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Static analysis of functionally graded carbon nanotube-reinforced plate and shell structures

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This paper deals with linear static analysis of functionally graded carbon nanotube-reinforced composite structures. Five types of distributions of uniaxially aligned reinforcements are considered, that is, uniform and four kinds of functionally graded distributions of carbon nanotubes along the thickness of shell structures. Material properties are estimated by a micro mechanical model (extended rule of mixture), using some effective parameters. The governing equations are developed based on a discrete double directors shell finite element. The obtained results in terms of deflection and stresses are illustrated by three numerical examples in order to outline the performance and the applicability of the proposed finite element method. The effects of carbon nanotube volume fraction, length-to-thickness ratio, boundary conditions and others geometrical parameters on the static behavior of shell structures are also examined.

1. Introduction

The carbon nanotubes (CNTs) were discovered by Iijima [1] in 1991. They consist of rolled graphene sheets with a cylindrical shape. They could be either single-walled (SWCNTs) or multi-walled (MWCNTs) in nanosized scale. In addition, these CNTs are considered the first advanced material of the twenty-first century due their unique morphology, novel physico-chemical properties, exceptional mechanical, electrical, and thermal properties and, also, their versatile applications. In fact, many experimental and theoretical results [2–11] have been focused on their material properties. For instance Esawi and Farag [6] have outlined that the Young's moduli of CNTs are greater than 1 TPa and tensile strength exceeds that of steel by over one order of magnitude. Such kinds of properties make them an alternative of reinforcements in composite structures [12]. Hence, the incorporation of CNTs into composite structures leads to a novel class of structural members labeled (CNTRCs). These CNTRCs can be embedded in beam, plate or shell as structural components with nonuniform distribution across the whole of structure. Indeed, according to the traditional approach of manufacturing of nanocomposites, these CNTRCs can be distributed either uniformly or randomly such that the resulting mechanical, thermal, or physical properties do not vary spatially at the macroscopic level.

To account for this distribution, the concept of functionally graded materials (FGMs) [13] can be combined with carbon nanotubes reinforcements formed hence the so called functionally graded carbon nanotube reinforced composites (FG-CNTRCs). These new trends of materials have attracted many industries such as aerospace, automobile, energy, structural and chemical industry. For instance, in the electronic field, these FG-CNTRCs are used to increase the conductivity of electrodes in lead-acid batteries due their superconducting properties at low temperature. On other hand, the good damping properties of FG-CNTRCs and thermal, chemical resistance influenced the aerospace industry to manufacture various parts, which include rotor blades, stabilizers and fuselage portions. Furthermore, regarding the weight reduction and good structural properties of CNTs, the FG-CNTRCs are the best replacements for composites. As well as, the lightweight metallic, ceramic, and polymeric composites for armor and armaments and barrier materials for chemical-biological protection in military applications focus on utilization of FG-CNTRCs. In the academic field, this combination was first proposed by Shen [14] and the results was shown that nonlinear bending behavior can be considerably improved through the use of a functionally graded distribution of carbon nanotubes in the matrix. Then, following his work, various investigations were reported on the mechanics behavior of FG-CNTRC structures and most of them are recorded in a recent review elaborated by Liew et al. [15]. In this review, the authors show that many aspects of mechanical behavior analysis of FG-CNTRCs were carried out covering static, free vibration, buckling, post-buckling and non-linear analysis.

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A relevant report, for each type of analysis, is presented here. For static and free vibration analysis, Zhu et al. [16] investigated the free vibration and static response of FG-CNTRCs plates using finite elements method. They concluded that CNT volume fractions, the width-to-thickness ratio and the boundary conditions have a significantly influence on the bending responses, natural frequencies and mode shapes of FG-CNTRC plates. Alibeigloo et al. was focused on the studies of static analysis of FG-CNTRCs rectangular plates [17] using differential quadrature method or cylindrical panels [18] using three-dimensional theory of elasticity. Using the same theory, a further static analysis of FG-CNTRC plate embedded in thin piezoelectric layers subjected to uniform mechanical load was also conducted by Alibeigloo [19]. Natarajan et al. [20] were studied static and dynamic responses of sandwich plates with CNT reinforced facesheets using various plate models and they outlined the effectiveness of higher order models compared to first order theory in the prediction of dynamic behavior of such structures. Lei et al. [21] presents also a linear and nonlinear analysis of FG-CNTRCs plates using free kp-Ritz method. Furthermore, Garcia-Macias et al. [22] were provided a linear static results for FG-CNTRC skew plates using the first-order shear deformation plate (FSDT) theory. In this study, Garcia-Macias et al. use a linear elastic transversely isotropic materials to describe the constitutive equations of FG-CNTRC skew plates, then a parametric studies is achieved to show the influences of several parameters on the static and free vibration characteristics of the FG-CNTRC skew plates. Moreover, Mehrabadi and Aragh [23] studied stresses caused by bending behavior of FG-CNTRC open cylindrical shells subjected to mechanical loads. Zhang et al. [24] presented also a parametric studies of static and dynamic behavior of FG-CNTRC cylindrical panels using FSDT theory. As well as, many survey articles have been published on buckling and post-buckling FG-CNTRC structures. These include the reviews by Shen and Zhang [25], Jafari et al. [26], Lei et al. [27], Rafiee et al. [28] and recently by Jam and Kiani [29]. On the other hand, non-linear FG-CNTRC analysis have been reported and one can refereed, for instance, to these publications [14,21,30,31].

