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Bending and vibration behaviors of matrix cracked hybrid laminated plates containing CNTR-FG layers and FRC layers

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ABSTRACT

The influence of matrix cracks on bending and vibration behaviors of hybrid laminated plates is investigated based on an element-free numerical framework. Carbon nanotube reinforced functionally graded (CNTR-FG) layers and conventional graphite fiber reinforced composite (FRC) layers are selected as layer elements for the considered hybrid laminated plates. To illustrate the degraded stiffness, a matrix-cracked model, namely self-consistent model (SCM), is employed. Based on the first-order shear deformation theory (FSDT), we can obtain the governing equation. An element-free numerical framework is proposed to solve the governing equation for obtaining the bending and vibration solutions. In addition, some selected calculations are furnished to illustrate the influences of matrix crack densities, boundary conditions, material parameters and geometric parameters on the bending and vibration behavior characteristics.

1. Introduction

Carbon nanotubes, having high strength, high stiffness and high aspect ratio but low density, have attracted much research interests from many areas of engineering and science. Considering CNT's remarkable properties, it can be selected as an excellent reinforcement for composite materials. In recent years, many studies have been carried out on CNTR-FG beam, plate and shell to investigate their mechanical properties of nanocomposites. A literature review on mechanical analysis of functionally graded carbon nanotube reinforced composites was reported by Liew et al. [1]. Some recent relevant research works on the mechanical properties of carbon nanotube reinforced composites were examined [2–7].

For static and free vibration analyses of CNTR-FG composites, Zhu et al. [8] have carried out the finite element analysis of CNTR-FG plates. For bending, buckling, and vibration behaviors of CNTR-FG beams, analytical results were given by Nuttawit and Variddhi [9]. Alibeigloo and Liew [10] have studied the bending behavior of CNTR-FG rectangular plate under thermo-mechanical loads. It was found that effect of CNT volume fraction on the longitudinal thermo-elastic behavior is greatest, and increasing the CNT volume fraction has little effect on the longitudinal stress of the top surface. Considering CNT-reinforced skew composite plates, an isogeometric analysis of the CNT orientation effect on the static and vibration behaviors was examined by Ardestani et al. [11]. For triangular and quadrilateral CNT-reinforced composite plates, vibration analysis was performed by Zhang et al. [12,13] using the element-free IMLS-Ritz method.

Furthermore, nonlinear investigations on CNTR-FG plates were also reported in the literature. Considering a CNTR-FG plate in temperature field, nonlinear bending analysis has been done by Shen [14]. Based on the element-free kp-Ritz method, Lei et al. [15,16] have considered large deformation studies of CNTR-FG plates and panels. Considering CNTR-FG panels subjected to axial compressions, Liew et al. [17] have carried out a postbuckling analysis. They found that there are no apparent buckling points for CNTR-FG panels with the central deflection increases relatively quickly in the mid-stage between pre-buckling and postbuckling stages. The geometrically nonlinear large deformation behavior of triangular CNTR-FG plates under transversely distributed loads was studied by Zhang et al. [18].

In practice, transverse matrix crack is likely the first mode of damage in laminated composite structures subjected to quasi-static, fatigue and impact loads. Overall stiffness and stress distribution may be altered due to presence of matrix cracks. In addition, mechanical behaviors and thermal stability of matrix-cracked structures may be changed. Therefore, it is necessary to investigate mechanical response and properties of matrix cracked CNTR-FG structures. An approximate elasticity theory solution was given for the stress-strain relations of a cracked composite lamina [19]. The development of constitutive

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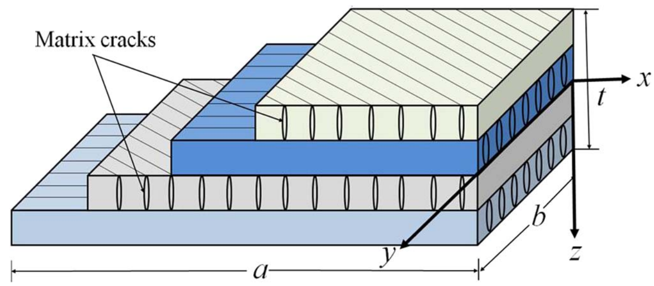

Fig. 1. Configuration of a hybrid matrix crack laminated composite plate composed of perfectly bonded CNTR-FG layers and FRC layers.

equations for fibrous composites which contain a family of longitudinal slit cracks were presented by Laws et al. [20]. For matrix cracked CNTR-FG structures, Guo et al. [21] have improved the mechanical properties of carbon nanotubes reinforced pure aluminum matrix composites by achieving non-equilibrium interface. Fan and Wang [22] have investigated the thermal postbuckling and large amplitude vibration of thermally postbuckled hybrid laminated plate resting on Pasternak elastic foundations. The effect of matrix cracks on nonlinear bending and thermal postbuckling was examined for a piezoelectric shear deformable laminated beam which contains both carbon nanotube reinforced composite layers and piezoelectric fiber reinforced composite layers [23].

