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Research Article

Dynamic Resonance of Curved Panels in Adverse Hygrothermal Environment

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The present paper deals with the dynamic resonance of composite curved panels subjected to periodic dynamic loadings. The effects of various parameters of four-sided clamped composite curved panels at elevated temperatures and moisture concentrations on the principal instability regions are investigated by finite element method which is used to study the antisymmetric angle-ply square plates. The results show that instability of composite plates occurs for different parameters in adverse hygrothermal environment. The experimental and numerical investigation is also carried out for four-sided clamped boundary condition for vibration and buckling of curved panels in hygrothermal environment.

1. Introduction

Structural elements under in-plane periodic forces may undergo unstable transverse vibrations, leading to parametric resonance, due to certain combination of the values of in-plane load parameters and natural frequency of transverse vibration. This instability may occur below the critical load of the structure under compressive loads over a range or ranges of excitation frequencies. Several means of combating parametric resonance such as damping and vibration isolation may be inadequate and sometimes dangerous with reverse results. A number of catastrophic incidents can be traced to parametric resonance. In contrast with the principal resonance, the parametric instability may arise not merely at a single excitation frequency but even for small excitation amplitudes and combination of frequencies. Thus, the parametric instability characteristics are of great technical importance for understanding the dynamic system under periodic loadings. The distinction between good and bad vibration regimes of a structure, subjected to in-plane periodic loading, can be made through an analysis of dynamic instability region (DIR) spectra. The calculation of these spectra is often provided in terms of natural frequencies and the static buckling loads. So, the calculation of these parameters with high precision is an integral part of dynamic instability analysis of composite plates and shells in adverse hygrothermal environment.

A review of earlier works on vibration and stability of plates subjected to thermal loadings is given by Tauchert [1]. A recent review of parametric instability studies is carried out by Sahu and Datta [2] who studied the dynamic stability of laminated composite curved panels with cutouts subjected to in-plane static and periodic compressive loads. L.-W. Chen and Y. M. Chen [3] studied the free vibration of the laminated rectangular composite plate exposed to steady-state hygrothermal environment. Ram and Sinha [4] investigated the effects of moisture and temperature on the free vibration of laminated composite plates using finite element method. Liu and Huang [5] examined the free vibration analysis of laminated composite plates subjected to temperature changes using finite element method to calculate the frequencies of vibration of symmetric cross-ply plates.

Studies involving behavior of composite plates subjected to in-plane loading with hygrothermal condition are in scanty literature. Noor and Burton [6] the analytically presented the three-dimensional solutions for the free vibrations and buckling of thermally stressed multilayered angle-ply composite plates. Shen [7] examined the influence of hygrothermal effects on the postbuckling of shear deformable laminated plates subjected to uniaxial compression using analytical model of a laminate. Jones [8] studied the thermal buckling of simply supported symmetric cross-ply laminated fiber-reinforced composite simply supported rectangular plates.

Some studies dealing with composite plates subjected to in-plane periodic loads under ambient temperature and moisture are also reported. Bert and Birman [9] examined the dynamic instability of shear deformable antisymmetric angle-ply plates by using finite element method. Chen and Yang [10] investigated the dynamic stability of laminated composite plates by Galerkin finite element method. Mond and Cederbaum [11] presented the dynamic stability of antisymmetric laminated plates by using the method of multiple scales. Wang and Dawe [12] studied the dynamic instability of composite laminated rectangular plates by using Lagrange's formulation. Fazilati and Ovesy [13] presented the dynamic instability analysis of composite laminated thin-walled structures using finite strip method. However, the behavior of composite curved panels under hygrothermal condition subjected to in-plane periodic loads is not reported in the literature.

The present work is based on experimental work on free vibration, buckling of curved panels in hygrothermal environment, and resonance characteristics of curved panels in advese hygrothermal environment to fill in the lacunae in the literature.

