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An Experimental Approach to Free Vibration Response of Woven Fiber Composite Plates under Free-Free Boundary Condition

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Abstract **-** The present study involves extensive experimental works to investigate the free vibration of woven fiber Glass/Epoxy composite plates in free-free boundary conditions. The specimens of woven glass fiber and epoxy matrix composite plates are manufactured by the hand-layup technique. Elastic parameters of the plate are also determined experimentally by tensile testing of specimens using Instron 1195. An experimental investigation is carried out using modal analysis technique with Fast Fourier Transform Analyzer, PULSE lab shop, impact hammer and contact accelerometer to obtain the Frequency Response Functions. Also, this experiment is used to validate the results obtained from the FEM numerical analysis based on a first order shear deformation theory. The effects of different geometrical parameters including number of layers, aspect ratio, and fiber orientation of woven fiber composite plates are studied in free-free boundary conditions in details. This study may provide valuable information for researchers and engineers in design applications.

Key words *- Woven composite, Frequency Response function, Modal Analysis, Finite element Method.*

I. INTRODUCTION

Woven fabrics as an attractive reinforcement provide excellent integrity and conformability for advanced structural composite applications. The reinforcement of composites with industry driven woven fiber materials lead to improved properties of composite structures in terms of acoustical, elastical and thermal properties. Glass fibers are the most commonly used ones in low to medium performance composites because of their high tensile strength and low cost. In woven fiber composites, fibers are woven in both principal directions at right angles to each other (warp and fill directions). To better understand any structural vibration problem, the resonant frequencies of a structure need to be identified and quantified. Today due to the advancement in computer aided data acquisition systems and instrumentation, experimental modal Analysis has become an extremely important tool in the hands of an experimentalist. A number of researchers have been developed numerous solution methods to analysis the dynamic behavior of laminated composite laminates. However experimental investigations on woven fabric composite laminated Structures are still limited. There have been few experimental investigations of the free vibration of free-free anisotropic plates. Clary [1] investigated theoretically and experimentally the effect of the effect of fiber orientation on the first five flexural modes of rectangular, unidirectional, boron-epoxy panels. The agreement between theoretical and experimental frequencies was generally good, though there were large errors in some of the predictions of thinner panels. Cawley and Adams [2] used finite element method which included transverse shear deformation to predict the natural modes of free-free CFRP plates. This method produced improved accuracy for the theoretical results for anisotropic plates. Dutt and Shivanand [3] studied the free vibration response of C-F-F-F and C-F-C-F woven carbon composite laminates using a FFT analyzer and compared with FEM tool ANSYS. This work presents an experimental study of modal testing of woven fiber Glass/Epoxy laminated composite plates using FFT analyzer. The main objective of this work is to contribute for a better understanding of the dynamic behavior of components made from industry driven woven fiber composite materials, specifically for the case of plates. The effects of different geometrical parameters including number of layers, aspect ratio and fiber orientation of industry driven woven fiber composite plates in free-free boundary condition are studied in details.

II. FINITE ELEMENT FORMULATIONS

The first order shear deformation theory is used to develop a finite element approach for the prediction of natural frequencies and modes of laminated composite pates. The formulation is essentially similar to that of chakraborty *et al.* [4]. Consider a laminate composite plate of length ‘a’ and width ‘b’ consisting of N number of thin homogenous arbitrarily oriented orthotropic layers having a total thickness ‘h’ is considered as shown in fig.1.T In the present investigation, an eight noded two dimensional quadratic isoparametric element having five degrees of freedom (u, v, w,θ_x, θ_y) per node is used for analysis. A program for vibration analysis of Laminated Composite plate is developed using the formulation based on finite element method (FEM) for free-free boundary conditions. Reduced integration technique is adopted to avoid possible shear locking. The overall stiffness and mass matrices are obtained by assembling the corresponding element matrices, using skyline technique.

