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Postbuckling of carbon nanotube-reinforced functionally graded cylindrical panels under axial compression using a meshless approach

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ABSTRACT

This paper presents a postbuckling analysis of carbon nanotube-reinforced functionally graded (CNTR-FG) cylindrical panels under axial compression. Based on kernel particle approximations for the field variables, the Ritz method is employed to obtain the discretized governing equations. The cylindrical panels are reinforced by single-walled carbon nanotubes (SWCNTs) which are assumed to be graded through the thickness direction with different types of distributions. The effective material properties of CNTR-FG cylindrical panels are estimated through a micromechanical model based on the extended rule of mixture. To eliminate shear locking for a very thin cylindrical panel, the system's bending stiffness is evaluated by a stabilized conforming nodal integration scheme and the membrane as well as shear terms are calculated by the direct nodal integration method. In the present study, the arc-length method combined with the modified Newton–Raphson method is used to trace the postbuckling path. Detailed parametric studies are carried out to investigate effects of various parameters on postbuckling behaviors of CNTR-FG cylindrical panels and results for uniformly distributed (UD) CNTR-FG cylindrical panel are provided for comparison.

1. Introduction

Carbon nanotube-reinforced composite (CNTRC) material, known as the replacement for conventional carbon fibers with carbon nanotubes (CNTs), has drawn considerable attention from researchers in many engineering fields [1–3]. CNTs have been demonstrated to have high strength and stiffness with high aspect ratio and low density. Considering these remarkable properties, CNTs can be selected as an excellent candidate for reinforcement of polymer composites. Sun et al. [4] analytically investigated the axial Young's modulus of single-walled carbon nanotube (SWCNT) arrays with diameters ranging from nanometer to meter scales. Their results confirmed that CNTs have mechanical properties superior than carbon fibers.

In recent years, many works have been carried out to study the constitutive models and mechanical properties of CNT polymer composites. Coleman et al. [5] reported a review and comparison of mechanical properties of CNTRCs fabricated by different processing methods. Tensile tests of CNT composites have demonstrated that reinforcement with only 1 wt%

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nanotubes resulted in 36–42% increase in elastic modulus and 25% increase in break stress [6]. Gojny et al. [7] investigated the influence of different types of nanofillers on mechanical properties of epoxy-based nanocomposites and the relevance of surface functionalisation. They discovered that the strength and stiffness of the nanocomposites produced can be considerably enhanced and a significant increase in fracture toughness was also observed. Pötschke et al. [8] studied rheological behavior of compression molded mixtures of polycarbonate and carbon nanotubes using oscillatory rheometry at 260 °C. They discovered that 2 wt% nanotubes caused an obvious improvement in electrical resistivity and complex viscosity. The thermo-mechanical properties of epoxy-based nanocomposites reinforced by randomly oriented single- and multi-walled CNTs were examined by Fidelus et al. [9]. These investigations indicated that the introduction of CNTs into a polymer matrix may greatly improve mechanical, electrical and thermal properties of the resulting nanocomposites.

Since structure elements (beam, plate and shell) are widely used in actual structural applications, it is necessary to obtain global responses of CNTRCs in actual structure elements. Wuite and Adali [10] presented a multiscale analysis of deflection and stress behavior of CNTRC beams and a pure bending and bending-induced buckling analysis of a nanocomposite beam was reported by Vodenitcharova and Zhang [11]. Yas and Samadi [12] studied free vibration and buckling of nanocomposite Timoshenko beams reinforced by SWCNTs resting on an elastic foundation. By using the finite element method (FEM) based on the first order shear deformation plate theory, Zhu et al. [13] carried out bending and free vibration analyses of functionally graded CNTRC plates. Shen [14] presented an analysis of nonlinear bending of functionally graded CNTRC plates in thermal environments using a two step perturbation technique. Based on a higher-order shear deformation plate theory, the large amplitude vibration of nanocomposite plates reinforced by SWCNTs resting on an elastic foundation in thermal environments was investigated by Wang and Shen [15]. Effective material properties estimated by either the Eshelby–Mori–Tanaka approach or the extended rule of mixture were used for investigating the impact of uniaxial and biaxial in-plane loadings on a functionally graded nanocomposite rectangular plate [16]. In addition to analysis of beams and plates, much research has been done about CNTRC cylindrical shells. Shen and Xiang [17] examined the large amplitude vibration behavior of nanocomposite cylindrical shells in thermal environments. Aragh et al. [18] studied natural frequency characteristics of a continuously graded CNT-reinforced cylindrical panel based on the Eshelby–Mori–Tanaka approach. Based on the multiscale approach, numerical simulations were carried out for thermal buckling and postbuckling analysis of nanocomposite cylindrical shells subjected to a uniform temperature rise [19]. For nanocomposite cylindrical shells subjected to axial and pressure loads, a postbuckling analysis was also conducted by Shen in [20,21].

The main purpose of the present work is to investigate the postbuckling behaviors of carbon nanotube-reinforced functionally graded (CNTR-FG) cylindrical panels under axial compression. The element-free *kp*-Ritz method previously used for plate problems [22,23] is now extended to study CNTR-FG cylindrical panel problems. In this study, the element-free *kp*-Ritz method based on the first-order shear deformation shell theory is adopted to derive the discretized governing equations which are solved by a combination of the arc-length iterative algorithm and the modified Newton–Raphson method, to trace the postbuckling path. In this paper, several different types of distributions of single-walled carbon nanotubes (SWCNTs) in the thickness direction are considered. The effective material properties of CNTR-FG cylindrical panels are estimated through a micromechanical model based on the extended rule of mixture. In computational simulation, several numerical examples are presented to investigate the influences of carbon nanotube volume fraction, length-to-thickness ratio and radius on the postbuckling behavior of CNTR-FG cylindrical panels. The effects of boundary condition and distribution type of CNTs are also examined in detail.

2. Carbon nanotube-reinforced composite cylindrical panels

As shown in Fig. 1, three types of CNTR-FG cylindrical panels (UD, FG-O and FG-X) with length a, radius R, span angle θ_0 and thickness h are considered in this paper. The CNTs are assumed uniaxially aligned in the axial direction of the cylindrical panels, that is, UD represents uniformly distributed; FG-O and FG-X denote the other two types of functionally graded distributions of CNTs which are symmetric about the middle surface of the cylindrical panel. For FG-O type panel, the middle surface of the cylindrical panel is CNT-rich and in case of FG-X, both top and bottom surfaces are CNT-rich. As it is well described that the structure of CNT extensively affects the effective material properties of CNT-reinforced materials [24–27], several micromechanical models have been successfully developed to predict the effective material properties of CNT-reinforced nanocomposites, such as Eshelby–Mori–Tanaka scheme [28–30] and the extended rule of mixture [14,31]. Compared with the Mori–Tanaka scheme applicable to microparticles, the rule of mixture is simple and convenient to obtain the overall material properties and responses of the CNTR-FG structures. In [32], the accuracy of the rule of mixture was discussed and an excellent agreement was reported between the Mori–Tanaka and Voigt models for functionally graded ceramic–metal beams. The effective material properties of CNTR-FG cylindrical panels are given according to [14]:

$$E_{11} = \eta_1 V_{CNT} E_{11}^{CNT} + V_m E^m, \tag{1}$$

$$\frac{\eta_2}{E_{22}} = \frac{V_{CNT}}{E_{22}^{CNT}} + \frac{V_m}{E^m}, \tag{2}$$