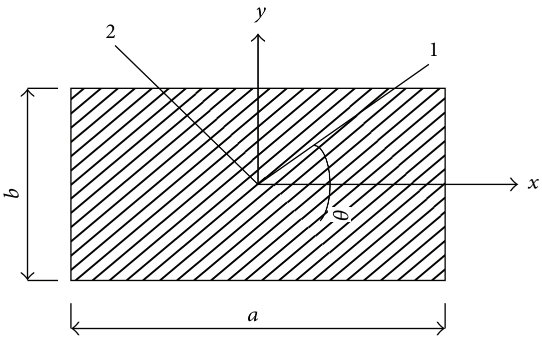

Figure 1: Arbitrarily oriented laminated plate.

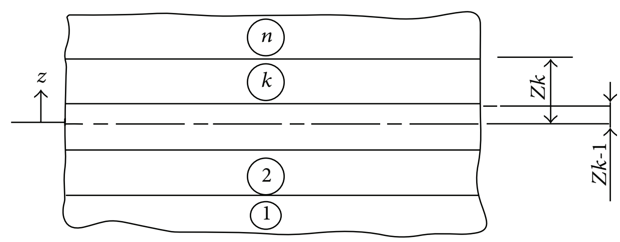

Figure 2: Geometry of an n-layered laminate.

2. Mathematical Formulation

The experimental and numerical models are given in Figures 1 and 2.

The governing equation of dynamic stability of laminated composite panel considering hygrothermal conditions and under in-plane periodic loads in matrix form is the following:

$$\left[[K]+\left[K_g^r\right]-\alpha P_{\mathrm{cr}}\left[K_g\right]\pm\frac{1}{2}\beta P_{\mathrm{cr}}\left[K_g\right]-\frac{\Omega^2}{4}[M]\right]\{q\}=0, \tag{1}$$

where $[K]$, $[K_g^r]$, $[K_g]$, and $[M]$ are global elastic stiffness, geometric stiffness matrix due to hygrothermal condition, geometric stiffness matrix due to in-plane axial load, and mass matrix, respectively. The equation represents an eigenvalue problem for known values of α, β and P_{cr}, where α, β, and P_{cr} are static load factor dynamic load factor, and critical load, respectively. The two conditions under the plus and minus signs correspond to two boundaries (upper and lower) of the dynamic instability region. The above eigenvalue solution gives Ω, the boundary frequencies of the instability regions for the given values of α and β. Vibration and buckling equations are derived using specific values of α and β.

Free vibration is given by

$$\left[[K]+\left[K_g^r\right]\right]-\omega_n^2[M]\{q\}=0 \tag{2}$$

and the buckling load is given by

$$\left[[K]+\left[K_g^r\right]\right]-\lambda\left[K_g\right]\{q\}=0, \tag{3}$$

where ω_n is the natural frequency and λ is the critical load of the composite plate considering hygrothermal conditions along with in-plane axial loads.

2.1. Finite Element Formulation. An eight-node isoparametric element is used for dynamic stability analysis of woven fiber composite plates subjected to hygrothermal environment. Five degrees of freedom u, v, w, θ_x, and θ_y are considered at each node. The element is modified to accommodate laminated materials and hygrothermal conditions of the panel, based on first-order shear deformation theory where u,v, and w are the displacement components in the x, y, and z directions and θ_x and θ_y are the rotations.

The element elastic bending stiffness matrix is given by

$$\left[K_e\right]=\iint_{-1}^{+1}[B]^T[D][B]|J|\,d\xi\,d\eta, \tag{4}$$

where $[B]$ and $[D]$ are strain displacement relation and elasticity matrix.

