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Dynamics of FG-CNT reinforced composite cylindrical panel subjected to moving load

Y. Kiani

Faculty of Engineering, Shahrekord University, Shahrekord, Iran

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ABSTRACT

Present study deals with the dynamic response of a functionally graded carbon nanotube reinforced composite (FG-CNTRC) cylindrical panel subjected to moving load on the panel surface. Panel is formulated within the framework of first order shear deformation shell theory. Formulation is restricted to be geometrically linear. Distribution of CNTs across the panel thickness is considered to be uniform or functionally graded. Effective properties of the composite media are estimated using a refined rule of mixtures approach with introduction of efficiency parameters. The matrix representation of dynamic equations is obtained according to the Ritz method whose orthogonal shape functions are obtained according to the Gram-Schmidt process. The resulting dynamic equations are traced in time following the Newmark time marching scheme. Parametric studies are given to explore the characteristics of CNTs as reinforcements and influences of boundary conditions. It is shown that, increasing the volume fraction of CNT as reinforcements decreases the dynamic response of the panel. Furthermore, in comparison to other patterns of CNT dispersion, in FG-X pattern of CNT distribution, panel becomes more stiff and dynamic deflection decreases.

1. Introduction

A novel class of composites known as functionally graded carbon nanotube composites (FG-CNTRC) have attracted increasing attention in the past five years. In these composites, a polymeric or metal matrix is reinforced with carbon nanotubes whose distribution pattern may be uniform or functionally graded. In the latter case, distribution of volume fraction of CNTs across the panel thickness is considered as a continuous and smooth function of thickness coordinate. It is shown that, in many cases, FG-CNTRC solid structures are superior to those with uniform distribution of CNTs. An excellent overview on structural response of FG-CNTRC beams, plates and shells is provided by Liew et al. [1].

Fundamental research on mechanical behaviour of FG-CNTRC structures belongs to Shen [2] who claimed that, bending moments may be alleviated significantly through usage of functionally graded pattern of CNTs in a matrix. This piece of work motivated the other investigators to explore the structural behaviour of FG-CNTRC structures. An overview of the works on the vibrational characteristics of FG-CNTRC plates and shells is provided in the next.

Wang and Shen [3,4] investigate the linear and nonlinear free vibration characteristics of FG-CNTRC plates [3] and sandwich plates with FG-CNTRC face sheets [4] using a two step perturbation method. The solution method of these researches is suitable for plates with all edges simply supported with movable or immovable features in in-plane directions. Zhu et al. [5] examined the free vibration characteristics of rectangular plate made of FG-CNTRC. In this research, first order shear deformation plate theory is used and finite element procedure is applied to solve the resulting equations. Yas et al. [6] examined the free vibration characteristics of FG-CNTRC cylindrical panels within the framework of three dimensional elasticity theory. Panel is assumed to be simply supported all around where Navier solution is used. After applying the conventional Navier solution to the governing equations, a new system of equations as a function of thickness coordinate are obtained which is solved using the generalized differential quadrature method. Natarajan et al. [7] investigated the free vibration response of FG-CNTRC plate using a higher order shear and normal deformable plate theory. Malekzadeh and Zarei [8] investigated the free vibration characteristics of laminated plates with FG-CNTRC layers using a two dimensional generalized differential quadrature. Free vibration characteristics of rotating FG-CNTRC conical shells is studied by Heydarpour et al. [9]. The influence of rotation is included as pre-stresses and the eigenvalue problem is established by means of the hybrid Fourier-generalized differential quadratures method. Zhang et al. studied the free vibration characteristics of FG-CNTRC cylindrical panels [10], triangular plate [11] and skew plates [12] using element free methods. Zhang et al. [13,14], also, investigated the free vibration characteristics of elastically restrained plates and plates with

E-mail addresses: y.kiani@eng.sku.ac.ir, y.kiani@aut.ac.ir.

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levy type boundary conditions. Zhang et al. [15] investigated the free vibration characteristics of FG-CNTRC plates resting on elastic foundation. Lei et al. [16] investigated the free vibration of composite laminated FG-CNTRC plates with general boundary conditions. Lei et al. [17] investigated the free vibration characteristics of rotating FG-CNTRC cylindrical panels. Based on a mixed Navier-layerwise formulation, Malekzadeh and Heydarpour [18] investigated the free vibration response of FG-CNTRC sandwich plates. In this research, plates with all edges simply supported are investigated. Kiani [19] obtained the natural frequencies of FG-CNTRC plates integrated with two piezoelectric layers at the bottom and top. In this research both the open circuit and closed circuit conditions are taken into considerations. Mirzaei and Kiani [20] investigated the free vibration characteristics of perforated FG-CNTRC rectangular perforated plates. Solution method of this research is based on Ritz method which is suitable for arbitrary boundary conditions on the exterior domain while the perforation is assumed to be free all around. Mirzaei and Kiani [21] applied the Chebyshev-Ritz method to the dynamic motion equations of the panel to investigate the free vibration characteristics of moderately thick FG-CNTRC cylindrical panels with arbitrary edge supports. Free vibration response of FG-CNTRC skew plates with arbitrary combinations of boundary conditions is studied by Kiani [22]. The governing equations of the plate are expressed in an oblique coordinate which is more simpler to apply the boundary conditions. Jooybar et al. [23] investigated the influences of thermal environment on the free vibration characteristics of FG-CNTRC conical panels using a two dimensional generalized differential quadratures method. It is shown that, critical buckling temperatures of the panel also may be obtained via the curves of natural frequency versus temperature elevation. Kiani [24] investigated the natural frequencies and the associated mode shapes of doubly curved FG-CNTRC shells using an energy based method. Kiani [25] investigated the free vibration characteristics of FG-CNTRC plates resting on point supports with the aid of the introduction of Lagrangian multipliers. Solution method of this research is general and may be used for arbitrary in-plane and out-of-plane boundary conditions.

