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PARAMETRIC STABILITY AND INSTABILITY OF WOVEN FIBRE COMPOSITE PLATES FOR DIFFERENT STRUCTURES

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Abstract : This study focuses on exploring the behavior of laminated woven fiber composite plates under harmonic in-plane periodic loads, which are common in aerospace, civil, automobile, and marine engineering applications. The research investigates free vibration, buckling, and parametric instability phenomena in these plates, considering various influential factors such as the number of layers, aspect ratios, ply orientations, and static load factors. Both experimental and numerical analyses using the finite element method (FEM) are employed. A simplified plate model based on the first-order shear deformation theory (FSDT) is developed to assess how composite plates respond to in-plane loading. The study identifies key instability regions using Bolotin's approach with FEM, employing an eight-node isoperimetric quadratic element that accounts for transverse shear deformation and rotary inertia effects. The composite plates, made from woven glass fiber and epoxy matrices, are tested and characterized through experiments. Free vibration characteristics are analyzed using tools like FFT analyzers and accelerometers. Buckling loads are determined both statically and dynamically, and the effects of varying parameters such as fiber orientation angle and lamination sequence on buckling behavior are investigated. The study finds that natural frequencies are influenced by boundary conditions, with the least frequency observed for cantilever and the highest for fully clamped conditions. Changes in fiber orientation notably affect buckling loads, with plates showing decreased buckling load values as the ply orientation angle increases. Additionally, static load factors impact excitation frequencies, which decrease with increasing static load factor. In summary, the parametric instability behavior of woven fiber composite plates is heavily affected by design parameters and loading conditions. The study emphasizes the importance of considering these factors in structural design, with implications for optimizing composite structures for specific engineering applications.

***Index Terms* - Laminated composite plates, Woven fiber composites, Parametric instability, Free vibration, Buckling, Harmonic in-plane periodic loads, Natural frequencies etc.**

I. INTRODUCTION

1.1 Introduction: Composite materials represent a remarkable innovation that has revolutionized engineering across various sectors including aerospace, civil engineering, marine technology, automotive design, biomedical applications, and sports equipment. These materials are prized for their exceptional properties, including remarkable strength, high specific stiffness, and excellent fatigue resistance, heightened sensitivity to moisture, exceptional impact resistance, and extended durability.

1.2 Importance of the Present Structural Parametric Instability Studies: Plate structures play a crucial role in structural systems as they serve as primary load-bearing components. When subjected to in-plane periodic loads, these structures can experience unstable transverse vibrations, leading to a phenomenon known as parametric instability or parametric resonance. This type of resonance occurs due to specific combinations of in-plane load parameters and the natural frequency of transverse vibrations. Parametric instability has been linked to various catastrophic incidents. In the field of structural mechanics, dynamic stability has been a key area of focus, encompassing a wide range of problems. Parametric instability can occur not only at a single excitation frequency but also for small excitation amplitudes and combinations of frequencies. The primary concern is identifying the primary instability region, which is the most critical and practically significant. Distinguishing between stable and unstable vibration regimes under in-plane periodic loading can be achieved by analyzing dynamic instability region (DIR) spectra. This analysis typically involves calculating natural frequencies and static buckling loads with precision. Therefore, understanding the vibration, buckling, and parametric instability characteristics of laminated composite plates under in-plane periodic loading is essential for comprehending the behavior of dynamic systems in engineering applications. A detailed examination of the vibration and buckling behavior of plates has been conducted extensively. Previous studies on the dynamic stability of composite plates have predominantly utilized analytical methods or various numerical techniques. Woven fabric composites belong to a class of textile composite materials characterized by a continuous spatial fiber network oriented on multiple axes, providing excellent integrity and adaptability for advanced structural applications. In a two-dimensional woven-fabric composite, the reinforcing element typically consists of two orthogonal families of fiber bundles. Woven glass fibers are used to achieve higher reinforcement loading and consequently, enhanced strength in composite materials. Woven roving, which is plain woven from roving, exhibits superior dimensional properties and even distribution of glass fibers with excellent bonding strength among laminates. This material is increasingly utilized in structural applications due to its higher fiber content, tensile strength, and impact resistance. While previous research has primarily focused on the impact response, damage initiation, or failure modes of woven composite plates, there is a lack of reported experimental work on the instability of woven composite plates under in-plane harmonic loading conditions. Studying dynamic stability necessitates investigating the vibration and buckling loads of structures. Therefore, a comprehensive review of earlier research in this field is crucial for defining the objectives and scope of the current investigation. The subsequent chapter will present a detailed literature review along with critical discussions to inform the study's focus.

II. LITERATURE REVIEW

Lei et al. [2010] reported the effects of woven structures on the vibration properties of the composites. The composites plates with adequate thickness were prepared by epoxy resin curing, and their fiber volume fractions were examined. Five typical weaving sets including the ordinary plain weaved and the warp interlocked were adopted in fabric processing. The result showed that the woven structure have a strong effect on the fiber volume fraction, resin-rich area, and the warp architectures of the composites, which determined the performances of the composites in vibration For laminated plates.

Natural frequency with different fiber orientations was studied. Due to the advancement in weaving processes, a woven composite evolved as an attractive structural material for structural applications and the modeling strategies are reviewed recently by **Mahmood et al. [2011].**

Laila [2008] presented aeroelastic characteristics of a cantilevered composite wing, idealized as a composite flat plate laminate. The composite laminate was made from woven glass fibers with epoxy matrix. The elastic and dynamic properties of the laminate were determined experimentally for aeroelastic calculations. Both resonant frequencies and corresponding mode shapes can be obtained experimentally.

Dutt and Shivanand [2011] 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.

Chakrabarti and Sheikh [2006] studied the dynamic instability of laminated sandwich plates subjected to inplane partial edge loading by using finite element method.

Dey and Singh [2006] examined the dynamic stability characteristics of simply supported laminated composite skew plates subjected to a periodic in-plane load by using finite element approach.