The element geometric stiffness matrix due to residual stresses is given by

$$\left[K_{ge}^r\right]=\iint_{-1}^{+1}[G]^T[S][G]|J|\,d\xi\,d\eta. \tag{5}$$

The element geometric stiffness matrix due to applied in-plane loads is given by

$$\left[K_{ge}\right]=\iint_{-1}^{+1}[H]^T[P][H]|J|\,d\xi\,d\eta. \tag{6}$$

The element mass matrix is given by

$$[M_e] = \iint_{-1}^{+1} [N]^T [P] [N] |J| \, d\xi \, d\eta. \quad (7)$$

2.2. Experimental Program for Fabrication. Composite plates are fabricated using hand-layup technique. In the present study, woven glass fiber and epoxy specimens were fabricated. However, to study the variation of ILSS, the polyester matrix is also tried along with three different fibers: matrix proportions. Woven roving E-Glass fibers (FGP, RP-10) were cut into required shapes and sizes. For preparation of epoxy resin matrix, hardener 8% (Ciba-Geigy, araldite LY556, and Hardener HY951) of the weight of epoxy was used, and for polyester matrix, 1% accelerator (cobalt octane 2%) was added first to the polyester resin;, then, 1.5% of catalyst (MEKP methyl ethyl ketone peroxide) was added to mixture and stirred thoroughly to get polyester matrix using woven roving glass fibers and epoxy/polyster matrix. Subsequent plies were placed one upon another with matrix in each layer to obtain required stacking plies. A hand roller was used to distribute resin uniformly, compact plies, and to remove entrapped air to minimize void contents in the samples. The mould and layup were covered with a release film to prevent the layup from bonding to the mould surface. The laminates were cured at normal temperature (25°C and 55% relative humidity) under a pressure of 0.2 mpa for 3 days. The specimens were cut for vibration and buckling testing by brick cutting machine into plate of size 235 mm × 235 mm, for-three point bend test into 45 mm × 6 mm size, and for tensile test into 200 mm × 25 mm as per specification.

2.3. Hygrothermal Treatment. The specimens were hygrothermally conditioned in a humidity cabinet where the conditions were maintained at a temperature of 323°K and relative humidity (RH) ranging 0%-1% for moisture concentration. The humidity cabinet had an inbuilt thermometer for temperature and hygrometer for relative humidity measurements. The temperature variation was maintained between 300°K and 425°K, whereas the RH was 0 in temperature bath. The hygrothermal conditioning was carried out for every six hours in a total period of thirty-six hours.

3. Results and Discussion

The present study deals with the vibration, buckling, and parametric resonance characteristics of woven fiber laminated composite panels. The results are presented as follows:

(i) Convergence Study,

(ii) New results.

The convergence study is done for free vibration of 4-layered symmetric cross-ply laminated composite flat panels at a temperature of 325°K as shown in Table 1. As observed, a mess of 10 × 10 shows good convergence of the numerical solution, and this mess is employed throughout for parametric resonance of curved panels in hygrothermal environment.

Table 1: Convergence study of free vibration for c-c-c-c four-layered laminated composite plates for two different lamination sequences at 325°K temperatures.

Mess division	Nondimensional frequencies at 325°K temperature	
	0/90/90/0	45/−45/−45/45
4 × 4	8.079	11.380
6 × 6	8.039	10.785
8 × 8	8.036	10.680
10 × 10	8.036	10.680

$a/b = 1$; and $a/t = 100$ at $T = 300$°K; $E_1 = 130$ Gpa; $E_2 = 9.5$ Gpa; $G_{12} = 6$ Gpa; $G_{13} = G_{12}$; $G_{23} = 0.5\,G_{12}$; $\nu_{12} = 0.3$; $\alpha_1 = -0.3 \times 10^{-6}$/°K; $\alpha_2 = 28.1 \times 10^{-6}$/°K.
Nondimensional frequency: $\lambda = \omega_n a^2 \sqrt{\rho/E_2 t^2}$.

Table 2: Convergence of nondimensional critical load for s-s-s-s four-layered laminated composite plates for two different lamination sequences at 0.1% moisture concentration.

Mess division	Nondimensional critical load at 0.1% moisture concentration	
	0/90/90/0	45/−45/−45/45
4 × 4	0.6095	0.7255
6 × 6	0.6079	0.7041
8 × 8	0.6078	0.7003
10 × 10	0.6078	0.7003

$a/b = 1$; and $a/t = 100$ at $T = 300$°K; $E_1 = 130$ Gpa; $E_2 = 9.5$ Gpa; $G_{12} = 6$ Gpa; $G_{13} = G_{12}$; $G_{23} = 0.5\,G_{12}$; $\nu_{12} = 0.3$; $\beta_1 = 0$; $\beta_2 = 0.44$.
Critical load: $\lambda = N_{\text{xcr}}/(N_{\text{xcr}})_{C=0\%}$ or $T = 300$°K.

