPLs can be used as the reinforcement of composite structures. By reinforcing the composite structures using the GPLs, it is possible to increase the thermal resistance of the nanocomposites without decreasing the mechanical strength of the structures. The GPLs are added to the matrix of nanocomposites as nanofillers [1–3]. When using the GPLs as the reinforcement of the composite structures, it is very important to obtain the thermal properties of the reinforced nanocomposite structures. Some of the previously published works were focused on the study and determination of the thermal properties of the GPLs reinforced nanocomposites by using experimental and theoretical methods [4–9]. The thermoelastic analysis is needed in designing and applying such composite structures, when the structures are subjected to thermal loads.

There exist some published works regarding the thermoelastic analysis or the thermal effects on the responses of the CNTs-reinforced composite structures. Zhang and Tanaka [10] studied on the thermal behavior of the CNT composite material using a hybrid boundary node method with the fast multipole method. Alibeigloo and Liew [11] and Alibeigloo [12] carried out the thermoelastic analysis of the FG carbon nanotube reinforced composite plate and cylindrical panel. Also, Alibeigloo [13,14], Alibeigloo and Pasha Zanoosi [15] presented the thermoelastic analysis of the FG carbon nanotube reinforced composite plate, cylindrical panel and shell, which were embedded in piezoelectric sensor and actuator layers. Recently, Moradi-Dastjerdi and Payganeh [16] presented the thermoelastic vibration analysis in FG cylinders, which were reinforced by wavy CNTs. Thermal buckling and post-buckling analysis of carbon nanotube reinforced composite structures were reported in references [17–20]. More related papers in this field can be found in the published review paper by Liew et al. [21], in which the researches on the analysis of the FG carbon nanotube reinforced composite structures have been addressed. Recently, Yang et al. [22] presented the thermoelastic anal-

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ysis for FG graphene reinforced rectangular plates. They employed the three-dimensional (3D) elasticity solution with considering the nonlinear grading patterns for the GPLs distribution [22].

It should be mentioned here that the above mentioned research works have been carried out without considering the coupling between the displacement and the temperature fields. It means that in the above mentioned works and other related papers on the thermoelastic analysis of the CNTs or GPLs reinforced composite structures, the coupled thermoelasticity has not been applied yet. The coupled thermoelasticity should be taken into account in engineering analysis, when the structures are subjected to the high-rate thermal loadings or thermal shock loadings. There are some effective theories for the generalized coupled thermoelastic analysis in which the propagation velocity of the thermal wave is considered to be a finite value. Some of the very well-known coupled thermoelasticity theories were presented by Lord–Shulman [23], Green–Lindsay [24] and Green–Naghdi [25–27]. It is convenient to carry out the coupled thermoelastic analysis with or without energy dissipation using the Green–Naghdi theory. Also, it is possible to study the thermoelastic damping in structures under thermal loadings by using the Green–Naghdi theory with energy dissipation. Regarding the thermoelastic analysis of the reinforced composite structures by GPLs, it should be noted that, when the structures are subjected to thermal shock loadings, the coupled thermoelastic analysis must be carried out to obtain a realistic behavior.

In the coupled thermoelastic analysis, numerical or analytical methods can be applied for the solution of the corresponding governing partial differential equation (PDE). One of the effective numerical methods is the meshless generalized finite-difference (GFD) method. The details of the meshless GFD method can be found in references [28–30]. Also, the authors have done some works on the application of the meshless GFD method for coupled thermoelastic analysis without energy dissipation in a thick hollow cylinder [31], coupled thermoelastic analysis of a layered FG thick hollow cylinder [32], natural frequency analysis of an FG CNTs-reinforced cylinder [33], and coupled non-Fickian diffusion-elasticity analysis of a cylinder [34]. Recently, Gu et al. [35] employed the meshless GFD method for solving the inverse heat source problem associated with the steady-state heat conduction. The meshless GFD method has a high performance as a numerical solution tool for coupled problems in engineering and sciences.

By reviewing the above addressed papers, it can be found that the coupled thermoelastic analysis based on the Green–Naghdi theory for the CNTs or GPLs reinforced composite structures has not been carried out yet. The most of the published works on thermoelastic analysis of the CNTs or GPLs reinforced nanocomposite structures were based on the uncoupled thermoelasticity. The coupled thermoelastic analysis of reinforced composite structures considering the interactions between the displacement and the temperature fields can be considered as a research gap in this research topic.