Analytic solutions [24,25] to the above problems are often difficult to obtain. Therefore, development of numerical methods are unavoidable. Many numerical methods have been successfully applied for mechanical behavior analysis of engineering structures, such as DSC-Ritz method [26,27]. In this paper, we examine the influence of matrix cracks on bending and vibration behavior characteristics of hybrid laminated plates based on an element-free numerical framework. CNTR-FG layers and FRC layers are used as structural elements. A SCM model is employed for the matrix cracked hybrid laminated plates. The first-order shear deformation theory (FSDT) is adopted to incorporate the effects of rotary inertia and transverse shear deformation. The element-free kp-Ritz method is used to obtain the bending and vibration solutions. In addition, we have selected some example problems to investigate the influences of matrix crack densities, boundary conditions, material parameters and geometric parameters on their bending and vibration behavior characteristics.

2. Configuration of hybrid laminated plates

The hybrid plate having the physical dimension of length a, width b and thickness t as shown in Fig. 1. The number of layers of the hybrid plate is N. Each layer has a constant thickness h_0. The plate is considered with UD, FG-V, FG-O and FG-X types of CNT distributions for the CNTR-FG layer as shown in Fig. 2.

2.1. FRC layers

The fiber reinforcements are uniformly aligned in the matrix and their material properties are determined based on a micromechanical model [28]

$$E_{11} = V_f E_{11}^f + V_m E^m, \tag{1}$$

$$E_{22} = 1 \Bigg/ \left(\frac{V_f}{E_{22}^f} + \frac{V_m}{E^m} - V_f V_m \frac{V_f^2 E^m/E_{22}^f + V_m^2 E_{22}^f E^m/E^m}{V_f E_{22}^f + V_m E^m} \right), \tag{2}$$

$$G_{ij} = \frac{G_{ij}^f G_m}{V_f G_m + V_m G_{ij}^f} \quad (ij = 12, 13 \text{ and } 23), \tag{3}$$

$$\nu_{12} = V_f \nu^f + V_m \nu^m, \tag{4}$$

where E, G, V and ν denote the Young's modulus, shear modulus, volume fraction and Poisson's ratio, respectively. The superscript and subscript, f and m, denote the fiber and matrix, respectively. We selected 0.6 for the value of volume fraction of graphite fibers for the FRC layers. The materials properties of the FRC layers are: $E_{11}^f = 233.05$ GPa, $E_{22}^f = 23.1$ GPa, $G_{12}^f = 8.96$ GPa, $\nu^f = 0.2$, $\nu_m = 0.34$, $E^m =(3.52–0.0034T)$ GPa, and $G_{23} = 1.2G_{13}$.

2.2. CNTR-FG layers

The CNTR-FG layers are considered with four different distributions of CNTs. Their distribution functions are represented by

$$V_{CNT}(z) = V_{CNT}^* \quad \text{(UD)} \tag{5}$$

$$V_{CNT}(z) = \left(1 + \frac{2z}{h}\right) V_{CNT}^* \quad \text{(FG-V)} \tag{6}$$

$$V_{CNT}(z) = 2\left(1 - \frac{2|z|}{h_0}\right) V_{CNT}^* \quad \text{(FG-O)} \tag{7}$$

$$V_{CNT}(z) = 2\left(\frac{2|z|}{h_0}\right) V_{CNT}^* \quad \text{(FG-X)} \tag{8}$$

For CNTR-FG layers, the matrix is same as the FRC layers but the reinforcements are replaced by the armchair (10,10) CNTs with $E_{11}^{CNT} = 5.6466$ TPa, $E_{22}^{CNT} = 7.0800$ TPa, and $G_{12}^{CNT} = 1.9455$ TPa. The material properties of a CNTR-FG layer is given by [14]

$$E_{11} = \eta_1 V_{CNT} E_{11}^{CNT} + V_m E^m, \tag{9}$$

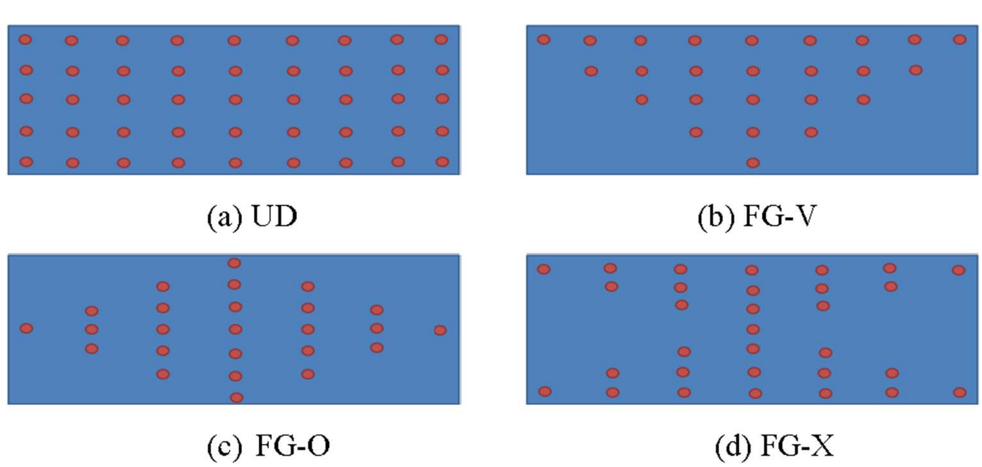

Fig. 2. CNT distributions in CNTR-FG layer.