Thin-Walled Structures 78 (2014) 79–86

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Effects of moisture on the frequencies of vibration of woven fibre composite doubly curved panels with strip delaminations

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ARTICLE INFO

Article history:
Received 28 June 2013
Accepted 15 January 2014
Available online 5 February 2014

Keywords:
Moisture effects
Free vibration
Woven fibre
Strip delamination
Doubly curved panels

ABSTRACT

The present study deals with the effects of moist environment on the natural frequencies of vibration of Glass/Epoxy woven fibre composite doubly curved panels with strip delamination using the finite element method (FEM). For modelling the delamination, multipoint constraint algorithm is incorporated in the analysis. The effects of boundary condition, delamination size and shape of panels on natural frequencies of vibration are investigated in the moisture content range. The frequencies of vibration reduce with increase of moisture in delaminated curved panels. The reductions of frequencies are more prominent for higher degree of moisture concentrations and significantly affected by boundary conditions.

1. Introduction

Laminated composites, because of their high specific strength and stiffness, are being increasingly used in the fields of aerospace, marine, civil, mechanical and other branches of engineering. These are susceptible to delamination damage, which can be induced by low velocity impact, by structure's free edge effect, by fabrication defect or by reversal of stresses during operation. Also, the effect of the moist environment poses a challenge to the designer due to loss of stiffness in the dynamic analysis and design of composite structures. A combination of these two is critical in case of ship structures, submarines and turbine blades because of the degraded properties of composites and the residual stresses due to moisture, which finally affects the vibration characteristics significantly.

Studies of vibration of laminated composite curved panels of various geometry, boundary conditions having different models were reviewed by Liew et al. [1] through 1992 and Qatu et al. [2] through 2009. Vibrations of thin laminated composite shallow shells with two adjacent edges clamped and remaining free were analysed by Qatu [3] by Ritz technique. Sahu and Datta [4] studied parametric resonance characteristics of laminated composite doubly curved panels by FEM. Using a layerwise B-spline finite strip method, Zhang et al. [5] presented the frequencies of vibration of rectangular composite laminates. Viola et al. [6] determined frequencies of free vibration of completely doubly curved laminated shells using general higher order shear deformation theory. Kumar et al. [7] used FEM with higher order shear deformation theory (HSDT) to calculate the fundamental frequencies of vibration of laminated composite skew hypar shells. Fazzolari and Carrera [8] investigated the free vibration response of doubly curved anisotropic laminated composite shallow and deep shells by advanced Ritz technique. Applying Sanders' theory, Strozzi and Pellicano [9] examined the nonlinear natural frequencies of vibrations of functionally graded cylindrical shells.

Acharyya et al. [10] calculated the natural frequencies of delaminated composite shallow cylindrical shells based on FEM. Dey and Karmakar [11] used FEM for computation of natural frequencies of vibration of multiple delaminated angle ply composite conical shells. Nanda and Sahu [12] determined the natural frequencies of delaminated composite shells in finite element environment using different shell theories. The free vibration studies considering the delamination of composite panels are much less in literature. Karmakar et al. [13] presented a numerical approach for determination of natural frequencies of composite pre-twisted shallow shells with delaminations. Jansen [14] studied the vibration behaviour of anisotropic cylindrical shells with geometric imperfections. Using FEM, Lee and Chung [15] determined the natural frequencies of composite spherical shell panels with delaminations around central cutouts. The above studies were on the vibration of delaminated composite shells under ambient moisture conditions.

Very few researchers have shown interest in the field of dynamic behaviour of composite panels in hygrothermal environments without considering the effects of delaminations. Chatterjee and Kulkarni [16] studied the flutter type instability of laminated fibre composite panels based on piston theory aerodynamics and shear deformable laminated plate theory taking into account the environmental factors

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http://dx.doi.org/10.1016/j.tws.2014.01.010

like temperature and moisture contents. Rao and Sinha [17] examined the effects of temperature and moisture on free vibration and transient response of multidirectional composites by finite element analysis. Shen et al. [18] investigated the hygrothermal effects on the dynamic response of shear deformable simply supported laminated plates resting on elastic foundations based on higher order shear deformation theory. Using FEM, Naidu and Sinha [19] presented the nonlinear free vibration frequencies of laminated composite doubly curved shells in hygrothermal environment. Under hygrothermal conditions, nonlinear static and dynamic behaviour of laminated composite shell panels were studied by Kundu and Han [20] using geometrically nonlinear finite element method.

