Thin-Walled Structures 100 (2016) 14–24

Contents lists available at ScienceDirect

Thin-Walled Structures

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

Full length article

Buckling analysis of circular sandwich plates with tapered cores and functionally graded carbon nanotubes-reinforced composite face sheets

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ARTICLE INFO

Article history:
Received 29 June 2015
Received in revised form
3 December 2015
Accepted 3 December 2015
Available online 10 December 2015

Keywords:
Buckling
Nano composites
Variable thickness sandwich plates
Carbon nanotube

ABSTRACT

This work investigates the buckling behavior of circular sandwich plates with tapered cores and functionally graded carbon nanotube (FG-CNT) reinforced composite face sheets under uniform radial compression based on the first order shear deformation plate theory. The sandwich plate is assumed to be constituted of a pure polymer core and two FG-CNT reinforced composite layers with constant thickness whose material properties are assumed to be graded through the thickness direction. Different distributions of multi walled CNTs (MWCNTs) in the thickness direction of face sheets are introduced. Effective properties of materials are estimated through the modified form of rule of mixture. In order to determine the distribution of the prebuckling load along the radius, the membrane equation is solved using the shooting method. Subsequently, employing the pseudospectral method, the stability equations are numerically solved to evaluate the critical buckling load. Parametric studies are conducted for various types of CNTs distributions and geometrical parameters under different boundary conditions. The results show that the buckling behavior is significantly influenced by the CNTs distributions, the thickness variation profile, the aspect ratio and the face sheet-to-core thickness ratio. Some conclusions are drawn on the parametric studies with respect to the buckling characteristics.

1. Introduction

In the history of structural analysis, the stability of tapered plate has always been considered as one of the interesting subjects. The most conspicuous usage of variable thickness plates is to reduce the weight of structures, either as an economic point of view or a design aspect in especial cases like aerospace industries. Wang et al. [1] investigated the elastic buckling of tapered circular plates using the shooting method and the Rayleigh-Ritz approach. Özakça et al. [2] carried out the buckling analysis of tapered circular and annular plates using the finite element method. A family of variable thickness, Mindlin–Reissner axisymmetric finite elements has developed which includes shear deformation and rotary inertia effects. Shufrin and Eisenberger [3] studied the buckling behavior of elastic rectangular plates with variable thickness, considering shear effects using both the first-order and high-order shear deformation plate theories, using the extended Kantorovich method.

Functionally graded materials (FGMs) are inhomogeneous materials characterized by smooth and continuous variations in both compositional profile and material properties and have found a wide range of applications in many industries [4]. The subject of FGM plates with variable thickness has also been taken under advisement by researchers. Xiang and Yang [5] presented the free and forced vibration of a laminated functionally graded Timoshenko beam of variable thickness, which consists of a homogeneous substrate and two inhomogeneous functionally graded layers, subjected to one-dimensional steady heat conduction in the thickness direction, employing the DQ method. Exact vibration analysis of an FGM annular plate of variable thickness, using the first-order shear deformation plate theory is presented using the exact element method by Efraim and Eisenberger [6]. Xu and Zhou [7] investigated the stress and displacement distributions of continuously varying thickness functionally graded rectangular plates simply supported at four edges. Applying the finite element method, Jalali et al. [8,9] studied both mechanical and thermal buckling analysis of circular plates with variable thickness cores and face sheets made of FGM using the pseudospectral method and reported the essential influence of tapering profile on the critical buckling load.

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http://dx.doi.org/10.1016/j.tws.2015.12.001

Recently, a class of new emerging composite materials, by the concept of functionally graded (FG) materials, the FG-CNT reinforced composite, has been proposed making use of CNTs as the reinforcements in a functionally graded pattern. This new type of FG-CNT reinforced composite will need further research so as to find out its mechanical properties. CNT-based FGMs were first proposed by Shen [10]. He considered the composite with CNT distributions within an isotropic matrix designed specifically to grade them with certain rules along the desired directions to improve its mechanical property. A series of investigations about FG-CNT reinforced composite beam, plate and shell were then conducted to study their mechanical behaviors. The vibrational behavior of continuously graded carbon nanotube-reinforced beam was studied by Heshmati et al. [11–15].

