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Review

Dynamic instability assessment of carbon nanotube/fiber/polymer multiscale composite skew plates with delamination based on HSDT

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ABSTRACT

We carried out a dynamic instability assessment of carbon nanotube reinforced composite (CNTRC) and carbon nanotubes/fiber/polymer composite (CNTFPC) skew plates with delamination based on the high-order shear deformation plate theory (HSDT). The multiscale interactions between carbon nanotube (CNT) ratios, skew angles and delamination sizes on the dynamic instability for various length-thickness ratios are studied using a two-dimensional finite element delamination model developed for this study. The results were verified by those reported in the literature for undelaminated cases show the interactions between the CNT reinforcement and delamination sizes in the skew laminate. Numerical examples show the importance of CNT reinforcement when assessing the dynamic instability of CNTRC and CNTFPC skew plates with delamination.

1. Introduction

The development of CNTs has played a significant role in the recent nanotechnology revolution, and the application of these materials has become a major trend in the field of reinforcing composites, electronic devices and more. In particular, the increased interest in new, multifunctional materials and structures is driven by need because CNT-reinforcements in polymers lead to large improvements in electrical conductivity as well as structural stiffnesses and strengths [1]. The micro-mechanical elastic and electrical characteristics of single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNT) have been studied previously by many researchers using various experimental and numerical methods [2–5].

The static and dynamic behaviors of functionally graded (FG) CNTRC structures have been studied by limited research groups using analytical and numerical approaches. Shen [6] studied the nonlinear bending characteristics of FG-CNTRC plates in thermal environments based on analytical and asymptotic solutions. Shen and Zhang [7] dealt with the thermal buckling and post-buckling behaviors of FG-CNTRC plates using the same approach. Zhu et al. [8] used the finite element method (FEM) for the static and free vibration of FG-CNTRC plates based on the first order shear deformation theory (FSDT). Sankar et al. [10] performed a dynamic instability analysis of sandwich plates with CNT reinforced face-sheets. Zarei et al. [11] studied the dynamic buckling characteristics of embedded laminated nanocomposite plates based on the sinusoidal shear deformation theory. However, all of these studies have been limited when dealing with plates with a square shape. Zhang et al. [9] extended the free vibration analysis of CNTRC rectangular plates to skew plates based on the FSDT. Skew plates are important structural components in the aircraft field.

Most of these studies are performed for two-phase CNT-reinforced polymeric composites. However, the sole reinforcing phase (two-phase CNTRC) is not practically efficient because of the high expense of CNTs [12]. Therefore, an additional reinforcing phase (three-phase CNTFPC) in conjunction with carbon or E-glass fiber in a hybrid composite is desirable from a practical point of view. A few investigators have carried out multiscale analyses of three-phase CNTFPC plates based on the FSDT. Rafiee et al. [13] examined the geometrically nonlinear free vibration of shear deformable piezoelectric nanotube/fiber/polymer multiscale laminated composite plates, and Bhardwaj et al. [14] analyzed the nonlinear flexural and dynamic responses of CNT-reinforced laminated composite plates. To perform multiscale analysis, these two studies applied a combination of the conventional Halpin-Tsai equation and the two-phase micromechanical approach. However, it has been reported that the conventional Halpin-Tsai equation for circular fibers in a square array gives reasonable results only for fiber volume fractions of up to 0.5. For a typical glass/epoxy lamina with a fiber volume fraction of 0.75, the value of in-plane shear modulus using the Halphin-Tsai equation is 30% lower than that given by elasticity solutions [15]. Because of this reason, we adopt the Hewitt and Malherbe equation modified from the Halpin-Tsai equation into the multiscale procedure. In addition, the

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existing multiscale theories for CNT reinforced composites are mostly applicable to square (rectangular) plates without delamination at the present time. In this paper, the Hewitt and Malherbe multiscale formulation is extended to study a dynamic instability of CNTFPC skew structures containing delamination.

