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Nonlinear low-velocity impact analysis of temperature-dependent nanotube-reinforced composite plates

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ABSTRACT

A nonlinear analysis is presented for impact response of carbon nanotube-reinforced composite (CNTRC) structures under thermal conditions. Two plate configurations (i.e., single-layer and sandwich plates) are considered, and the nanotube reinforcement is either uniformly-distributed or functionally-graded in the plate thickness direction. The material properties of nanotube reinforced composites are estimated using micromechanical models. The equations of motion are based on a higher-order shear deformation theory with a von Kármán-type of kinematic nonlinearity, and the thermal effects are included by considering the nanotube reinforced composites as temperature-dependent. The equations of motion are solved with a two-step perturbation technique, and the initial stresses caused by either the thermal or in-plane edge loads as in-plane boundary conditions are introduced. The influences of material property gradient, volume fraction distribution, temperature change, initial stress, initial velocity of the impactor, and core-to-face sheet thickness ratio on impact response of plate structures are discussed. The analysis presented can help better understand the nonlinear impact response of functionally-graded materials and facilitate design and optimization of nanocomposite structures against impact and under thermal and other environments.

1. Introduction

Owing to their extremely advantageous properties, carbon nanotubes (CNTs) have drawn considerable attention from researchers. As their extraordinary mechanical properties over carbon fibers [1], CNTs are accepted as a potential candidate for the reinforcement of polymer composites. It showed that adding 1 wt% CNTs could improve elastic moduli of polystyrene composites by 36–42% [2]. The overwhelming advantages offered by the carbon nanotube-reinforced composites have prompted an increased use of laminated structures with nanotube reinforced layers.

The major difference between the carbon fiber-reinforced composites and carbon nanotube-reinforced composites lies in that the latter contain a low percentage of CNTs (2–5 wt%) [3–6]. This is due to the fact that their mechanical properties will deteriorate if the volume fraction increases beyond certain limit [7]. Therefore, to better utilize the nanotube reinforcement effect, the concept of functionally-graded materials was considered for designing microstructure of nanocomposites. Shen [8] first studied the nonlinear bending behavior of nanotube-reinforced composite plates and found that the load–bending moment curves of the plates can be considerably improved through the use of a functionally-graded distribution of CNTs in the matrix. Applying the concept of functionally-graded materials to the nanocomposites, Shen and his co-workers [9–14] investigated the postbuckling and nonlinear free/forced vibration of functionally-graded nanotube-reinforced composite plates and shells under a low nanotube volume fraction. They found that the linear functionally-graded nanotube reinforcements can increase the buckling load as well as postbuckling strength of the plate/shell structures under mechanical load; whereas this effect is less pronounced for the thermal buckling of the same plate/shell structures. They also concluded that the functionally-graded nanotube reinforcements have a significant influence on the nonlinear vibration characteristics of nanotube-reinforced composite plates and shells. Moreover, Zhu et al. [15] presented the linear bending and free vibration of functionally-graded nanotube-reinforced composite plates with various boundary conditions using the finite element method. Mehrabadi et al. [16] presented the linear buckling of functionally-graded nanotube-reinforced composite plates subjected to uniaxial and biaxial compression. Hedayati and Aragh [17] studied the linear vibration of annular sectorial plates resting on Pasternak foundation based

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Table 1
Temperature-dependent material properties for the (10,10) SWCNT (tube length = 9.26 nm, tube mean radius = 0.68 nm, tube thickness = 0.067 nm, $\nu_{12}^{CN} = 0.175$) [9].

Temperature (K)	E_{11}^{CN} (TPa)	E_{22}^{CN} (TPa)	G_{12}^{CN} (TPa)	α_{11}^{CN} ($\times 10^{-6}$/K)	α_{22}^{CN} ($\times 10^{-6}$/K)
300	5.6466	7.0800	1.9445	3.4584	5.1682
500	5.5308	6.9348	1.9643	4.5361	5.0189
700	5.4744	6.8641	1.9644	4.6677	4.8943

on the Eshelby–Mori–Tanaka approach, considering the influence of nanotube agglomeration. Lei et al. [18,19] studied the buckling and nonlinear bending of functionally-graded nanotube-reinforced composite plates using the element-free *kp*-Ritz method based on the first-order shear deformation plate theory and used the effective material properties estimated by either the Eshelby–Mori–Tanaka approach or the extended rule of mixture. On the other hand, Rafiee and Moghadam [20] simulated the impact and post-impact behavior of nanotube-reinforced polymer based on a multi-scale finite element model. Their results showed that the deflection of the composite with adding only 5% volume fraction of CNT was much smaller than that of neat resin. Khalili and Haghbin [21] investigated the effect of diameter chirality and volume fraction of single-walled CNT (SWCNT) reinforced composites on impact loads by modeling SWCNTs in the finite element software based on their atomic structures in molecular mechanics.