In comparison to free vibration analysis of FG-CNTRC plates and panels, less attention is devoted to forced vibration. Wang and Shen [26] examined the geometrically nonlinear dynamic response of an FG-CNTRC rectangular plate under the action of lateral pressure. In this research, von-Kármán type of geometrical non-linearity is included into the formulation and plate is operating at various thermal environment. A two step perturbation technique suitable for plates with all edges simply supported is developed which may be used for both movable and immovable plates. Dynamic response of rectangular plates made of FG-CNTRC subjected to dynamic loading is also studied by Lei et al. [27] using a mesh free method. Thomas and Roy [28] applied an eight-noded shell element to the motion equations of a doubly curved FG-CNTRC doubly curved panel. Attention is devoted to damping and settle times of the dynamic response of the doubly curved panel. Malekzadeh et al. [29] investigated the dynamic response of rectangular plate made of FG-CNTRC subjected to the action of a single moving mass. Finite element formulation is proposed to solve the motion equations of the plate suitable for arbitrary edge supports. Also Malekzadeh and Dehbozorgi [30] performed a throughout investigation on the dynamic response of a skew plate made of FG-CNTRC materials subjected to the lateral low velocity impact of a single mass.

Present research deals with the dynamic response of a functionally graded carbon nanotube reinforced composite cylindrical panel subjected to the action of a moving load. Solution method is based on the Ritz method whose shape functions are estimated according to the Gram-Schmidt process. The general motion equations are obtained in a matrix representation and are traced in time based on the Newmark time marching scheme. Numerical results are provided to explore the influences of load velocity, boundary conditions, CNT volume fraction and CNT dispersion pattern.

Table 1
Volume fraction of CNTs as a function of thickness coordinate for various cases of CNTs distribution [32–37].

CNTs Distribution	V_{CN}
UD CNTRC	V_{CN}^*
FG-V CNTRC	$V_{CN}^*\left(1+2\frac{z}{h}\right)$
FG-Λ CNTRC	$V_{CN}^*\left(1-2\frac{z}{h}\right)$
FG-O CNTRC	$2V_{CN}^*\left(1-2\frac{\vert z\vert}{h}\right)$
FG-X CNTRC	$4V_{CN}^*\frac{\vert z\vert}{h}$

2. Basic formulation

A cylindrical panel with thickness h, curved edge b and straight edge a made of a polymeric matrix reinforced with single walled carbon nanotubes (SWCNT) is considered. Orthogonal Cartesian coordinate system is assigned to the middle of the mid-surface of the panel where as usual $-0.5a \le x \le +0.5a$ is through the length, $-0.5b \le y \le +0.5b$ is through the width and $-0.5h \le z \le +0.5h$ is through the thickness.

Distribution of CNTs across the thickness of the cylindrical panel may be uniform or functionally graded. When distribution of CNTs across the panel is functionally graded, it is usually referred to as functionally graded carbon nanotube reinforced composite (FG-CNTRC) cylindrical panel. From the mathematical point of view, various dispersion profiles may be considered for the CNTs across the thickness of the panel, however, linearly graded patterns of CNTs are more observed in the researches due to their consistency with the fabrication processes [31]. As a result, four types of FG-CNTRC panels may be achieved which are known as FG-Λ, FG-V, FG-X and FG-O. These four types along with the uniformly distributed (UD)-CNTRC cylindrical panel are considered in the present research. Table 1 presents the distribution of volume fraction of CNT as a function of thickness coordinate in various CNTRC panels.

It is easy to check from Table 1 that, both uniform and functionally graded patterns of CNTRC panels will have the same total volume fraction of CNTs which is denoted by V_{CN}^*. Through such feature, the dynamic characteristics of UD- and FG-CNTRC may be compared with respect to each other. V_{CN}^* may be obtained as a function of mass density of CNTs, ρ^{CN}, mass density of matrix ρ^{m} and mass fraction of CNTs w^{CN} as

$$V_{CN}^* = \frac{w^{CN}}{w^{CN} + \rho^{CN}/\rho^{m} - w_{CN}\rho^{CN}/\rho^{m}} \tag{1}$$

A comparison among the distribution pattern of CNTs reveals that, in FG-X pattern, the top and bottom surfaces of the panel are enriched by the maximum volume fraction of CNTs whereas the mid-surface is free of CNTs. In FG-O, distribution pattern is inverse. The top and bottom surfaces are free of CNTs and the mid-surface is enriched with the maximum volume fraction of CNTs. In type FG-V, the bottom surface is free of CNT and the top one is enriched with the maximum volume fraction of CNT. In type FG-Λ the regime in inverse and the bottom surface is enriched with CNTs whereas the top one is free of CNTs. In UD type, unlike the other four FG types, volume fraction of CNT is constant at each surface of the panel.

Various methods are proposed to estimate the effective material properties of the CNTRC media. Among them, Mori-Tanaka scheme [38] and the rule of mixtures [39] approach are more observed through the researches. Rule of mixtures approach is a simple and efficient