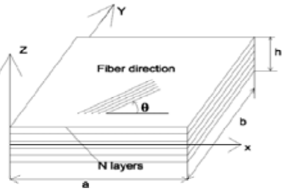

Fig. 1 : Laminated Composite Plate

The displacement field is in the form of

$$u(x, y, z) = u_0(x, y) + z\theta_Y(x, y)$$

$$v(x, y, z) = v_0(x, y) + z\theta_X(x, y)$$

$$w(x, y, z, t) = w_0(x, y)$$

Where u, v, w and u_0, v_0 and w_0 are displacement components in the x, y and z directions anywhere in the plate and at mid-plane respectively. θ_x and θ_y represent rotations of the mid-plane normal about x and y axes respectively. The associated strain components are:

$$\begin{Bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \gamma_{xy} \\ \gamma_{xz} \\ \gamma_{yz} \end{Bmatrix} = \begin{Bmatrix} \varepsilon^0_{xx} \\ \varepsilon^0_{yy} \\ \varepsilon^0_{xy} \\ \varepsilon^0_{xz} \\ \varepsilon^0_{yz} \end{Bmatrix} + z \begin{Bmatrix} k_{xx} \\ k_{yy} \\ k_{xy} \\ k_{xz} \\ k_{yz} \end{Bmatrix}$$

Where ε^0_x, ε^0_y and ε^0_z are the midplane strains and k_{xx}, k_{yy} and k_{xy} are the curvatures of the laminated plate

A. *Stress –Strain Relations:*

$$\begin{Bmatrix} N_{xx} \\ N_{yy} \\ N_{xy} \\ M_{xx} \\ M_{yy} \\ M_{xy} \\ Q_{xz} \\ Q_{xz} \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} & 0 & 0 \\ A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} & 0 & 0 \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} & 0 & 0 \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} & 0 & 0 \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} & 0 & 0 \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & S_{44} & S_{45} \\ 0 & 0 & 0 & 0 & 0 & 0 & S_{45} & S_{55} \end{bmatrix} \begin{Bmatrix} \varepsilon^0_{xx} \\ \varepsilon^0_{yy} \\ \gamma^0_{xy} \\ K_{xx} \\ K_{yy} \\ K_{xy} \\ \gamma^0_{xz} \\ \gamma^0_{yz} \end{Bmatrix}$$

A_{ij}, B_{ij}, D_{ij}, and S_{ij} are the extensional, bending-stretching coupling, bending and transverse stiffnesses. They may be defind as

$$A_{ij} = \sum_{k=1}^{n} \left(\overline{Q_{ij}}\right)_k \left(z_k - z_{k-1}\right)$$

$$B_{ij} = \frac{1}{2} \sum_{k=1}^{n} \left(\overline{Q_{ij}}\right)_k \left(z_k^2 - z_{k-1}^2\right)$$

$$D_{ij} = \frac{1}{3} \sum_{k=1}^{n} \left(\overline{Q_{ij}}\right)_k \left(z_k^3 - z_{k-1}^3\right) \quad \text{For } i, j = 1, 2, 6$$

$$S_{ij} = \alpha \sum_{k=1}^{n} \left(\overline{Q_{ij}}\right)_k \left(z_k - z_{k-1}\right) \quad \text{For } i, j = 4, 5$$

α = shear correction factor =5/6 (Assumed for the numerical solutions)

z_k, z_{k-1}= top and bottom distance of lamina from mid-plane.

B. Finite Element Matrices:

The element matrices are derived as given below

1) *Element stiffness matrix:*

$$[K]_e = \int_{-1}^{+1}\int_{-1}^{+1} [B]^T [D][B] |J| \, d\xi \, d\eta$$

2) *Element mass matrix or consistent mass matrix:-*

$$[M]_e = \int_{-1}^{+1}\int_{-1}^{+1} [N]^T [P][N] |J| \, d\xi \, d\eta$$

C. Governing Equations

The equations of equilibrium of a discretised elastic structure undergoing small deformations can be expressed as

$$[\boldsymbol{M}]]\{\ddot{\mathbf{u}}\} + [\boldsymbol{c}]]\{\dot{\boldsymbol{u}}\} + [\boldsymbol{k}]\{\boldsymbol{u}\} = \{\boldsymbol{F}(\boldsymbol{t})\}$$

For free undamped vibration, the equation reduces to

$$[\boldsymbol{M}]]\{\ddot{\mathbf{u}}\} + [\boldsymbol{k}]\{\boldsymbol{u}\} = \{\mathbf{0}\}$$

If modal co-ordinates are employed the equation becomes

$$\left[[\boldsymbol{K}] - \boldsymbol{\omega}^2[\boldsymbol{M}]\{\boldsymbol{\phi}\}\right] = \{\mathbf{0}\}$$

Where ω and $\{\varphi\}$ represents the natural frequencies and the corresponding Eigen vectors of the generalized Eigen value problem.