III. MATHEMATICAL FORMULATION

The mathematical framework for analyzing vibration, static, and dynamic stability of laminated composite plate structures. Finite Element Method (FEM) is preferred over analytical methods due to its effectiveness in handling composite laminates. FEM divides the structure into finite elements, simplifying the analysis by converting infinite degrees of freedom into finite ones. Each element, typically of simple geometry, is easier to analyze compared to the entire structure.

The problem focuses on a composite laminated plate with sides 'a' and 'b', subjected to harmonic in-plane edge loading N(t) (see Figure 3.1). Figures 3.2 and 3.3 depict the lamination sequence and plan-form under the in-plane load N(t), respectively.

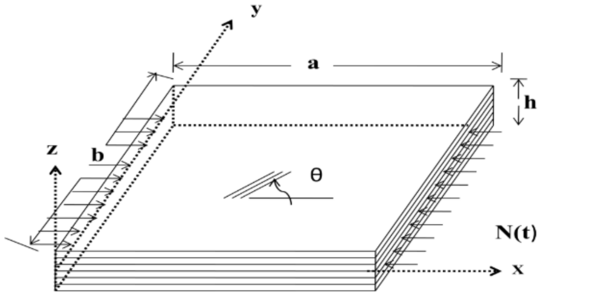

Figure 3.1: **Laminated Composite Plate under in-plane harmonic Loading**

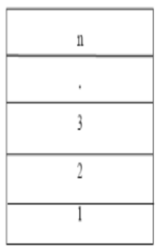

Figure 3.2: **Lamination sequence**

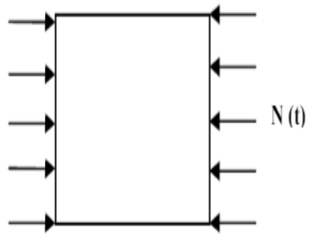

Figure 3.3: **Plan-form subjected to in-plane load N (t)**

3.1 GOVERNING EQUATIONS

The governing differential equations, the strain energy due to loads, kinetic energy and formulation of general buckling problems are derived on the basis of minimum potential energy and Lagrange's equation.

$$\frac{\partial N_x}{\partial x} + \frac{\partial N_{xy}}{\partial y} = P_1 \frac{\partial^2 u}{\partial t^2} + P_2 \frac{\partial^2 \theta_x}{\partial t^2}$$

$$\frac{\partial N_{xy}}{\partial x} + \frac{\partial N_y}{\partial y} = P_1 \frac{\partial^2 v}{\partial t^2} + P_2 \frac{\partial^2 \theta_y}{\partial t^2}$$

$$\frac{\partial Q_x}{\partial x} + \frac{\partial Q_y}{\partial y} + N_x^0 \frac{\partial^2 w}{\partial x^2} + N_y^0 \frac{\partial^2 w}{\partial y^2} = P_1 \frac{\partial^2 w}{\partial t^2}$$

$$\frac{\partial M_x}{\partial x} + \frac{\partial M_{xy}}{\partial y} - Q_x = P_3 \frac{\partial^2 \theta_x}{\partial t^2} + P_2 \frac{\partial^2 u}{\partial t^2}$$

$$\frac{\partial M_{xy}}{\partial x} + \frac{\partial M_y}{\partial y} - Q_y = P_3 \frac{\partial^2 \theta_y}{\partial t^2} + P_2 \frac{\partial^2 v}{\partial t^2}$$

3.2 Dynamic Stability Studies

The equation of motion for vibration of a laminated composite panel, subjected to generalized in-plane load N (t) May be expressed in the matrix form as:

$$[M]\{\ddot{q}\} + [[K] - N(t)[K_g]]\{q\} = 0$$

Where 'q' is the vector of degrees of freedoms (u, v, w, □x, □y). The in-plane load 'N (t)' may be harmonic and can be expressed in the form:

$$N(t) = N_s + N_t \mathrm{Cos}\Omega t$$

Where Ns the static portion of load N (t), Nt the amplitude of the dynamic portion of N (t) and Nt is the frequency of the excitation. The stress distribution in the panel may be periodic. Considering the static and dynamic component of load as a function of the critical load.

$$[M]\{\ddot{q}\} + [[K] - \alpha N_{cr}[K_g] - \beta N_{cr}[K_g]\mathrm{Cos}\Omega t]\{q\} = 0$$

The above Eq. represents a system of differential equations with periodic coefficients of the Mathieu-Hill type. The development of regions of instability arises from Floquet's theory which establishes the existence of periodic solutions of periods T and 2T. The boundaries of the primary instability regions with period 2T, where T=2 □/Ω are of practical importance and the solution can be achieved in the form of the trigonometric series:

$$q(t) = \sum_{k=1,3,5,..}^{\infty} [\{a_k\}Sin(k\Omega t/2) + \{b_k\}Cos(k\Omega t/2)]$$

Putting this Eq. in above eq. and if only first term of the series is considered, equating coefficients of Sin Ωt/2 and Cos Ωt/2, the Eq. reduces to

$$[[K] - \alpha N_{cr}[K_g] \pm \frac{1}{2}\beta N_{cr}[K_g] - \frac{\Omega^2}{4}[M]]\{q\} = 0$$

This equation represents a solution to a number of related problems:

(1) Free vibration: α = 0, β = 0 and ω = Ω/2

$$[[K] - \omega^2[M]]\{q\} = 0$$

(2) Vibration with static axial load: β = 0 and ω = Ω/2

$$[[K] - \alpha N_{cr}[K_g] - \omega^2[M]]\{q\} = 0$$

(3) Static stability: α = 1, β = 0, Ω = 0

$$[[K] - \alpha N_{cr}[K_g]]\{q\} = 0$$

3.3 Constitutive Relations

A macro-mechanical analysis was carried out to establish the relationship between the forces and general strains of a laminate. The elastic behavior of each lamina is essentially two dimensional and orthotropic in nature. So the elastic constants for the composite lamina are given below.

