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Nonlinear Dynamic Response Analysis of Carbon Fiber Reinforced Polymer Enhanced with Carbon Nanotubes on Elastic Foundations in Thermal Environments

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ABSTRACT: In this study, nonlinear dynamic response of carbon fiber reinforced polymer composite plates enhanced with carbon nanotubes resting on elastic foundations in thermal environments using the finite element method is investigated. The effective material properties of the multiscale composite are calculated using Halpin–Tsai equations and fiber micromechanics in the hierarchy. Three types of distribution of temperature through the thickness of the plate namely, uniform, linear, and nonlinear are considered. The governing equations are derived based on Inverse Hyperbolic Shear Deformation Theory and von Kármán geometrical nonlinearity. Five types of impulsive loads namely the step, sudden, triangular, half-sine, and exponential pulses are considered. Numerical results reveal that the deflections of multi-phase composites significantly decrease with a small percentage of carbon nanotubes. Also, it is found that in thermal environment, central deflection of the plate was reduced using a maximum of 1% of the carbon nanotube in polymer composites and adding higher weight percentage showed no significant change in the peaks of central deflection.

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1- Introduction

Extraordinary properties such as high strength, high stiffness, high aspect ratio and low density of the carbon nanotubes (CNT), make it an opportunity for combining potential advantages of nanoscale reinforcement and functionality with well-accepted CFRPs to develop multiphase composites. Rafiee et al. [1] investigated nonlinear vibration of CNT multiphase laminated composites integrated with piezoelectric. Nonlinear dynamic response and flexural of polymer/CNT/fiber multiphase nanocomposite plates were analyzed by Bhardwaj et al. [2]. They used double Chebyshev polynomials to solve the problem. To the best of authors' knowledge, there is no analysis of the dynamic response of CNTs/fiber/polymer multi-phase composites in the thermal environment have been carried out till now. Therefore, in the present study, nonlinear dynamic response of polymer-CNT-fiber multiscale nanocomposite plate in thermal environments using the finite element method is performed.

2- Theoretical Formulation

The effective mechanical properties of these composites can be obtained based on a combination of Halpin-Tsai [3] and micromechanics approach scheme [4], with two steps in the hierarchy as depicted in Fig. 2. The resulting properties of the CNT reinforced multi-phase laminated composite plate are orthotropic and can be expressed as [4]:

$$E_{11} = V_F E_{11}^F + V_{MNC} E^{MNC} \tag{1}$$

$$\frac{1}{E_{22}} = \frac{1}{E_{22}^F} + \frac{V_{MNC}}{E^{MNC}} - V_F V_{MNC} - \frac{\dfrac{v_F^2 E^{MNC}}{E_{22}^F} + \dfrac{v_{MNC}^2 E_{22}^F}{E^{MNC}} - 2 v^F v^{MNC}}{V_F E_{22}^F + V_{MNC} E^{MNC}} \tag{2}$$

$$\frac{1}{G_{12}} = \frac{V_F}{G_{12}^F} + \frac{V_{MNC}}{G^{MNC}} \tag{3}$$

where E , G , ρ , V and v denote the Young's modulus, shear modulus, mass density, volume fractions and Poisson's ratio, respectively.

Based on the Halpin–Tsai model, the tensile modulus of composites may be stated as [3]:

$$E^{MNC} = \frac{E^M}{8}\left[5\left(\frac{1+2\beta_{dd} V_{CN}}{1-\beta_{dd} V_{CN}} \right) + 3\left(\frac{1+2(\ell^{CN}/d^{CN})\beta_{dl} V_{CN}}{1-\beta_{dl} V_{CN}} \right) \right] \tag{4}$$

$$\beta_{dl} = \frac{\left(E_{11}^{CN}/E^M\right) - \left(d^{CN}/4t^{CN}\right)}{\left(E_{11}^{CN}/E^M\right) + \left(\ell^{CN}/2t^{CN}\right)} \tag{5}$$

$$\beta_{dd} = \frac{\left(E_{11}^{CN}/E^M\right) - \left(d^{CN}/4t^{CN}\right)}{\left(E_{11}^{CN}/E^M\right) + \left(d^{CN}/2t^{CN}\right)} \tag{6}$$

According to the Inverse Hyperbolic Shear Deformation Theory [5], the displacement field of laminated plate theory

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can be expressed as:

$$u(x,y,z,t)=u_0(x,y,t)-z\frac{\partial w_0}{\partial x}+\Theta(z)\phi_x(x,y,t)$$
$$v(x,y,z,t)=v_0(x,y,t)-z\frac{\partial w_0}{\partial y}+\Theta(z)\phi_y(x,y,t) \quad (7)$$
$$w(x,y,z,t)=w_0(x,y,t)$$

where u_0, v_0, and w_0 denote the displacements at the mid-plane of the reference plane of the plate and ϕ_x and ϕ_y are rotations about the y and x axes, respectively. $\Theta(z)$ indicates the transverse shear function and is presented by [5]:

$$\Theta(z)=cot^{-1}\left(\frac{rh}{z}\right)-\frac{4rz}{\left[h\left(4r^2+1\right)\right]};r=0.46 \quad (8)$$

The governing equations are derived based on the principle of virtual work and solved by the finite element method with Newmark's numerical integration method. In this paper, the four-noded rectangular conforming element based on HSDT is used. The element is C[1]-continuous via 15 DOF at each node.