The geometrical and material properties of the laminated composite plates are $a = b = 0.235$ m and $h = 0.006$ m (unless otherwise stated). The material properties obtained from tensile testing of glass/epoxy composite plates at different temperature and moisture are as shown in Tables 3 and 4 which are used in numerical analysis.

The present formulation is then validated for buckling analysis of composite plates as shown in Table 2. The square plate has four layers of graphite/epoxy composite. The nondimensional critical load due to hygrothermal loadings obtained by the present finite element is compared with analytical solution published by Ram and Sinha [4] and Patel et al. [14].

Numerical results are presented to study the effects of different parameters for vibration, buckling, and dynamic instability behavior of woven fiber composite curved panels in adverse hygrothermal environment. The geometrical and material properties of the composite plates are $a = b = 0.235$ m and $h = 0.006$ m, and the material properties are used for different temperature and moisture concentration, respectively.

Table 3: Elastic moduli of glass fiber/epoxy lamina at different temperatures.

Elastic moduli	Temperature in (°K)					
	300 K	325	350	375	400	425
E_1	7.9	7.6	7.1	6.7	6.5	6.3
E_2	7.4	6.8	6.4	6.2	5.9	5.7
G_{12}	2.9	2.6	2.3	2.1	1.8	1.6
ν_{12}	0.4	0.43	0.41	0.35	0.36	0.35

$\alpha_1 = -0.3 \times 10^{-6}/°\text{K}$; $\alpha_2 = 28.1 \times 10^{-6}/°\text{K}$; $\beta_1 = 0$; $\beta_2 = 0.44$.

Table 4: Elastic moduli of glass fiber/epoxy lamina at different moisture concentrations.

Elastic moduli	Moisture concentration in %				
	0.0	0.25	0.5	0.75	1.0
E_1	7.9	7.6	7.5	7.3	7.2
E_2	7.4	7.4	7.3	7.1	7.0
G_{12}	2.9	2.9	2.8	2.7	2.6
ν_{12}	0.4	0.4	0.4	0.39	0.39

$\alpha_1 = -0.3 \times 10^{-6}/°\text{K}$; $\alpha_2 = 28.1 \times 10^{-6}/°\text{K}$; $\beta_1 = 0$; $\beta_2 = 0.44$.

3.1. Vibration. The frequencies of vibration of woven fiber composite plates subjected to hygrothermal environment are obtained by using the experimental setup and numerically using the finite element method. The variation of frequencies of vibration in Hz of laminated plates (both experimental and numerical) for the lowest four modes subjected to temperature is shown in Figure 3. The frequencies of vibration of composite plates decrease with increase of temperature due to reduction of stiffness. The variation of frequencies in Hz of woven fiber laminated plates, for the lowest four modes subjected to moisture concentration, is shown in Figure 4. The frequencies of vibration decrease with increase of percentage of moisture. The frequencies of vibration of composite flat panels reduce significantly by 67.6%, 62.68%, 51.40%, and 47.43%, respectively, for the first four lowest modes with increase of temperature from 300°K to 400°K due to reduction of stiffness.

However, with increase of moisture concentration from 0.25% to 1%, the frequencies of vibration of laminated composite plates reduce by 25.76%, 52.72%, 44.94%, and 36.63%, respectively, due to reduction of stiffness for the first four lowest modes. As shown in Figures 3 and 4, there is a significant decrease of the frequencies of vibration of higher modes of vibration than fundamental frequency.

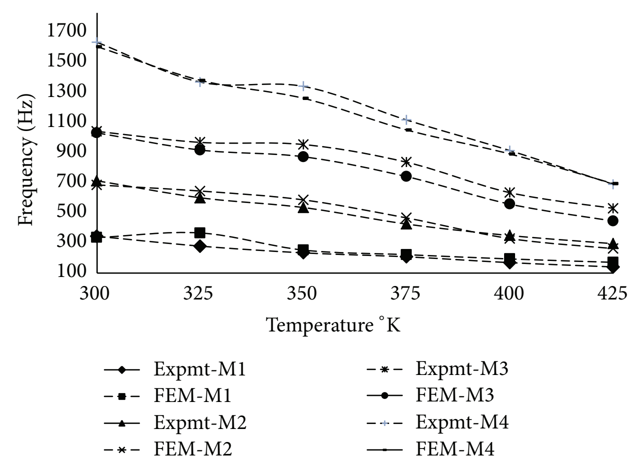

Figure 3: Variation of frequency in Hz with temperature for clamped supported (c-c-c-c) in the lowest four modes of 16-layer $[0/0]_{4S}$ woven fiber composite plates.