E11 = Modulus of Elasticity of Lamina along 1-direction
E22 = Modulus of Elasticity of Lamina along 2-direction
G12 = Shear Modulus
ν12= Major Poisson's ratio
ν21 = Minor Poisson's ratio

The stress strain relation for the Kth lamina is,

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \\ \tau_{xz} \\ \tau_{yz} \end{Bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 & 0 & 0 \\ Q_{12} & Q_{22} & 0 & 0 & 0 \\ 0 & 0 & Q_{66} & 0 & 0 \\ 0 & 0 & 0 & Q_{44} & 0 \\ 0 & 0 & 0 & 0 & Q_{55} \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \\ \gamma_{xz} \\ \gamma_{yz} \end{Bmatrix}$$

Where,

$$Q_{11}=\frac{E_{11}}{(1-\nu_{12}\nu_{21})},Q_{12}=\frac{E_{11}\nu_{21}}{(1-\nu_{12}\nu_{21})},Q_{21}=\frac{E_{22}\nu_{12}}{(1-\nu_{12}\nu_{21})},Q_{22}=\frac{E_{22}}{(1-\nu_{12}\nu_{21})}$$

$$Q_{66}=G_{12}$$

$$Q_{44}=kG_{13}$$

$$Q_{55}=kG_{23}$$

The on-axis elastic constant matrix [Qij]k corresponding to material axes 1-2 for kth layer is given by

$$\left[Q_{ij}\right]_k=\begin{bmatrix}Q_{11} & Q_{12} & 0\\ Q_{12} & Q_{22} & 0\\ 0 & 0 & Q_{66}\end{bmatrix}\text{For}\quad i,j=1,2,6$$

$$\left[Q_{ij}\right]_k=\begin{bmatrix}Q_{44} & 0\\ 0 & Q_{55}\end{bmatrix}\quad\text{For}\quad i,j=4,5$$

For obtaining the off-axis elastic constant matrix, [Qij]k corresponding to any arbitrarily oriented reference x-y axes for the kth layer ,appropriate transformation is required. Hence the off-axis elastic constant matrix is obtained from the on axis elastic constant matrix by the relation:

$$\left[\overline{Q}_{ij}\right]_k=\begin{bmatrix}\overline{Q}_{11} & \overline{Q}_{12} & \overline{Q}_{16}\\ \overline{Q}_{12} & \overline{Q}_{22} & \overline{Q}_{26}\\ \overline{Q}_{16} & \overline{Q}_{26} & \overline{Q}_{66}\end{bmatrix}\text{for i ,j =1,2,6}\qquad [\,\overline{Q}_{ij}\,]_k=\begin{bmatrix}\overline{Q}_{44} & \overline{Q}_{45}\\ \overline{Q}_{45} & Q_{55}\end{bmatrix}_k\qquad \left[\overline{Q}_{ij}\right]_k=\left[T\right]^{-1}\left[Q_{ij}\right]_k\left[T\right]$$

Where [T] = Transformation matrix

$$\begin{bmatrix}m^2 & n^2 & 2mn\\ n^2 & m^2 & -2mn\\ -mn & mn & m^2-n^2\end{bmatrix}_k$$

The off-axis stiffness values are

$$\overline{Q}_{11}=Q_{11}m^4+2(Q_{12}+2Q_{66})m^2n^2+Q_{22}n^4$$

$$\overline{Q}_{12}=(Q_{11}+Q_{22}-4Q_{66})m^2n^2+Q_{12}(m^4+n^4)$$

$$\overline{Q}_{22}=Q_{11}n^4+2(Q_{12}+2Q_{66})m^2n^2+Q_{22}m^4$$

$$\overline{Q}_{16}=(Q_{11}-Q_{12}-2Q_{66})m^3n+(Q_{12}-Q_{22}+2Q_{66})n^3m$$

$$\overline{Q}_{26}=(Q_{11}-Q_{12}-2Q_{66})mn^3+(Q_{12}-Q_{22}+2Q_{66})m^3n$$

$$\overline{Q}_{66}=(Q_{11}+Q_{22}-2Q_{12}-2Q_{66})m^2n^2+Q_{66}(m^4+n^4)$$

The stiffness corresponding to transverse deformations are

$$\overline{Q}_{44}=G_{13}m^2+G_{23}n^2$$

$$\overline{Q}_{45}=(G_{13}-G_{23})mn$$

$$\overline{Q}_{55}=G_{13}n^2+G_{23}m^2$$

Where m=cosθ and n=sinθ; and θ=angle between the arbitrary principal axis with the material axis in a layer.

The force and moment resultants are obtained by integrating the stresses and their moments through the laminate thickness as given by

$$\begin{Bmatrix}N_x\\ N_y\\ N_{xy}\\ M_x\\ M_y\\ M_{xy}\\ Q_x\\ Q_y\end{Bmatrix}=\begin{bmatrix}A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} & 0 & 0\\ A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} & 0 & 0\\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} & 0 & 0\\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} & 0 & 0\\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} & 0 & 0\\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 0 & S_{44} & S_{45}\\ 0 & 0 & 0 & 0 & 0 & 0 & S_{45} & S_{55}\end{bmatrix}\begin{Bmatrix}\varepsilon_x\\ \varepsilon_y\\ \gamma_{xy}\\ k_x\\ k_y\\ k_{xy}\\ \gamma_{xz}\\ \gamma_{yz}\end{Bmatrix}$$

3.4 ELASTIC STIFFNESS MATRIX

The element matrices in natural coordinate system are derived as

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

Where [B] is called the strain displacement matrix

3.5 GEOMETRIC STIFFNESS MATRIX [Kg]e

The element geometric stiffness matrix is derived using the non-linear in-plane strains. The strain energy due to initial stresses is

$$[U]_2 = \frac{1}{2}\int_v [f]^T[S][f]\,dV$$

Where

$$[f] = \left[\frac{\partial u}{\partial x}, \frac{\partial u}{\partial y}, \frac{\partial v}{\partial x}, \frac{\partial v}{\partial y}, \frac{\partial w}{\partial x}, \frac{\partial w}{\partial y}, \frac{\partial \theta_x}{\partial x}, \frac{\partial \theta_x}{\partial y}, \frac{\partial \theta_y}{\partial x}, \frac{\partial \theta_y}{\partial y}\right]^T$$