Researches on the dynamic response of delaminated composite panels in hygrothermal environment are scanty in literature. Parhi et al. [21] determined frequencies of vibration of only simply supported delaminated composite shells of mid plane square area delamination in hygrothermal environment. Nanda et al. [22] studied the effects of delaminations on the nonlinear transient behaviour of composite shells in hygrothermal environment. Nanda and Pradyumna [23] presented the results of free vibration frequencies of laminated shells with geometric imperfections in hygrothermal environments. All these researchers studied the response of delaminations on dynamic characteristics of composite panels having unidirectional fibres only.

However, studies related to the dynamic behaviour of industry driven woven fibre composite shells with strip delaminations in moist environment are not available in literature. In the present study, the authors utilise for the first time, the woven fibre Glass/Epoxy composite doubly curved panels with mid plane strip delamination to study the free vibration behaviour in moist environment having variety of boundary conditions.

2. Theory and formulation

A delaminated doubly curved composite panel of length '*a*', width '*b*' and uniform thickness '*h*' consisting of '*n*' arbitrary number of thin laminae, each of which may be oriented at an angle θ with respect to the *x*-axis of the co-ordinate system is considered as shown in Fig. 1. The layer details of the delaminated composite panels are shown in Fig. 2. For computing the frequencies of vibration, single mid plane strip delamination of four different sizes like 12.5% (d_1), 25% (d_1+d_2), 37.5% ($d_1+d_2+d_3$) and 50% ($d_1+d_2+d_3+d_4$) of the total shell area are considered for composite panels, as shown in Fig. 3.

2.1. Governing equations

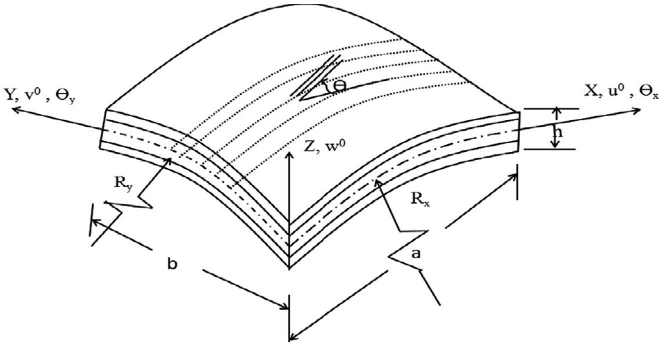

Fig. 1. Doubly curved composite shell configuration with strip delamination.

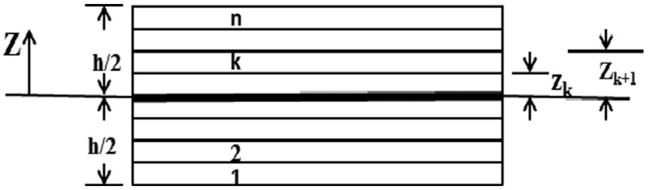

Fig. 2. Laminate configuration.

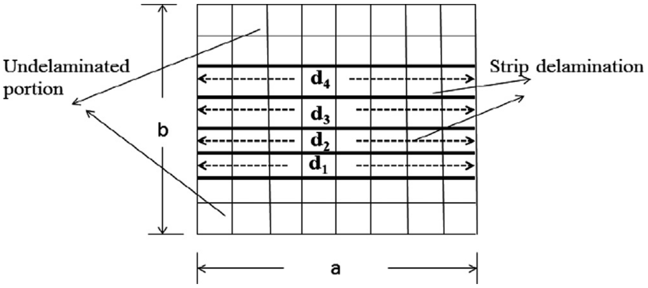

Fig. 3. Planform showing strip delaminations at mid plane.