III. EXPERIMENTAL PROGRAMME:

A. Materials Required for Fabrication of Plates:

The constituent materials used for fabricating the epoxy/glass fiber plates are: E-glass woven roving as reinforcement (from Owens corning), Epoxy as resin, Hardener as catalyst (10% of the weight of epoxy), Polyvinyl alcohol as a releasing agent.

B. Fabrication Procedure:

The composite plate specimens used in this research were made from 0/90 woven glass fiber with epoxy matrix. Specimens were fabricated by hand layup technique**.** The percentage of fiber and matrix has taken as 50:50 in weight for fabrication of the plates. A flat plywood rigid platform is selected. A plastic sheet i.e. a mould releasing sheet was kept on the plywood platform and a thin film of polyvinyl alcohol is applied as a releasing agent by use of spray gun. Laminating Starts with the application of a gel coat (epoxy and hardener) deposited on the mould by brush, whose main purpose was to provide a smooth external surface and to protect the fibers from direct exposure to the environment. Ply was cut from roll of woven roving. Layers of reinforcement were placed on the mould at top of the gel coat and gel coat was applied again by brush. Any air which may be entrapped was removed using steel rollers. The process of hand lay-up was the continuation of the above process before the gel coat had fully hardened. After completion of all layer, again a plastic sheet was covered the top of last ply by applying polyvinyl alcohol inside the sheet as releasing agent. Again one flat ply board and a heavy flat metal rigid platform were kept top of the plate for compressing purpose. The plates were left for a minimum of 48 hours in room temperature before being transported and cut to exact shape for testing.

Fig. 2 : Plate Casting

C. Determination of Material constants:

The material constants (i.e. of: E_1, E_2, E_{45}) of woven fiber Glass/Epoxy composite plate were determined experimentally by performing tensile tests on specimens cut in longitudinal and transverse directions, and at 45° to the longitudinal direction using INSTRON 1195 machine as per ASTM standard : D 3039/D 3039M-2008[5]. The shear modulus was determined using the formula from Jones [6].

Table1. Material properties of composite plates:

Layer	E_1 GPa	E_2 GPa	E_{45} GPa	G_{12} GPa	ν_{12}
8	7.4	7.4	5.81	2.15	0.17

D. Experimental Setup and Test Procedure for Free Vibration Test:

To simulate free boundary conditions, all the four edges of the plate are hanged in an iron frame using a flexible string as shown in Figure 1. The connections of FFT analyzer, laptop, transducers, modal hammer, and cables to the system were done as per the guidance manual shown in fig.2. The pulse lab shop software key was inserted to the port of laptop. The plate was excited in a selected point by means of Impact hammer (Model 2302-5), fixed on the hammer. The resulting vibrations of the specimens on the selected point were measured by an accelerometer (B&K, Type 4507) mounted on the specimen by means of bees wax.

Fig. 3 : Iron Frame for making Free-Free B.C

Fig. 4 : Vibration test set up

For FRF, at each singular point the modal hammer was struck five times and the average value of the response was displayed on the screen of the display unit At the time of striking with modal hammer to the points on the specimen precaution were taken for making the stroke to be perpendicular to the surface of the plates. Then By moving the cursor to the peaks of the FRF the frequencies are measured.

IV. RESULTS AND DISCUSSIONS:

Numerical results are carried out to determine the capability of the present formulation to predict the natural frequency of woven fiber composite plates.

A. Comparison with Previous Studies:

The present formulation is validated for vibration analysis of composites panels in free-free boundary conditions as shown in Table 2. The four lowest non-dimensional frequencies obtained by the present finite element are compared with numerical solution published by Ju *et al*. [7].

