Composite Structures 132 (2015) 35–43

Contents lists available at ScienceDirect

Composite Structures

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

Low velocity impact response of functionally graded carbon nanotube reinforced composite beams in thermal environment

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ARTICLE INFO

Article history:
Available online 14 May 2015

Keywords:
Low velocity impact
Functionally graded carbon nanotube
Temperature dependent
Ritz method
First order shear deformation beam theory
Hertz contact law

ABSTRACT

Response of functionally graded carbon nanotube reinforced composite (FG-CNTRC) beam subjected to the action of an impacting mass is analyzed. Timoshenko beam theory is used to estimate the kinematics of the beam. Material properties of the fibers and polymeric matrix are assumed to be temperature dependent. Both uniform and functionally graded distribution of CNTs are taken into account. Material properties of the composite are obtained using a refined rule of mixture. Contact force between the impactor and the beam is obtained with the aid of the conventional Hertz law. The governing dynamic equations of the system, are obtained using the conventional polynomial Ritz method applied to the total energy of the system. The solution of the resulting equations is traced in time using the well-known Runge–Kutta method. After examining the validity of the present solution, parametric studies are conducted to examine the influences of thermal environment, volume fraction of the CNTs, distribution of CNTs, initial velocity of the impactor and the impactor mass. Numerical results reveal that as the volume fraction of CNTs increases in the beam, peak contact force increases and the contact time decreases. Furthermore, temperature rise results in higher contact time duration and lower peak contact force.

1. Introduction

Carbon nanotubes (CNTs) are known as a novel class of materials which have attracted increasing attention in recent years. These materials have exceptional mechanical, thermal and electrical material properties which make them as a potential candidate for the reinforcement of the composites. It is widely known that, addition of CNTs in a matrix enhances the thermal and mechanical properties of composites [1]. Distribution of CNTs in a polymeric matrix may be uniform or functionally graded (FG) [2]. However, compatible with the fabrication of FG-CNTRC structures, in the open literature only the linear variation of CNTs volume fraction across an structural element have been considered. Starting from the fundamental research of Shen [2], many other researchers analyzed the vibration characteristics, buckling and postbuckling resistance and static and dynamic stress analysis of simple structural composite elements, such as beams, rectangular, skew and triangle plates and cylindrical shells and panels reinforced with CNTs. An overview of such works is reported in the next.

Lin and Xiang analyzed the linear [3] and nonlinear [4] free vibration characteristics of first order and third order shear deformable FG-CNTRC beams. Various distribution of CNTs across the beam thickness is considered in this research. Analysis on solutions for CNT beams involving hard clamped and soft clamped supports shows substantial differences between frequency parameters based on the first order and third order beam theories. Pourasghar and Kamaian analyzed the parametric stability of FG-CNTRC beams based on Euler–Bernoulli beam theory [5]. In this research variation of thickness across the beam length is also taken into consideration. However, axial vibration and stretching-bending coupling effects are ignored in this research. Rafiee et al. [6] analyzed the thermal buckling and postbuckling of a composite beam reinforced with uniform or graded CNTs. This analysis is based on the Euler–Bernoulli beam theory accompanied with the von-Kármán type of geometrical non-linearity. Only the case of a beam with both edges clamped is taken into consideration and a closed form solution is presented to trace the post-buckling path and detect the critical buckling temperatures. Free vibration and mechanical buckling of FG-CNTRC beams resting on a two parameter elastic foundation are analyzed by Yas and Samadi [7]. Generalized differential quadrature is used to discrete the governing dynamic equations. The obtained results show the beams with symmetric distribution

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http://dx.doi.org/10.1016/j.compstruct.2015.04.045
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of fibers with respect to midsurface where free surfaces are enriched by CNTs (referred to as FG-X distribution) have higher fundamental frequency as well as critical buckling load in comparison with other distributions. Ansari et al. [8] examined the nonlinear forced vibration of FG-CNTRC beams within the framework of Timoshenko beam theory. To consider the large deformations, von-Kármán type of geometrical nonlinearity is taken into consideration. The resulting partial differential equations are solved via the generalized differential quadrature method and the Galerkin technique. It is shown that, FG-X has higher fundamental frequency in comparison to other types of CNTs distribution. Ke et al. [9] analyzed the large amplitude free vibration of FG-CNTRC Timoshenko beams. Only the uniform and a specific graded profile are considered in this research. The solution method of this research is based on the conventional Ritz method using the polynomial basic functions suitable for arbitrary edge supports. It is shown that, nonlinear frequency ratios of both simply supported-simply supported and clamped-simply supported FG-CNTRC beams are dependent to the sign of the vibration amplitudes, i.e., their nonlinear frequency ratio versus amplitude curves are unsymmetrical. Applying a two-step perturbation technique, Shen and Xiang [10] analyzed the nonlinear bending, thermal post-buckling and large amplitude vibration of third order shear deformable beams. Materials properties in this research are assumed to be temperature dependent. Only the case of a beam with both edges simply supported is analyzed in this research. It is shown that for beams with unsymmetrical distribution of CNTs, thermal postbuckling equilibrium path is no longer of the bifurcation type. Influence of piezoelectric layers on the large amplitude free vibration of FG-CNTRC beams is analyzed by Rafiee et al. [11]. The nonlinear coupled motion equations are obtained based on the Timoshenko beam theory using the physical neutral surface concept. Galerkin method is used to construct a time-dependent ordinary differential equation which governs the large amplitude free vibration characteristics of the beam. Solution of such equation is obtained based on the multiple scales method. It is shown that, the effect of the applied voltage is relatively small. Ke et al. [12] also analyzed the parametric stability of FG-CNTRC beams based on the Timoshenko beam theory. Three coupled partial differential equations are obtained and discreted by means of the generalized differential quadrature method. The instability regions are obtained using the first order Bolotin approximation. It is shown that beam with FG-X distribution has higher fundamental frequency and buckling load. Alibeigloo and Liew [13] analyzed the free vibration and static response of FG-CNTRC beams bonded with two piezoelectric layers. Formulation of this research is based on the two dimensional elasticity. Solution method of this research is based on the differential quadrature method along the axial direction accompanied with the state space solution across the thickness.

