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Surface stress effects on the postbuckling behavior of geometrically imperfect cylindrical nanoshells subjected to combined axial and radial compressions

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ABSTRACT

Because of surface free energy effects at nanoscale, study of the mechanical behavior of nanostructures including surface stress effects is a topic of substantial interest. Herein, the nonlinear buckling and postbuckling characteristics of geometrically imperfect cylindrical nanoshells under combined axial and radial compressive loads are investigated in the presence of surface stress effects. An efficient size-dependent shell model is proposed based on Gurtin–Murdoch elasticity theory and von Karman–Donnell-type of kinematic nonlinearity. On the basis of variational approach using the principle of virtual work, the non-classical governing differential equations are derived. Afterwards, a boundary layer theory is employed incorporating surface stress effects in conjunction with nonlinear prebuckling deformations, initial geometric imperfections and large postbuckling deflections. Then a two-stepped singular perturbation methodology is put to use in order to solve the size-dependent nonlinear problem corresponding to axial dominated and radial dominated loading cases. It is shown that in the case of radial dominated loading, the combination of hydrostatic pressure with axial compression causes to decrease approximately the effect of surface stress compared to the absence of axial load. However, for the axial dominated loading case, in comparison with no applied radial load, the surface stress effects is more significant in the presence of hydrostatic pressure.

1. Introduction

Because of rapidly developing nanotechnology, the range of application of nanostructures extends, an increasing impetus is being devoted to the nanostructured material, devices and systems. In this special length scale, size effects become dominant, which cause to the essential change in material properties, triggering ever-wider applications. In order to successfully design and manufacture the nanosized structures, it is required to predict their size-dependent mechanical behavior. In this regard, several experimental techniques, computational methodologies and theoretical approaches have been proposed to study the mechanics of structures at nanoscale.

Due to superior computational efficiency and versatility, the continuum mechanics has been restored by many researchers to investigate the mechanical properties of nanostructures. However, because the classical continuum theory is a scale independent theory, various modified continuum theories have been introduced and employed to characterize the size effects in nanostructures by introducing an intrinsic length scale [1–20].

The surface free energy is one of important reasons which give rise to the extraordinary characteristics of nanosized structures. Because the atoms at a free surface are exposed to different environment than those at the bulk of a material, the equilibrium energy of these atoms will be consequently different from the bulk energy. Especially for nanostructures with thickness at nanoscale where there are a great number of atoms near the free surface in comparison with those in the bulk, the influence of surface effects plays a substantial role. Gurtin and Murdoch [21,22] introduced a general theoretical framework based upon the concepts of continuum mechanics which takes surface free energy effects. In accordance with their proposed model, the surface of nanostructure is considered as a mathematical layer of zero thickness attached to the underlying bulk with no slipping. By defining surface Lame constants and residual surface stress, the surface properties are different from those of the bulk of material.

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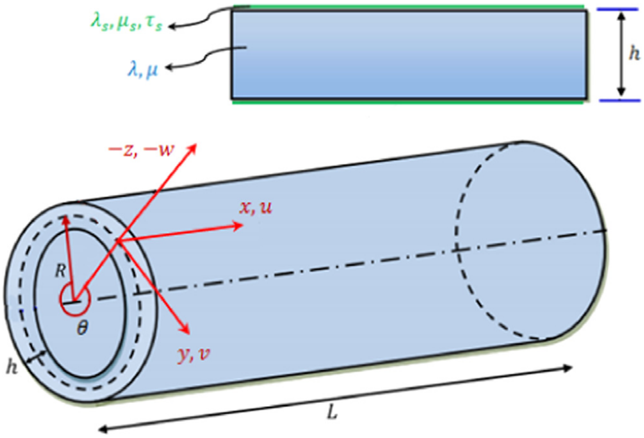

Fig. 1. Schematic view of a cylindrical nanoshell with surface layers.

Table 1
Material properties of a cylindrical nanoshell made of silicon [50].

E (GPa)	210
ν	0.24
μ_s (N/m)	-2.774
λ_s (N/m)	-4.488
τ_s (N/m)	0.6048

Table 2
Comparison of the critical buckling pressures of isotropic cylindrical shells with clamped edge supports subjected to lateral pressure ($\nu=0.3$, E=200 GPa).

L/R	R/h	Present work (Pa)	Ref. [51] (Pa)
2	300	84,991.09	85,860
	3000	275.82	276.5
5	300	32,897.22	32,954
	3000	108.13	109

In recent years, several investigations have been carried out in which Gurtin–Murdoch surface elasticity theory is put to use in order to predict the mechanical responses of nanostructures including surface effects. Lim and He [23] obtained the deformations of nanofilms under bending load in the presence of surface stress effects. Lu et al. [24] performed an investigation to complete the work of Lim and He [23] by taking the normal stress variation along the nanofilm thickness into account. Wang and Feng [25] and Abbasion et al. [26] predicted, respectively, the free vibration response of microbeams including surface effects on the basis of Euler–Bernoulli and Timoshenko beam theories. He and Lilley [27] reported the influence of surface stress on the static bending and bending resonance of nanowires with various end supports. Zhao and Rajapakse [28] developed the axisymmetric solutions for an elastic layer subjected to surface loading incorporating the effects of surface energy. Fu et al. [29] investigated the influences of surface free energy on the free vibration and buckling behavior of nanobeams in the both linear and nonlinear regimes using Galerkin's technique. Sahmani and Ansari [30] examined the surface stress effects on the bending and buckling responses of nanobeams within the framework of various types of beam theory. Sahmani and Ansari [31] also studied the free vibrations of rectangular nanoplates modeled via different plate theories in the presence of surface free energy effects. Wang [32] analyzed the postbuckling behavior of nanobeams containing internal flowing fluid incorporating surface stress effects. Ansari et al. [33,34] investigated the postbuckling characteristics of Euler–Bernoulli and Timoshenko nanobeams, respectively, based on surface elasticity theory. Liu et al. [35] presented a theoretical analysis of the propagation of shear horizontal waves in an ultra-thin plate-like film with nanoscale thickness via the surface elasticity theory. Wang and Wang [36] developed a continuum finite element model for the nanoscale plates considering the surface effects of the material. Ansari et al. [37] examined the surface stress effects on the pull-in instability phenomenon of hydrostatically and electrostatically actuated circular nanoplates. Sahmani et al. [38] presented the free vibration response of postbuckled third-order shear deformable nanobeams based on Gurtin–Murdoch elasticity theory. Sahmani et al. [39] proposed a non-classical beam model to study the nonlinear forced vibrations of nanobeams including surface effects. Sahmani et al. [40] predicted the free vibration of postbuckled circular higher-order shear deformable nanoplates incorporating the effect of surface free energy. Sahmani et al. [41] studied the free vibration characteristics of postbuckled functionally graded third-order shear deformable nanobeams using surface elasticity theory. Hosseini-Hashemi et al. [42] analyzed nonlinear free vibrations of nanobeams considering surface effects within the framework of Euler–Bernoulli beam theory.

The objective of the current study is to predict the influence of surface stress on the nonlinear buckling and postbuckling behavior of geometrically imperfect cylindrical nanoshells subjected to combined axial and radial compressive loads. For this purpose, Gurtin–Murdoch elasticity theory is implemented into the classical shell theory to develop a size-dependent shell model taking surface stress effects into account efficiently. A boundary layer theory is employed including surface stress effects in conjunction with nonlinear prebuckling