Composite Structures 141 (2016) 79–90

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Aeroelastic analysis of CNT reinforced functionally graded composite panels in supersonic airflow using a higher-order shear deformation theory

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A R T I C L E I N F O

Article history:
Available online 11 January 2016

Keywords:
A. Plates
B. Vibration
C. Numerical analysis

A B S T R A C T

This paper presents an aeroelastic analysis of carbon nanotube (CNT) reinforced functionally graded composite panels in supersonic airflow using a higher-order shear deformation theory. There are four types of CNT distributions considered in this investigation. Since the panel studied here is relatively thick, Reddy's third-order shear deformation theory is applied to evaluate the displacement fields of the panel. Applying Hamilton's principle, the equation of motion of the structural system is formulated. The CNT reinforced functionally graded composite panels investigated in this study are simply-supported on two opposite edges and therefore, in order to solve the coupling set of differential equations of motion, the state-space Levy method is applied. Based on the Levy solution, the aeroelastic properties of the CNT reinforced composite panels are analyzed using the frequency-domain method. The effects of CNT distributions and boundary conditions on the aeroelastic stabilities of the CNT reinforced functionally graded panels are researched. Different types of aeroelastic instability under different boundary conditions are observed. Moreover, vacuo and fluttering mode shapes of the CNT reinforced functionally graded panels are presented.

1. Introduction

In recent years, due to high levels of structural and physical performances, carbon nanotubes have been widely used as the reinforcement of polymer composites [1–4]. Combining the concept of functionally graded material, CNT reinforced functionally graded composite materials are introduced [5]. In the FG-CNT material, distribution of the CNTs is spatially varied in a smooth and continuous way. A large volume of literature has studied the mechanical behaviors of FG-CNT beams, plates and shells. Zhang et al. [6] investigated the nonlinear bending behaviors of CNT reinforced functionally graded composite thick plates using the element-free IMLS-Ritz method. The plate was rested on Pasternak foundations. Lei et al. [7] conducted a vibration analysis of thin-to-moderately thick laminated CNT reinforced functionally graded composite plates, wherein the element-free kp-Ritz method was used to formulate the equation of motion. They also investigated the buckling properties of CNT reinforced functionally graded composite plates subjected to different in-plane loads and researched the free vibration characteristics of CNT reinforced functionally graded plates in thermal environments [8,9]. Yas et al. [10] investigated the three-dimensional vibration properties of CNT reinforced functionally graded composite cylindrical panels reinforced with single-walled carbon nanotubes. The results showed that the distribution and volume fractions of CNTs have a significant effect on the normalized natural frequency. Zhu et al. [11] studied the bending and free vibration characteristics of moderately thick CNT reinforced composite plate applying the FSDT by the finite element method (FEM). Alibeigloo [12] studied the static behavior of CNT reinforced functionally graded composite plate with piezoelectric layers, considering the thermal load and electric fields. Parametric studies were performed.

Aeroelastic behavior is another significant characteristic of structures. It is a coupling effect of elastic force, inertial force and aerodynamic load. Panel flutter is a kind of aeroelastic phenomenon. Much literature has researched the aeroelastic properties of various structures. Based on the FEM, Song and Li [13] studied the aeroelastic behaviors of isotropic panels with different boundary conditions. Sohn and Kim [14] investigated the thermal

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http://dx.doi.org/10.1016/j.compstruct.2016.01.005
0263-8223/