Recently, the functionally-graded CNT-reinforced and CNT-nano Silicon carbide dual-reinforced aluminum matrix composites were fabricated by a powder metallurgical approach to support the concept of functionally-graded materials [22,23]. In the present study, the nonlinear low-velocity impact response of nanotube-reinforced composite plate-type structures is studied. Two plate configurations (i.e., single-layer and three-layer sandwich plates) are considered, and two different kinds of nanotube distribution layers (i.e., uniformly-distributed and functionally-graded reinforcements) are studied in the analysis. For the functionally-graded reinforcements, the material properties are assumed to be graded in the layer thickness direction, and they are estimated using micromechanical models in which the efficiency parameter CNT is obtained by matching the elastic moduli of nanocomposites observed from the molecular dynamics (MD) simulation results with the numerical ones computed from the extended rule of mixture. The equations of motion are based on a higher-order shear deformation theory [24] and general von Kármán-type equations [25]. The material properties of both nano-reinforced layer and homogeneous core layer are assumed to be temperature-dependent, and the initial stresses caused by either thermal loads or in-plane edge loads as the in-plane boundary conditions are introduced. All four edges of the plate are simply supported. The numerical illustrations show the nonlinear impact response of nanotube-reinforced composite plate-type structures under different sets of thermal conditions.

2. Nonlinear dynamics of nanotube-reinforced composite plates

Sandwich structures usually consist of two thin stiff and strong face sheets separated by a relatively thick, lightweight, and soft core material. Recently, the sandwich plate with relatively stiff core has also drawn considerable attention [26]. The rectangular sandwich plate studied in this paper is composed of two nanotube reinforced composite face sheets and a homogeneous core, as shown in Fig. 1. The length, width and total thickness of the sandwich plate are designated as a, b and h, respectively. The thickness of each face sheet is h_F; while the thickness of the homogeneous core layer is h_H. The nanotube reinforcement in the face sheet is either uniformly-distributed (UD) or functionally-graded (FG) in the plate thickness direction. The plate is exposed to thermal con-

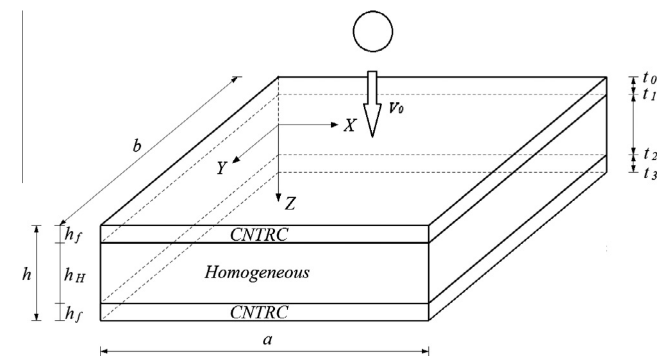

Fig. 1. Configuration of a carbon nanotube reinforced composite (CNTRC) laminated plate subjected to low velocity impact.

ditions and subjected to transverse low-velocity impact combined with initial in-plane edge loads, if any. The coordinate system has its origin at the corner of the plate on the mid-plane (see Fig. 1). 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 and Z are longitudinal and perpendicular to the plate, respectively. $\overline{\Psi}_x$ and $\overline{\Psi}_y$ are the mid-plane rotations of the normals about the Y and X axes, respectively.

For hybrid laminated and/or sandwich plates, the layer-wise methods were commonly proposed to trace the local variations in each layer, and they describe a piecewise continuous displacement field in the thickness direction of the plate and incorporate the interlaminar continuity of the transverse stresses at each layer interface. However, these models need a huge amount of computational efforts because the number of unknown variables depends on the number of layers in the laminate. Reddy [24] developed a simple higher order shear deformation plate theory in which the parabolic distribution of the transverse shear strains is assumed through the plate thickness. Different from the first order shear deformation theory, no shear correction factors are required in this higher order theory, though there are the same number of independent unknowns ($\overline{U}$, $\overline{V}$, $\overline{W}$, $\overline{\Psi}_x$ and $\overline{\Psi}_y$) in both the theories. Shen [25] extended Reddy's higher order shear deformation plate theory and proposed a set of general von Kármán-type equations which are expressed in terms of the transverse displacement $\overline{W}$, rotations $\overline{\Psi}_x$ and $\overline{\Psi}_y$, and stress functions $\overline{F}$ as defined by $\overline{N}_x = \overline{F}_{,YY}$, $\overline{N}_y = \overline{F}_{,XX}$ and $\overline{N}_{xy} = -\overline{F}_{,XY}$. Then, the equations of motion for a laminated or sandwich plate can be expressed by

$$\widetilde{L}_{11}(\overline{W}) - \widetilde{L}_{12}(\overline{\Psi}_x) - \widetilde{L}_{13}(\overline{\Psi}_y) + \widetilde{L}_{14}(\overline{F}) - \widetilde{L}_{15}(\overline{N}^T) - \widetilde{L}_{16}(\overline{M}^T) = \widetilde{L}(\overline{W},\overline{F}) + \widetilde{L}_{17}(\ddot{\overline{W}}) + I_8\left(\frac{\partial \ddot{\overline{\Psi}}_x}{\partial X} + \frac{\partial \ddot{\overline{\Psi}}_y}{\partial Y}\right) + Q \tag{1}$$

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

$$\widetilde{L}_{31}(\overline{W}) + \widetilde{L}_{32}(\overline{\Psi}_x) - \widetilde{L}_{33}(\overline{\Psi}_y) + \widetilde{L}_{34}(\overline{F}) - \widetilde{L}_{35}(\overline{N}^T) - \widetilde{L}_{36}(\overline{S}^T) = I_9\frac{\partial \ddot{\overline{W}}}{\partial X} + I_{10}\ddot{\overline{\Psi}}_x \tag{3}$$