Jafari et al. [14] analyzed the buckling of FG-CNTRC plates subjected to uniaxial or biaxail loadings based on the first order plate theory assumptions. Lei et al. [15] analyzed the buckling of FG-CNTRC plates subjected to various in-plane loading conditions based on the element free kp Ritz method. Two different models are used to estimate the mechanical properties of the FG-CNTRC plates. For the case of a plate perfectly bonded with two piezoelectric layers and subjected to biaxial compression, Wu and Chang [16] estimated the buckling loads using a three-dimensional approach. Shen and Zhang [17] analyzed the thermal buckling and post-buckling of FG-CNTRC plates. Rafiee et al. [18] analyzed the dynamic stability of FG-CNTRC rectangular plates comprising of two piezoelectric layers at the bottom and top and the reinforced layer at the middle. Plate is assumed to be under thermal and electrical loads. Harmonic balance method is used to obtain the periodic solutions and their stability. It is shown that volume fraction of CNTs and their distribution have significant effect on the size of stability regions. Zhang et al. [19,20] analyzed the free vibration characteristics of skew and triangular FG-CNTRC plate using a mesh-less method. Wang et al. [21] analyzed the low velocity impact response of FG-CNTRC plates and also sandwich plates containing FG-CNTRC layers. In this research, geometrical non-linearity is also taken into account. Hertz law is used to estimate the contact force between the plate and the impactor. Numerical results reveal that temperature field is an important factor in contact force history. Furthermore, in-plane force influence on peak contact force and contact time is almost negligible.

Liew et al. [22] presented a post-buckling analysis of carbon nanotube-reinforced functionally graded cylindrical panels under axial compression. Lei et al. [23] analyzed the dynamic stability of FG-CNTRC cylindrical panels using the element free kp Ritz method. Bolotin approximation technique is applied to the Mathieu equations to obtain the instability regions. Zhang et al. analyzed the geometrically nonlinear [24] and static and dynamic response [25] of FG-CNTRC cylindrical panels. Properties of the composite media are obtained using either Eshelby-Mori–Tanaka approach or the rule of mixture approach. Shen and Xiang [26] analyzed the postbuckling of axially compressed FG-CNTRC cylindrical panels resting on elastic foundation in thermal environment. Numerical results reveal that the CNT volume fraction, temperature rise, foundation stiffness, and the panel geometric parameters have significant effects on the buckling load and postbuckling behavior of CNTRC cylindrical panels.

Shen also analyzed the thermal buckling and post-buckling [27], buckling and postbukling of pressure loaded [28], buckling and postbuckling of axially loaded [29], buckling and postbuckling of combined loaded [30] and buckling and post-buckling of torsion loaded [31] FG-CNTRC cylindrical shells. Thermal environment influences are also included in the investigations of Shen [17,27–31]. Results of Shen reveal that, by symmetric distribution of CNTs with respect to mid-surface of the cylindrical shell, where inner and outer surfaces of the shell are enriched by CNTs, buckling capacity of shell may be enhanced and post-buckling deflections may be alleviated.

As the above literature survey accepts, and to the best of authors knowledge, there is no work on the low velocity impact response of FG-CNTRC beams. The only theoretical available work on the low velocity impact response of FG-CNTRC structural elements belongs to Wang et al. [21] which is focused on rectangular plates. The present work aims to analyze the response of FG-CNTRC beams under low velocity impact based on the first order Timoshenko beam theory. Material properties of the CNTs and the polymeric matrix are assumed to be temperature dependent. Equivalent properties of the composite media are estimated using a refined rule of mixture approach. The motion equations of the beam and the sole impactor are extracted by means of the polynomial Ritz formulation applied to the Hamilton principle. The resulting time dependent equations are solved in time using the fourth order Runge–Kutta method. After validating the present formulation and solution method, parametric studies are conducted to examine the influence of main parameters, such as thermal environment, volume fraction of CNTs, type of distribution of CNTs, initial velocity and mass of the impactor. As the numerical results reveal, FG-X type of distribution has the highest contact force and the least contact time.

2. Governing equations

Consider an FG-CNTRC beam of thickness h, width b, and length L referred to the conventional coordinates system (x, y, z), where as usual $0 \leqslant x \leqslant L$ is through the length, $-h/2 \leqslant z \leqslant +h/2$ is through the thickness and $-b/2 \leqslant y \leqslant +b/2$ is through the width.