As can be remarked from this report of the open literature, several researches on mechanical behavior of FG-CNTRCs structures are available but in this paper attention will be paid especially to static analysis of FG-CNTRCs structures which still remains interesting to investigate it with a refined finite element model. In fact, the most of mentioned papers on static analysis uses generally three-dimensional 3D theory of elasticity [17–19,23] or FSDT theory [16,21,22,24]. Nevertheless, the FSDT theory assumes a constant variation of transverse shear deformations through the structure thickness and requires hence the computation of shear correction coefficients which can be prohibitively expensive (one can be referred to [32] among others). In addition, 3D solutions are difficult to obtain in the most general case of geometries and boundary conditions and the use of two-dimensional 2D (plate and shell) models appears more convenient in most structural applications due to the low computational effort required for 2D compared to 3D models. Consequently, the development of 2D refined theories has attracted many researchers in the past few years and several high order theories (HSDT) are introduced to describe the mechanical behavior of composite or FGM structures [33–38].

In this paper, the static behavior of FG-CNTRC structures is presented using discrete double directors shell element. Motivated by the efficiency and accuracy of this theory regarding FGM shell structures analysis [37–40] and since FG-CNTRC are based on the FGM concept, the use of this model for FG-CNTRC structures appears attractive. Material properties are assumed to vary continuously through thickness direction. The effective material properties of FG-CNTRCs are estimated using a micro-mechanical model. Numerical examples for various types of composite structures (plate, skew plate and cylindrical panel) are presented. The deflections and stresses curves for various types of distributions and volume fractions of CNTs are computed and compared with those presented in the open literature in order to highlight the applicability and the efficiency of the proposed double directors shell formulation for FG-CNTRCs.

2. Material properties of functionally graded carbon nanotube reinforced composites

The studied CNTRC structure is made from a mixture of isotropic matrix and fibers of CNTs. The CNT reinforcements can be uniformly (referred to as UD) or functionally graded (referred to as FG) along the thickness of the structure as shown in Fig. 1. Hence, an appropriate approach should be considered to model the mechanical behavior of such materials. Two mainly approaches are often used to estimate the mechanical properties of these CNTRCs: The Eshelby-Mori–Tanaka approach [4,7] and the rule of mixture [5,6]. Even the two approaches have proving their efficiency in the homogenization scheme, the rule of mixture is more simple and convenient. However, when using CNTRCs, the conventional rule of mixture does not provide an accurate estimation of the mechanical properties of such materials. Meanwhile, as explained by Shen [14,41–43] and used extensively by other researchers [16,18,19,22,24], the conventional rule of mixture approach may be extended with the introduction of the efficiency parameters. Hence, the effective material properties of the CNTRCs can be expressed as [14]:

$$\begin{aligned} E_{11} &= \eta_1 V_{CNT} E_{11}^{CNT} + V_m E_m, \\ \frac{\eta_2}{E_{22}} &= \frac{V_{CNT}}{E_{22}^{CNT}} + \frac{V_m}{E_m}, \\ \frac{\eta_3}{G_{12}} &= \frac{V_{CNT}}{G_{12}^{CNT}} + \frac{V_m}{G_m}, \end{aligned} \tag{1}$$

Where $E_{11}^{CNT}, E_{22}^{CNT}$ and G_{12}^{CNT} are the Young's moduli and shear modulus of CNT, respectively; E_m and G_m represent the corresponding properties of the isotropic matrix. The CNT efficiency parameters, η_i (i = 1, 2, 3), are calculated by matching the effective parameters of CNTRCs obtained from the molecular dynamic (MD) [44,45] simulations with those from the rule of mixture and introduced to account for the size dependent material properties. V_{CNT} and V_m are the volume fractions of CNTs and the matrix material respectively, which satisfy the condition:

$$V_m + V_{CNT} = 1. \tag{2}$$

On other hand, the mass density ρ of nanotube reinforced composite is defined by:

$$\rho = V_{CNT}\rho^{CNT} + V_m \rho^m, \tag{3}$$

While the effective Poisson ratio depends weakly on position [29,46] and is expressed as:

$$\nu_{12} = V_{CNT}^{*} \nu_{12}^{CNT} + V_m \nu_m, \tag{4}$$

where ν_{12}^{CNT} and ρ^{CNT} (resp. ν_m and ρ^m) denote the Poisson ratio and density of the CNTs (resp. of the matrix). V_{CNT}^{*} represent the total volume fraction of CNTs which can be given as follows:

$$V_{CNT}^{*} = \frac{w_{CNT}}{w_{CNT} + \frac{\rho^{CNT}}{\rho^m} - \frac{\rho^{CNT}}{\rho^m} w_{CNT}}, \tag{5}$$

with w_{CNT} is the mass fraction of the carbon nanotube in the composite structure.

In this paper, Uniform (UD) and four types of FG-CNTRCs are considered: FG-O, FG-X, FG-V and FG-Λ for each the CNTs volume