Composite Structures 174 (2017) 45–58

Contents lists available at ScienceDirect

Composite Structures

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

Nonlinear resonant dynamics of geometrically imperfect higher-order shear deformable functionally graded carbon-nanotube reinforced composite beams

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ARTICLE INFO

Article history:
Received 4 March 2017
Revised 10 April 2017
Accepted 17 April 2017
Available online 20 April 2017

Keywords:
Geometrically imperfect shear deformable FG-CNTRC beams
Nonlinear resonant dynamics
Unified higher-order shear deformable beam model
Initial imperfection

ABSTRACT

This study aims at numerically analyzing the nonlinear resonant dynamics of geometrically imperfect higher-order shear deformable functionally graded carbon nanotube-reinforced composite (FG-CNTRC) beams with various end conditions subjected to a harmonic transverse load. Introducing a generalized displacement field including various beam theories, employing Hamilton's principle and taking into account geometrical nonlinearity and initial imperfection, three nonlinear coupled equations and associated boundary expressions are obtained for geometrically imperfect FG-CNTRC beams. These equations formulate the longitudinal, transverse and rotational motions of FG-CNTRC beams. An efficient multistep numerical solution approach based on the generalized differential quadrature (GDQ) method, a numerical Galerkin-based scheme and time periodic discretization is employed to convert the time-dependent nonlinear partial differential equations (PDEs) into a Duffing-type nonlinear set of ordinary differential equations (ODEs) which can be solved via the pseudo arc-length continuation technique. Nonlinear resonant dynamics characteristics are illustrated in the form of frequency-response and force-response curves; highlighting the influences of initial geometrical imperfection, geometrical parameters, excitation frequency and boundary conditions.

1. Introduction

Remarkable mechanical, thermal and electrical properties of carbon nanotubes (CNTs) including their high stiffness and strength, light weight and high aspect ratio [1–4] enable them to extensively utilized in reinforcing polymer [5,6], ceramic [7] and metal [8] matrixes instead of traditional fibers. Accordingly, a new class of advanced materials known as functionally graded-carbon nanotube reinforced (FG-CNTRC) materials have received a lot of attention of the researchers and engineers due to their potential applications in the novel nano- and micro-electro-mechanical systems (NEMs and MEMS) and electronic devices as well as numerous industrial fields such as aerospace, automotive, sports and electronics [9,10]. In the last few years, a wide range of examinations are carried out by scientists and researchers to experimentally and theoretically distinguish various aspects of materials properties as well as mechanical behaviors of CNTRC materials [11–17]. Especially, the dynamics of mechanical structures made of CNTRC materials has been investigated expensively in the literature; however, a thorough literature review on this subject will not be undertaken in this work. Most of these examinations are limited to linear mechanical characteristics; few investigations have been carried out on the geometrically nonlinear dynamics of CNTRC structures.

The linear studies generally concentrated on investigation of the linear free vibration characteristics, linear static and dynamic stability, determining the critical buckling loads and natural fundamental frequencies and linear bending [18–22]. For instance, using the finite element approach, the buckling and free vibration of FG-CNT reinforced polymer composite beams subjected to nonuniform temperature fields was examined by George and Murigendrappa [23]. Ghorbani Shenas et al. [24] analyze the free vibration behavior of the pre-twisted FG-CNTRC beams with different sets of boundary conditions using the Chebyshev–Ritz method. It was illustrated that in addition to the type of boundary condition, the pre-twist angle on the fundamental natural frequencies depend on the vibration mode number. Utilizing a unified formulation of finite prism method and a variational

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http://dx.doi.org/10.1016/j.compstruct.2017.04.042
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approach, the three-dimensional free vibration of FG-CNTRC plates as well as laminated fiber-reinforced composite plates was analyzed by Wu and Li [25]. Recently, Ansari et al. [26] tried to use an efficient and novel numerical variational approach to examine the buckling of axially-loaded FG-CNTRC conical panels.

A further few investigations on this subject incorporated the geometric nonlinearities in the mathematical formulation as well as nonlinear mechanical behaviors [27–31]. For example, Ansari et al. [32] developed the nonlinear Timoshenko beam model in order to numerically analyze the nonlinear forced vibration of shear deformable FG-CNTRC beams with different edge supports. Based on the first-order shear deformable beam model and employing the Ritz method and an iteration approach, the effect of various possible types of geometric imperfection on the nonlinear free vibration of FG-CNTRC beams was investigated by Wu et al. [33]. On the basis of the first-order shear deformation plate theory and a numerical solution strategy, the large amplitude vibration analysis of FG-CNTRC rectangular plates subjected to a harmonic excitation was carried out by Ansari et al. [34]. The imperfection sensitivity on the nonlinear postbuckling equilibrium path of FG-CNTRC beams was analyzed by Wu et al. [35]. Furthermore, a third-order shear deformable plate model was proposed by Ansari and Gholami [14] to investigate the effect of important design parameters such as CNT distribution, CNT volume fraction, geometry, boundary condition and excitation frequency on the frequency-response and force-response curves of FG-CNTRC rectangular plates. An improved perturbation technique was utilized by Shen and Xiang [36] to describe the large amplitude free vibration characteristics of nanocomposite cylindrical shells reinforced by single-walled carbon nanotubes (SWCNTs) in thermal environments. Ansari et al. [37] presented an analytical solution to study the nonlinear buckling and postbuckling of FG-CNTRC circular cylindrical shells with piezoelectric layers subjected to the combined electro-thermal loadings, axial compression and lateral forces.

