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Snap-through phenomenon in a thermally postbuckled temperature dependent sandwich beam with FG-CNTRC face sheets

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ABSTRACT

Snap-through phenomenon due to a uniform lateral pressure in a thermally post-buckled sandwich beam is analyzed in this research. It is assumed that material properties of the core and face sheets are temperature dependent. Face sheets are reinforced with carbon nanotube whose distribution may be uniform or functionally graded. Thermomechanical properties of the face sheets are obtained using a refined rule of mixtures approach. To capture the large deflections, geometrical nonlinearity in von-Kármán sense is taken into account. Chebyshev polynomial based Ritz method is implemented into the virtual displacement principle to construct the matrix representation of the equilibrium equations. A successive displacement control strategy is used to trace the temperature dependent post-buckling equilibrium path. Due to the possibility of snap-through phenomenon, cylindrical arch-length technique is used to trace the equilibrium path of a pressurized thermally post-buckled sandwich beam beyond the limit loads. It is shown that, upper limit load of the beam increases as the temperature gradient increases. Furthermore, volume fraction of CNTs affects the snap-through load and snap-through intensity of the beam, meanwhile, the influence of graded profile of CNTs on snap-through features is almost negligible.
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1. Introduction

Carbon nanotubes (CNTs) are known as an excellent candidate to reinforce the composites due to their exceptional mechanical, thermal and electrical properties [1]. As fibers, distribution of CNTs in a polymeric matrix may be uniform or functionally graded (FG) [2]. Compatible with the reported fabrication methods, only linearly graded volume fraction of CNTs across, for instance, the thickness of a structural element is considered extensively by the researchers. Composites reinforced with functionally graded carbon nanotube fibers are often called FG-CNTRC. In the next, an overview of the available works on the static and dynamic analysis of FG-CNTRC beams is reported.

Based on a polynomial-based Ritz formulation, suitable for arbitrary in-plane and out-of-plane boundary conditions, Lin and Xiang [3] reported the free vibration characteristics of FG-CNTRC beams based on both first order and third order shear deformable beam theories. It is shown that, especially for the case of both edges clamped beams, divergence of results based on first order and third order beam theories is remarkable. In another study Lin and Xiang [4] used the same solution methodology to analyze the nonlinear free vibration of FG-CNTRC beams based on both first order and third order shear deformable beam theories. Euler Bernoulli beam theory formulation is used by Pourasghar and Kamaian [5] to obtain the instability regions of an FG-CNTRC beam with non-uniform thickness and subjected to periodically varying axial force. However, in this research, stretching–bending coupling due to the non-symmetric distribution of fibers and in-plane vibration effects are ignored. Solution method of this research is based on the differential quadrature algorithm and the established eigenvalue problem is solved via the Bolotin approximation technique. Rafiee et al. [6] applied a straightforward analytical solution to obtain the critical buckling temperature and thermal post-buckling equilibrium path of FG-CNTRC beams with both edges clamped. It is shown that, critical buckling temperature of CNTRC beams may be postponed by employing the graded distribution of fibers. However, solution method of this research is suitable only for thin beams since in CNTRC beams the ratio of E/G is of order 100. Therefore accounting for through the thickness shear deformation becomes important even in moderately thick FG-CNTRC beams. Yas and Samadi [7] applied the generalized differential quadrature method to obtain the free vibration and mechanical buckling of FG-CNTRC Timoshenko beams. It is verified that, through functionally

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graded distribution of fibers across the beam thickness, where the volume fraction of top and bottom surfaces is much more than the middle surface, the buckling phenomenon in the beam may be delayed. Nonlinear force vibration characteristics of CNTRC beams with both uniform and graded fiber distributions is analyzed by Ansari et al. [8]. To capture the geometrical nonlinearity effects, von-Kármán assumptions are established to construct the governing nonlinear dynamic equations. Galerkin and differential quadrature methods are used to discrete the equations.

