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Original Research Article

Imperfection sensitivity of the size-dependent postbuckling response of pressurized FGM nanoshells in thermal environments

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ABSTRACT

The purpose of the current study is to address the nonlinear buckling and postbuckling response of nanoscaled cylindrical shells made of functionally graded material (FGM) under hydrostatic pressure aiming to investigate the sensitivity to the initial geometric imperfection in the presence of surface effects and thermal environments. According to a power law distribution, the material properties of the FGM nanoshell are considered change through the shell thickness. Also, the change in the position of physical neutral plane corresponding to different volume fractions is taken into account to eliminate the stretching-bending coupling terms. In order to acquire the size effect qualitatively, the well-known Gurtin-Murdoch elasticity theory is incorporated within the framework of the classical shell theory. Using the variational approach, the non-classical governing equations are displayed and deduced to boundary layer type ones. Afterwards, explicit expressions for the size-dependent radial postbuckling equilibrium paths of imperfect FGM nanoshells are proposed with the aid of a perturbation-based solution methodology. It is displayed that by moving from the ceramic phase to the metal one, the critical buckling pressure decreases, but the postbuckling stiffness increases, because in contrast to the ceramic phase, the surface modulus and residual surface stress associated with the metal phase have the same sign.

1. Introduction

In contrast to the traditional layered composites in which the mechanical properties vary from layer to layer with sharp discontinues, functionally graded materials (FGMs) have gradually varying properties with specific alternation the micromechanical characteristics. The rapid advances in technology make FGM nanostructures as building blocks of potential designs and applications of nano electro mechanical systems (NEMS) [1–5].

In order to have a predictability and reliability design for these miniaturized systems, it is necessary to take small scale effects into account. To capture the small scale effects at nanoscale using continuum-based modeling, several nonconventional continuum theories have been introduced in which

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new length-scale parameters have been considered in the constitutive equations. There are a number of investigations on prediction of size-dependent behavior of nanostructures based upon different non-classical continuum theories. Ansari et al. [6] examined the free vibration response of single-layered graphene sheets using nonlocal continuum elasticity. Ansari and Sahmani [7] used nonlocal elasticity theory within the framework of different beam theories to predict natural frequencies of single-walled carbon nanotubes. Thai and Vo [8] implemented nonlocal elasticity theory into a sinusoidal shear deformation beam theory for mechanical behaviors of nanobeams. Ansari and Sahmani [9] anticipated the biaxial buckling behavior of single-layered graphene sheets based on various nonlocal plate models. Wang and Li [10] studied the nonlinear primary resonance of nanobeams on the basis of Eringen's nonlocal elasticity. Sahmani et al. [11] used strain gradient elasticity theory for nonlinear free vibrations of FGM microbeams. El-Borgi et al. [12] analyzed the size-dependent free and forced vibration responses of FGM nanobeams resting on elastic foundation. Simsek [13] obtained the nonlinear frequencies of FGM nanobeams based upon nonlocal strain gradient elasticity theory. Tang et al. [14] investigated the viscoelastic wave propagation in embedded carbon nanotubes using the combination of nonlocal and strain gradient elasticity theories.

Among various non-classical continuum theories, surface elasticity theory incorporates the effect of surface free energy as one of the most important size effects. The surface free energy effect is particularly significant in nanoscaled structures due to their high surface to volume ratio. Motivated by this issue, Gurtin and Murdoch [15,16] introduced a very elegant mathematical modeling within the framework of continuum elasticity to consider the effect of surface free energy in the classical continuum mechanics. On the basis of Gurtin-Murdoch elasticity theory, the free surfaces of structure are simulated as layers, the thickness of which is zero and the material properties of which are different from those of the bulk of structure. Later, for better understanding of mechanical response of nanostructures, several researchers employed Gurtin-Murdoch elasticity theory to analyze the static and dynamic behaviors of various structures at nanoscale.

For instance, Jing et al. [17] used surface elasticity theory in conjunction with contact atomic force microscope to measure the elastic properties of nanowires made of silver. Jammes et al. [18] employed the surface elasticity theory to analyze the multiple interacting circular nano-inhomogeneities and nano-pores located in one of two joined, dissimilar isotropic elastic half-planes. Mogilevskaya et al. [19] studied the effects of surface elasticity and surface tension on the transverse overall behavior of unidirectional nano-scale fiber-reinforced composites described by the Gurtin-Murdoch elasticity theory. Based upon surface elasticity theory, Wang et al. [20] investigated the influences of surface tension and the residual stress in the bulk induced by the surface tension on the elastic properties of nanostructures. Intarit et al. [21] presented analytical solutions for shear and opening dislocations in an elastic half-plane with surface stresses by using the Gurtin–Murdoch continuum theory of elastic material surfaces. Ansari and Sahmani [22] developed non-classical beam models through implementation of surface elasticity theory into the various classical beam theories to analyze bending and buckling behavior of nanobeams. They also examined the effect of surface free energy on the free vibration response of rectangular nanoplates corresponding to different plate theories [23]. Nazemnezhad et al. [24] predicted the nonlinear free vibration of nanobeams with considering surface effects including surface elasticity, tension and density using Euler–Bernoulli beam theory in conjunction with the von Kármán geometric nonlinearity. Shaat et al. [25] investigated the bending behavior of ultra-thin functionally graded plates in the presence of the surface free energy effect. Malekzadeh and Shojaee [26] studied simultaneously the surface and nonlocal effects on the nonlinear flexural free vibrations of elastically supported non-uniform cross section nanobeams. On the basis of an efficient numerical solution procedure, Sahmani et al. [27] predicted the surface free energy effect on the free vibration characteristics of postbuckled third-order shear deformable nanobeams. Also, Sahmani et al. [28] used surface elasticity theory to analyze the nonlinear forced vibration behavior of third-order shear deformable nanobeams with various boundary conditions. Wang and Wang [29] proposed a general model for nano-cantilever switches with consideration of surface stress, nonlinear curvature, the location and length of the fixed electrode. Mohebshahedin and Farrokhabadi [30] demonstrated the influence of surface layer on the instability of NEMS tweezers and cantilevers fabricated from conductive cylindrical nanowires. Sahmani et al. [31] studied the free vibration response in both the prebuckling and postbuckling regimes for third-order shear deformable nanobeams made of FG material incorporating surface free energy effect. Rungamornrat et al. [32] presented the analysis of an infinite, rigid-based, elastic layer under the action of axisymmetric surface loads, taking the surface energy effects into account. Fan and Xu [33] examined the Saint-Venant end effect in the nanotubes via a continuum mechanics with consideration of surface elasticity.

Herein, the surface effects are evaluated on the developed non-classical imperfection sensitive shell model for the postbuckling characteristics of FGM cylindrical nanoshells under hydrostatic pressure and thermal environments. By considering the difference between the positions of the physical neutral plane and the geometric middle plane, the terms of stretching-bending coupling are removed. The size-dependent governing equations are constructed using the principle of minimum potential energy and then they are deduced to boundary layer-type ones. Finally, based on a singular perturbation solution methodology, explicit expressions for the size-dependent postbuckling equilibrium paths are proposed.

2. Non-classical FGM shell model based on surface elasticity

As illustrated in Fig. 1, an FGM cylindrical nanoshell with the length L, thickness h, and mid-surface radius R made from a mixture of silicon as the ceramic phase and aluminum as the metal phase is considered. The nanoshell is assumed to be