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Nonlocal strain gradient shell model for axial buckling and postbuckling analysis of magneto-electro-elastic composite nanoshells

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The present study deals with the size-dependent nonlinear buckling and postbuckling characteristics of magneto-electro-elastic cylindrical composite nanoshells incorporating simultaneously the both of hardening-stiffness and softening-stiffness size effects. To accomplish this purpose, the nonlocal strain gradient elasticity theory is applied to the classical shell theory. Via the virtual work's principle, the size-dependent governing differential equations are constructed including the coupling terms between the axial mechanical compressive load, external magnetic potential and external electrical potential. The nonlinear prebuckling deformations and the large postbuckling deflections are taken into consideration based upon the boundary layer theory of shell buckling. Finally, an improved perturbation technique is employed to achieve explicit analytical expressions for nonlocal strain gradient stability curves of magneto-electro-elastic nanoshells under various surface electric and magnetic voltages. It is seen that a positive electric potential and a negative magnetic potential cause to increase both of the nonlocality and strain gradient size dependencies in the nonlinear instability behavior of axially loaded magneto-electro-elastic composite nanoshells, while a negative electric potential and a positive magnetic potential play an opposite role.

1. Introduction

In those early years, a new group of composite materials containing simultaneously the piezoelectric and piezomagnetic phases have been attracted the attention of research community due to their smart characteristics. This attraction has been even somehow more than that dedicated previously to functionally graded composite materials [1–3]. The novel magneto-electro-elastic coupling feature of these smart composites makes them more sensitive and adaptive as an eminent candidate in numerous areas of technology such as semiconducting capacitors, robotics, structural health monitoring, sensors and actuators and so on [4–7]. In recent years, the mechanical responses of magneto-electro-elastic macrostructures have been investigated extensively based on the classical continuum mechanics [8–15].

The synthesis of nanotechnology-based products is one of the important fields of engineering sciences because of their wide range of application. It is well recognized that nanostructures possess unique characteristics which are greatly depend on their shape as well as their crystalline arrangement. Accordingly, several non-classical continuum theories of elasticity have been proposed and employed to anticipate different size dependencies in mechanical behaviors of nanostructures [16–46]. Recently, some studies have been carried out to predict the mechanical behavior of nanoscaled structures made of magneto-electro-elastic (MEE) composite materials. Ke and Wang [47] analyzed the size-dependent free vibrations of MME composite Timoshenko nanobeams based on the nonlocal elasticity theory. Ke et al. [48,49] reported the size-dependent natural frequencies of MEE composite nanoplates and cylindrical nanoshells via nonlocal theory of

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elasticity implemented in, respectively, the Kirchhoff plate theory and Love's shell theory. Li et al. [50] analyzed bending, buckling and free vibration of MEE composite Timoshenko nanobeams on the basis of nonlocal continuum theory. Farajpour et al. [51] established a nonlocal plate model to study the size effect on the nonlinear vibration behavior of MEE composite nanoplate under external electromagnetic loading condition. Jamalpoor et al. [52] used a nonlocal plate model to investigate the free vibration and biaxial buckling double-MEE nanoplate-system subjected to electric and magnetic potentials.

Generally, in the previous investigations, it has been demonstrated that the small scale effect in type of the stress nonlocality results in softening-stiffness influence, while the strain gradient size dependency leads to a hardening-stiffness effect. As a consequence, Lim et al. [53] proposed a new size-dependent elasticity theory namely as nonlocal strain gradient theory which includes the both softening and stiffening influences to describe the size dependency in a more accurate way. Subsequently, a few studies have been performed on the basis of nonlocal strain gradient elasticity theory. Li and Hu [54] reported the size-dependent critical buckling loads of nonlinear Euler-Bernoulli nanobeams based upon nonlocal strain gradient theory of elasticity. They also presented the size-dependent frequency of wave motion on fluid-conveying carbon nanotubes via nonlocal strain gradient theory [55]. Yang et al. [56] established a nonlocal strain gradient beam model to evaluate the critical voltages corresponding to pull-in instability FG carbon nanotube reinforced actuators at nanoscale. Simsek [57] used nonlocal strain gradient theory to capture the size effects on the nonlinear natural frequencies of FGM Euler-Bernoulli nanobeams. Farajpour et al. [58] proposed a new size-dependent plate model for buckling of orthotropic nanoplates based on nonlocal strain gradient elasticity theory. Tang et al. [59] studied the wave propagation in a viscoelastic carbon nanotube via nonlocal strain gradient elasticity theory. Ebrahimi and Dabbagh [60] employed nonlocal strain gradient elasticity theory to study the flexural wave propagation in functionally graded MEE higher-order shear deformable nanoplates. Li et al. [61] utilized the nonlocal strain gradient elasticity theory within the framework of the Euler-Bernoulli beam theory to explore bending, buckling and free vibration of axially functionally graded nanobeams. Sahmani and Aghdam [62] employed the nonlocal strain gradient elasticity theory within the framework of the hyperbolic shear deformation shell theory to analyze the size-dependent nonlinear instability of a microtubule embedded in an elastic foundation related to the cytoplasm of a living cell.

