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Dynamic extended high order sandwich panel theory for transient response of sandwich beams with carbon nanotube reinforced face sheets

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ABSTRACT

The dynamic version of the Extended High Order Sandwich Panel Theory (EHSAPT) for a sandwich beam with soft core and carbon nanotube reinforced composite (CNTRC) face sheets is first formulated. Distribution of fibers through the thickness of the face sheets could be uniform or functionally graded (FG). The influences of boundary conditions on dynamic response of the sandwich panel are investigated. In each type of boundary condition the effects of nanotube volume fraction and their distribution pattern, core-to-face sheet thickness ratio, on many essential involved parameters of the sandwich beam with functionally graded carbon nanotube reinforced composite (FG-CNTRC) face sheets are studied in detail. The results for a transient displacement of sandwich beam with isotropic face sheets reveal that the EHSAPT is very accurate during the initial, transient phase of dynamic loading in comparison with conventional high order sandwich panel theory (HSAPT). Finally, it is concluded that the sandwich beam with V distribution figure of face sheets is the strongest and the smallest transverse displacement, followed by the X, UD, O and ∧-ones, respectively.

1. Introduction

Carbon nanotubes (CNTs) with remarkable physical and chemical properties, such as high strength, high stiffness, high aspect ratio and very low density, have generated huge research interest from many areas of science [1]. A small weight percentage of the carbon nanotubes (2–5%) as the reinforcements in the composites, in comparison with using traditional carbon fibers, can considerably enhance the stiffness and strength of the composites [2]. On the other hand, increasing more CNTs to the composites can actually lead to the degradation of their mechanical properties [3]. In order to effectively make use of the low weight percentage of CNTs in the composites, Shen [4] introduced the functionally graded material concept into the CNT composites on the nonlinear bending behavior of CNTRC plates. A linear distribution pattern of CNTs along the thickness direction of the plates was applied and found that the functionally graded CNT reinforcements can significantly improve the bending behavior of the CNT plates. The concept of functionally graded nanocomposites has been realized in a recent experimental study [5] where a functionally graded CNT reinforced aluminum composite was fabricated using a powder metallurgy route. CNTs can be single-walled CNT (SWCNT) or multi-walled CNT (MWCNT). SWCNT is in a cylindrical shape which is rolled seamlessly by a single sheet of graphene with ∼1 nm diameter and length of order of centimeters. By contrast, MWCNT has an array of such cylinders formed concentrically and separated by 0.35 nm, similar to the basal plane separation in graphite with diameters from 2 nm to 100 nm and lengths of tens of microns [1]. These pioneer works have stimulated extensive studies on the bending, buckling and vibration responses of CNTRC structures in recent years [6–8].

Zhang et al. [9] investigated the vibration behavior of thick functionally graded carbon nanotube-reinforced composite (FG-CNTRC) plates resting on elastic foundation. The reinforcement is considered to be functionally graded (FG) through the thickness according to a micromechanical model. The First-order Shear Deformation Theory is employed based on the element-free IMLS-Ritz method for computation of vibration solution. The effects of CNT volume fraction and CNT distribution were studied under different boundary conditions. It is observed that the distribution type of CNTs affects the vibrational behavior of plate significantly. Recently, Zafarmand and Kadkhodayan [10] presented the nonlinear elasticity solution of functionally graded nanocomposite rotating thick disks with variable thickness reinforced with single-walled carbon nanotubes (SWCNTs). The obtained results show that the

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displacement and stress fields can be controlled by changing the type of distribution and volume fraction of CNTs as well as the thickness profile. Moreover, the difference between linear and nonlinear results is noticeable in high angular velocities; thus, for obtaining accurate results, the geometric nonlinearity must be considered.

The high shear strength and lightness of the foam cores along with considerable bending stiffness of the face sheets are specific advantageous of sandwich structures. Therefore, face sheets made of FG-CNTRC improve static and dynamic behaviors of sandwich panels with soft cores.

To date, only few studies regarding sandwich panels with FG-CNTRC face sheets are available in the literature. Wang and Shen [11] carried out the nonlinear free vibration and nonlinear bending analysis of sandwich plates with CNTRC face sheets resting on an elastic foundation of Pasternak-type. The analysis is based on Reddy's higher order shear deformation plate theory. Two kinds of CNTRC face sheets, namely, uniformly distributed (UD) and functionally graded (FG) reinforcements, are considered. The material properties of FG-CNTRC face sheets are assumed to be graded in the thickness direction. The thermal effects are also included and the material properties of both CNTRC face sheets and homogeneous core layer are considered to be temperature-dependent. The results illustrate that the linear functionally graded reinforcement of face sheet has a quantitative effect on the nonlinear bending behavior as well as nonlinear vibration characteristic of the sandwich plate. Shen and Zhu [12] developed a higher order shear deformation plate theory to study compressive postbuckling behavior of sandwich plates with CNTRC face sheets resting on an elastic foundation of Pasternak-type. The results reveal that the foundation stiffness, the temperature changes, the nanotube volume fraction of face sheet, and the core-to-face sheet thickness ratio affect the compressive buckling load and postbuckling behavior of the sandwich plate considerably, whereas this effect on the thermal postbuckling behavior is less pronounced for the same sandwich plate. Wu et al. [13] analyzed free vibration and buckling loads of beams with stiff host layer, and FG-CNTRC face sheets. Generalized differential quadrature was applied to discrete the governing equations. Buckling loads and natural frequencies were obtained via the standard eigenvalue algorithm. Kamarian et al. [14] investigated free vibration behaviors of FG nanocomposite sandwich beams resting on Pasternak foundation. The material properties of the FG nanocomposite sandwich beam were estimated using the Eshelby Mori–Tanaka approach based on an equivalent fiber. The equations of motion were derived based on Timoshenko beam theory. Detail parametric studies were carried out to investigate the influences of CNTs agglomeration, different profiles of CNT volume fraction such as symmetric, asymmetric, and classic, Winkler foundation modulus, shear elastic foundation modulus, length to span ratio, thicknesses of face sheets, and boundary conditions on the vibrational behavior of the structure. It is shown that the natural frequencies of structure are seriously affected by the influence of CNTs agglomeration.