And

$$[S] = \begin{bmatrix} s & 0 & 0 & 0 & 0 \\ 0 & s & 0 & 0 & 0 \\ 0 & 0 & s & 0 & 0 \\ 0 & 0 & 0 & s & 0 \\ 0 & 0 & 0 & 0 & s \end{bmatrix}$$

3.6 ELEMENT MASS MATRIX

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

Where the shape function matrix

$$[N] = \sum_{i=1}^{8}\begin{bmatrix} N_i & 0 & 0 & 0 & 0 \\ 0 & N_i & 0 & 0 & 0 \\ 0 & 0 & N_i & 0 & 0 \\ 0 & 0 & 0 & N_i & 0 \\ 0 & 0 & 0 & 0 & N_i \end{bmatrix} \qquad [P_1] = \begin{bmatrix} P_1 & 0 & 0 & 0 & 0 \\ 0 & P_1 & 0 & 0 & 0 \\ 0 & 0 & P_1 & 0 & 0 \\ 0 & 0 & 0 & I & 0 \\ 0 & 0 & 0 & 0 & I \end{bmatrix}$$

3.7 COMPUTER PROGRAM

A computer program is developed by using MATLAB environment to perform all the necessary computations. The element stiffness, geometric stiffness and mass matrices are derived using the formulation. Numerical integration technique by Gaussian quadrature is adopted for the element matrices. Since the stress field is non-uniform, plane stress analysis is carried out using the finite element techniques to determine the stresses and these stresses are used to formulate the geometric stiffness matrix. The overall matrices [K], [Kg], and [M] are obtained by assembling the corresponding element matrices. The boundary conditions are imposed restraining the generalized displacements in different nodes of the discretized structure. The program features and flow charts, used in this study are presented in the Appendix.

IV. EXPERIMENTAL PROGRAMME

4.1 THE SUBSEQUENT ANALYSES IN THIS SECTION ARE CATEGORIZED INTO THREE MAIN AREAS:

- Examination of vibration characteristics in woven fiber composite plates
- Investigation of buckling phenomena in woven fiber composite plates
- Exploration of dynamic stability issues affecting woven fiber composite plates.

4.2 MATERIALS

The following constituent materials were used for fabricating the plate:

- Glass woven roving fibers as reinforcement.
- Epoxy as resin
- Hardener as catalyst (10% of the weight of epoxy)
- Polyvinyl Alcohol (PVA) as a releasing agent

4.3 FABRICATION PROCEDURE

The (Fibre Reinforced Plastic) FRP composite specimens were crafted using the hand layup technique, where a liquid resin and woven glass fiber reinforcement were applied onto the finished surface of an open mold. The resin underwent chemical reactions to solidify into a durable, lightweight product. The composition of the composite was maintained at a 50:50 ratio of fiber to matrix by weight for the fabrication of the plates.

The process began with selecting a flat plywood platform as the base. A plastic sheet, serving as a mold release agent, was placed on the plywood, and a thin film of polyvinyl alcohol was applied to aid in releasing the cured composite from the mold surface (see Figure 4.1[a]).

Laminating commenced with the application of a gel coat made from epoxy and hardener using a brush (shown in Figure 4.1[b]). The gel coat served two main purposes: to provide a smooth external finish and to shield the fibers from direct exposure to the environment. Woven glass fiber was cut from a roll of woven roving and applied in layers onto the mold surface above the gel coat. Additional layers of gel coat were applied between the fiber layers, and any trapped air was removed using steel rollers (depicted in Figure 4.1[c]).

The hand layup process continued until all desired layers were applied but before the gel coat had fully cured. After completing the layers, another plastic sheet coated with polyvinyl alcohol was placed over the topmost fiber layer as a releasing agent. A flat plywood board and a heavy, flat metal platform were then positioned on top of the composite for compression purposes.

The plates were left to cure for a minimum of 48 hours at room temperature before they were transported and cut to their final shape for testing. The resulting fabricated plate, post-drying, is illustrated in Figure 4.1[d].

Figure 4.1[a] Figure 4.1[b] Figure 4.1[c] Figure 4.1[d]

Figure 4.1 [a]: Application of gel coat on mould releasing sheet, Figure 4.1 [b]: Placing of woven roving glass fiber on gel coat, Figure 4.1 [c]: Removal of air entrapment using steel roller, Figure 4.1 [d]: Plate after casting.

4.4 DETERMINATION OF MATERIAL CONSTANTS

The woven fiber Glass/Epoxy composite plate exhibits specific mechanical characteristics that can be fully defined by four material constants: E1, E2, G12, and υ12, where the subscripts 1 and 2 indicate principal material directions. To accurately characterize the material properties, a total of 12 samples of 8-layer Glass/Epoxy plates were subjected to testing using a Universal Testing Machine (UTM) to determine tensile strength and Young's modulus in different orientations. Among these samples, 4 were tested in the X-direction, 4 in the Y-direction, and 4 at a 45-degree angle to the principal directions.

The test data obtained from these samples were then used to calculate the material constants E1, E2, and G12 for the Glass/Epoxy plate according to the guidelines outlined in ASTM standard D 3039/D 3039M-2008. The specimen dimensions used in the testing are detailed in Table 4.1, providing a standardized approach to ensure accurate and reliable characterization of the composite material's mechanical properties. This process aims to establish a comprehensive understanding of how the material behaves under different loading conditions and orientations, enabling informed design and engineering decisions for applications utilizing Glass/Epoxy composite plates.

Table 4.1: Dimensions of tensile specimens for tensile test

Angle(degree)	Length(mm)	Width(mm)	Thickness(mm)	Overall Length(mm)
00	150	25	3	250
900	150	25	3	250
450	150	25	3	250

The specimens were cut from the plates themselves by diamond cutter. At least four replicate sample specimens were prepared. The tests specimens are shown in Figure 4.2[a], Figure 4.2[b] and Figure 4.2[c] for specimen in x, y and 450directions respectively.

