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Buckling analysis of functionally graded carbon nanotube-reinforced curved panels under axial compression and shear

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A B S T R A C T

The need for high-performance lightweight materials for the design of aerospace structures predicts a remarkable future role of carbon nanotubes (CNTs). In particular, thin curved fuselage panels are widely employed. However, the theoretical difficulties in the underlying differential problem induced by the curvature, as well as a still under development technology of CNT-based composites, the number of studies dealing with buckling behavior of this structural typology is limited. The present study aims to provide some insight into the linear buckling analysis of functionally graded carbon-nanotube reinforced (FG-CNTRC) cylindrical curved panels under compressive and shear loading. Effective properties of materials of the panels reinforced by single-walled carbon nanotubes (SWCNTs) are estimated through a micromechanical model based on either the Eshelby-Mori-Tanaka approach or the extended rule of mixtures. A series of numerical simulations have been carried out to inspect the influence of curvature, panel aspect ratio, the distribution profile of reinforcements (uniform and three non-uniform distributions) and CNTs orientation angle on the buckling critical load under compressive and shear loading in uniform thermal environments. Results demonstrate that the change of fiber orientation, CNTs distribution, panel aspect ratio, loading condition and temperature have noticeable effects on the buckling strength and buckling modes of FG-CNTRC curved panels.

1. Introduction

The interest in composite materials for the design of aerospace structures has been steadily growing over the last decades. The upsurge in the need for lightweight structures able to give high level performances has led to a more intensive use of advanced materials, such as fiber reinforced composites, laminates, sandwiches, foams and nanostructures [1]. In particular, carbon nanotubes (CNTs) exhibit manifold interesting features as reinforcing fibers for high strength materials [2] and smart materials with self-sensing capabilities [3,4]. The introduction of composite materials to a larger extent on commercial aircrafts such as Boeing 787 and Airbus A380, predicts a remarkable role of carbon nanotube-reinforced composites (CNTRC) for both aeronautical and aerospace industry [5]. A promising direction is the application of CNTs as reinforcements in Functionally Graded Materials (FGM). This branch of advanced materials is characterized by spatially continuous varying properties [6]. These materials are inhomogeneous composites characterized by smooth and continuous variations in both compositional profile and material properties, feature that eludes characteristic issues of laminates such as delamination and debonding [7–9]. An interesting application of these new materials is on curved fuselage panels. However, due to the mathematical difficulties involved in their formulation, works on prediction of the critical buckling loads of CNTRC cylindrical unstiffened curved panels subjected to uniform axial compression and shear are scarce in the literature.

Papers related to the buckling theory of curved panels are not so numerous in comparison to the literature devoted to flat shell or cylindrical shell buckling. In the case of isotropic curved panels under axial compressive loading, some analytical solutions were proposed under the assumption of critical loads equal to the case of full revolution cylinders. This is the case of the reference

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expressions developed by Redshaw [10] and Timoshenko [11]. Stowell [12] proposed a modified form of Redshaw's expression taking into account the influence of the boundary conditions. However, gross differences have been found with these simplifications in comparison to some experimental results in the literature [13–15]. Further investigations were conducted by Yamura et al. [16] who studied numerically the buckling plastic collapse and by Park et al. [17,18] who provided a simplified method to estimate the ultimate strength based on Faulkner's formule for a single plate with a newly defined slenderness parameter including curvature effect. Le Tran et al. [19] proposed semi-empirical formulae for predicting the elastic buckling and ultimate strength based on finite element simulations. Similar analyses were also conducted for the case of buckling of curved shells under shear loading. The initial analysis were conducted by Legget [20] for long, slightly curved plates under uniform shear stresses. There are some other analytical results in the literature (see e.g. Refs. [21,22]) although due to the nonexistence of simple trigonometric shape functions for shear buckling modes of curved panels, numerical simulations by finite element analysis has proven to be more feasible [23,24].

