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A new approach to reinforce the fiber of nanocomposite reinforced by CNTs to analyze free vibration of hybrid laminated cylindrical shell using beam modal function method

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ABSTRACT

This research deals with a study of the free vibration of fiber metal laminate thin circular cylindrical shell reinforced by single walled carbon nanotubes with different boundary conditions. The representative volume element is consisting of four phases: fiber, carbon nanotubes (CNTs), polymer matrix and metal. Initially, the CNTs have been added to the matrix and then the fiber phase has been reinforced by them. Finally, the adhesive fiber prepreg has been combined with the thin metal layers. The generated cylindrical shell can be named CNT/fiber/polymer/metal laminate (CNTFPML) cylindrical shell. In this study, Love's first approximation shell theory has been used to obtain the strain-displacement relations and also, beam modal function model has been utilized to satisfy the governing equations of motion. The effects of mass fraction of CNTs, volume fraction of fiber and metal, axial and circumferential modal numbers, and different distributions of CNTs subjected to different boundary conditions on the vibration of the shell have been considered. In addition, the influences of different lay-ups and different material properties of fiber have been investigated.

1. Introduction

Composite materials have high value of stiffness and strength to weight ratios. Therefore, because of need to light structures with high strength and stiffness in the modern engineering, the composite structures are used more than the heavy metallic structures. Therefore in the past decades, the applications of composite materials have increased in the most advanced engineering fields such as aerospace and mechanical especially automobile engineering structures. Composite materials have been used to study free vibrations of various structures such as beams (Ghasemi and Mohandes, 2017; Ghasemi et al., 2016; Mohandes and Ghasemi, 2016a, 2016b), plates (Zhang et al., 2014; Zhu et al., 2014; Zhang and Liew, 2016) and cylindrical shells (Soldatos and Tzivanidis, 1982; Khdeir et al., 1989; Lam and Loy, 1995b; Lee and Kim, 1998). Vibrations of laminated composite cylindrical shells have been studied by Zhang (2001) who used the wave propagation method to obtain natural frequencies of the shell subjected to different boundary conditions. He found that the effect of boundary conditions at small circumferential modes was more than the large ones. Lee et al. (2003) determined the natural frequencies of laminated composite cylindrical shells with an interior plate. Malekzadeh et al. (2008) investigated free vibration of laminated cylindrical shell based on three-dimensional elasticity theory. A mixed layerwise theory was used in their work for obtaining the equations of motion and differential quadrature method (DQM) was utilized for solving them. Three dimensional state equations with DQM were used to analyze the static and free vibration of unsymmetric laminated composite cylindrical shell subjected to different boundary conditions by Alibeigloo (2009).

A new advanced hybrid composite material is FML which is composed by alternately thin metal with adhesive fiber prepreg. In the past decades, the FMLs have been used in mechanical and aerospace industries due to good characteristics of the metal such as ductility, impact and damage tolerances as well as benefits of the fiber composite materials such as high strength and stiffness to weight ratios, excellent fatigue resistance and acceptable corrosion.

Studies on the FMLs are not widespread. Several researches, which have been conducted on the vibrational behavior of different structures are presented. Botelho et al. (2006) investigated damping behavior of the FMLs including different materials based on Voigt-Kelvin model. Shooshtari and Razavi (2010) obtained linear and nonlinear natural frequencies of cross-ply laminated composite and the FML rectangular plates subjected to simply supported boundary condition by multiple time scale method. Rahimi et al. (2014) studied free vibration of the FML annular plate with a central hole based on the three-dimensional

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elasticity theory. They determined the natural frequencies of the plate with different boundary conditions using a combination of the DQM, state-apace and Fourier series. The DQM was used for considering dynamic response of geometrically nonlinear FML Timoshenko beam under unsteady temperature field by Fu et al. (2014).

In the recent years, CNTs-reinforced composite materials have attracted considerable attention for usage in different industries. Addition of CNT to a matrix can significantly amend thermal, mechanical and electrical behaviors. Also, substituting the carbon fibers by CNTs can improve composite properties such as tensile strength and elastic modulus. The CNTs are categorized as single-walled and multi-walled structures. When a single graphene sheet is being rolled to form a cylindrical shell with diameter 1 nm and length of order of centimeter, is called single-walled carbon nanotubes (SWCNTs). The multi-walled carbon nanotubes (MWCNTs) are an array of these cylinders consisting of multi rolled graphene sheets which are formed concentrically. The MWCNT is a cylinder with diameter from 2 to 100 nm and length of tens microns and also distance between the graphene sheets are approximately 0.35 nm. There are some researches about the vibration of different structures reinforced by CNTs (Lei et al., 2015; Zhang et al., 2015a, 2015b; Zhang, 2017a; Zhang and Selim, 2017). Zhang et al. (2016b) obtained non-dimensional frequencies of triangle composite plate reinforced by CNTs subjected to in-plane stresses using an element-free method based on first order shear deformation theory. Zhang et al. (2016c) investigated post-buckling of laminated composite plates reinforced by CNTs under biaxial and uniaxial compressions based on first order shear deformation theory. The effects of different parameters such as number of layers, plate geometry, the distribution of CNT, volume fraction of CNT and boundary conditions were studied in their research. Thomas and Roy (2016) studied vibration of uniform and various functionally graded carbon nanotube-reinforced composite (FG-CNTRC) shells including FG − X, FG − ∨, FG − O and FG − ∧ distributions. The results showed that the volume fraction and distribution of CNT influenced on all of the elastic properties of the composites. Also, Thomas and Roy (2015) in the other research investigated vibration and damping of functionally graded carbon nanotube-reinforced hybrid composite (FG-CNTRHC) shells. Ansari et al. (2016) applied variation differential quadrature method (VDQM) for vibration analysis of various FG-CNTRC spherical shells resting on elastic foundation subjected to different boundary conditions. They found out that the most value of the fundamental frequencies occurred for FG − X distribution. Also, the results indicated with increasing the thickness-to-radius ratio, the non-dimensional frequencies decreases remarkably. The effect of thermal environment on the nonlinear vibration of FG-CNTRC cylindrical shells was considered by Shen and Xiang (2012). The VDQM was used for considering buckling and vibration of FG-CNTRC conical shells under axial loading by Ansari and Torabi (2016). The results revealed that with increasing the volume fraction of CNTs, the non-dimensional frequencies and axial buckling loads of the shells were increased. Kamarian et al. (2016) studied the agglomeration effect of CNTs on the free vibration analysis of CNTRC conical shells. The equations of motion were obtained using first-order shear deformation theory (FSDT) and then they solved by generalized differential quadrature method (GDQM). Shen (2014) employed perturbation method to determine buckling and postbuckling of the FG-CNTRC cylindrical shells subjected to torsion in thermal environment. They found out that buckling and post-buckling of the shells were influenced by volume fraction of CNT considerably. Zhang et al. (2017) investigated dynamic behavior of FG-CNTRC cylindrical shells based on Reddy's high-order shear deformation theory. They found out that the amplitude of the impact responses of FG-X CNTRC cylindrical shell is lower than that of the shell with FG-O and UD CNT distributions. Ghasemi et al. (2017a) analyzed residual stresses for disk and cylinder which were included three phases that are CNT, polymer matrix and fiber. They reinforced the composite layers by CNTs to amend thermal and mechanical behaviors for reduction of residual stresses. Also, Ghasemi et al. (2017b) in the other research investigated creep behavior of composite cylinder which has been reinforced by CNTs. In their work the nano composite cylinder is consist of three phases which are CNT, polymer matrix and fiber. They found out that the addition of CNTs to the vinylester can decrease the absolute value of creep strains and dimensionless effective stresses.