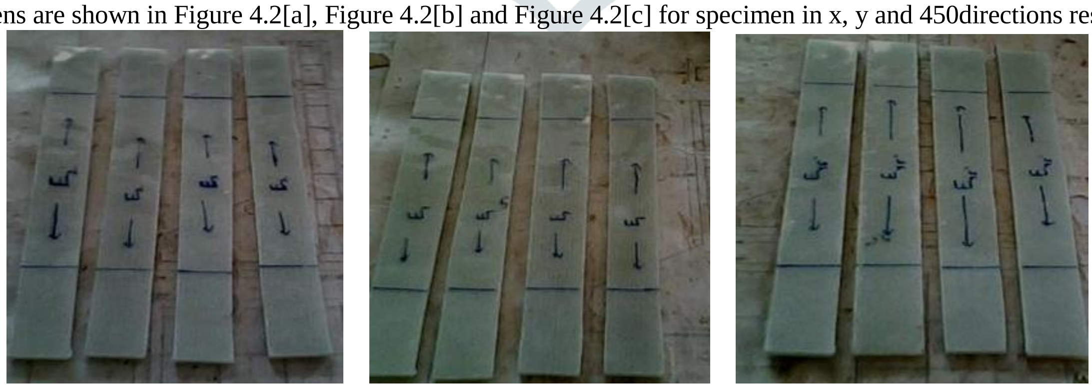

Figure 4.2 [a]: Specimens in "x" direction, [b] Specimens in "y' direction, [c] Specimens in "450" direction.

For measuring the Young's modulus, the specimen is loaded in universal testing machine as shown in Figure 4.3, monotonically to failure with a recommended rate of extension (rate of loading) of 0.2in/minute. Specimens were fixed in the upper jaw first and then gripped in the movable jaw (lower jaw).Gripping of the specimen was as much as possible to prevent the slippage. Here, it was taken as 50mm in each side for gripping. Initially strain was kept at zero. The load, as well as the extension, was recorded digitally with the help of a load cell and an extensometer respectively. From these data, engineering stress vs. strain curve was plotted; the initial slope of which gives the Young's modulus. The ratio of transverse to longitudinal strain directly gives the Poisson's ratio by using two strain gauges in longitudinal and transverse direction.

$$G_{12} = \frac{1}{\frac{4}{E_{45}} - \frac{1}{E_1} - \frac{1}{E_2} + \frac{2\nu_{12}}{E_1}}$$

4.6 VIBRATIONS OF WOVEN FIBER COMPOSITE PLATES

In order to achieve the right combination of material properties and service performance, the dynamic behavior is the main point to be considered. To avoid the typical problems caused by vibrations, it is important to determine natural frequency of the structure.

The fundamental frequency is a key parameter. The natural frequencies are sensitive to the orthotropic properties of composite plates and design-tailoring tools may help in controlling this fundamental frequency. Due to the advancement in computer aided data acquisition systems and instrumentation, experimental modal analysis or free vibration analysis has become an extremely important tool in the hands of an experimentalist.

Equipment Required for Vibration Test

The apparatus which are used in free vibration test are

- Modal hammer.
- Accelerometer.
- FFT Analyzer.
- PULSE software.

V. RESULT AND DISCUSSION

5.1 FREE VIBRATION OF WOVEN FIBER LAMINATED COMPOSITE PLATES

5.1.1 COMPARISON WITH PREVIOUS STUDIES

Numerical computations were done to test how well our current method can predict the natural frequencies of woven fiber composite plates. To make sure our program is accurate, we compared our results to data published by other researchers.

Specifically, we validated our method by comparing natural frequencies calculated using our finite element model with results from previous studies:

We looked at a graphite/epoxy composite plate with specific dimensions and fiber orientation (laminate sequence [02/±30]s) studied by Crawley in 1979 using FEM.

We also compared our findings to Chakraborty et al.'s 2000 study on woven roving [0]5 composite plates under clamped boundary conditions. Additionally, we considered the work of Ju et al. in 1995, which looked at composite plates under various boundary conditions using FEM.

The comparison showed that our finite element model's predictions closely matched those from these previous studies. This agreement demonstrates that our approach is effective and reliable for analyzing the vibration characteristics of composite panels under different conditions. Essentially, it confirms that our method is producing accurate results similar to what has been found in earlier research.

5.1.2 EXPERIMENTAL AND NUMERICAL RESULTS OF VIBRATION

Geometrical Dimensions:

The dimensions of the woven roving composite plates used in the study are:

Length (a) = Width (b) = 0.24 meters

Thickness (h) = 0.0031 meters (for an eight-layer configuration)

Material Properties:

The material properties of the woven roving composite plates were determined through tensile testing according to ASTM standards. The key properties used in the numerical studies are:

Young's Modulus (E11 = E22) = 7.4 GPa

Shear Modulus (G12 = G23 = G31) = 2.15 GPa

Poisson's Ratio (ν) = 0.17

Parameters Studied for Vibration Analysis:

- Effect of number of Layers: Investigating how changing the number of layers in the laminate affects vibration characteristics.
- Effect of fiber Orientations: Exploring the impact of different fiber orientations on vibration responses.
- Effect of aspect Ratio: Studying how altering the aspect ratio (ratio of length to width) influences vibration properties.
- Boundary Conditions: Examining the effects of different boundary conditions (ways in which the plates are fixed or supported) on vibration behavior.

5.1.3 EFFECT OF NUMBER OF LAYERS OF LAMINATE

For In this study, we wanted to see how the number of layers in a laminate affects the natural vibration frequencies of woven fiber composite plates. To do this, we made four different types of laminates with varying numbers of layers: 8 layers, 12 layers, and 16 layers.

We then tested these composite plates under free vibration conditions, both in real experiments and through numerical simulations (using computer models). The plates were set up in a cantilever (fixed at one end) boundary condition.