With regard to the analysis of CNTRC and FG-CNTRC structural elements, the number of publications has considerably increased in recent years with plenty of newly results. One of the first works concerning non-uniform distributions of CNTs within an isotropic matrix was published by Shen [25]. In this work, a nonlinear vibration analysis of FG-CNTRC plates in thermal environments was presented. Shen and Zhang [26] analyzed the thermal buckling and postbuckling behavior of uniform and symmetric FG-CNTRC plates under in-plane temperature variation. The results showed that functionally graded CNT distributions can rise the buckling temperature as well as the thermal postbuckling strength of plates. However, it is also observed that in some cases the plate with intermediate nanotube concentration may not present intermediate buckling temperature and initial thermal postbuckling strength. Based on the homogenization framework of Eshelby-Mori-Tanaka, Arani et al. [27] investigated analytically and numerically the buckling behavior of moderately thick CNTRC rectangular plates subjected to uniaxial compression. Adopting classical laminate plate theory and third-order shear deformation theory, the authors optimized the orientation of CNTs to achieve the highest critical load. A similar contribution by Mehrabadi et al. [28] analyzed the mechanical buckling of FG-CNT reinforced composite Mindlin plates subjected to both uniaxial and biaxial in-plane loadings. The buckling analysis of FG-CNTRC plates under in-plane mechanical loads was also carried out by Lei et al. [29] using the element-free kp-Ritz method. In that work, a micromechanical model based on either the Eshelby-Mori-Tanaka approach or the extended rule of mixture showed good synergism between both methodologies for the case of uniaxially CNT reinforced composites. Zhu et al. [30] proposed a meshless local Petrov-Galerkin approach based on the moving Kriging interpolation technique for the geometrically nonlinear thermoelastic analysis of FG plates in thermal environments. Later work of the same group dealt with the mechanical and thermal buckling analysis of ceramic-metal FG plates [31]. Lei et al. [32] employed the IMLS-Ritz method for the buckling analysis of thick FG-CNT skew plates resting on Pasternak foundations. Similar results can be found in the literature concerning the buckling analysis of FG-CNTRC thick plates resting on Winkler [33] and Pasternak foundations [34], the buckling analysis of thick FG-CNTRC skew plates under biaxial compression [35], the postbuckling behavior of FG-CNTRC plates with elastically restrained edges under axial compression [36], as well as of biaxial compressed arbitrarily straight-sided quadrilateral ceramic-metal FGM plates [37]. This methodology has been found useful for other manifold applications such as the free vibration of moderately thick laminated CNTRC plates [38] and triangular plates [39], large deformation of FG-CNT reinforced composite quadrilateral plates [40], and FG-CNTRC plates with elastically restrained edges [41]. Those studies concluded that the FG-X profile results in the stiffest CNT configuration, unlike the FG-O profile which generates the least stiff configuration. Similar conclusions were reached by Zhang et al. [42] who investigated the large deflection behavior of FG-CNTRC plates resting on elastic foundations under transversely distributed loads. It is also worth mentioning the proposal of these authors of a state-space Levy method for the vibration analysis of FG-CNTRC plates subjected to in-plane loads based on higher-order shear deformation theory [43]. Nevertheless, the number of publications dealing with cylindrical panels is less numerous. It is noteworthy the work of Lei et al. [44] which presented parametric studies of the dynamic stability of CNTRC-FG cylindrical panels under static and periodic axial forces using the mesh-free-kp-Ritz method and the Eshelby-Mori-Tanaka homogenization scheme. Shen and Xiang [45] employed the higher-order shear deformation theory with a von Kármán-type of kinematic nonlinearity to study the postbuckling of axially compressed FG-CNTRC cylindrical panels resting on elastic foundations in thermal environment.

Regarding the state of the art of mechanical analysis of FG-CNTRC composites [46], only a limited number of works reported on the buckling analysis of FG-CNTRC cylindrical panels under axial compressive and tangential forces. The influence of the different variables involved in the micromechanics of functionally graded materials, such as volume fraction, CNT distributions, fiber orientation angle and temperature-dependent material properties, on the buckling behavior of curved panels is still unexplored. The objective of the present study is to investigate the effect of the main design variables which influence the linear buckling behavior of FG-CNTRC unstiffened curved panels. The panels have been modeled with the commercial FEA software ANSYS v15.0 with effective properties of materials estimated by means of a micromecamechanical model based on either the Eshelby-Mori-Tanaka approach or the extended rule of mixtures. Detailed parametric studies have been carried out to inspect the influence of curvature, panel aspect ratio, the distribution profile of reinforcements (uniform and three non-uniform distributions) and CNTs orientation angle on the buckling critical load under compressive and shear loading in uniform thermal environments. The results show substantial influence of these variables on the buckling strength and buckling modes of FG-CNTRC curved panels.

The paper is organized as follows. Section 2 introduces the terminology used for the parametrization of FG-CNTRC cylindrical curved panels as well as the homogenization schemes. Section 3 sets up the basis of the eigenvalue buckling analysis of FG-CNTRC cylindrical curved panels. Section 4 presents some comparison analyses with the existing literature, buckling analysis of FG-CNTRC curved panels under axial compressive and tangential forces. Finally, Section 5 presents the conclusions derived from this work.

2. FG-CNTRC cylindrical curved panels

The FG-CNTRC cylindrical curved panel and the corresponding local coordinate system $\{u,v,w\}$ considered in this paper are shown in Fig. 1a. This panel is assumed to be thin and of projected width b, straight length a, radius R, span angle β and uniform constant thickness t. In order to characterize the curvature of the panels, it is defined a non-dimensional parameter $Z{=}s^2/R{\cdot}t$ (modified Bartdorf's parameter deprived of the effects of Poisson's ratio), being s the curved length of the panel. From a physical point of view, this parameter is proportional to the sagitta of the curved edges h (given