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Buckling of boron nitride nanotube reinforced piezoelectric polymeric composites subject to combined electro-thermo-mechanical loadings

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Abstract

Unlike widely used carbon nanotubes, boron nitride nanotubes (BNNTs) have shown to possess stable semiconducting behavior and strong piezoelectricity. Such properties along with their outstanding mechanical properties and thermal conductivity, make BNNTs promising candidate reinforcement materials for a verity of applications especially nanoelectronic and nanophotonic devices. Motivated by these abilities, we aim to study the buckling behavior of BNNT-reinforced piezoelectric polymeric composites when subjected to combined electro-thermo-mechanical loadings. For this, the multi-walled structure of BNNT is considered as elastic media and a set of concentric cylindrical shells with van der Waals interaction between them. Using three-dimensional equilibrium equations, Donnell shell theory is utilized to show that the axially compressive resistance of BNNT varies with applying thermal and electrical loads. Also, a new equivalent spring constant model of piezoelectric matrix under electro-thermo-mechanical loadings is developed according to the concept of Whitney–Riley model. Results indicate that the support of piezoelectric matrix significantly enhances the buckling resistance of BNNT. Alternatively, the effect of BNNT piezoelectric property on the buckling behavior of composites is demonstrated. Furthermore, it is demonstrated that the supporting effect of elastic medium depends on the direction of applied voltage and thermal flow. More specifically, it is shown that applying direct and reverse voltages to BNNT changes the buckling loads for any axial and circumferential wavenumbers. Such capability could be uniquely utilized when designing BNNT-reinforced composites for structural vibration control applications.

Keywords: A. Nanostructures; Shell theory; Boron nitride nanotube reinforced composite; C. Piezoelectric material

1. Introduction

Carbon nanotubes (CNTs) have attracted worldwide interest because of their unique properties and great potential for technological applications. Numerous studies have shown that CNTs possess extraordinary mechanical properties such as high stiffness to weight and strength to weight ratios, and enormous electrical and thermal conductivities [1–8]. However, their applications are limited in high strength and uniform electronic structures. This is due to the fact that the electrical properties of these tubes are not stable and range from metallic to semiconducing depending upon the radius and chirality of the tubes [9]. Unlike CNTs, boron nitride nanotubes (BNNTs) have stable semiconducting behavior with a large band gap of 4–5 eV, regardless of radius and chirality of the structure [10]. This property of BNNTs makes them promising candidate materials in a large variety of nanosized electronic and photonic devices. Furthermore, BNNTs seem to be more suitable as reinforcement in composite structures due to their high resistance to oxidation at elevated temperatures, outstanding mechanical properties and high thermal conductivity [11].

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To investigate these potentials theoretically, molecular dynamic (MD) simulation and continuum mechanic are two promising approaches. In particular, for a nanotube structure subjected to a compressive load which is the subject of this study, Yakobson et al. [12] introduced an MD simulation model and found a synergism between the shell theory prediction and MD simulation results. More specifically, they showed that the critical buckling load can be estimated by a continuum shell model. However, due to the importance of van der Waals (vdW) forces between adjacent layers of multi-walled nanotube (MWNT) and interaction of outer layer of nanotube with surrounding elastic medium, the existing continuum shell models cannot be directly used. Recently, a continuum model has been proposed for infinitesimal buckling of a double-walled nanotube where the effect of surrounding elastic medium and vdW forces are taken into account [13]. This model was further extended for MWNT composites subjected to radial pressure, torsion, bending and combined loadings of axial and radial pressure [14–17].

Motivated by these considerations, we aim to study the buckling behavior of BNNT-reinforced piezoelectric polymeric matrix such as polyvinylidene fluoride (PVDF) subject to combine electro-thermo-mechanical loadings. As both BNNT and matrix are piezoelectric materials [18–21], the buckling instability of current structures can be controlled by applying thermal and electrical loads along with external force. To the best of our knowledge, there has been no report in the literature regarding the effect of complex (i.e., electrical, thermal and mechanical) loadings on buckling instability of nanostructures. Hence, this work introduces a new approach for the possible tuning of nanostructures' properties. Furthermore, the role of elastic medium on the buckling of composite structure is investigated under electro-thermo-mechanical loadings.