3- Results and discussion

To validate the results of the present work, an example previously used by Kant et al. [6] is re-solved. In Fig.1, the results of this study for the central deflection histories are compared with those presented by Knat et al. [6]. There is a good agreement between the results obtained through the proposed method and the results of those of Kant et al. Table.1 presents the effect of temperature rise and volume fraction of fibers on the maximum deflection for simply supported CNT reinforced multi-phase laminated composite plate with different SWCNTs weight percentage. As may be observed, when the plate temperature increases, the peak central deflection increases, as well. That is because increasing the plate temperature causes the structure to lose the stiffness generally. Also, as may be noted, increasing the CNTs weight percentage leads to a plate with a higher bending rigidity and subsequently, higher natural frequencies and smaller response times. Due to this reason, central deflection has decreased with the increase of the weight percentage. From Table 1, it is noticed that under thermal environment, central deflection of the plate was reduced using a maximum of 1% of the CNT in polymer composites and adding higher percentage of weight showed no significant change in the peaks of central deflection. The reason is that, the thermal expansion coefficients of nanocomposite decreases as weight percentage of carbon nanotube changes from 0 to 1% while increases when the weight of carbon nanotubes is more than 1%.

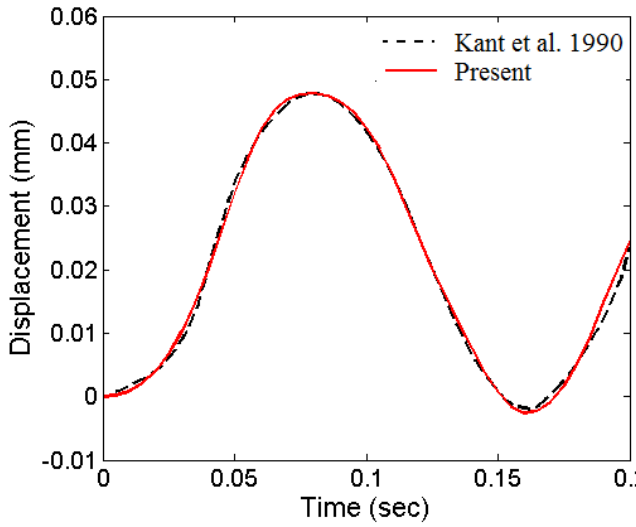

Figure 1. Comparisons of central deflection history of a CFRC composite plate subjected to an applied uniform load

4- Conclusions

The nonlinear dynamic response of polymer-CNT-fiber multiscale nanocomposite plate in thermal environments has been studied using the finite element method. Results are to

Table 1. Effect of temperature rise and volume fraction of fibers on the central deflection (10^{-5} m) for simply supported CNT reinforced multi-phase laminated composite plate with different SWCNTs weight percentages.

l^{CN}/d^{CN}	w_{cn}	ΔT=0 [K]			ΔT=100 [K]			ΔT=200 [K]		
		V_F			V_F			V_F		
		0.6	0.7	0.8	0.6	0.7	0.8	0.6	0.7	0.8
100	0	15.3957	12.9177	10.7348	17.1322	14.4282	12.0757	18.8687	15.9386	13.4166
	1	13.8950	11.7734	9.91972	15.9384	13.5083	11.4112	17.9818	15.2432	12.9141
	2	12.8871	11.0236	9.40035	15.1758	12.9420	11.0232	17.4671	14.8603	12.6460
	3	12.1691	10.4771	9.03984	14.6656	12.5405	10.7543	17.1622	14.6038	12.4687
500	0	15.3957	12.9177	10.7348	17.1322	14.4282	12.0757	18.8687	15.9386	13.4166
	1	13.1253	11.1857	9.52336	15.3646	13.0627	11.1209	17.6039	14.9397	12.7184
	2	11.9065	10.2848	8.90396	14.5008	12.4293	10.6699	17.0950	14.5738	12.4359
	3	11.1138	9.70095	8.51021	13.9972	12.0425	10.3927	16.8978	14.3890	12.2870
1000	0	15.3957	12.9177	10.7348	17.1322	14.4282	12.0757	18.8687	15.9386	13.4166
	1	12.9530	11.0698	9.43509	15.2390	12.9833	11.0553	17.525	14.8968	12.6756
	2	11.7197	10.1429	8.80562	14.3873	12.3387	10.6040	17.0549	14.5346	12.4024
	3	10.9259	9.56605	8.42291	13.9013	11.9703	10.3437	16.8767	14.3745	12.2645

explore the effects of various parameters. It is concluded that:

- A small amount of CNT (1–2 percent) can decrease the maximum central deflection of plates subjected to dynamic loads.
- Under the thermal environment, central deflection of the plate was reduced using a maximum of 1% of CNT in polymer composites and adding higher weight percentage showed no significant change in peaks of central deflection.

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