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Nonlinear analysis of functionally graded fiber reinforced composite laminated beams in hygrothermal environments, Part II: Numerical results

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ABSTRACT

In this part, the extensive parametric studies performed are reported and numerical results are presented for the nonlinear vibration, nonlinear bending and thermal postbuckling of uniformly distributed and functionally graded fiber reinforced cross-ply and angle-ply laminated beams resting on Pasternak elastic foundations under different sets of hygrothermal environmental conditions. The numerical results reveal that a functionally graded reinforcement has a significant effect on the nonlinear vibration characteristics, nonlinear bending behaviors, and thermal postbuckling behaviors of fiber reinforced composite (FRC) laminated beams. The results show that the temperature/moisture variation has a moderately effect on the natural frequencies of the FRC laminated beam, but only has a small effect on the nonlinear to linear frequency ratios of the same beam. In contrast, it has a significant effect on the nonlinear bending load–deflection curves of the FRC laminated beam. The results confirm that the thermal postbuckling equilibrium path of mid-plane unsymmetric FG-FRC laminated beams with immovable simply supported end conditions is no longer the bifurcation type.

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1. Introduction

The solution methodology is described with sufficient detail in Part I. Results are presented herein for nonlinear free vibration, nonlinear bending and thermal postbuckling of $(0/90)_{2S}$ symmetric cross-ply, $(0/90)_{4T}$ unsymmetric cross-ply, $(45/-45)_{2S}$ symmetric angle-ply and $(45/-45)_{4T}$ antisymmetric angle-ply laminated beams resting on elastic foundations in hygrothermal environments. The geometric parameters are taken to be $L/h = 10$, $b = 0.06$ m, each layer has the same thickness and the total thickness of the beam $h = 0.0508$ m. Four types of FG-FRC beams are considered. For Type V, the fiber volume fractions are assumed to have graded distribution [0.8/0.75/0.7/0.65/0.55/0.5/0.45/0.4] for eight plies, referred to as FG-V. For Type Λ, the distribution of fiber reinforcements is inversed, i.e. [0.4/0.45/0.5/0.55/0.65/0.7/0.75/0.8], referred to as FG-Λ. For Type X, a mid-plane symmetric graded distribution of fiber reinforcements is achieved, i.e. [0.8/0.7/0.5/0.4/0.4/0.5/0.7/0.8], and for type O the fiber volume fractions are assumed to have [0.4/0.5/0.7/0.8/0.8/0.7/0.5/0.4], referred to as FG-X and FG-O, respectively. A uniformly distributed (UD) FRC laminated beam with the same thickness is also considered as a comparator for which the fiber volume fraction of each ply is identical and $V_f = 0.6$. In such a way, the two cases of UD and FG-FRC laminated beams will have the same value of total fraction of fiber.

For all cases discussed below, the beam is made of FRCs with polymer matrix. Unlike in [1–16], the material properties of fibers are assumed to be anisotropic and are taken to be [17,18] $E^f_{11} = 233.05$ GPa, $E^f_{22} = 23.1$ GPa, $G^f_{12} = 8.96$ GPa, $\nu^f = 0.2$, $\alpha^f_{11} = -0.54 \times 10^{-6}/°C$, $\alpha^f_{22} = 10.08 \times 10^{-6}/°C$ and $\rho^f = 1750\ kg/m^3$. The material properties of matrix are assumed to be $c_{fm} = 0$, $\nu^m = 0.34$, $\rho^m = 1200\ kg/m^3$, $\beta^m = 2.68 \times 10^{-3}$/wt percent H_2O, $\alpha^m = 45.0 \times (1 + 0.001\,\Delta T) \times 10^{-6}/°C$ and $E^m = (3.51–0.003T–0.142C)$ GPa, in which $T = T_0 + \Delta T$ and $T_0 = 25$ °C (room temperature), and $C = C_0 + \Delta C$ and $C_0 = 0$ wt percent H_2O.

Two foundation models are considered. The stiffnesses are $(k_1, k_2) = (100, 10)$ for the Pasternak elastic foundation, $(k_1, k_2) = (100, 0)$ for the Winkler elastic foundation and $(k_1, k_2) = (0, 0)$ for the beam without any elastic foundation. As mentioned in Part I, the boundary conditions are pinned–pinned and two ends are immovable.