Table. 2: Comparison of natural frequencies (Hz) of vibration of 8 layer laminated composite plate $[0°/90°/45°/90°]_s$ at free-free boundary conditions.

a=b=0.25m, t=0.00212, E_1 = 132 Gpa, E_2 = 5.35 Gpa

G_{12} = 2.79 Gpa, ν_{12}=0.3, **ρ**=1446.20 kg/m ^{3}

Reference	Natural frequencies at free-free boundary conditions			
	1	2	3	4
Ju *et* al.[6]	73.30	202.59	243.37	264.90
Present FEM	72.53	201.39	243.54	263.26

B. Experimental and Numerical Results:

Results:

After validating the formulation with the existing literature, both the experimental and numerical results for vibration study of laminated composite plates are presented. Here for free vibration analysis, the study is aimed upon the following parameters:

1) Effect of number of layers of a laminate
2) Effect of fiber orientations
3) Effect of aspect ratio

1) Effect of Number of layers of laminate:

To examine the effects of no. of layers of laminate, three different types of laminate are fabricated, which are made up of 8, 12 and 16 layers. The natural frequencies for free vibration are obtained both experimentally and numerically for free-free boundary condition. The variation of natural frequencies with increasing layer of laminate for both experimental results and numerical results are shown graphically in figure-5. All the geometrical dimensions of the composite plates are same as described in table-3. From figure 5 it is observed that as the number of layers increases, the natural frequency also increases as excepted. There is a considerable variation in the natural frequency made up of 12 and 16 layers whereas for 8 layers of composite plates it is less.

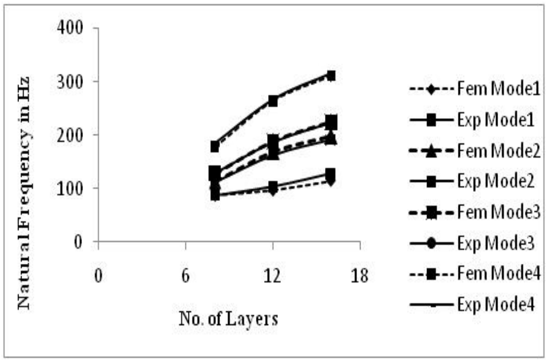

Fig. 5 : Variation of natural frequency of Experimental and numerical results with different no. of layers

2) *Effect of fiber orientation:*

In order to know the effect of fiber orientations on natural frequencies of laminated plate, (8-layers) three types of plates with fiber orientations i.e. $[0]_8$, $[30/-30]_4$, $[45/-45]_4$ are considered having thickness 0.0032m and **ρ** is taken as 1580 kg/m^3. The variations of natural frequency with fiber orientation are presented in fig.6 for free-free boundary condition. The results obtained from free vibration of the plates of both experiment and present FEM are in good agreement. As observed from fig.6 the experimental results show a good agreement with the FEM proving that the fiber angle has influence on the dynamic behavior of the laminated plates. As the fiber angle increases, the natural frequencies decrease. It is observed that the maximum frequency occurs at $\theta = 0^0$ and the minimum occurs at $\theta = 30^0$.

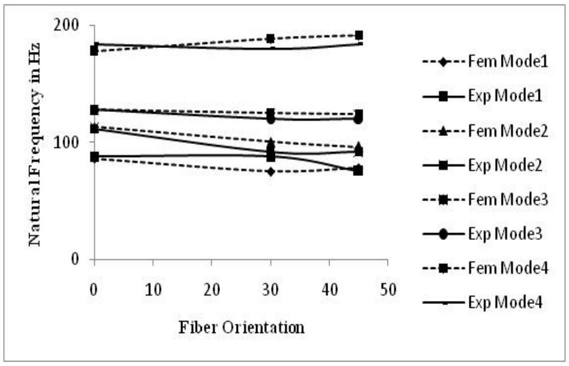

Fig. 6 : Variation of natural frequency of experimental and numerical results with different fiber orientation

From the experimental results, it is observed that increasing the angle of the fibers from 0^0 to 30^0 reduces the natural frequency by about 13% (i.e. from 86 to 75 Hz) for the 1st mode and by about 11.5% (i.e. from 113 to 100 Hz) for the 2nd mode.

