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On buckling and postbuckling behavior of nanotubes

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ABSTRACT

For the first time, the size-dependent thermal buckling and post-buckling behavior of nanotubes made of functionally graded materials (FGMs) with porosities is investigated by using a refined beam theory. This non-classical nanotube model is based on Eringen nonlocal elasticity model which incorporates the small scale effect. Two types of porosity distribution, including even and uneven distribution, are taken into account. The material properties of the nanotubes are temperature-dependent and vary in the radial direction. The size-dependent governing differential equations are derived by employing the generalized variation principle and solved by using a two-step perturbation method. The effects of small scale parameter, porosity volume fraction, the volume fraction index and boundary conditions on thermal buckling and post-buckling of FGM nanotubes are studied by several numerical examples. It can be concluded that the porosity volume fraction and small scale parameter change the buckling and post-buckling behavior of the nanotubes.

1. Introduction

For decades, functionally graded materials (FGMs) have caused extensive concern in various fields due to their unique mechanical properties. Usually, FGMs consist of two or more than two materials with different properties, and the reasonable unified application of the fraction of each component have the effect of complementary advantages, making the overall performance of the composites better than the original materials (Kiani & Eslami, 2013; Kiani, Sadighi, Salami, & Eslami, 2013; Şimşek & Reddy, 2013). In recent years, it has been revealed that materials and structures on the micro and nanometer scale demonstrate many characteristics different from macro dimensions, and nanostructures made of functionally graded materials are being increasingly applied in various fields, usually, nanostructures can be modeled using atomistic simulation techniques or continuum mechanics, compared to the atomistic simulation approach, the continuum mechanics method has been used widely due to its computational efficiency (Thai, 2012). In order to incorporate the small scale effect at the nano scale, the size-dependent continuum theories should be used instead of the classical continuum mechanics. This may be described by using the nonlocal elasticity theory, there are some nonlocal elasticity theories, such as the strain gradient theory (Nix & Gao, 1998), couple stress theory (Hadjesfandiari & Dargush, 2011), modified couple stress theory (Asghari, Kahrobaiyan, & Ahmadian, 2010), and Eringen nonlocal elasticity model (Eringen, 1983; Shen, 2011). Based on these nonlocal elasticity theory, a number of paper have been published attempting to investigate the buckling, bending and free vibration behaviors of nanostructures made of functionally graded materials

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(Akgöz & Civalek, 2014a,b; Attia, 2017; Dehrouyeh-Semnani & Bahrami, 2016; Dehrouyeh-Semnani, Dehrouyeh, Torabi-Kafshgari, & Nikkhah-Bahrami, 2015; Dehrouyeh-Semnani, Dehrouyeh, Zafari-Koloukhi, & Ghamami, 2015; Dehrouyeh-Semnani, Mostafaei, & Nikkhah-Bahrami, 2016; Ebrahimi & Salari, 2015a,b,c; Ebrahimi & Zia, 2015; Eltaher, Alshorbagy, & Mahmoud, 2013; Eltaher, Khater, & Emam, 2016; Farokhi & Ghayesh, 2015; Ghayesh & Farokhi, 2017; Ghayesh, Farokhi, & Gholipour, 2017; Ghayesh, Farokhi, Gholipour, & Tavallaeinejad, 2017; Ke, Yang, Kitipornchai, & Wang, 2014; Li & Hu, 2016; Li & Pan, 2015; Li, Li, & Hu, 2016; Luan, Nguyen, Vo, & Nguyen, 2016; Nazemnezhad & Hosseini-Hashemi, 2014; Nejad & Hadi, 2016a,b; Nejad, Hadi, & Rastgoo, 2016; Rahmani & Pedram, 2014; Salehipour, Shahidi, & Nahvi, 2015; Shafiei, Kazemi, & Ghadiri, 2016a,b; Shafiei, Kazemi, Safi, & Ghadiri, 2016; Shafiei, Mousavi, & Ghadiri, 2016; Shahverdi & Barati, 2017; Shenas, Malekzadeh, & Ziaee, 2017; Shenas, Ziaee, & Malekzadeh, 2017; Shenas, Ziaee, & Malekzadeh, 2016; Şimşek, 2016; Şimşek & Reddy, 2013; Şimşek & Yurtcu, 2013; Taati, 2016; Thai, 2012; Thai & Vo, 2012; Thai, Vo, Nguyen, & Li, 2015; Wattanasakulpong & Chaikittiratana, 2015; Wattanasakulpong & Ungbhakorn, 2014).