3.2. Buckling Analysis. The results for buckling loads in KN of both the numerical analysis and experimental values with increase in temperature from 300°K to 425°K in every 25°K rise in temperature and from 0% to 1% in every 0.25% rise in moisture concentration of sixteen-layered woven roving glass fiber/epoxy composite plates are presented for four sided clamped (c-c-c-c) boundary condition. The variation of critical buckling loads with increase in temperature and moisture concentration of the curved panels is shown in Figures 5 and 6. This shows that there is good agreement between experimental and numerical results. It is observed that the increase in temperature and moisture concentration there is decreased in critical buckling loads by approximately 27% when the plate is subjected to 1% moisture concentration and temperature increase to 400°K due to reduction of stiffness. The effect of temperature generally causes a softening of the fibers, and the effect of moisture causes plasticization due to absorbed moisture.

The variation of excitation frequency with dynamic load factor of composite laminated simply supported symmetric cross-ply square shells subjected to temperature from 300°K to 325°K is shown in Figure 7. It is observed that the onset of instability occurs earlier with wider DIR for laminated

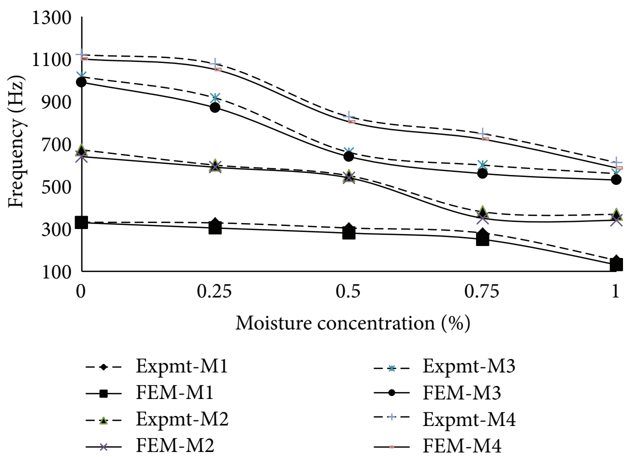

Figure 4: Variation of frequency in Hz with moisture concentration for clamped supported (c-c-c-c) in the lowest four modes of 16-layer $[0/0]_{4S}$ woven fiber composite plates.

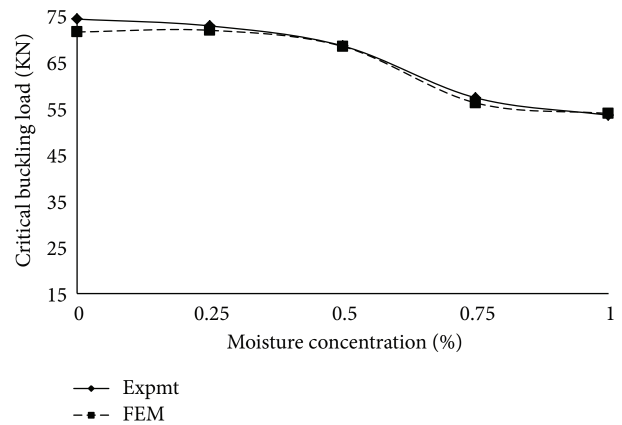

Figure 6: Variation of critical buckling load in KN with moisture concentration of 16-layer $[0/90]_{4S}$ woven fiber laminated composite plates (c-c-c-c).