The governing differential equations for vibration of shear deformable delaminated composite doubly curved shell panels in moist environment are [24]

$$\begin{aligned}
&\frac{\partial N_x}{\partial x}+\frac{\partial N_{xy}}{\partial y}+\frac{Q_x}{R_x}+\frac{Q_y}{R_{xy}}=P_1\frac{\partial^2 u}{\partial t^2}+P_2\frac{\partial^2 \theta_x}{\partial t^2}\\
&\frac{\partial N_{xy}}{\partial x}+\frac{\partial N_y}{\partial y}+\frac{Q_y}{R_y}+\frac{Q_x}{R_{xy}}=P_1\frac{\partial^2 v}{\partial t^2}+P_2\frac{\partial^2 \theta_y}{\partial t^2}\\
&\frac{\partial Q_x}{\partial x}+\frac{\partial Q_y}{\partial y}-\frac{N_x}{R_x}-\frac{N_y}{R_y}-2\frac{N_{xy}}{R_{xy}}+N_x^N\frac{\partial^2 w}{\partial x^2}+N_y^N\frac{\partial^2 w}{\partial y^2}+N_{xy}^N\frac{\partial^2 w}{\partial x\partial y}=P_1\frac{\partial^2 w}{\partial t^2}\\
&\frac{\partial M_x}{\partial x}+\frac{\partial M_{xy}}{\partial y}-Q_x=P_3\frac{\partial^2 \theta_x}{\partial t^2}+P_2\frac{\partial^2 u}{\partial t^2}\\
&\frac{\partial M_{xy}}{\partial x}+\frac{\partial M_y}{\partial y}-Q_y=P_3\frac{\partial^2 \theta_y}{\partial t^2}+P_2\frac{\partial^2 v}{\partial t^2}
\end{aligned} \tag{1}$$

where $(P_1,P_2,P_3)=\sum_{k=1}^{n}\int_{z_{k-1}}^{z_k}(\rho)_k(1,z,z^2)dz$ and N_x, N_y, N_{xy} are in-plane stress resultants per unit length, M_x, M_y, M_{xy} are moment resultants per unit length, Q_x, Q_y are transverse shear stress resultants and R_x, R_y are the radii of curvature in the x, y directions and R_{xy} is the radius of twist. The terms with superscript $(^N)$ represents the corresponding non-mechanical in-plane stress and moment resultants due to moisture. $(\rho)_k$ is the mass density of kth layer and z_k is the distance of kth layer from the mid plane.

2.2. Moist analysis

The stress strain relations in the presence of moisture are represented as

$$\begin{Bmatrix}\sigma_{xx}\\ \sigma_{yy}\\ \tau_{xy}\end{Bmatrix}=\begin{bmatrix}\overline{Q_{11}} & \overline{Q_{12}} & \overline{Q_{16}}\\ \overline{Q_{12}} & \overline{Q_{22}} & \overline{Q_{26}}\\ \overline{Q_{16}} & \overline{Q_{26}} & \overline{Q_{66}}\end{bmatrix}\begin{Bmatrix}\varepsilon_{xx}-e_{xx}\\ \varepsilon_{yy}-e_{yy}\\ \gamma_{xy}-e_{xy}\end{Bmatrix} \tag{2}$$

and

$$\begin{Bmatrix}r_{xz}\\ r_{yz}\end{Bmatrix}-\begin{bmatrix}\overline{Q_{44}} & \overline{Q_{45}}\\ \overline{Q_{45}} & \overline{Q_{55}}\end{bmatrix}\begin{Bmatrix}\gamma_{xz}\\ \gamma_{yz}\end{Bmatrix} \tag{3}$$

where σ_{xx}, σ_{yy}, τ_{xy}, τ_{xz}, τ_{yz} are normal and shear stresses; ε_{xx}, ε_{yy}, γ_{xy}, γ_{xz}, γ_{yz} are normal and shear strains. The e_{xx}, e_{yy} and e_{xy} are the strain components due to moisture in the x–y reference axes, which are derived from the corresponding values in the fibre axes after applying the transformations as given below

$$\{e\}=\begin{Bmatrix}e_{xx}\\ e_{yy}\\ e_{xy}\end{Bmatrix}=\begin{bmatrix}m^2 & n^2\\ n^2 & m^2\\ -2mn & 2mn\end{bmatrix}\begin{Bmatrix}\beta_1\\ \beta_2\end{Bmatrix}(C-C_0) \tag{4}$$

where β_1, β_2 are the moisture coefficients of lamina in longitudinal and lateral directions. C_0 is the reference moisture content in % and its value considered here is 0. C is exposed moisture content in %.