flutter characteristics of functionally graded panels in supersonic airflow. Natarajan et al. [15] studied the flutter characteristics of functionally graded panels using a cell-based smoothed finite element method. Natarajan et al. [16] also investigated the flutter behaviors of functionally graded panels with cracks. Kouchakzadeh et al. [17] conducted a panel flutter analysis of general laminated composite panels using Galerkin's method. Xie et al. [18] employed the proper orthogonal decomposition method for analyzing the nonlinear panel flutter in supersonic airflow. Li and Song [19] studied the flutter and buckling control of composite laminated panels in supersonic airflow using piezoelectric materials. The assumed mode method was used in the structural modeling. Koo and Hwang [20] studied the panel flutter characteristics of composite plates including structural damping through the FEM. Also based on the FEM, Shin et al. [21] analyzed the aerothermoelastic behaviors of aerothermally buckled cylindrical composite shells with various damping treatments. Song and Li [22] investigated the aeroelastic properties of lattice sandwich beams with a pyramidal truss core in supersonic airflow. A robust nonlinear flutter control method was also presented in this investigation. Fazelzadeh et al. [23] studied the aeroelastic characteristics of thin FG-CNT plate in supersonic airflow using Galerkin's method. Sankar et al. [24,25] studied the flutter characteristics of sandwich panels and doubly curved shells with carbon nanotube reinforced face sheets based on the finite element method. From the above literature review, it is noted that the vibration and buckling behaviors of CNT reinforced functionally graded composite panels have been systematically investigated. However, few studies have conducted aeroelastic analyses of the CNT reinforced functionally graded panels. Although in [23,24], aeroelastic analysis of CNT reinforced functionally graded panels has been carried out, only two boundary conditions were taken into account. In this paper, aeroelastic properties of high-order CNT reinforced functionally graded panels with different boundary conditions are studied. The Levy method is applied to solve the coupling set of the equation of motion, which is formulated using Hamilton's principle. Based on the Levy solution, aeroelastic properties of the CNT reinforced functionally graded composite panels are analyzed using the frequency-domain method. The effects of CNT distributions and boundary conditions on the aeroelastic stabilities of the CNT reinforced functionally graded panels are researched. Different aeroelastic instability types under different boundary conditions are observed. Moreover, vacuo and fluttering mode shapes of the CNT reinforced functionally graded panels are also presented.

2. Formulation for the equation of motion

Fig. 1 displays the CNT reinforced functionally graded composite panel in supersonic airflow. The freestream is along the x direction. In the figure, a, b and h define the length, width and thickness

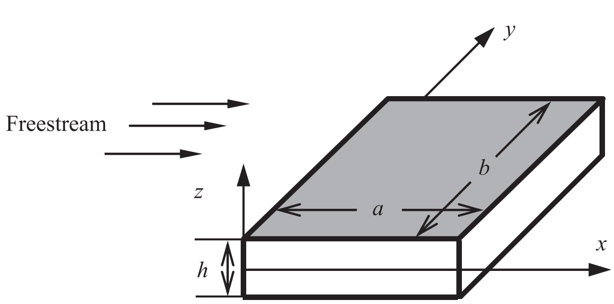

Fig. 1. Schematic diagram of the panel in supersonic airflow.

of the panel. Since the CNT reinforced functionally graded panel studied here is relatively thick, Reddy's third-order shear deformation theory is used. The displacement fields of the panel are [26]:

$$u = u_0 + z\phi_x - \frac{4}{3h^2}z^3\left(\phi_x + \frac{\partial w}{\partial x}\right),$$
$$v = v_0 + z\phi_y - \frac{4}{3h^2}z^3\left(\phi_y + \frac{\partial w}{\partial y}\right), \quad w = w_0, \tag{1}$$

where u_0, v_0 and w_0 are the in-plane and transverse displacements of the neutral plane in the x, y and z directions, ϕ_x and ϕ_y are the rotations of the transverse normal about the y and x axes, and z is the transverse coordinate. The geometric equations of the CNT reinforced functionally graded composite panel are given as:

$$\varepsilon = \varepsilon_0 + z\varepsilon_1 + z^3\varepsilon_3, \quad \gamma = \gamma_0 + z^2\gamma_2, \tag{2}$$

where

$$\varepsilon_0 = \left[\frac{\partial u_0}{\partial x} \quad \frac{\partial v_0}{\partial y} \quad \frac{\partial u_0}{\partial y} + \frac{\partial v_0}{\partial x}\right]^{\mathrm{T}}, \varepsilon_1 = \left[\frac{\partial \phi_x}{\partial x} \quad \frac{\partial \phi_y}{\partial y} \quad \frac{\partial \phi_x}{\partial y} + \frac{\partial \phi_y}{\partial x}\right]^{\mathrm{T}},$$
$$\varepsilon_3 = -c_1\left[\frac{\partial \phi_x}{\partial x} + \frac{\partial^2 w_0}{\partial x^2} \quad \frac{\partial \phi_y}{\partial y} + \frac{\partial^2 w_0}{\partial y^2} \quad \frac{\partial \phi_x}{\partial y} + \frac{\partial \phi_y}{\partial x} + 2\frac{\partial^2 w_0}{\partial x \partial y}\right]^{\mathrm{T}}, \tag{3a}$$