More specifically, using three-dimensional equilibrium equations in the cylindrical coordinate, we employ the Donnell shell theory for piezoelectric materials. The MWNTs embedded in an elastic medium are considered as elastic media and a set of concentric cylindrical shells with vdW interaction forces between them. Also, the concept of Whitney–Riley model is used to determine equivalent spring constant of piezoelectric matrix. Depending upon the direction of applied voltage and thermal flow, the equivalent spring constant is made up different combinations of elastic, thermal and electrical parts which correspond to components of complex loadings. It is also shown that applying electrical and thermal loads could affect the equivalent spring constant, and consequently changes the supporting effect of elastic medium. Moreover, the effect of piezoelectric property of BNNT on the buckling behavior of this structure is demonstrated. It is shown that applying direct and reverse voltages to BNNT changes the buckling loads for any axial and circumferential wavenumbers.

The remainder of paper is organized as follows. Section 2 presents the mathematical modeling of current piezoelectric structure based on Donnell shell theory. Section 3 describes the spring constants of piezoelectric elastic medium under complex loadings. Section 4 gives the numerical results for BNNT and BNNT + PVDF composites in order to demonstrate the advantages of using BNNT over CNT and also to show the supporting role of PVDF under different loadings, and finally Section 5 summarizes the work.

2. Elastic shell model for piezoelectric structures

The classical three-dimensional mechanical equilibrium equations for a cylindrical shell with coordinates r, θ and x denoting the radial, circumferential and axial coordinate directions, respectively, can be written as

$$\begin{aligned}
&\frac{\partial \sigma_{rr}}{\partial z}+\frac{1}{R}\frac{\partial \sigma_{r\theta}}{\partial \theta}+\frac{\partial \sigma_{rx}}{\partial x}+\frac{\sigma_{rr}-\sigma_{\theta\theta}}{R}=0\\
&\frac{\partial \sigma_{r\theta}}{\partial z}+\frac{1}{R}\frac{\partial \sigma_{\theta\theta}}{\partial \theta}+\frac{\partial \sigma_{\theta x}}{\partial x}+\frac{2\sigma_{\theta r}}{R}=0\\
&\frac{\partial \sigma_{rx}}{\partial z}+\frac{1}{R}\frac{\partial \sigma_{\theta x}}{\partial \theta}+\frac{\partial \sigma_{xx}}{\partial x}+\frac{\sigma_{rx}}{R}=0
\end{aligned} \tag{1}$$

where σ_{rr}, $\sigma_{\theta\theta}$, σ_{xx}, $\sigma_{r\theta}$, σ_{rx} and $\sigma_{\theta x}$ are the components of the Cauchy stress tensor in a cylindrical coordinate system. Also, the forces and moments per unit length of the shell can be expressed in the term of Cauchy stresses as (see Fig. 1)

$$N_{ij}=\int_{-t/2}^{t/2}\sigma_{ij}\,\mathrm{d}z,\quad M_{ij}=\int_{-t/2}^{t/2}\sigma_{ij}z\,\mathrm{d}z\quad\text{and}\quad Q_i=\int_{-t/2}^{t/2}\sigma_{ir}\,\mathrm{d}z \tag{2}$$

where $i = x, \theta$ and $j = x, \theta$. t is the thickness of shell and R is the radius at the mid thickness of shell (see Fig. 1).

Integrating Eq. (1) through the thickness of shell and using Eq. (2) results in

$$\begin{aligned}
&\frac{1}{R}\frac{\partial Q_\theta}{\partial \theta}+\frac{\partial Q_x}{\partial x}-\frac{N_\theta}{R}+P_r=0\\
&\frac{1}{R}\frac{\partial N_\theta}{\partial \theta}+\frac{\partial N_{x\theta}}{\partial x}+P_\theta=0\\
&\frac{1}{R}\frac{\partial N_{\theta x}}{\partial \theta}+\frac{\partial N_x}{\partial x}+P_x=0
\end{aligned} \tag{3}$$

where P_r, P_θ and P_x are the respective radial, circumferential and axial components of load per unit mid-surface area due to the tractions in the bottom and top surfaces of the shell [22].

Multiplying Eq. (1) by z, integrating through the thickness of shell, and using Eq. (2) leads to

$$\begin{aligned}
&\frac{1}{R}\frac{\partial M_\theta}{\partial \theta}+\frac{\partial M_{x\theta}}{\partial x}-Q_\theta+\Phi_\theta=0\\
&\frac{\partial M_x}{\partial x}+\frac{1}{R}\frac{\partial M_{\theta x}}{\partial \theta}-Q_x+\Phi_x=0
\end{aligned} \tag{4}$$

where Φ_θ and Φ_x are the respective moments per unit mid-surface area due to circumferential and axial components of traction in the bottom and top surfaces of the shell [22].