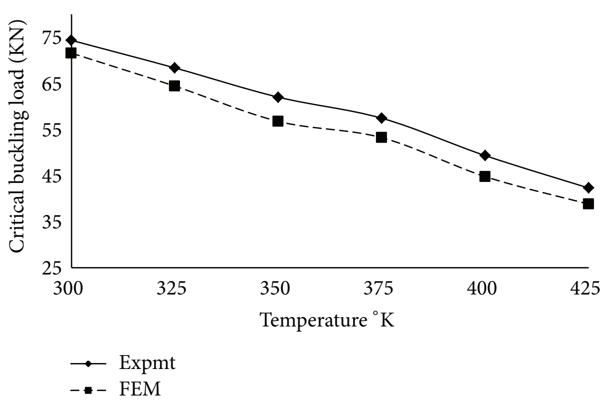

Figure 5: Variation of critical buckling load in KN with temperature of 16-layer $[0/90]_{4S}$ woven fiber laminated composite plates (c-c-c-c).

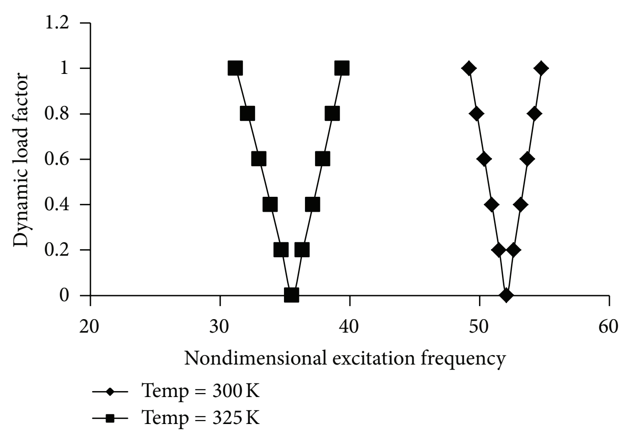

Figure 7: Variations of instability region with temperature of composite laminated symmetric cross-ply (0/90/90/0) curved panel ($a/b = 1$; $b/t = 100$; $Ry/b = 5$).

composite panels subjected to elevated temperature compared to composite panels with normal temperature. With increase in temperature from 300°K to 325°K, the excitation frequency is reduced by 31.6%. The width of instability region for laminated panel with elevated temperature is increased by 46.67% from the plate with normal temperature for a dynamic load factor of 0.6. The variation of excitation frequency with dynamic load factor of composite laminated simply supported curved panel subjected to uniform distribution of moisture concentration from 0% to 0.1% is shown in Figure 8. It is revealed that the onset of instability occurs earlier with wider DIR for symmetric cross-ply laminated composite shells subjected to elevated moisture condition compared to ambient conditions. When moisture concentration is increased from 0% to 0.1%, then excitation frequency reduces by about 21%. The width of instability region for laminated shell with elevated temperature is increased by 46.67% from the shell with normal temperature for a dynamic load factor of 0.6.

4. Conclusion

The results of the dynamic resonance studies of the composite curved panels in adverse hygrothermal environment can be summarized as follows.

(i) There is a good agreement between the numerical and experimental results on vibration and buckling of composite panels under hygrothermal environment.

(ii) The natural frequencies of vibration and buckling loads of fiber composite panels decrease with increase of temperature and moisture concentration due to reduction of stiffness for all laminates.

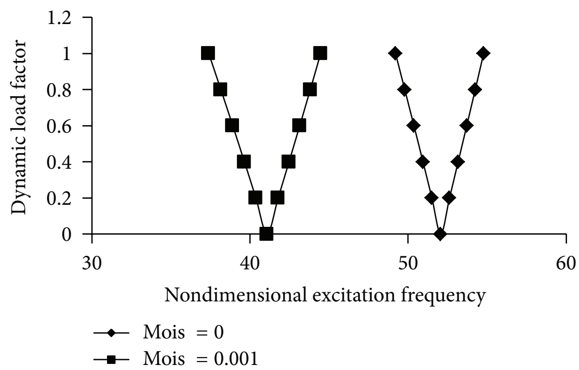

Figure 8: Variations of instability region with moisture of composite laminated symmetric cross-ply (0/90/90/0) shell ($Ry/b = 5$; $a/b = 1$; $b/t = 100$).

(iii) The onset of instability occurs later with increasing number of layers of the laminated composite panels with hygrothermal loads.

(iv) The excitation frequencies of laminated composite curved panels decrease with increase of temperature and moisture concentration due to reduction of stiffness for all laminates.

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