2. Nonlinear vibration of FRC laminated beams

Before generating extensive results, a few check cases are considered in order to test the derived solutions.

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Table 1
Comparisons of nondimensional frequencies $\bar{\omega}$ of $(45/-45)_{2T}$ antisymmetric angle-ply laminated beams.

Source	$\bar{\omega}_1$	$\bar{\omega}_2$	$\bar{\omega}_3$	$\bar{\omega}_4$
Vo & Thai [19]	0.9078	3.5255	7.5850	12.7587
Teboub & Hajela [20]	0.897	3.487	7.504	12.636
Aydogdu [22]	0.891	3.377	6.997	8.702
Chandrashekhara et al. [21]	0.8278	3.2334	7.0148	10.7449
Chen et al. [23]	0.7998	3.1638	6.9939	12.1471
Present (Model 2)	0.7960	3.1059	6.717	11.3417
Present (Model 1)	0.8996	3.4915	7.4925	12.5353

As part of the validation of the present method, the first four dimensionless natural frequencies of antisymmetric $(45/-45)_{2T}$ laminated beams are calculated in Table 1 and are compared with FEM results of Vo and Thai [19] based on a refined shear deformation theory, the theoretical solutions of Teboub and Hajela [20] and Chandrashekhara et al. [21] based on the first order shear deformation theory with the shear correction factor taken to be 5/6, the Ritz method results of Aydogdu [22] based on a parabolic higher order shear deformation theory (named as PSDPT in [22]), and the state-space-based differential quadrature method results of Chen et al. [23].

As a second example, the first four dimensionless natural frequencies of $(75/-75)_S$ and $(60/-60)_S$ symmetric laminated beams are calculated in Table 2 and are compared with a semi-analytical–numerical method results of Qu et al. [24] based on a higher order shear deformation theory (named as $\mathrm{HPT}_{[LMR]}$ in [24]), and the perturbation method results of Li and Qiao [14] based on a refined shear deformation theory. The geometric parameters and material properties adopted are: $L = 0.381$ m, $b = h = 0.0254$ m, $E_{11} = 144.8$ GPa, $E_{22} = 9.65$ GPa, $G_{12} = G_{13} = 4.14$ GPa, $G_{23} = 3.45$ GPa, $\nu_{12} = 0.3$, $\rho = 1389.23$ kg/m^3. The dimensionless frequency is defined by $\bar{\omega} = \Omega(L^2/h)\sqrt{\rho/E_{11}}$.

As a third example, the first four dimensionless natural frequencies of unsymmetric $(30/-30/30)$ laminated beams are calculated in Table 3 and are compared with FEM results of Marur and Kant [25] based on a higher order shear deformation theory proposed by Lo et al. [26]. The geometric parameters and material properties adopted are: $L = 30$ in, $b = 1$ in, $L/h = 5$, $E_{11} = 76.2 \times 10^6$ psi, $E_{22} = 3.048 \times 10^6$ psi, $G_{12} = G_{13} = G_{23} = 1.524 \times 10^6$ psi, $\nu_{12} = 0.25$, $\rho = 0.72567 \times 10^{-4}$ lb.s^2/in^4. The dimensionless frequency is defined by $\bar{\omega} = \Omega(L^2/h)\sqrt{12\rho/E_{11}}$.

As a fourth example, the linear frequencies and nonlinear to linear frequency ratios ω_{NL}/ω_L at $\overline{W}_m/h = 1.0$ for cross-ply laminated beams are calculated in Table 4 and are compared with the Ritz method results of Gunda et al. [3] based on Euler–Bernoulli beam theory, and the perturbation method results of Li and Qiao [14] based on a refined shear deformation theory. The geometric parameters and material properties adopted are: $L = 0.25$ m, $b = 0.01$ m, $h = 0.01$ m, $E_{11} = 155$ GPa, $E_{22} = 12.1$ GPa, $G_{12} = G_{13} = 4.4$ GPa, $G_{23} = 2.1$ GPa, $\nu_{12} = 0.248$, $\rho = 1570$ kg/m^3.