The results, showing how the natural vibration frequencies change with increasing layers of laminate, are displayed in Figure 5.1. This figure compares the experimental measurements with the numerical predictions. It helps us understand how the number of layers impacts the vibration characteristics of these composite plates.

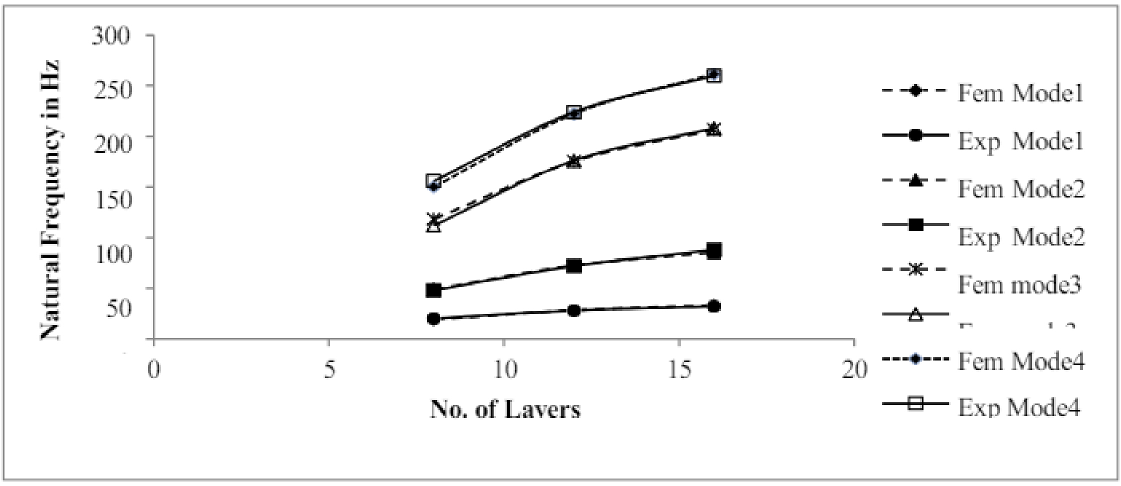

Figure 5.1: Variation of natural frequency with different no. of layers of woven fiber composite plates.

From Figure 5.1, it is observed that as the number of layers increases, the natural frequency also increases due to bending stretching coupling as excepted. There is a considerable Variation in the different modes of natural frequency made up of 12 and 16 layers whereas for 8 layers of composite plates it is less. This variation is much more significant for higher modes of vibration of woven fiber laminated composite plates.

5.1.4 Effect of Fiber Orientation

In this study, we looked at how different fiber orientations affect the natural frequencies of an 8-layer laminated plate. We considered three types of fiber orientations:

[(0/0)2]s: All fibers aligned in the same direction within each layer.

[(30/-30)2]s: Fibers oriented at ±30 degrees in alternating layers.

[(45/-45)2]s: Fibers oriented at ±45 degrees in alternating layers.

We studied the variation of natural frequencies using both experimental testing and numerical simulations (FEM) on cantilever composite plates. The results from our experiments and the FEM simulations showed good agreement. Fiber orientations lead to different natural frequencies in the composite plate. Both the experimental measurements and the numerical predictions (from FEM) matched well, indicating the reliability of our approach.

Figure 5.2: This figure presents the variation of natural frequencies for each fiber orientation, showing how they influence the plate's vibrational behavior.

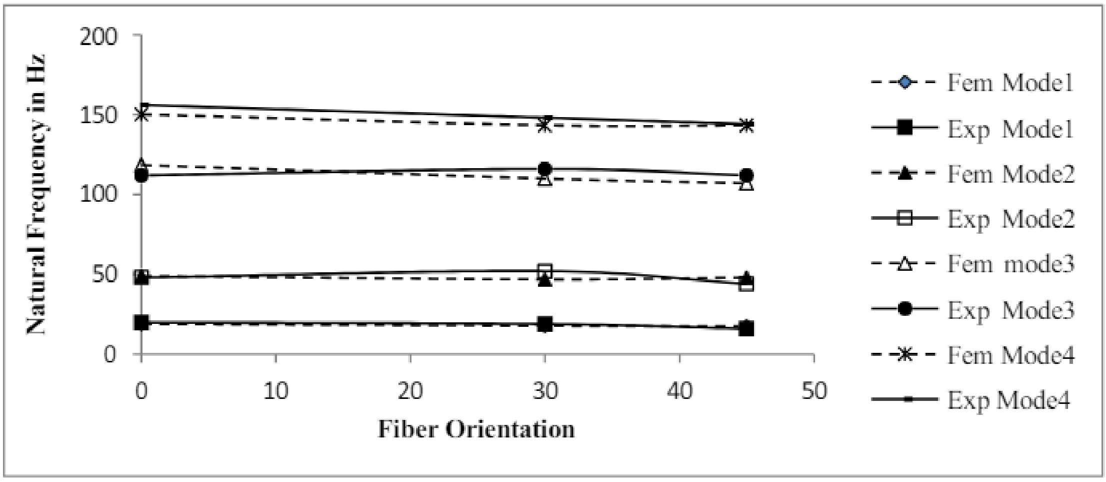

Figure 5.2: Variation of natural frequency with different fiber orientations of woven fiber composite plates

As observed from Figure 5.2, the natural frequency of laminated composite plates decreases for 1st and 3rd frequency but for 2nd natural frequency it decreases and then increases. When angle of ply changes from 00 to 300 the natural frequency decreases and then increases up to 450 for this material and geometry.

5.1.5 Effect of Aspect Ratio

In this study, we investigated how the aspect ratio of laminated composite plates affects their natural frequencies. We considered four different aspect ratios: 0.5, 1.0, 1.5, and 2.0.

Aspect Ratios Considered:

Aspect ratio (a/b) of 0.5 means the length (a) is half the breadth (b). For this ratio, the plate dimensions were set to length (a) = 120 mm and breadth (b) = 240 mm.