The objective of this work is to capture simultaneously the nonlocality and strain gradient size dependencies on the nonlinear buckling and postbuckling behavior of axially loaded MEE composite nanoshells under external electric and magnetic potentials. Thereby, the nonlocal strain gradient elasticity theory is incorporated to the classical shell theory to develop a more comprehensive size-dependent shell model. On the basis of the variational approach, the non-classical differential equations are derived. Afterwards, the boundary layer theory of shell buckling and an improved perturbation technique are put to use to achieve explicit analytical expressions for the nonlocal strain gradient stability curves of MEE composite nanoshells under combination of axial compressive load, electric and magnetic potentials.

2. Nonlocal strain gradient MEE shell model

As illustrated in Fig. 1, an MEE composite cylindrical nanoshell with length L, radius R and thickness h is supposed under axial compressive load combined with external electric and magnetic potentials. Based upon the nonlocal strain gradient elasticity theory, the total nonlocal strain gradient stress tensor Λ can be expressed as below [53].

$$\Lambda_{ij} = \sigma_{ij} - \nabla\sigma^{*}_{ij}; \quad i,j = x,y \tag{1}$$

where ∇ is the gradient symbol, σ and σ^{*} represent, respectively, the stress and higher-order stress tensors which can be introduced for an MEE composite material as follows

$$\begin{aligned}\sigma_{ij} = \int_{\Omega} \Big\{ \varrho_1\left(\left|\mathscr{X}' - \mathscr{X}\right|\right)\Big[c_{ijkl}\varepsilon_{kl}\left(\mathscr{X}'\right) - e_{mij}\mathscr{E}_m\left(\mathscr{X}'\right) \\ - q_{nij}\mathscr{M}_n\left(\mathscr{X}'\right)\Big]\Big\} d\Omega\end{aligned} \tag{2a}$$

$$\begin{aligned}\sigma^{*}_{ij} = l^2 \int_{\Omega} \Big\{ \varrho_2\left(\left|\mathscr{X}' - \mathscr{X}\right|\right)\Big[c_{ijkl}\nabla\varepsilon_{kl}\left(\mathscr{X}'\right) - e_{mij}\mathscr{E}_m\left(\mathscr{X}'\right) \\ - q_{nij}\mathscr{M}_n\left(\mathscr{X}'\right)\Big]\Big\} d\Omega\end{aligned} \tag{2b}$$

in which c_{ijkl}, e_{mij}, q_{nij} in order are the elastic, piezoelectric and piezomagnetic constants. Also, $\varrho_1$and ϱ_2 are, respectively, the principle attenuation kernel function including the nonlocality and additional kernel function associated with the nonlocal effect of the first-order strain gradient field, $\mathscr{X}$ and $\mathscr{X}'$ in order denote a point and any point else in the body, and l stands for the internal strain gradient length scale parameter. $\mathscr{E}$ and $\mathscr{M}$ are the electric field and magnetic intensity, respectively.

In a similar way, the other basic equations for an MEE composite material can be expressed based upon the nonlocal strain gradient elasticity theory as below

$$\begin{aligned}D_i = \int_{\Omega} \Big\{ \varrho_1\left(\left|\mathscr{X}' - \mathscr{X}\right|\right)\Big[e_{ikl}\varepsilon_{kl}\left(\mathscr{X}'\right) - s_{im}\mathscr{E}_m\left(\mathscr{X}'\right) \\ - d_{in}\mathscr{M}_n\left(\mathscr{X}'\right)\Big]\Big\} d\Omega\end{aligned} \tag{3a}$$

$$\begin{aligned}D^{*}_i = l^2 \int_{\Omega} \Big\{ \varrho_2\left(\left|\mathscr{X}' - \mathscr{X}\right|\right)\Big[e_{ikl}\nabla\varepsilon_{kl}\left(\mathscr{X}'\right) - s_{im}\mathscr{E}_m\left(\mathscr{X}'\right) \\ - d_{in}\mathscr{M}_n\left(\mathscr{X}'\right)\Big]\Big\} d\Omega\end{aligned} \tag{3b}$$