Table 3
Comparisons of nondimensional frequencies $\bar{\omega}$ of $(30/-30/30)_T$ angle-ply laminated beams.

Source	$\bar{\omega}_1$	$\bar{\omega}_2$	$\bar{\omega}_3$	$\bar{\omega}_4$
Marur & Kant [25]	2.6689	8.8087	16.1638	23.8443
Present (Model 2)	2.6562	8.8451	15.1823	21.8529
Present (Model 1)	4.5185	12.3397	21.0333	30.8798

Table 4
Comparisons of linear and nonlinear frequencies of cross-ply laminated beams.

Lay-up	Source	Ω (in rad/s)	ω_{NL}/ω_L ($\overline{W}_m/h = 1.0$)
$(0/90/90)_S$	Gunda et al. [3]	387.0870	1.4807
	Li & Qiao [14]	386.4859	1.4809
	Present	388.2312	1.4829
$(90/90/0)_S$	Gunda et al. [3]	152.0934	2.9525
	Li & Qiao [14]	152.2072	2.9569
	Present	153.1264	2.9509
$(90/0)_{3T}$	Gunda et al. [3]	331.4190	1.6087
	Li & Qiao [14]	322.5284	1.9176
	Present	320.4642	1.7575

As a last example, the nonlinear to linear frequency ratios ω_{NL}/ω_L for $(45/-45)_{4T}$ and $(0/90)_{2S}$ laminated beams are plotted in Fig. 1 and are compared with the perturbation method results of Li and Qiao [14]. The computing data adopted are: $E_{11} = 37.41$ GPa, $E_{22} = 13.67$ GPa, $G_{12} = 5.478$ GPa, $G_{13} = 6.03$ GPa, $G_{23} = 6.666$ GPa, $\nu_{12} = 0.3$, $\rho = 1968.9$ kg/m^3, $L/h = 10$ and $h = 0.008$ m. Note that in these five examples the material properties are assumed to be independent of temperature and moisture. PSDPT and $\mathrm{HPT}_{[LMR]}$ are the same as Reddy's higher order shear deformation theory due to the same displacement field. These comparison studies confirm that there are unresolved discrepancies between the results obtained by different authors for angle-ply laminated beams by using different methods based on the different theories. Usually, the state-space method is more accurate than others. It can be found that, for the cases of cross-ply laminated beams, the present results of model 1 and model 2 are identical, whereas in most cases of angle-ply laminated beams, the present results of the model 2 are compared well with the existing results than the model 1 does. Hence, in the following examples in this section only model 2 is adopted.

Table 5 presents the first four dimensionless natural frequencies of $(0/90)_{2S}$ laminated beams with four types of FG distribution of fiber reinforcements. The results for the same beam with UD distribution of fiber reinforcements are also listed for direct comparison. Three sets of hygrothermal environmental conditions, i.e. $(\Delta T(°C), \Delta C(\%)) = (0,0)$, $(50,1)$ and $(100,2)$, are considered. The dimensionless natural frequency is defined by $\widetilde{\Omega} = \Omega(L^2/h)\sqrt{\rho_0/E_0}$, where ρ_0 and E_0 are the reference values of ρ^m and E^m at $\Delta T = \Delta C = 0$. It is seen that the natural frequencies are reduced with increase in temperature and moisture.

Table 2
Comparisons of nondimensional frequencies $\bar{\omega}$ of symmetric angle-ply laminated beams.

Lay-up	Source	$\bar{\omega}_1$	$\bar{\omega}_2$	$\bar{\omega}_3$	$\bar{\omega}_4$
$(75/-75)_S$	Qu et al. [24]	0.7325	2.8675	6.2400	10.6340
	Li & Qiao [14]	0.7404	2.8923	6.3257	10.8469
	Present (Model 2)	0.7248	2.8336	6.1471	10.4161
	Present (Model 1)	0.7220	2.8232	6.1255	10.3815
$(60/-60)_S$	Qu et al. [24]	0.7583	2.9650	6.4408	10.9539
	Li & Qiao [14]	0.7660	2.9900	6.5277	11.1679
	Present (Model 2)	0.7313	2.8597	6.2058	10.5198
	Present (Model 1)	0.7999	3.1189	6.7389	11.3644

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