For the CNTFPC laminates, the CNT weight ratios and skew angles could play a significant role in identifying the dynamic instability characteristics. Thus, this study is further extended to investigate the interaction between CNT weight ratios, skew angles and delamination sizes in the dynamic instability assessment of CNTFPC plates. The significance of the HSDT in analyzing laminated composite skew plates is explored in this paper.

2. Multi-scale formulation

In this study, we consider two different types of CNTRC and CNTFPC plates. For CNTRC plates, two different matrix materials are considered: Poly(m-phenylenevinylene)-co-[(2.5-dioctoxy-p-phenylene) vinylene] (referred as PmPV) and Polymethyl methacrylate (PMMA). The CNT reinforcement (referred as SWCNT-1) in the CNTRC plates was influenced by Zhang and Shen [16]. We applied the epoxy matrix to the CNTFPC plates, as well as E-glass fiber and CNT reinforcement (referred as SWCNT-2) as introduced by Han and Elliott [17].

2.1. CNTRC plates

To predict effective material properties of CNTRC plates, we consider the Mori-Tanaka scheme and the rule of mixture [18]. The material properties of CNTRC plates can be expressed as

$$E_{11}^{cnc} = \kappa_1 V_{cn1} E_{11}^{cn1} + V_{pv} E^{pv} \tag{1}$$

$$\frac{\kappa_2}{E_{22}^{cnc}} = \frac{V_{cn1}}{E_{22}^{cn1}} + \frac{V_{pv}}{E^{pv}} \tag{2}$$

$$\frac{\kappa_3}{G_{12}^{cnc}} = \frac{V_{cn1}}{G_{12}^{cn1}} + \frac{V_{pv}}{G^{pv}} \tag{3}$$

$$\nu_{12}^{cnc} = \nu^{cn1} V_{cn1} + \nu^{pv} V_{pv} \tag{4}$$

$$\rho^{cnc} = \rho^{cn1} V_{cn1} + \rho^{pv} V_{pv} \tag{5}$$

where, E_{11}^{cn1}, E_{22}^{cn1}, G_{12}^{cn1}, ν^{cn1}, and ρ^{cn1} are the Young's modulus and the shear modulus, the Possion's ratio, and the mass density of the SWCNT1, respectively. The properties, E^{pv}, G^{pv}, ρ^{pv}, ν^{pv}, and V_{pv} indicate the Young's modulus, the shear modulus, the mass density, the Possion's ratio and the volume fraction of the PmPV, respectively. In Eqs. (1)–(5), the PMMA can be alternatively selected as the matrix material instead of the PmPV. The CNT efficiency parameters κ_1, κ_2, and κ_3 are properly chosen from the molecular simulation [19]. The volume fraction V_{cn1} of SWCNT-1 can be express as

$$V_{cn1} = \frac{w^{CNT}}{w^{CNT} + (\rho^{cn1}/\rho^{pv}) - (\rho^{cn1}/\rho^{pv}) w^{CNT}} \tag{6}$$

where, w^{CNT} is the weight ratio of the SWCNT. Definitions of all symbols used in equations are described in Table 1.

2.2. CNTFPC plates

The evaluation of the elastic properties in the E-glass fiber-reinforced epoxy composites and the CNT-reinforced multiscale composites is performed using the modified Halpin-Tsai model and micromechanical approaches. Fig. 1 illustrates the concept of laminated CNTs/fiber/polymer multi-phase composites. The tensile modulus of the CNTRCs based on the Halpin-Tsai equation can be written as

Table 1
Material and geometrical properties of the materials used in this study. Where, $T = T_0 + \Delta t$ and $T = 300$ K is considered as a room temperature.