Regarding the state of the art of mechanical analyses performed on the FG-CNTRC composites, the large amplitude resonant dynamics of geometrically imperfect higher-order shear deformable FG-CNTRC beams with various edge conditions subjected to a harmonic transverse excitation is still unexplored. Therefore, the objective of the present paper is to investigate the effect of the initial geometrical imperfection on the nonlinear resonant dynamics of FG-CNTRC higher-order shear deformable beams with various edge conditions subjected to the distributed harmonic transverse load. By defining a generalized displacement field as well as applying the von Kármán hypotheses and taking into account the initial imperfection, three coupled nonlinear governing equations associated with the longitudinal, transverse and rotational motions of geometrically imperfect FG-CNTRC beams can be achieved by means of Hamilton's principle. These equations include the influences of transverse shear deformation, rotary inertia, initial imperfection and geometrical nonlinearity. Furthermore, by selecting an appropriate shape function, the unified developed relations can be reduced to simpler beam models based on the existing beam theories such as the Euler-Bernoulli and Timoshenko beam theories as well as third-order, parabolic, trigonometric, hyperbolic and exponential shear deformation beam theories. Afterwards, an efficient multistep numerical solution approach based on the generalized differential quadrature (GDQ) method, numerical-Galerkin-based scheme and time periodic discretization is utilized to transform the time-dependent nonlinear continuous partial differential equations (PDEs) into a Duffing-type nonlinear set of ordinary differential equations (ODEs). Then, the pseudo arc-length continuation technique is utilized to the nonlinear resonant dynamics responses of FG-CNTRC by plotting the frequency-response and force-response curves; illustrating the effects of initial geometric imperfection, geometric parameters, excitation frequency and boundary conditions.

The paper is organized as follows. Section 2 deals with developing a unified coupled nonlinear governing equations of motion of geometrically imperfect higher-order shear deformable FG-CNTRC beams. Section 3 sets up an efficient multistep solution procedure used in solving the nonlinear vibration problems. Section 4 provides the numerical results corresponding to the nonlinear resonant dynamics behaviors of imperfect FG-CNTRC beams with various edge conditions. The study is completed by a summary of the main findings in Section 5.

2. Mathematical formulation

A schematic representation of shear deformable FG-CNTRC beams with the rectangular cross-section, length L, thickness h and considered Cartesian coordinate system (i.e., $0 \leqslant x \leqslant L$ and $-h/2 \leqslant z \leqslant h/2$) are illustrated in Fig. 1. The motion of any point of considered beam in the longitudinal and transverse directions are denoted by $u_x(t,x,z)$ and $u_z(t,x,z)$. Also, the displacements of any point located on the middle-axis in the longitudinal and transverse directions are represented by $u(t,x)$ and $w(t,x)$, respectively; $\psi_x(t,x)$ signifies the rotation of the transverse normal. Moreover, It is assumed that the FG-CNTRC beam subjects an initial geometric imperfection in the positive out-of-plane direction indicated by $w^* = w^*(x)$. Furthermore, a harmonic uniformly-distributed load per unit length $F(t,x) = \bar{f}_0 \sin(\bar{\Omega} t)$ is applied on the FG-CNTRC beams in the transverse direction, in which $\bar{f}_0$, $\bar{\Omega}$ and t are forcing amplitude, excitation frequency and time, respectively.

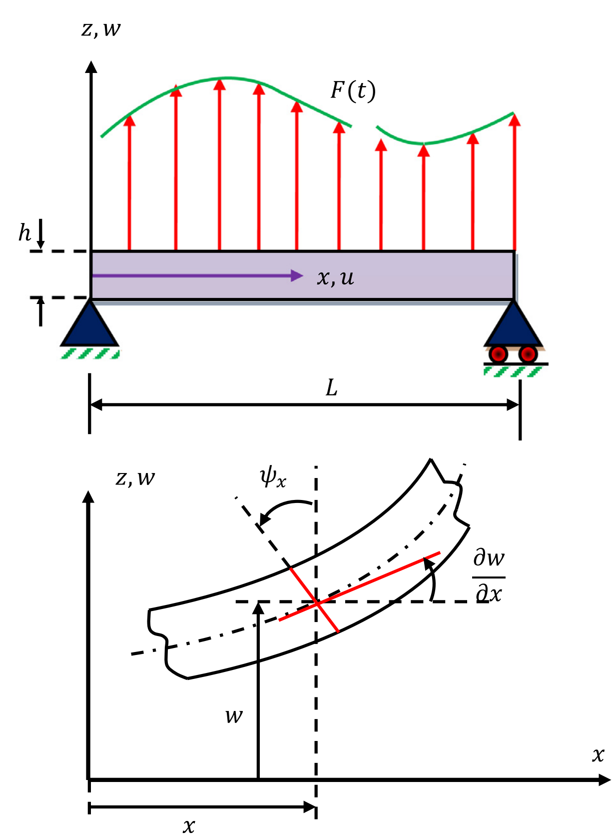

Fig. 1. Schematic view of a shear deformable FG-CNTRC beams: geometry, kinematic parameters and Cartesian coordinate system.