As illustrated, there are some references about the free vibration of composite cylindrical shells reinforced by CNTs, but none work perform on the vibration of CNT/fiber/polymer/metal laminate (CNTFPML) cylindrical shells. Studying this type of cylindrical shell which is included four phases can has the advantages of FML cylindrical shell as well as nanocomposite cylindrical shells. So, it can improve the fatigue resistance and damage tolerance properties as well as modifying thermal, mechanical and electrical behaviors. So, the mixture of these four phases can obtain attractive results. This research focuses on the free vibration of CNTFPML circular cylindrical shells. It means that in the first step, the CNTs are added to the matrix for amending the matrix properties, and then this composition is used for reinforcing the fiber phase. The reinforced fiber organizes the laminated composite cylindrical shell with different lay-ups. In the final step, the adhesive fiber prepreg is combined with the thin metal layers and they make the CNTFPML cylindrical shells. The novelty of the present study consists of considering free vibration of CNTFPML circular cylindrical shell which is included four phases including fiber, CNTs, polymer matrix and metal.

2. Governing equations of motion

The equations of motion related with the stress resultants N_{ij} and M_{ij} for thin circular cylindrical shells are given by (Loy et al., 1997):

$$N_{x,x} + \frac{1}{R}N_{x\theta,\theta} - \rho h\ddot{u} = 0 \tag{1a}$$

$$N_{x\theta,x} + \frac{1}{R}N_{\theta,\theta} + \frac{1}{R}M_{x\theta,x} + \frac{1}{R^2}M_{\theta,\theta} - \rho h\ddot{v} = 0 \tag{1b}$$

$$M_{x,xx} + \frac{2}{R}M_{x\theta,x\theta} + \frac{1}{R^2}M_{\theta,\theta\theta} - \frac{1}{R}N_{\theta} - \rho h\ddot{w} = 0 \tag{1c}$$

where h, ρ and R are the thickness, density and radius of the cylindrical shell. Forces N_{ij} and moments M_{ij} are defined as following (Zhang and Liew, 2015b):

$$\{N_x,\ N_\theta,\ N_{x\theta}\} = \int_{-h/2}^{h/2}\{\sigma_x,\ \sigma_\theta,\ \sigma_{x\theta}\}dz \tag{2a}$$

$$\{M_x,\ M_\theta,\ M_{x\theta}\} = \int_{-h/2}^{h/2}\{\sigma_x,\ \sigma_\theta,\ \sigma_{x\theta}\}zdz \tag{2b}$$

where σ_x, σ_θ and $\sigma_{x\theta}$ are the axial, circumferential and shear stresses at an arbitrary point of the cylindrical shell. The stress resultants are obtained with considering the axial ε_{xx}, circumferential $\varepsilon_{\theta\theta}$ and shear $\gamma_{x\theta}$ strains at an arbitrary point of the cylindrical shell related to the middle surface strains $\varepsilon_{x,0}$, $\varepsilon_{\theta,0}$ and $\gamma_{x\theta,0}$ and to the changes in the curvature and torsion of the middle surface k_x, k_θ and $k_{x\theta}$. So, stress resultants can be introduced based on the Love's first approximation shell theory (Tsai, 1980; Lei et al., 2014) as following:

$$\begin{bmatrix} N_x \\ N_\theta \\ N_{x\theta} \\ M_x \\ M_\theta \\ M_{x\theta} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_{x,0} \\ \varepsilon_{\theta,0} \\ \varepsilon_{x\theta,0} \\ k_x \\ k_\theta \\ k_{x\theta} \end{bmatrix} \tag{3}$$

Since cross-ply and unidirectional lay-ups are considered in this study; so $A_{16} = A_{26} = B_{16} = B_{26} = D_{16} = D_{26} = 0$.

The governing equations of motion for the CNTFPML circular