In this paper, the Green–Naghdi coupled thermoelasticity is applied for the thermoelastic analysis of a functionally graded multilayer graphene platelets reinforced nanocomposite cylinder using the meshless GFD method and considering the energy dissipation. A modified micromechanical model is employed to calculate the mechanical and thermal properties, which is based on the nonlinear variation of the GPLs distribution along the radial direction of the cylinder. The FG multilayer graphene platelets reinforced nanocomposite cylinder is assumed to be made of several sub-cylinders (layers), and each sub-cylinder is reinforced by a uniform distribution of the GPLs in an isotropic epoxy matrix. The weight fraction of the GPLs in each layer is different from that of the neighboring layers. Using a proper arrangement of the layers, nonlinear grading patterns for the GPLs distribution in the whole reinforced cylinder can be obtained along the radial direction. The proposed modified micromechanical model is utilized to calculate the mechanical and thermal properties in each layer considering nonlinear grading patterns of the GPLs distribution along the radial direction in the whole cylinder. The inner surface of the cylinder is excited by a thermal shock loading. The thermoelastic wave propagation is illustrated at various time instants for different geometrical and material parameters. Also, the time histories of the temperature and the displacements are computed to assess the dynamic and transient behaviors of the physical quantities. The effects of the reinforcement by GPLs on the thermoelastic damping are investigated for various values of geometrical and material parameters.

2. Micromechanical modeling

A multilayer thick hollow cylinder with a finite length L, an inner radius r_{in} and an outer radius r_{out} is considered in this analysis, with each layer being made of a reinforced-nanocomposite by the GPLs. It is assumed that the GPLs are uniformly distributed along the radial direction of the cylinder in an isotropic polymer matrix in each layer. The GPLs are distributed within the polymer matrix of each layer with a uniform distribution and a random orientation. Also, it is assumed that the distribution of the GPLs in each layer is different from the two neighboring layers and varies as a nonlinear function along the radial direction of the whole FG multilayer GPLs reinforced nanocomposite cylinder (see Fig. 1).

To find the GPLs volume fraction in each layer, it is needed to describe the variation of the GPLs distribution along the radial direction of the whole FG multilayer GPLs reinforced nanocomposite cylinder. So, in this work, three types of the GPLs nonlinear distribution are considered for V^k_{GPL} as follows:

- Type X

$$V^k_{GPL} = 2V^*_{GPL}\left(\left|2k - N_L - 1\right|/N_L\right)^{\alpha_{FG}}, \tag{1}$$

- Type O

$$V^k_{GPL} = 2V^*_{GPL}\left(1 - \left|2k - N_L - 1\right|/N_L\right)^{\alpha_{FG}}, \tag{2}$$

- Type A

$$V^k_{GPL} = V^*_{GPL}\left((2k - 1)/N_L\right)^{\alpha_{FG}}, \tag{3}$$

where

$$V^*_{GPL} = \frac{W_{GPL}}{W_{GPL} + \left(\rho_{GPL}/\rho_m\right)\left(1 - W_{GPL}\right)}, \tag{4}$$

in which W_{GPL} is the GPLs weight fraction, and ρ_{GPL} and ρ_m are the mass densities of the GPLs and the polymer matrix, respectively. The parameter α_{FG} is the volume fraction index. The variations of the GPLs volume fraction for the above three types are illustrated in Fig. 2 for three values $\alpha_{FG} = 0.5$, $\alpha_{FG} = 1$ and $\alpha_{FG} = 2$ in the whole reinforced nanocomposite cylinder. It can be clearly observed that the volume fraction in each layer is a fixed value. When $\alpha_{FG} = 1$, the linear distribution of GPLs in the whole FG cylinder is recovered by the proposed model. Recently, the buckling and postbuckling [36] as well as nonlinear free vibration [37] analyses were carried out for an FG multilayer composite beam reinforced by GPLs using a micromechanical model based on the linear distribution of GPLs along the thickness direction of the multilayer beam.

2.1. Mechanical properties

Based on the Halpin–Tsai micromechanical model, the elastic modulus of the nanocomposites with a random distribution of the fillers can be approximated for the kth layer by [20]

$$E^k = \frac{3}{8}E^k_L + \frac{5}{8}E^k_T, \tag{5}$$

where E^k_L and E^k_T stand for the longitudinal and transverse moduli for a unidirectional lamina. The elastic moduli E^k_L and E^k_T can be calculated by the Halpin–Tsai model in the kth layer as [20]