Thin-Walled Structures 108 (2016) 225–233

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Full length article

Imperfection sensitivity of postbuckling behaviour of functionally graded carbon nanotube-reinforced composite beams

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ARTICLE INFO

Article history:
Received 28 May 2016
Received in revised form
25 August 2016
Accepted 28 August 2016

Keywords:
Postbuckling
Functionally graded materials
Carbon nanotube reinforced composites
Imperfection sensitivity
Differential quadrature method

ABSTRACT

The imperfection sensitivity of the postbuckling behaviour of functionally graded carbon nanotube-reinforced composite (FG-CNTRC) beams subjected to axial compression is investigated based on the first-order shear deformation beam theory with a von Kármán geometric nonlinearity. The material properties of FG-CNTRC are assumed to vary in the beam thickness direction and are estimated according to the extended rule of mixture. The differential quadrature method is employed to discretize the governing differential equations and the modified Newton-Raphson iterative technique is used to obtain the postbuckling equilibrium paths of FG-CNTRC beams with various imperfections. Parametric studies are carried out to examine the effects of imperfection modes, half-wave number, location, and amplitude on the postbuckling response of beams. The influences of CNT distribution pattern and volume fraction, boundary conditions, and slenderness ratio are also discussed. Numerical results in graphical form show that the postbuckling behaviour is highly sensitive to the imperfection amplitude. The imperfection mode and its half-wave number also moderately affect the imperfection sensitivity of the postbuckling response, whereas the effects of other parameters are much less pronounced.

1. Introduction

Due to various manufacturing and environmental factors, geometric imperfections of engineering structures, like beams and plates, are inevitably generated during the manufacturing process. The static and dynamic behaviours of imperfect beams have been extensively studied. Among those, Sheinman and Adan [1] studied the imperfection sensitivity of an isotropic beam on a nonlinear elastic foundation. They found that the effect of imperfection shape and amplitude on the nonlinear behaviour is significant. Fang and Wickert [2] investigated the static deformation of micromachined beams with slight imperfections under in-plane compressive stress in both pre-buckling and postbuckling domain. It was found that buckling behaviour in the transition region is sensitive to the net level of imperfection. Azrar et al. [3] reported linear and nonlinear vibrations of deformed sandwich piezoelectric beams with initial imperfections. Based on the classical beam theory, Emam [4] investigated the static and dynamic response of geometrically imperfect composite beams; Yaghoobi and Torabi [5] carried out postbuckling and nonlinear vibration analysis of geometrically imperfect FGM beams resting on nonlinear elastic foundation. However, these studies are based on the simplified assumption that the initial geometric imperfection shape is the same to the first buckling mode of the beam or is assumed to be a particular shape for simplicity, like a sinusoidal shape. The investigations involving generic geometric imperfections are limited in number owing to the lack of sufficient information about the exact size and shape of the actual imperfections [6]. Most recently, Li [7] conducted a thermal postbuckling analysis of imperfect 3D braided composite beams based on first-order shear deformation beam theory. Li and Qiao [8] examined the postbuckling behaviour of shear deformable anisotropic laminated composite beams with initial imperfections. In their studies, a generic imperfection function from the one-dimensional imperfection mode for struts by Wadee [9] was adopted to simulate various possible initial geometric imperfections. All these studies mentioned above indicate that the mechanical behaviour of beam structures is sensitive to the presence of a small imperfection, which means that the geometric imperfections may result in a significant deterioration of the beams' resistance ability to compressive load. Therefore, the accurate prediction of the postbuckling response of imperfect beams is a great of importance in engineering design.

Since discovered in 1991 by Iijima [10,11], carbon nanotubes (CNTs) are considered as one of the strongest and stiffest material in terms of tensile strength and elastic modulus [12,13]. Due to the

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http://dx.doi.org/10.1016/j.tws.2016.08.024
0263-8231/

extraordinary mechanical, thermal and electrical properties [14,15], CNTs find promising applications as reinforcements for polymer composites. Composites reinforced with CNTs (CNTRCs) possess the advantages of significantly increased strength and stiffness over the conventional carbon fibre-reinforced composites [16–18]. However, previous studies [19,20] concerning CNTRCs have indicated that increasing the amount of CNTs beyond a certain weight fraction reduces the interfacial strength between CNTs and the matrix, which results in a deterioration of their mechanical properties [21]. This can be attributed to that distributing CNTs uniformly or randomly in the matrix, the resulting mechanical properties do not vary spatially at the macroscopic level. Stimulated by the concept of functionally graded materials (FGMs), which are inhomogeneous composites characterised by a smooth and continuous variation in composition and material properties [22,23], Shen [24] suggested distributing CNTs functionally in the matrix so as to improve mechanical properties of CNTRC with a low CNT volume fraction. In 2011, Kwon et al. [25] successfully fabricated the functionally graded CNT-reinforced aluminium matrix composite by a powder metallurgy route, which strongly supports the concept of functionally graded CNTRCs (FG-CNTRCs).