3) *Effect of Aspect ratio:*

To study the effect of aspect ratio, four different types of aspect ratios for laminated composite plates are considered i.e. for a/b value (1.0, 1.5 and 2.0).For different aspect ratios, the plate dimension varies, whereas the thickness of the plate i.e. (h=0.0031m) remains unchanged. The Variations of natural frequencies of Experimental results with present FEM results of different aspect ratio of woven GFRP under free-free boundary condition are shown in fig7

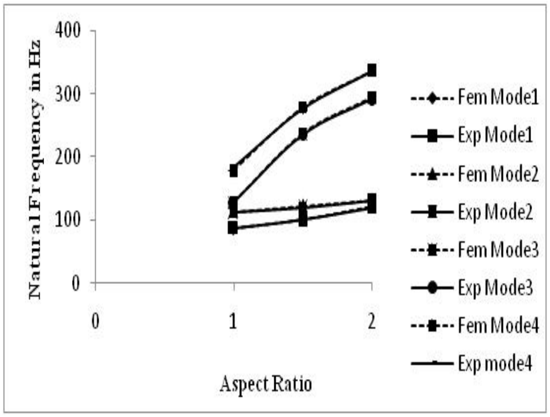

Fig. 7 : Variation of natural frequency of Experimental and numerical results with different aspect ratio.

V. CONCLUSION:

In the present study, both experimental and numerical study is conducted for woven roving G/E composite plates. Quantitative results are presented to show the effect of different Parameter like no. of layers, aspect ratio and fiber orientation in free-free boundary conditions. Based on the first order shear deformation theory, a finite element formulation is presented for the analysis of the free vibration of composite plates. The percentage of difference between numerical results and experimental results are due to non uniformity in the specimens properties (Voids, variations in thickness, non uniform surface finishing) and also positioning of the accelerometers. This experimental method represents to predict the dynamical behavior of woven composite, in order to design panels or other similarly structure used in different applications such as automotive industry, aerospace, civil, marine and other high performance structures.

PULSE REPORT:

Pulse report for 12-layer Woven Fiber Glass/Epoxy Cantilever Composite Plate

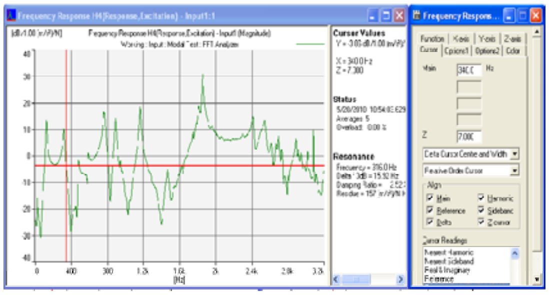

Fig. 8 : Typical FRF of test specimen.

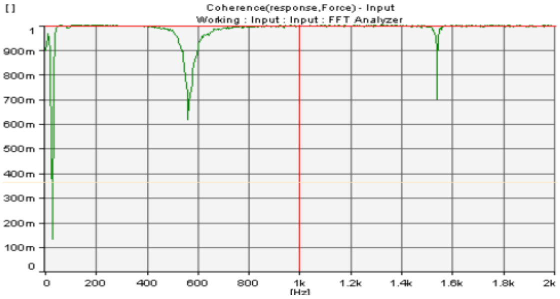

Fig. 9 : Typical coherence of test specimen.

Table 3. Geometrical dimensions of composite plate: The plate dimensions are 24cmx24cm with different thickness as the no. of layers varies.

Plate no	Stacking sequence	h (m)	ρ(kg/m^3)
1	$[0]_8$	0.0031	1580
2	$[0]_{12}$	0.0047	1650
3	$[0]_{16}$	0.0056	1686
4	$[0]_8$ (a/b=0.5)	0.0031	1523
5	$[0]_8$ (a/b=1)	0.0031	1580
6	$[0]_8$ (a/b=1.5)	0.0031	1512

VI. ACKNOWLEDGMENTS

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Technology (DST), New Delhi, India. (Project No.SR/S3/MERC/009/2008).

NOMENCLATURE:

a, b, h	Plate dimensions along x, y and z axes respectively
E_1, E_2	Young's moduli of a lamina along and across the fibers, respectively
G_{12}	Shear moduli of a lamina with respect to 1 and 2 axis
$[K_e]$	Elastic stiffness matrix
$[M_e]$	Element mass matrix of the plate
[B]	Strain displacement matrix of the plate
[N]	Shape function of the plate
ν_{12}	Poisson's ratios
ρ	Mass density
ω_n	Natural frequency

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