$$\gamma_0 = \left[\phi_y + \frac{\partial w_0}{\partial y} \quad \phi_x + \frac{\partial w_0}{\partial x}\right]^{\mathrm{T}}, \gamma_2 = -c_2\left[\phi_y + \frac{\partial w_0}{\partial y} \quad \phi_x + \frac{\partial w_0}{\partial x}\right]^{\mathrm{T}}, \tag{3b}$$

in which $c_1 = 4/3h^2$ and $c_2 = 3c_1$.

The equation of motion of the CNT reinforced functionally graded composite panel in supersonic airflow will be derived using Hamilton's principle [27]. The kinetic energy T, strain energy Π and virtual work δW inflicted by the aerodynamic pressure are given by:

$$T = \frac{1}{2}\int_V \rho(z)(\dot{u}^2 + \dot{v}^2 + \dot{w}^2)\mathrm{d}V, \tag{4a}$$

$$\Pi = \frac{1}{2}\int_A (\boldsymbol{N}_0^{\mathrm{T}}\varepsilon_0 + \boldsymbol{M}_0^{\mathrm{T}}\varepsilon_1 + \boldsymbol{P}_0^{\mathrm{T}}\varepsilon_3 + \boldsymbol{Q}_0^{\mathrm{T}}\gamma_0 + \boldsymbol{R}_0^{\mathrm{T}}\gamma_2)\mathrm{d}A, \tag{4b}$$

$$\delta W = \int_A \Delta p \delta w \mathrm{d}A, \tag{4c}$$

where A and V denote the surface area and volume of the CNT reinforced functionally graded composite panel, respectively, Δp is the aerodynamic pressure, which is evaluated by the supersonic piston theory, and

$$\rho(z) = V_{CNT}(z)\rho^{CNT} + V_m(z)\rho^m, \tag{5a}$$

$$\begin{Bmatrix} \boldsymbol{N}_0 \\ \boldsymbol{M}_0 \\ \boldsymbol{P}_0 \end{Bmatrix} = \begin{bmatrix} \boldsymbol{A}_0 & \boldsymbol{B}_0 & \boldsymbol{E}_0 \\ \boldsymbol{B}_0 & \boldsymbol{D}_0 & \boldsymbol{F}_0 \\ \boldsymbol{E}_0 & \boldsymbol{F}_0 & \boldsymbol{H}_0 \end{bmatrix} \begin{Bmatrix} \varepsilon_0 \\ \varepsilon_1 \\ \varepsilon_3 \end{Bmatrix}, \begin{Bmatrix} \boldsymbol{Q}_0 \\ \boldsymbol{R}_0 \end{Bmatrix} = \begin{bmatrix} \boldsymbol{A}_1 & \boldsymbol{D}_1 \\ \boldsymbol{D}_1 & \boldsymbol{F}_1 \end{bmatrix} \begin{Bmatrix} \gamma_0 \\ \gamma_2 \end{Bmatrix}, \tag{5b}$$

$$\Delta p = -\frac{2q_\infty}{\kappa}\left(\frac{M_\infty^2 - 2}{M_\infty^2 - 1}\frac{1}{U_\infty}\frac{\partial w_0}{\partial t} + \frac{\partial w_0}{\partial x}\right). \tag{5c}$$

In Eq. (5a), ρ^m and ρ^{CNT} are densities of the matrix and CNTs, and V_m and V_{CNT} are volume fractions of the matrix and CNTs, and the sum of them must be equal to 1, that is, $V_{CNT} + V_m = 1$. Four types of distributions for the CNTs in the CNT reinforced functionally graded composite panels are studied. These CNT configurations are displayed in Fig. 2, where the uniform distribution and the other three CNT distributions are denoted by UD, FGX, FGV and FGO, respectively. For different CNT distributions, the volume fractions are expressed as follows [28]:

$$V_{CNT}(z) = V_{CNT}^*, (UD) \tag{6a}$$