Large amplitude free vibration of FG-CNTRC beams using the polynomial Ritz formulation is solved by Ke et al. [9]. Only a specific case of graded fiber distribution and uniform distribution are considered in this work. Geometrical nonlinearity of this research is restricted to von-Kármán type suitable for small strains and large deflections. 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. Shen and Xiang [10] used a two step perturbation technique to obtain the linear and nonlinear free vibration, nonlinear bending, thermal buckling and thermal post-buckling of FG-CNTRC beams where the temperature dependency of the constituents is also included. In this research the interaction of a two parameter elastic foundation is also considered. Numerical results of this study are limited to the case of FG-CNTRC beams with both edges simply supported in flexure with movable or immovable feature in in-plane direction. It is shown in this research that, for nonsymmetric distribution of fibers, the equilibrium path of simply supported beams under even uniform heating is no longer of the bifurcation type. Based on the concept of physical neutral surface formulation, in which the stretching–bending coupling vanishes in formulation, the governing nonlinear motion equations of FG-CNTRC Timoshenko beam integrated with two identical piezoelectric layers are obtained by Rafiee et al. [11]. Galerkin method is used to construct the time dependent ordinary differential equations. Time dependency of the motion equations is obtained using the multiple scales method. Using the first order Bolotin technique, Ke et al. [12] obtained the instability regions of Timoshenko beams subjected to harmonically varying in-plane compressive loads. It is shown that, using FG-X type of fibers distribution, buckling load of FG-CNTRC beam increases. A two dimensional elasticity solution is developed by Alibeigloo and Liew [13] to obtain the stress analysis and free vibration characteristics of FG-CNTRC beams integrated with sensor and actuator piezoelectric layers. In this research, both ends of the beam are assumed to be simply supported. Navier solution through the beam length accompanied with the differential quadrature method through the beam depth are used to discrete the governing equations. Yang et al. [14] obtained the instability regions of a slender Euler–Bernoulli beam subjected to the simultaneous effects of uniform heating, constant voltage and periodically varying compressive force. Response of FG-CNTRC beams subjected to low velocity impact of a single mass is analyzed by Jam and Kiani [15]. Thermal environment effects are also included in this research. It is shown that, impact characteristics of FG-CNTRC beams are highly dependent to distributed pattern and volume fraction of fibers. Wu et al. [16] analyzed the free vibration and buckling loads of beams with stiff host layer, and FG-CNTRC face sheets. Generalized differential quadrature is used to discrete the governing equation. Buckling loads and natural frequencies are obtained via the standard eigenvalue algorithm. He et al. [17] investigated the nonlinear large amplitude vibration of fractionally damped viscoelastic CNTs/-fiber/polymer multiscale composite beams. The Caputo fractional derivative is employed to incorporate the viscoelastic material having nonlinear behavior.

Similar to beams, literature on the subject of FG-CNTRC plates is wealth. Shen and Zhu [18] investigated the post-buckling behavior of a sandwich plate with FG-CNTRC face sheets. In this research, a two step perturbation solution is proposed to obtain the buckling loads and post-buckling equilibrium path. Malekzadeh et al. [19] investigated the response of an FG-CNTRC plate under the influence of a moving load. Mechanical properties of the plate are obtained by means of an Eshelby–Mori–Tanaka micromechanical model. Finite element model is used to discrete the motion equations in space domain and Newmark time marching scheme is applied to obtain the temporal evolution of displacement components. Lei et al. [20] investigated the buckling of FG-CNTRC rectangular plates using an element free kp-Ritz method. Liew and his co-authors applied various numerical methods to analyze the dynamic stability of FG-CNTRC cylindrical panels [21], static and free vibration of FG-CNTRC cylindrical panels [22], vibration of FG CNTRC plates resting over a two parameter elastic foundation [23], buckling of FG-CNTRC skew plates [24], free vibration of FG-CNTRC triangular plates [25], vibration characteristics of FG-CNTRC skew plates [26], large deflection analysis of FG-CNT reinforced composite skew plates resting on Pasternak foundations [27] and thermoelastic analysis of FG-CNTRC plates using the three dimensional elasticity theory [28].

Unlike the case of single layer FG-CNTRC beams, researches on sandwich beams with FG-CNTRC face sheets or host are rare in the open literature. To the best of author's knowledge, thermal buckling, postbuckling and snap-through of post-buckled sandwich beams with FG-CNTRC face sheets are not reported in the open literature. In this work, response of a sandwich beam with axially immovable edges subjected to uniform heating and lateral pressure is examined. Sandwich beam is symmetric with respect to its midsurface whose face sheets are composed from isotropic polymeric matrix reinforced with CNT. To account for large deformations, von-Kármán type of geometrical nonlinearity is included in the formulation. Various types of volume fraction profile and various magnitudes of CNTs volume fraction are used for the face sheets. Only uniform case of temperature distribution is considered. After establishing a nonlinear eigenvalue problem through applying the Chebyshev polynomial based Ritz method to the Hamilton principle, an iterative displacement control procedure is used to trace the thermal post-buckling equilibrium path. Afterwards, cylindrical arch-length technique is used to trace the equilibrium path of a pressurized thermally post-buckled beam. After comparing the numerical results of this study for single FG-CNTRC beams with the available data in the open literature, numerical results are given for the sandwich beams with FG-CNTRC face sheets to examine the influence of boundary conditions, volume fraction of fibers, graded profile of volume fraction of fibers, length to thickness ratio and host thickness to face thickness ratio. It is shown that critical buckling temperature, thermal postbuckling and snap-through equilibrium paths are sensitive to the mentioned parameters.

2. Basic formulation

A sandwich structure, generally consist of a core which may be soft or stiff and thick and two face sheets, generally identical, thin and stiff. Sandwich beam of the present study is assumed to be symmetric with respect to the mid-plane. Face sheets are made from a composite with polymeric matrix and carbon nanotubes as reinforcements whose distribution across the matrix may be uniform or functionally graded. Thickness of each face sheet is assumed as h_f and core thickness is denoted by h_H. Total thickness of the sandwich beam, in such case becomes $h = h_H + 2h_f$. As usual, a Cartesian coordinate system is applied to the beam where

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