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Size-dependent torsional buckling analysis of functionally graded cylindrical shell

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ABSTRACT

The size-dependent torsional buckling behavior of functionally graded (FG) cylindrical shell is investigated on the basis of modified couple stress theory using the shell model. The material properties of FG nanoshell are considered change through thickness direction according to power law distribution. The modified couple stress shell theory with the von Karman geometrical nonlinearity is utilized to establish theoretical formulations. The governing equations and boundary conditions are derived using the minimum potential energy principle. As a special case, the torsional buckling of simply supported and clamped FG cylindrical shell is examined using the GDQ method. Afterwards, the influences of geometrical parameters, such as length scale parameter, length, and thickness, as well as material property gradient index of the FG cylindrical shell on the critical torsional buckling moment are studied.

1. Introduction

Due to the development of the materials science, functionally graded materials (FGMs) have been widely used in various nanostructures. Micro and nanoelectromechanical systems (MEMS and NEMS) [1–3], atomic force microscopes (AFMs) [4] and as thin films in shape memory alloys [5,6] are only a few of their potential applications. Functionally graded material as a new type of composite material, which typically contains the specific ceramic and metallic constituents, takes advantages of its components. The ceramic constituent, because of its low thermo-conductivity, provides high temperature resistance while the metal component supplies high strength and toughness [7]. The mechanical properties, in most of FGMs, which change smoothly and continuously along specific direction, can provide a solution for delamination, usual problem in composite structures regarding the sudden change properties across interfaces among constituents, and even further, can be adjusted to a specific demand of the design requirements [8,9]. FGMs was initially introduced by a group of Japanese material scientists in 1984 [10]. Since then, many investigations, due to their fascinating features and potential applications, have been carried out to study the free vibration, buckling and dynamic stability of the FGM structures [11–22].

Nanoscience and nanotechnology are science at the nanoscale which deal with extremely small things. According to both experimental and molecular dynamic simulation results, the size effect plays an important role in studies at nanoscales. Among different methods for investigating the static and dynamic behavior and mechanical properties of nanostructures, the continuum mechanics have been increasingly used since the experimental approach at the nanoscale is difficult and the atomistic simulation is very time consuming and computationally expensive for large-scale systems [23,24]. On the other hand, in view of the independency of the classical continuum theory to the scale of the structures, this theory cannot accurately predict and represent the static and dynamic behaviors of nanostructures. Thus, since the classical continuum theory is based on the assumption in which matter is continuously distributed in the body, many researchers attempted to expand the classical continuum theory to the atomic discrete structures, but any attempt to drop the continuity assumption leads to so difficult analysis [25]. Therefore, the non-classical continuum theories, which are able to include nanoscale size effects, were developed [26]. The new measures of deformation which are size-dependent, were required in a non-classical continuum theory.

Thus, the couple stress theory in which the higher order rotation gradients are included as the deformation matrix and

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contains two material length scale parameters, was initially introduced by Toupin, Mindlin and Tiersten and Koiter [27–30]. Using this theory, Zhou et al. studied the static and dynamic behavior of microbar under torsion, Kang et al. examined the resonant frequency of microbeams and Anthonie investigated the pure bending of a circular cylinder [31–33]. Afterwards, the modified couple stress theory was presented by Yang et al., in which in addition to the classical equilibrium equations of forces and moments of forces, a new additional one, as the equilibrium of moments of couples to govern the behavior of higher-order stresses, was included [34]. Therefore, the modified couple stress theory has received considerable attention, due to its desirable features such as having only one material length scale parameter and utilizing the symmetric couple stress tensor. For example, Shojaeian et al. studied the electromechanical buckling of FG beam type nano-electromechanical systems (NEMS) based on the modified couple stress theory by considering the nonlinear geometrical effect and intermolecular forces and using the Euler–Bernoulli beam theory [35]. The effects of the distance between two fixed and movable electrodes, length and size on the buckling of the system were discussed. A size-dependent model for bending and free vibration of functionally graded Reddy plate was presented by Thai et al. based on the modified couple stress theory [36]. The effects of small scale was shown significant when the plate thickness is small. Jung et al. investigated the buckling of sigmoid functionally graded nanoplates on elastic foundation based on the modified couple stress theory and the influences of parameters such as material property gradient index, small scale coefficient and side to thickness ratio on the buckling load were shown [37]. Ghayesh et al. studied the nonlinear resonant dynamics of a microscale beam numerically using the modified couple stress theory and showed the effect of different parameters on the resonant dynamic response [38]. Thermal buckling of annular functionally graded plates on an elastic medium was investigated by Ashoori et al. based on the modified couple stress theory [39]. Different types of thermal loading including uniform temperature rise, linear temperature distribution and heat conduction across the thickness were considered and the effects of various parameters such as material length scale parameter, power law index and elastic foundation coefficients on the thermal stability of FG plates were shown. Tadi et al. developed the size dependent equations of FG cylindrical shell using the shear deformation model and rotation inertia based on the modified couple stress theory and then the considerable effect of the size parameter on natural frequency, particularly in bigger thickness and shorter lengths based on the modified couple stress theory, was shown [40].