On the other hand, due to manufacturing production, porosities are easy to occur inside carbon nanotubes, in fact, carbon nanotube has porous microstructure and large surface-volume ratio, which makes nanotubes possesses many characteristic, such as energy-absorption, sound insulation, heat insulation (Chen, Kitipornchai, & Yang, 2016; Chen, Yang, & Kitipornchai, 2015; Chen, Yang, & Kitipornchai, 2016; Chen, Yang, & Kitipornchai, 2017). There are some researches about the application of porous nanotubes. For example, Du, Zhang, Chen, Wu, Ma, Liu, et al. (2010) developed a novel and simple method to synthesizing the porous Co_3O_4 nanotubes with the diameter of about 30 nm, and shown that the porous Co_3O_4 nanotubes exhibit the superior li-battery performance with good cycle life and high capacity. Wang, Liu, Zhang, Chen, Guo, Xu, et al. (2012) synthesized the Co_3O_4 nanotubes through modified micro-emulsion method, and investigated the structural and the chemical information of the porous nanotubes by means of electron microscopy and x-ray diffraction. Bucior, Chen, Liu, and Johnson (2016) shown that the porous nanotubes can effectively separate gas mixtures with high selectivity and high permeance. Kim, Lee, and Jung (2011) studied the mechanical properties of porous Al_2O_3 composite with surface modified multi-walled carbon nanotubes. Liu, Li, Zhang, Wang, and Liu (2015) investigated the microstructure and mechanical properties of nanotubes reinforced Si_3N_4 Porous Composites. Long, Bi, Wang, Du, and Bai (2012) discussed the mechanical properties and microstructure of porous BN–SiO_2 –Si_3N_4 composite ceramics. Rao, Lu, Meng, Wang, Lu, and Liu (2014) explored the energy application of porous graphene nanotubes.

From the literature survey, there are a lot of studies on buckling, bending and free vibration characteristics of FGM nanoscaled beams and plates. Literature search indicates that there is no research effort has been devoted to analyze the thermal buckling and post-buckling behavior of porous FGM nanotubes. Therefore, in this study, the size-dependent thermal buckling and post-buckling behavior of FGM nanotubes made of porous material based on the refined beam theory is presented. This non-classical nanotube model is based on Eringen nonlocal elasticity model (Eltaher et al., 2016; Eltaher et al., 2013; Eringen, 1983; Nejad & Hadi, 2016a,b; Nejad et al., 2016; Shen, 2011; Tuna & Kirca, 2016a,b; Rahmani & Pedram, 2014; Eltaher et al., 2013; Şimşek & Yurtcu, 2013) which incorporates the small scale effect. The material properties are temperature-dependent and vary in the radial direction according to the power law function. The governing equation are based on Zhang-Fu beam model (Chen et al., 2017; Fu, Zhong, Shao, & Chen, 2015; Zhong, Fu, Wan, & Li, 2016) and von Kármán type nonlinear strain-displacement relationship. Effects of different parameters on the critical buckling temperature and post-buckling equilibrium path are explored by using the two-step perturbation method.

2. Basic equations

A small-scaled FGM nanotube whose inner radius, outer radius and length are denoted by R_i R_0 and L can be seen in Fig. 1(a). The nanotube is assumed to carry porosities that disperse evenly and unevenly in the radial direction (see Fig. 1(b)). A Cartesian coordinate system (O, x, y, x) on the middle-plane surface of the nanotube is employed to describe the tube, and u_1, u_2, u_3 are the displacement components in the x, y, z directions. Meanwhile, the polar cylindrical coordinates (O,x, r,θ) is established, according to the relation between the Cartesian coordinate and polar cylindrical coordinate system, we have the following relations:

$$y = r\cos\theta, \quad z = r\sin\theta, \quad r = \sqrt{y^2 + z^2} \tag{1}$$

Suppose that the FGM nanotube is made from two different materials (Si_3N_4 and SUS304), and the effective material properties P_f (including Young's modulus $E_f$and thermal expansion coefficient α_f) are assumed to a nonlinear function of temperature, which can be described as (Kiani & Eslami, 2013; Kiani et al., 2013; Zhong et al., 2016)

$$P_f = P_0\left(P_{-1}T^{-1} + 1 + P_1T + P_2T^2 + P_3T^3\right) \tag{2}$$

where P_0, P_{-1}, P_1, P_2 and P_3 are the coefficients of Kelvin's temperature which are listed in Table 1.

For FGM whose material composition follows a simple power law distribution in the radial direction, $V_c(r)$ and $V_m(r)$ can be written as (Chen et al., 2017; She, Yuan, & Ren, 2017a; Zhong et al., 2016)

$$V_c(r) = \left(\frac{r - R_i}{R_0 - R_i}\right)^N, \quad V_m(r) = 1 - V_c(r) \tag{3}$$

where, the subscript c and m denote ceramic and metal. Furthermore, two types of porosity distribution are considered and described as follows (See Fig. 1):