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Aerospace Science and Technology

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Rectangular and skew shear buckling of FG-CNT reinforced composite skew plates using Ritz method

Y. Kiani [a,*], M. Mirzaei [b]

[a] *Faculty of Engineering, Shahrekord University, Shahrekord, Iran*
[b] *Department of Mechanical Engineering, Faculty of Engineering, University of Qom, Qom, Iran*

A R T I C L E I N F O

Article history:
Received 23 December 2017
Received in revised form 7 February 2018
Accepted 17 March 2018
Available online xxxx

Keywords:
Carbon nanotube reinforced composite
Ritz method
Gram–Schmidt process
Skew plate
Functionally graded
Rectangular and skew shear

A B S T R A C T

Present research deals with the shear buckling behaviour of composite skew plates reinforced with aligned single walled carbon nanotubes (CNTs). Distribution of CNTs across the thickness of the skew plate are assumed to be uniform or functionally graded. Two different types of shear loads are considered. The case of rectangular shear which produces pure shear and the case of skew shear which results in a combined uniform shear and uniaxial tension/compression. Suitable for moderately thick plates, first order shear deformation plate theory is used to estimate the displacement field of the plate. The equivalent properties of the composite media are obtained by means of the refined rule of mixtures approach which contains efficiency parameters to capture the size dependent properties of the CNTs. With the aid of the Hamilton principle, transformation of the orthogonal coordinate system to an oblique one and the conventional Ritz method whose shape functions are constructed according to the Gram–Schmidt process, the stability equations of the plate are established and solved for two different types of loading, namely rectangular and skew shear loads. As shown, through introduction of a proper functionally graded pattern, i.e., FG-X pattern, the buckling load of the plate may be increased, significantly.

1. Introduction

Carbon nanotubes (CNTs) stand as a promising candidate for reinforcement of the composites due to their exceptional mechanical, thermal and electrical properties. Volume fraction of CNT in a polymeric/metal matrix is an important factor to improve the mechanical properties of a composite media reinforced with CNTs. It is shown that, through introduction of CNTs as reinforcements, stiffness of the structure may be enhanced significantly, more than other conventional reinforcements.

Distribution type of CNTs through a specific direction of an structural element is another factor which may affect the global or local properties of an structural element reinforced with CNT. Consequently, CNTs as reinforcement may be distributed in a functionally graded pattern across the thickness of a structural element. This type of composite is known as functionally graded carbon nanotube reinforced composites (FG-CNTRC). An extensive overview on the modelling and analysis of FG-CNTRC beams, plates and shells is provided by Liew et al. [1].

The fundamental research on the subject of FG-CNTRC structures belongs to Shen [2]. In this research, it is shown that with the introduction of CNTs, as reinforcements with nonuniform distribution across the plate thickness, the bending moments induced by lateral loading may be alleviated significantly. Shen proposed that due to higher elasticity modulus of CNTs in comparison to matrix, to reach higher flexural rigidity in plate, CNTs should be inserted in surfaces near the top and bottom of the plate.

Motivated by the mentioned interesting work of Shen, various investigators analysed the influences of CNTs on the stability behaviour of CNTRC structures. An overview of the works on the stability of FG-CNTRC rectangular and skew plates is mentioned in the next.

Thermal buckling response of FG-CNTRC rectangular plates with arbitrary combinations of boundary conditions is analysed by Mirzaei and Kiani [3]. In this research, both uni-axial and bi-axial types of edge compression induced by uniform temperature rise loading are covered. Properties of the plate are considered to be temperature dependent. Lei et al. [4] investigated the buckling of rectangular plates with symmetric distribution of CNTs across the plate thickness using an element free kernel particle Ritz method. The equivalent properties of the media are estimated according to either the Eshelby–Mori–Tanaka approach or extended

* Corresponding author.
E-mail addresses: y.kiani@aut.ac.ir, y.kiani@eng.sku.ac.ir (Y. Kiani), m.mirzaei@qom.ac.ir (M. Mirzaei).

https://doi.org/10.1016/j.ast.2018.03.022
1270-9638/

rule of mixtures. The fact that enrichment of the matrix with more CNT enhances the critical buckling loads of plate is highlighted in this research. Kiani [5] analysed the shear buckling response of FG-CNTRC rectangular plates using an energy formulation. In this research, various combinations of free, simply supported and clamped boundary conditions are analysed. As shown, when surfaces near the top and bottom faces of the plate are enriched with more CNT, the buckling load of the plate may be increased significantly. Kiani [6] also obtained the buckling loads and buckled shapes of rectangular plates subjected to the case of nonuniform uni-axial compression. In this study the case of a plate subjected to parabolic edge compression is investigated. With the aid of Airy stress formulation, at first, the distribution of in-plane stresses due to the applied parabolic loads is obtained. The effect of Winkler elastic foundation, CNT volume fraction and CNT dispersion profile on the buckling loads of rectangular FG-CNTRC plates is studied by Zhang et al. [7] using an IMLS Ritz method. Lei et al. [8] investigated the buckling behaviour of composite laminated rectangular plates composed of FG-CNTRC layers using a meshless kp-Ritz method.