For aspect ratios of 1.0, 1.5, and 2.0, the length (a) was kept constant at 240 mm, while the breadth (b) varied to 240 mm, 160 mm, and 120 mm respectively.

The thickness of the plate (h = 0.0031 meters) remained the same across all aspect ratios.

Natural Frequencies:

We determined the natural vibration frequencies of these cantilever laminated woven fiber composite plates through both experimental testing and numerical simulations.

Figure 5.3 shows how the natural frequencies vary with different aspect ratios, comparing the experimental results with the numerical (simulation) results.

By examining this figure, we can understand how changes in aspect ratio (proportions of length to breadth) impact the vibrational behavior of the composite plates.

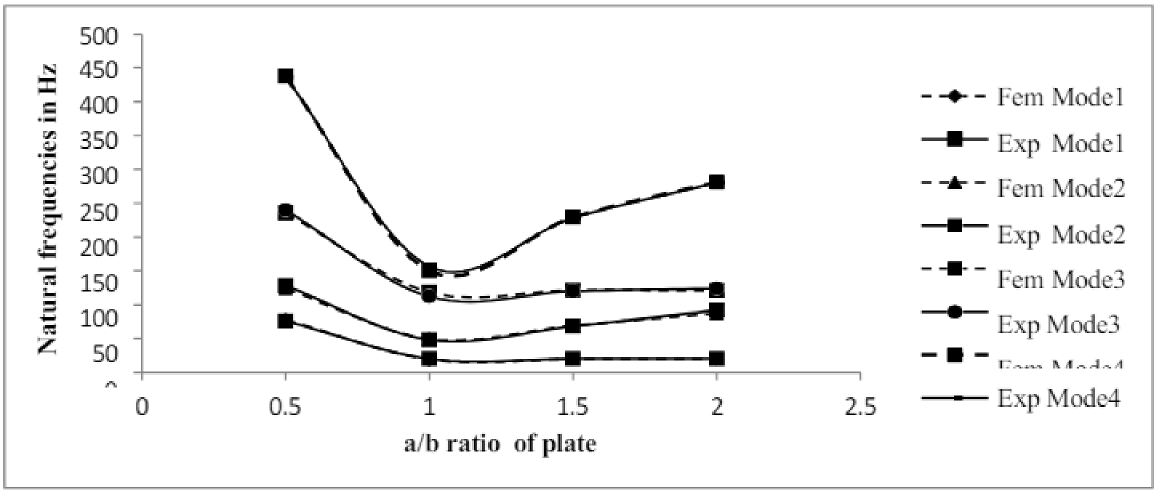

Figure 5.3: Variation of natural frequency with different aspect ratio of woven fiber composite plates.

As observed from Figure 5.3, there is decrease in fundamental natural frequency from 76 Hz to 20 Hz, with increasing value of a/b ratio from 0.5 to 2 experimentally. However, the frequencies of vibration of higher modes decrease significantly from aspect ratio a/b=0.5 to 1 and then the variation is not much significant except fourth lowest mode for both experimental and numerical result.

5.2 Buckling Effects on Woven Fiber Laminated Composite Plates

5.2.1 Comparison with Previous Studies

Numerical computations were done to test how well our current method can predict the natural frequencies of woven fiber composite plates. To make sure our program is accurate, we compared our results to data published by other researchers.

Specifically, we validated our method by comparing natural frequencies calculated using our finite element model with results from previous studies:

We looked at a graphite/epoxy composite plate with specific dimensions and fiber orientation (laminate sequence [02/±30]s) studied by Crawley in 1979 using FEM.

We also compared our findings to Chakraborty et al.'s 2000 study on woven roving [0]5 composite plates under clamped boundary conditions.

Additionally, we considered the work of Ju et al. in 1995, which looked at composite plates under various boundary conditions using FEM.

The comparison showed that our finite element model's predictions closely matched those from these previous studies. This agreement demonstrates that our approach is effective and reliable for analyzing the vibration characteristics of composite panels under different conditions. Essentially, it confirms that our method is producing accurate results similar to what has been found in earlier research.

5.2.2 Experimental and Numerical Results of Vibration

Geometrical Dimensions:

The dimensions of the woven roving composite plates used in the study are:

Length (a) = Width (b) = 0.24 meters

Thickness (h) = 0.0031 meters (for an eight-layer configuration)

Material Properties:

The material properties of the woven roving composite plates were determined through tensile testing according to ASTM standards. The key properties used in the numerical studies are:

Young's Modulus (E11 = E22) = 7.4 GPa

Shear Modulus (G12 = G23 = G31) = 2.15 GPa

Poisson's Ratio (v) = 0.17

Parameters Studied for Vibration Analysis:

- Effect of number of Layers: Investigating how changing the number of layers in the laminate affects vibration characteristics.
- Effect of fiber Orientations: Exploring the impact of different fiber orientations on vibration responses.
- Effect of aspect Ratio: Studying how altering the aspect ratio (ratio of length to width) influences vibration properties.
- Boundary Conditions: Examining the effects of different boundary conditions (ways in which the plates are fixed or supported) on vibration behavior.

x

5.2.3. Effect of Number of Layers of Laminate

For In this study, we wanted to see how the number of layers in a laminate affects the natural vibration frequencies of woven fiber composite plates. To do this, we made four different types of laminates with varying numbers of layers: 8 layers, 12 layers, and 16 layers.

We then tested these composite plates under free vibration conditions, both in real experiments and through numerical simulations (using computer models). The plates were set up in a cantilever (fixed at one end) boundary condition

The results, showing how the natural vibration frequencies change with increasing layers of laminate, are displayed in Figure 5.1. This figure compares the experimental measurements with the numerical predictions. It helps us understand how the number of layers impacts the vibration characteristics of these composite plates.

