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Non-linear bending analysis of nanocomposites reinforced by graphene-nanotubes with finite shell element and membrane enhancement

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A B S T R A C T

The purpose of this paper is to investigate the non-linear bending behavior of functionally graded shell structures reinforced by carbon nanotubes (FG-CNTRC) using non-linear double directors shell model and membrane enhancement. This model induces a high order variation of the displacement field along the thickness direction and imposes a zero transverse shear stresses condition in the top and bottom surfaces. The effective material properties of FG-CNTRC are estimated by the modified rule of mixtures using some efficiency parameters. Uniformly (UD) and three graded distributions, known as FG-V, FG-O and FG-X, are considered to show the effects of carbon nanotubes (CNTs) profiles and their volume fractions on non-linear deflections of various shapes of shell structures. To illustrate these effects, a set of numerical examples including beams, plates, cylindrical panels and hemispherical shells are presented. The effects of some geometrical parameters are also examined. A convergence studies are carried out to validate the proposed non-linear model, then non-linear results for FG-CNTRC shell structures are provided leading hence to outline the applicability and the efficiency of the present model.

1. Introduction

The analysis of shell structures is of considerable interest in various areas of structural mechanics. It is therefore natural that with the development of the finite element method a large number of different finite elements have been formulated for the analysis of shell problems. In these developments, basically two aspects have been investigated: linear and non-linear analysis. For linear analysis, an extensive researches have been made to investigate the bending, vibration, buckling and post-buckling of the shell structures based notably on three kinematic models: the first one is the Kirchhoff-love model which neglects the contribution of shear deformations and it is restricted to thin structures analysis [1,2]. The second one is the Reissner-Mindlin model which was elaborated to overcome the disadvantages of the classical approach by introducing the effect of transverse shear deformations. However, this model requires the introduction of shear correction factors which can be prohibitive for such applications [3,4]. Thereby, a high-order-models are developed to describe the mechanical behavior of isotropic, orthotropic, composite and recently functionally graded (FGM) structures (one can be refereed to these publications among others [5–9]). Nevertheless, the linear behavior remains limited notably when the whole of the structure is subjected to large displacements and rotations. Hence, the linear models are revisited and many attempts are made to describe the non-linear behavior of various shell structures [10–15].

Recently, a novel class of materials has emerged which are the functionally graded materials reinforced by Carbon nanotubes, known as (FG-CNTRC). In fact, with the discovery of CNTs by Iijima in 1991 [16] which constitutes of enrolled graphene sheets into seamless cylinder, many researchers have focused in the studies of the mechanical behavior of these materials notably that they possess a unique morphology, novel physico-chemical properties, exceptional mechanical, electrical, and thermal properties [17–20]. As well as, the CNTs constitute the ultimate candidates for composite reinforcements of the twenty-first century and they can be incorporated into beams, plates and shells forming hence an interesting structural components for several engineering applications. As a result, extensive studies have been conducted to study the linear and non-linear behaviors of FG-CNTRCs. The linear behavior including static, dynamic, free vibration, buckling and post-buckling analysis is presented by a comprehensive review of Liew et al. [21].

Firstly, the major works related to linear static analysis of FG-CNTRCs are presented. In fact, Zhu et al. [22] investigated the linear static and free vibration behavior of FG-CNTRC plates using the first order shear deformation Theory (FSDT). They demonstrate that bending moments can be enhanced considerably by the addition of

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CNTs reinforcements, as well as, they show the influence of CNT profiles and volume fractions, the width-to-thickness ratios, the boundary conditions and others geometrical parameters on the bending responses, natural frequencies and mode shapes of FG-CNTRC plates. Zhang et al. [23,24] have shown a parametric studies of the linear static and dynamic behavior of FG-CNTRCs cylindrical panels using the FSDT theory. Moreover, Mehrabadi et al. [25] were studied the bending behavior of FG-CNTRC open cylindrical shells using the 3D elasticity theory and also the third order shear deformation theory (TSDT) and then the results obtained by the two methods are compared for different range of geometric and agglomeration parameters. Garcia-Macias et al. [26] were provided a linear static results for FG-CNTRCs skew plates using the FSDT theory for the kinematics and a linear elastic transversely isotropic materials for the constitutive equations of FG-CNTRCs skew plates, then a parametric studies are achieved to show the influences of several parameters on the static and free vibration characteristics of the FG-CNTRC skew plates. Moreover, Tornabene et al. [27] have presented recently linear static responses of composite plates and shells reinforced by agglomerated nanoparticles made of CNTs. Several Higher-order Shear Deformation Theories (HSDTs) are taken into account and compared. The governing equations of motion are numerically solved by the Generalized Differential Quadrature (GDQ) method. The effect of CNT reinforcements on the static response of these nanocomposite plates and shells is also examined via numerical examples and comparison studies were carried out with the results available in the literature. As well as, Zghal et al. [28,29] conducted linear analysis including static and free vibration analysis of FG-CNTRC plates and shells using a high order refined theory. A parametric studies are carried out in order to show the effect of CNT volume faction, the CNT profiles distributions and several geometrical parameters on deflections and stresses responses as well as the vibrational behavior of such structures. However, the linear analysis are based on small displacements and rotations and the materials properties are linear elastic which doesn't acceptable for such cases notably if the whole of the structure undergo large displacements and rotations. For that, the linear models should be revisited in order to describe with accuracy the mechanical behavior of such structures. Therefore, some authors have been focused on the non-linear analysis of FG-CNTRC shell structures and some of the relevant researches regarding the geometrically non-linear behavior of FG-CNTRC shells are provided in the next paragraph.