Similar to linear buckling analysis which results in the buckling loads and buckled shapes of FG-CNTRC plates, nonlinear stability analysis which results in buckling load as well as postbuckling equilibrium path is also observed in the researches. Thermal postbuckling response of shear deformable thick rectangular plates made of FG-CNTRC is investigated by Shen and Zhang [9]. In this research, plates which are simply supported all around are analysed. Solution method of this research is based on the two step perturbation technique. It is shown that, critical buckling temperatures of the plate may be enhanced significantly through achieving a nonuniform distribution of CNTs across the thickness, however plates with intermediate volume fraction of CNTs does not have necessarily intermediate critical buckling temperatures. The Ritz method is used to obtain the eigenvalue problem associated with the buckling temperature and buckled shape of the plate. Based on a single term Galerkin formulation, Rafiee et al. [10] proposed a closed form solution for thermal postbuckling analysis of rectangular plates using the first order shear deformable plate model. Shen and Zhu [11] investigated the postbuckling of FG-CNTRC rectangular plates subjected to uniform compression using a two step perturbation technique. In this research, plates with all edges simply supported are considered and distribution of CNTs across the plate thickness is considered to be symmetric with respect to the mid-surface. Kiani [12] investigated the thermal postbuckling of FG-CNTRC rectangular plates using an energy method. Various combinations of simply supported and clamped boundary conditions are taken into consideration in this research. Results of this study show that, in the temperature-deflection curves of FG-CNTRC plates, secondary instability takes place which is designated as a snap-through phenomenon in the postbuckling range. Shen and Zhu [13] discussed the effects of FG-CNTRC face sheets on the postbuckling of sandwich rectangular plates subjected to uniform compression using a two step perturbation technique.

In comparison to rectangular plate, less attention is devoted to skew plates which is due to the more complex geometry of the plate. In skew plates, in general, equations should be transformed into an oblique coordinate to apply the boundary conditions directly. Zhang et al. [14] applied an element free formulation to the stability equations of a skew plate to analyse the buckling of skew plates subjected to uniaxial compression, biaxial compression and combined compression/tension. The developed solution method is suitable for arbitrary combinations of free, simply supported and clamped types of boundary conditions. Let et al. [15] analysed the effects of Pasternak elastic foundation on the buckling of FG-CNTRC skew plates using an element-free approach. Based on a two dimensional generalised differential quadrature method,

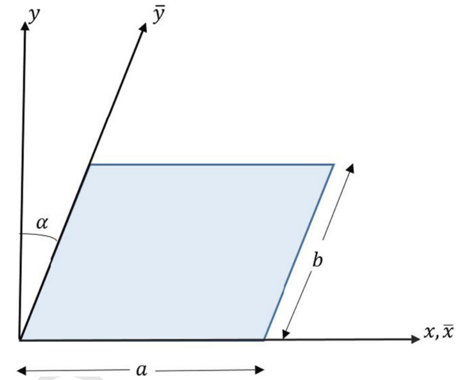

Fig. 1. Schematic, coordinate system and geometrical characteristics of FG-CNTRC skew plate.

Malekzadeh and Shojaee [16] investigated the buckling of arbitrary quadrilateral plates comprising of FG-CNTRC laminates. The stability equations of the plate are obtained according to the Trefftz criterion and the first order shear deformation plate theory. Using an isogeometric approach, Zhang et al. [17] obtained the optimal orientation of CNTs as reinforcements to reach the maximum buckling capacity of CNT-reinforced composite plates. This study is developed based on the third order shear deformation plate theory of Reddy. It is shown that, the efficiency of the skew plate can be significantly improved by simply placing the CNTs in the correct orientation. Kiani [18] investigated the thermal buckling of skew plates with different simply supported or clamped boundary conditions using a Ritz formulation.

To the best of the present author knowledge and as the above literature survey reveals, the buckling response of skew plates subjected to shear stresses on the boundary is not reported yet. This research aims to fill this gap in the open literature. To this end, two different types of shear loads, namely, rectangular shear and skew shear loads are considered. Plate is made of a polymeric matrix reinforced by aligned single walled CNTs. Distribution of CNTs across the plate thickness may be uniform or functionally graded. Effective mechanical properties of the media are obtained by using a refined rule of mixtures approach. Prebuckling loads due to such applied stresses are obtained. The stability equations of the plate are obtained by transforming the orthogonal coordinate system to an oblique one which makes it possible to apply the boundary conditions directly. The discreted form of the governing equations is obtained using the Ritz method where shape functions are constructed by means of the Gram–Schmidt process. The eigenvalue problem is solved for different patterns of CNT, different CNT volume fractions, various skew angles, side to thickness ratios, aspect ratios and types of loading.

2. Basic formulation

A skew plate with thickness h, edges a and b and skew angle α is considered. Orthogonal coordinate system is assigned to the corner of the mid-surface of the plate. The assigned coordinate system, geometrical characteristics and the schematic of the plate are shown in Fig. 1.

The composite plate is made from a polymeric matrix which is reinforced with aligned single walled carbon nanotubes. As mentioned earlier, distribution of CNTs as reinforcements across the skew plate thickness may be uniform or functionally graded. When distribution of CNTs across the plate is functionally graded, it is usually referred to as functionally graded carbon nanotube reinforced composite (FG-CNTRC) skew plate. From the mathematical point of view, various dispersion profiles may be considered for the CNTs across the thickness of the plate, however, linearly graded

Please cite this article in press as: Y. Kiani, M. Mirzaei, Rectangular and skew shear buckling of FG-CNT reinforced composite skew plates using Ritz method, Aerosp. Sci. Technol. (2018), https://doi.org/10.1016/j.ast.2018.03.022