Since the nanotubes are applied as basic components in many nanostructures, the performance of the cylindrical nanostructures is needed to be well interpreted in order to predict and obtain the most accurate results. Among different nanostructural elements, like nanobeams, nanoplates and nanoshells, considerable attention has been drawn to nanoshells from the research community due to their unique properties and extensive applications in nanodevices, such as NEMS [41]. Hence, the shell model has been widely used to investigate the response of nanostructures [42]. For instance, using the size dependent first order shear deformable FG shell model, Gholami et al. studied the axial buckling of FG cylindrical microshells and evidenced the influences of material length scale parameter, material property gradient index and length to radius ratio on critical buckling load [43]. Based on the modified couple stress theory, the size dependent FG cylindrical thin shell model was proposed by Tadi et al. focusing on the free vibration of the cylindrical shell and the influences of material property gradient index, length scale parameter and length to radius ratio on natural frequency were discussed and compared with the classical continuum theory [44].

The stability of shell structures, i.e. shell buckling, is an essential problem and the torsional buckling, due to its practical importance, is a basic problem for circular cylindrical shells than compression buckling. In addition, due to the difficulty of the stability and vibration solutions of the circular cylindrical shell under torsion, the torsional analysis may be one of the basic concerns in the practical applications [45,46]. Thus, there are some publications on the torsional analysis of cylindrical shell [47–50]. The stability of FG cylindrical thin shells under time variable torsional loading was presented by Sofiyev et al. and the effect of the constituent materials variations shown considerable on the torsional parameters [51]. Dung et al. studied the nonlinear buckling and post-buckling of FG stiffened thin circular cylindrical shells subjected to torsion analytically and the influence of different parameters and stiffeners on the stability of shell was shown as well [52]. The torsional bifurcation buckling of FG cylindrical shells in a thermal environment was investigated by Sun et al. using a new accurate solution methodology and the influence of different parameters was discussed in detail [53]. Dung et al. examined the nonlinear dynamic behavior of stiffened FG thin circular cylindrical shells subjected to a time-dependent torsional load surrounded by elastic medium using the semi-analytical method [54]. Then, the effects of various parameters such as material, dimensional parameters and stiffener on the dynamic buckling behavior of the shell were shown. The buckling behavior of elastoplastic FG circular cylindrical shells under torsional load and the buckling behaviors of combined-loaded functionally graded cylindrical shells were studied by Huang et al. and the effect of material flow on the buckling of elastoplastic FG cylindrical shells was discussed [55,56]. Moreover, there are some publications on the torsional buckling of cylindrical nanoshell [57–61]. For example, Yao et al. studied the combined torsional buckling behavior of carbon nanotubes by considering the scale effect and discussed the effects of different parameters on the buckling behavior of carbon nanotubes [62]. The nonlinear torsional buckling and postbuckling of geometrically imperfect cylindrical nanoshells including surface stress effects was examined by Sahmani et al. [63]. Khademolhosseini et al. studied the size dependent torsional response of single walled carbon nanotubes based on the modified nonlocal continuum shell model and molecular dynamic simulations [64]. The critical buckling load obtained based on the size dependent nonlocal shell model and molecular dynamic simulations were compared with the classical continuum theory. The buckling and postbuckling of double walled carbon nanotubes under torsion was examined by Shen et al. in thermal environments based on the nonlocal shear deformable cylindrical shell model and the sensitivity of the buckling torque and postbuckling behavior to the small scale parameter was evidenced [65].

In the present study, the size dependent formulation is presented to investigate the buckling characteristics of FG circular cylindrical nanoshells subjected to torsion based on the modified couple stress theory with regard to the geometrical nonlinear effect. According to the present authors' knowledge, no study to date has been carried out. Thus, the equilibrium equations and boundary conditions are derived through the minimum potential energy principle. According to power law distribution, the material properties of FG nanoshell are supposed to change in thickness direction. Thus, the torsional buckling of FG circular cylindrical nanoshell based on the shell model is examined and the influence of different parameters such as length scale parameter, length to radius ratio, thickness, boundary conditions and distribution of constituents on critical buckling load is discussed based on the modified couple stress theory and compared with the classical one.