According to the open literature, few studies have been focused on the non-linear bending analysis of FG-CNTRC shell structures. In fact, Shen [30] was the first one which investigated the non-linear bending behavior of a simply supported FG-CNTRC rectangular plates subjected to a transverse uniform or sinusoidal load in thermal environments and he was shown the significant effect of CNT reinforcements in the improvement of the mechanical properties of FG-CNTRC plates. Following this interesting research, Shen and his co-authors have been conducted numerous works on non-linear analysis of FG-CNTRC cylindrical panels concerning either bending and bostbuckling behaviors [31,32] and also beams [33]. In non-linear bending analysis [31], the governing equations are derived based on a higher-order shear deformation theory with a Von Karman type of kinematic non-linearity and they are then solved by a two-step perturbation technique. The non-linear bending behaviors of the FG-CNTRC panels with different CNT volume fraction distributions, foundation stiffnesses, temperature rise, and the character of in-plane boundary conditions are studied in details. For postbuckling analysis of FG-CNTRC cylindrical panels [32] the sense of Von Karman assumptions is taken into account where the governing equations are elaborated by including non-linear prebuckling deformations and initial geometric imperfections of the panel. These equations are then solved by means of a singular perturbation technique along with a two-step perturbation approach. A detailed parametric studies are also carried out in order to show the effects of various parameters on the post-buckling behavior of FG-CNTRC cylindrical panels are investigated. As well as, Lei et al. [34] have carried out large deflections analysis of FG-CNTRC plates using the FSDT theory with Von Karman assumptions. In this study, the discretization of the displacement field is achieved by a set of mesh-free kp-Ritz method and a parametric studies are achieved in order to show the effect of CNT volume fraction, the plate aspects ratios and the boundary conditions on the non-linear deflections of FG-CNTRC plates. In the same context, Zhang and Liew [35] was presented geometrically non-linear large deformation analysis of FG-CNTRC quadrilateral plates using the FSDT theory with Von Karman assumption to incorporate the transverse shear strains, rotary inertia and moderate rotations. A detailed parametric studies are carried out leading hence to perform the effect of several parameters on the non-linear behavior of such structures. As well as, Zhang and his co-authors were conducted non-linear analysis of FG-CNTRC cylindrical panels [36], triangular plates [37] and skew plates resting on Pasternak foundations [38]. The same kinematic model is used, which reposes on the (FSDT) theory with Von Karman assumption, to approximate the displacement field of the structure and the element-free IMLS-Ritz method is also employed in their studies. The results show the significant effect of CNT distributions, volume fractions on the non-linear bending characteristics under different boundary conditions. Moreover, Reinoso and Blazquez [39] have presented geometrically non-linear analysis of functionally graded power-based and carbon-nanotubes reinforced composites using a first-order solid shell element. A combination of the EAS and ANS method have been analyzed to achieve a locking-free element performance. Numerical tests have been conducted to investigate especially the effect of carbon nanotubes distributions and their volume fractions. The results show that CNTs constitute a good solution for composite reinforcements in terms of the enhancement of the structural stiffness of the structure. Recently, Feng et al. [40] were presented non-linear free vibration analysis of a multilayer polymer nanocomposite beam reinforced by graphene platelets (GPLs). Theoretical formulations are based on Hamiltons principle, Timoshenko beam theory, and Von Karman non-linear strain-displacement relationship. The results show that adding a very small amount of GPLs into polymer matrix as reinforcements significantly increases the natural frequencies of the beam. As well as, in the same context for Large deflections analysis, Frikha et al. [41] were provided recently a novel non-linear model based on Kirchhoff-Love assumptions with finite rotations three and four nodes shell elements for FG-CNTRC thin shells.

As can be remarked from the works regarding geometrically non-linear analysis of FG-CNTRC shell structures, there are no existing publications on the non-linear bending of FG-CNTRC shells with a high order model. In fact, the most of the presented papers are based on the FSDT theory with Von Karman assumptions. Nevertheless, the FSDT theory is limited in its application to thin structures and the Von Karman assumption includes only membrane forces, so it is restricted to moderately small deformations. Therefore, to analyze large deflections with a good representation of finite rotations, we propose in this paper a refined non-linear model based on a double directors finite element shell. This model takes into account the transverse shear deformations with cubic distribution of the displacement field along the thickness direction and it imposes a zero condition of the shear transverse stresses in the top and bottom surfaces enabling hence to describe the membrane, bending and shear contributions of the strains with large deformations and rotations. Furthermore, the membrane contribution of strains is enhanced to reach notably the membrane behavior for in-plane bending dominated cases. This constitutes an advantage for the presented formulation especially that the contribution of membrane apart or coupled with bending and shear parts has an essential role to describe the kinematics of the shell structure. As well as, the enrichment of the strain field is new compared to the model presented by Frikha et al. [42] for FGM materials. In the previous work [42], the constitutive material law is isotropic while in this paper for FG-CNTRC, the constitutive material law is orthotropic. Hence, the present model constitutes an alternative to analyze large displacements with a good