The famous theory belongs to the group of multilayer theories, is high order sandwich panel theory (HSAPT) which was introduced in 1990's by Frostig et al. [15]. The HSAPT is based on a superposition method for sandwich panels with flexible core. In this theory, face sheets and core are modeled as separate parts, the continuity of deformations in top and bottom face sheet–core interfaces bridge the face sheets and core theories. The theory that is used for core are 2-D elasticity and the common theories for face sheets are Euler–Bernoulli beam theory (EBT) [16]. As a progressive step for increasing in accuracy of results in HSAPT, the transverse shear effect of face sheets is considered and faces are analyzed based on Timoshenko beam theory (TBT) [17,18].

In most of articles that have been used HSAPT, neglecting longitudinal stresses in core is a common assumption. It is because of low modulus of elasticity and low flexural rigidity of soft cores in comparison with those of the face sheets. Recently, Carlsson and Kardomateas [19] extended HSAPT for superior accuracy of results in all cases, particularly for the stiffer cores and developed extended high order sandwich panel theory (EHSAPT). This theory includes the in-plane rigidity of the core and can predict shear and in-plane stress distributions in the core. Also, in this approach, three generalized coordinates in the core as the in-plane and transverse displacement and rotation at centroid of the core are considered. This approach assumes quadratic and cubic polynomial functions for the transverse and in-plane displacement fields of the core through the thickness, respectively. So, the unknowns in this model consist of displacements of the face sheets and coefficients of polynomials in the core. It should be noted that Jedari Salami et al. carried out EHSAPT on the bending analysis of sandwich beams with bilinear core shear behavior [20,21].

So far, the structural analysis of sandwich panels with FG-CNTRC face sheets, follow Equivalent Single Layer (ESL) theories such as Euler–Bernoulli, Timoshenko or Third order theory of Reddy. According to the concept of these theories, the compressibility of the core is neglected and it might fail to predict structural responses for some sandwich panels with a soft core [11]. On the other hand, the benefit of using the EHSAPT is that it can be used to investigate sandwich panels with any combinations of core and face sheets and not only the very soft cores that the other high-order sandwich theories demand [19]. To date, only one work dealing with investigation of sandwich beam with soft core and carbon nanotube reinforced composite (CNTRC) face sheets has been presented based on EHSAPT [22]. In this study, bending analysis of a sandwich beam with polyurethane soft core and CNTRC face sheets under static loading was investigated. The effect of distribution pattern of CNTRCs on many essential involved parameters of the sandwich beam with functionally graded carbon nanotube reinforced composite (FG-CNTRC) face sheets were studied. Motivated by this idea, in the present work, the author focuses his attention on the dynamic response of sandwich beams with FG-CNTRC face sheets and flexible cores based on EHSAPT. The influences of nanotube volume fraction and their distribution pattern, core-to-face sheet thickness ratio, and boundary conditions on the time domain transverse displacement and shear force and moment resultants of the face sheet are studied.

2. Basic formulation

A sandwich beam is composed from two stiff thin face sheets separated by relatively thick soft core. In this study, the two face sheets are made of CNTRCs where the SWCNT reinforcement is either uniformly distributed (UD) or functionally graded (FG) in the thickness direction. The length of the sandwich beam is L and the thickness of the top and bottom CNTRC face sheets are h_t and h_b, respectively. Also, the thickness of the homogeneous soft core layer is C (see Fig. 1).

To date, five different types of carbon nanotube reinforced beams have been developed which include a uniformly distributed (UD) case and four different functionally graded (FG) cases, namely FG-V, FG-O, FG-X and FG-Λ. In this study, all types are considered for each of the face sheets. As a convention, an FG-V sandwich beam is referred to a beam where the top face sheet is of FG-V type and the bottom one is of FG-Λ. Also, the distribution pattern of face sheets for an FG-Λ sandwich beam is vice versa.

It is assumed that CNTRC face sheets are made from a mixture of (10, 10) armchair single walled carbon nanotubes (SWCNT) as reinforcement, graded distribution in the thickness direction, and a matrix which is supposed to be isotropic and homogeneous. The