Material	Source	Symbol	Value	Definition
PmPV	[8]	E^{pv}	(3.51−0.0047T) GPa	Young's modulus of PmPV
		ρ^{pv}	1150 kg/m^3	Mass density of PmPV
		ν^{pv}	0.3	Possion's ratio of PmPV
PMMA	[30]	E^{pm}	(3.52−0.0034T) GPa	Young's modulus of PMMA
		ρ^{pm}	1150 kg/m^3	Mass density of PMMA
		ν^{pm}	0.3	Possion's ratio of PMMA
Epoxy resin	[31]	E^{ep}	2.72 GPa	Young's modulus of epoxy resin
		ρ^{pm}	1200 kg/m^3	Mass density of epoxy resin
		ν^{pm}	0.33	Possion's ratio of epoxy resin
SWCNT-1	[16]	E_{11}^{cn1}	5.6466 TPa	Young's modulus of SWCNT 1
		E_{22}^{cn1}	7.0800 TPa	Young's modulus of SWCNT 1
		G_{12}^{cn1}	1.9455 TPa	Shear modulus of SWCNT 1
		ρ^{cn1}	1350 kg/m^3	Mass density of SWCNT 1
		ν^{cn1}	0.175	Possion's ratio of SWCNT 1
		t^{cn1}	0.067 nm	Thickness of SWCNT 1
		R^{cn1}	0.68 nm	Radius of SWCNT 1
		l^{cn1}	9.26 nm	Length of SWCNT 1
SWCNT-2	[17]	E_{11}^{cn2}	640 GPa	Young's modulus of SWCNT 2
		E_{22}^{cn2}	10 GPa	Young's modulus of SWCNT 2
		G_{12}^{cn2}	17.2 GPa	Shear modulus of SWCNT 2
		ρ^{cn2}	1350 kg/m^3	Mass density of SWCNT 2
		ν^{cn2}	0.33	Possion's ratio of SWCNT 2
		t^{cn2}	0.34 nm	Thickness of SWCNT 2
		d^{cn2}	1.4 nm	Diameter of SWCNT 2
		l^{cn2}	25 µm	Length of SWCNT 2
E-Glass fiber	[31]	E^f	69 GPa	Young's modulus of E-Glass fiber
		ρ^f	1200 kg/m^3	Mass density of E-Glass fiber
		ν^f	0.2	Possion's ratio of E-Glass fiber

$$E^{cep} = \frac{E^{ep}}{8}\left[3\left(\frac{1 + 2(l^{cn2}/d^{cn2})\gamma_{dl} V_{cn2}}{1-\gamma_{dl} V_{cn2}}\right) + 5\left(\frac{1 + 2\gamma_{dd} V_{cn2}}{1-\gamma_{dd} V_{cn2}}\right)\right] \tag{7}$$

$$\gamma_{dd} = \frac{(E_{11}^{cn2}/E^{ep}) - (d^{cn2}/4t^{cn2})}{(E_{11}^{cn2}/E^{ep}) + (d^{cn2}/2t^{cn2})},\ \gamma_{dl} = \frac{(E_{11}^{cn2}/E^{ep}) - (d^{cn2}/4t^{cn2})}{(E_{11}^{cn2}/E^{ep}) + (l^{cn2}/2t^{cn2})} \tag{8}$$

where, E^{cep}, E^{ep}, and E_{11}^{cn2} are tensile modulus of SWCNT-2 reinforced composites, epoxy resin matrix, and SWCNT-2, respectively, and l^{cn2}, d^{cn2}, and t^{cn2} indicate the length, diameter, and thickness of SWCNT-2, respectively. The CNT reinforced matrix is further reinforced with E-glass fibers in CNTFPC plates. The longitudinal Young's modulus of CNTFPC plates can be determined as

$$E_{11} = E^f V^f + E^{cep}(1-V^f). \tag{9}$$

This is the rule of mixtures for the apparent Young's modulus of the composite materials in the direction of the fibers. It is known in general that the fibers do not contribute much to the transverse modulus unless the percentage of fibers is impractically high. Thus, the modulus E_{22} of