Several studies on perfect FG-CNTRC beams are available in the literature [26]. Among those, Ke et al. investigated the nonlinear free vibration [27] and dynamic stability [28] of FG-CNTRC beams and found that frequencies of FG-CNTRC beam with symmetrical functional distribution of CNTs are higher than those of beams with uniform or unsymmetrical distribution of CNTs. Yas and Samadi [29] conducted a free vibration and buckling analysis of FG-CNTRC beams resting on an elastic foundation. Their results showed that the natural frequencies and critical buckling load increase by using an elastic foundation. The similar problem was analytically studied by Wattanasakulpong and Ungbhakorn [30] using different shear deformation theories. It was found that the higher-order shear deformation theories play an important role in predicting shear stress. Based on the first- and third-order beam theories, Lin and Xiang [31] studied the linear free vibration of nanocomposite beams reinforced by SWCNTs. Their results showed that the frequencies increases significantly when CNT volume fraction varies from 0.12 to 0.17 but have only a small increase when CNT volume fraction changes from 0.17 to 0.28. In recent years, researches [32–34] on the forced vibration of FG-CNTRC beams have also been conducted based on Timoshenko beam theory. Rafiee et al. [35] reported a nonlinear thermal bifurcation buckling analysis of FG-CNTRC beams with surface-bonded piezoelectric layers. It was found that the beam with intermediate CNT volume fraction does not have intermediate buckling temperature in some cases. Most recently, Wu et al. [36] analysed the free vibration and buckling of sandwich beams with FG-CNTRC face sheets and found that the sandwich beam with FG-CNTRC face sheets has higher natural frequency and buckling load than the beam with UD-CNTRC face sheets. Yang et al. [37] investigated the dynamic buckling behaviour of FG-CNTRC beams integrated with two surface bonded piezoelectric layers and found that the dynamic buckling behaviour is remarkably affected by temperature change, compressive force and beam geometry but is much less sensitive to the applied voltage.

All of the aforementioned works dealt with perfect CNTRC beam structures only. To the best of the authors' knowledge, however, no previous work has been done on the sensitivity of the postbuckling behaviour of shear deformable FG-CNTRC beams to initial generic geometric imperfections. This paper investigates the nonlinear postbuckling behaviour of shear deformable FG-CNTRC beams with initial geometric imperfections within the framework of first-order shear deformation beam theory. Instead of assuming the imperfection possesses the same shape as the buckling mode, a variety of sine-type, local type, and global type imperfections are considered. The differential quadrature (DQ) method and an iteration procedure are utilised to obtain the postbuckling equilibrium paths for imperfect beams. Comprehensive numerical results are provided to examine the effects of the geometric imperfections as well as other system parameters on the postbuckling behaviour of FG-CNTRC beams under axial compression.

2. Effective material properties of CNTRCs

The CNTRC is made from a mixture of CNTs and an isotropic matrix. The volume fraction of CNTs is assumed to vary continuously along the thickness of the beam. Two distribution patterns of CNTs, i.e. functionally graded distributions (FGX and FGO) and uniform distribution (UD) are considered here and shown in Fig. 1. According to the extended rule of mixture, the effective material properties of CNTRC can be calculated from [24]

$$E_{11} = \eta_1 V_{cn} E_{11}^{cn} + V_m E_m \tag{1a}$$

$$\frac{\eta_2}{E_{22}} = \frac{V_{cn}}{E_{22}^{cn}} + \frac{V_m}{E_m} \tag{1b}$$

$$\frac{\eta_3}{G_{12}} = \frac{V_{cn}}{G_{12}^{cn}} + \frac{V_m}{G_m} \tag{1c}$$

in which E_{11}^{cn}, E_{22}^{cn} and G_{12}^{cn} are the Young's moduli and shear modulus of CNTs, respectively. E_m and G_m are the counterparts of the matrix. η_i $(i=1, 2, 3)$ are the CNT efficiency parameters accounting for the size-dependent material properties and are determined by matching the elastic modulus of CNTRCs observed from the molecular dynamics (MD) simulation with those predicted from the rule of mixture. V_{cn} and V_m, related by $V_{cn}+V_m=1$, are the volume fractions of the CNTs and matrix, respectively. Similarly, the effective Poisson's ratio and density of the CNTRC can be expressed as

$$\nu_{12} = V_{cn} \nu_{12}^{cn} + V_m \nu_m \tag{2}$$

$$\rho = V_{cn} \rho_{cn} + V_m \rho_m \tag{3}$$

where ν_{12}^{cn} and ν_m are Poisson's ratios of the CNT and matrix; ρ_{cn} and ρ_m are the densities of the CNT and matrix, respectively.

The volume fraction V_{cn} for the three distribution patterns in Fig. 1 are assumed to be as follows

$$\text{FGX:}\quad V_{cn} = 4\frac{|z|}{h} V_{cn}^{*} \tag{4a}$$

$$\text{FGO:}\quad V_{cn} = \left(2 - 4\frac{|z|}{h}\right) V_{cn}^{*} \tag{4b}$$

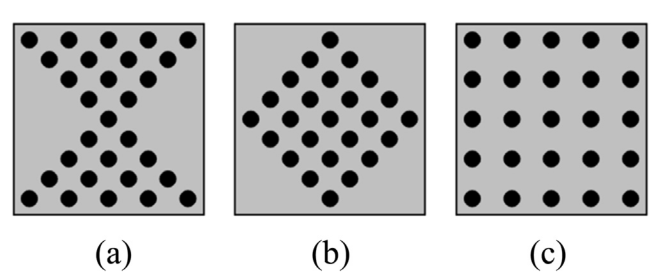

Fig. 1. CNT distribution patterns in the cross section of a CNTRC beam: (a) FGX-CNTRC, (b) FGO-CNTRC and (c) UD-CNTRC.