The influences of functionally graded carbon nanotube reinforced composites (FG-CNTRC) on the buckling capacity and post-buckling strength of composite beams, plates and shell have been studied by several researchers. The mechanical buckling of FG-CNT reinforced composite plates subjected to uniaxial and biaxial in-plane loadings was studied by Jafari Mehrabadi et al. [16]. The first-order shear deformable plate theory was employed to derive the equilibrium and stability equations. The buckling behavior of quadrilateral laminated thin-to moderately thick plates consisting of perfectly bonded carbon CNT reinforced composite layers was studied by Malekzadeh and Shojaee [17]. The Trefftz buckling criterion was used in obtaining the stability equations. A mapping-differential quadrature technique was used to solve the stability equations subjected to arbitrary boundary conditions. The buckling analysis of FG-CNT reinforced composite plates under various in-plane mechanical loads was conducted by Lei et al. [18]. The kp-Ritz method was employed in their study. The effective material properties of plates reinforced by CNTs were estimated using a micromechanical model based on either the Eshelby–Mori–Tanaka approach or the extended rule of mixture. Based on Reissner's mixed variational theorem [19], a unified formulation of finite layer methods for three-dimensional buckling of FG-CNT reinforced composite plates was developed by Wu and Chang [20]. The FG-CNT reinforced composite plates with their surface-bonded piezoelectric actuator and sensor layers were studied under bi-axial compressive loads. The thermal buckling and postbuckling behaviors of functionally graded carbon nanotube reinforced composite cylindrical shells was studied by Shen [21]. The same method of Ref. [21] was employed by Shen and Xiang [22] to study the postbuckling of axially compressed nanotube reinforced composite cylindrical panels resting on elastic foundations in thermal environments.

Optimum design is a big concern in many applications such as aerospace and nano-devices where reducing the weight of structural members is essential. Therefore, FG-CNT reinforced composite may constitute a significant part of structural applications in future. Considering these facts demonstrates the importance of researches dealing with the behavior of FG-CNT reinforced composite plates with variable thickness. To the best of authors' knowledge, there is no work on buckling of FG-CNTRC plate with variable thickness subjected to mechanical loading. Therefore, the present research deals with the buckling of circular plate with variable thickness and FG-CNTRC layers subjected to radial compression having clamped and simply supported boundary conditions. In the theoretical formulation, the transverse shear deformation will be taken care through employing the first order shear deformation theory (FSDT). Linear distribution patterns of CNTs in the thickness directions of composite layers are studied as this distribution can readily be achieved in practice. The effective material properties of FG-CNT reinforced composite plates are estimated through a new form of rule of mixture. The experimental data for the Young's modulus of MWCNT/epoxy composites, reported by the Andrews et al. [23] for different volume percentage of MWCNTs, is utilized to create a realistic model of the nanocomposite plate. Finally, detailed parametric studies will be carried out to examine the influences of variations of the CNT distribution, the plate geometric parameters, the face sheet-to-core thickness ratio, and boundary conditions on the critical buckling loads of the plates.

2. Theoretical formulation

2.1. Geometry of sandwich plates with variable thickness

Consider a circular sandwich plate having a tapered core perfectly bonded to carbon nanotube-reinforced composite (CNTRC) layers as face sheets. The physical coordinate system with coordinate variables r and z is used to label the material points of the CNTRC plate in the radial and thickness directions, respectively. b is the radius of circular plate which is mid-plane symmetric (See Fig. 1). The plate is under radial compression P. The origin of the cylindrical coordinates system lies on the center of the mid-plane, φ defines the rotation about the radial axis, and u and w are the displacements in r and z directions, respectively. The studied plate is considered as a sandwich plate with a homogenous core of variable thickness, $h_c(r)$, and two FG-CNT reinforced face sheets with constant thickness, h_f. Therefore, the overall thickness of the plate, $h(r)$, would be a function of r.

$$h_c(r) = h_{c1} + \left(h_{c2} - h_{c1}\right)\left(\frac{r}{b}\right)^p \tag{1}$$

$$h(r) = h_c(r)+2h_f \tag{2}$$

where h_{c1} and h_{c2} are the thicknesses of the core at the center and the edge of the plate, respectively, and p defines the profile of the thickness. Despite of possibility of considering any general form for profile changes, only plates with linear and parabolic profiles with $p=1$, and 2, respectively, will be considered in the presented results. The plate has three layers that the kth layer is between z_k and z_{k+1} ($k=1$, 2, and 3) coordinates.

$$z_1(r)=-\frac{h_c(r)}{2} - h_f \tag{3a}$$

$$z_2(r)=-\frac{h_c(r)}{2} \tag{3b}$$

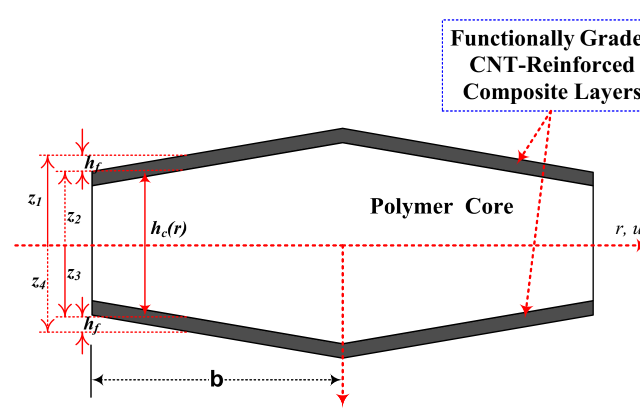

Fig. 1. Geometry and coordinate system of the nanocomposite circular plate with variable thickness.