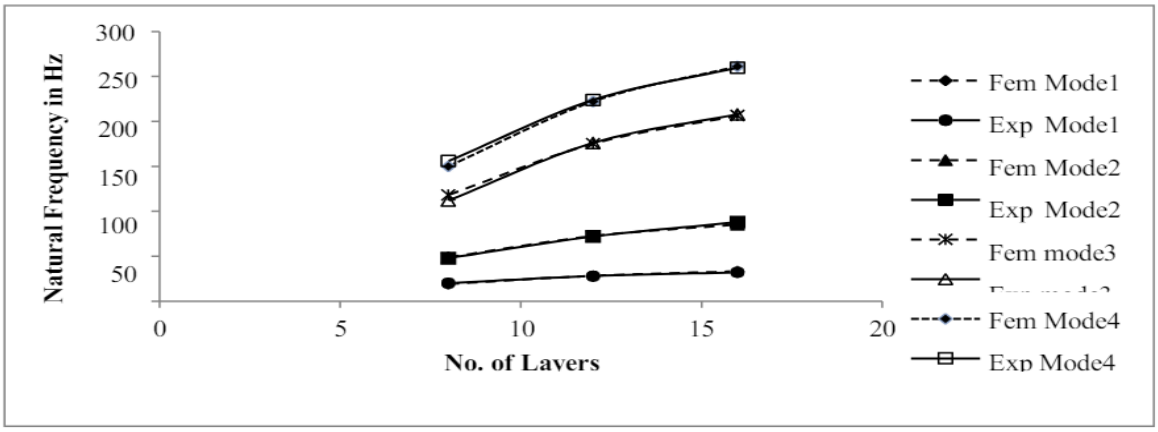

Figure 5.4: Variation of natural frequency with different no. of layers of woven fiber composite plates.

From Figure 5.4, it is observed that as the number of layers increases, the natural frequency also increases due to bending stretching coupling as excepted. There is a considerable Variation in the different modes of natural frequency made up of 12 and 16 layers whereas for 8 layers of composite plates it is less. This variation is much more significant for higher modes of vibration of woven fiber laminated composite plates.

5.2.3. Effect of Fiber Orientation

In this study, we looked at how different fiber orientations affect the natural frequencies of an 8-layer laminated plate. We considered three types of fiber orientations:

[(0/0)2]s: All fibers aligned in the same direction within each layer.

[(30/-30)2]s: Fibers oriented at ±30 degrees in alternating layers.

[(45/-45)2]s: Fibers oriented at ±45 degrees in alternating layers.

We studied the variation of natural frequencies using both experimental testing and numerical simulations (FEM) on cantilever composite plates. The results from our experiments and the FEM simulations showed good agreement. Fiber orientations lead to different natural frequencies in the composite plate. Both the experimental measurements and the numerical predictions (from FEM) matched well, indicating the reliability of our approach.

Figure 5.5: This figure presents the variation of natural frequencies for each fiber orientation, showing how they influence the plate's vibrational behavior

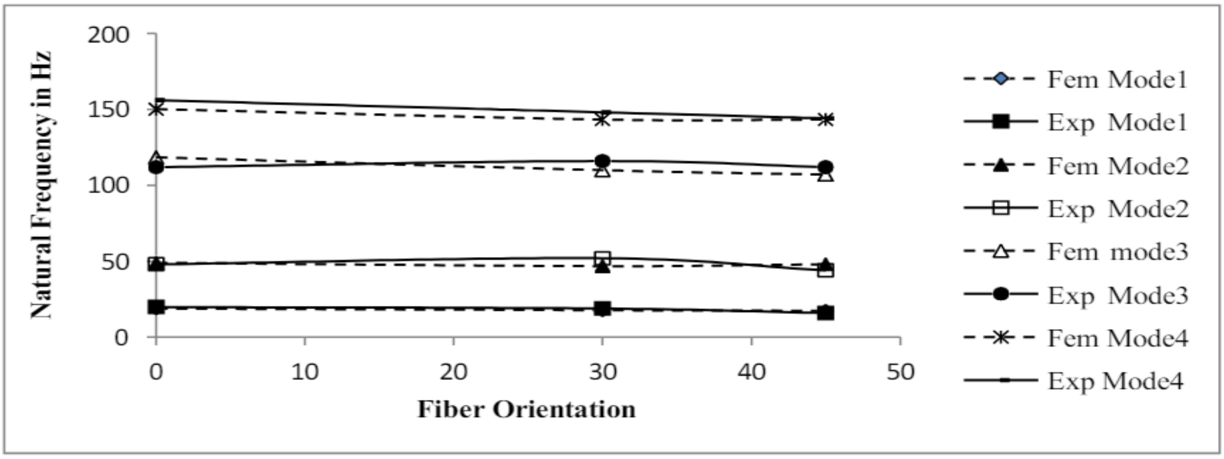

Figure 5.5: Variation of natural frequency with different fiber orientations of woven fiber composite plates.

As observed from Figure 5.5, the natural frequency of laminated composite plates decreases for 1st and 3rd frequency but for 2nd natural frequency it decreases and then increases. When angle of ply changes from 00 to 300 the natural frequency decreases and then increases up to 450 for this material and geometry.

5.2.4. Effect of Aspect Ratio

In this study, we investigated how the aspect ratio of laminated composite plates affects their natural frequencies. We considered four different aspect ratios: 0.5, 1.0, 1.5, and 2.0.

Aspect Ratios Considered:

Aspect ratio (a/b) of 0.5 means the length (a) is half the breadth (b). For this ratio, the plate dimensions were set to length (a) = 120 mm and breadth (b) = 240 mm.

For aspect ratios of 1.0, 1.5, and 2.0, the length (a) was kept constant at 240 mm, while the breadth (b) varied to 240 mm, 160 mm, and 120 mm respectively.

The thickness of the plate (h = 0.0031 meters) remained the same across all aspect ratios.

Natural Frequencies:

We determined the natural vibration frequencies of these cantilever laminated woven fiber composite plates through both experimental testing and numerical simulations.

Figure 5.6 shows how the natural frequencies vary with different aspect ratios, comparing the experimental results with the numerical (simulation) results.

By examining this figure, we can understand how changes in aspect ratio (proportions of length to breadth) impact the vibrational behavior of the composite plates

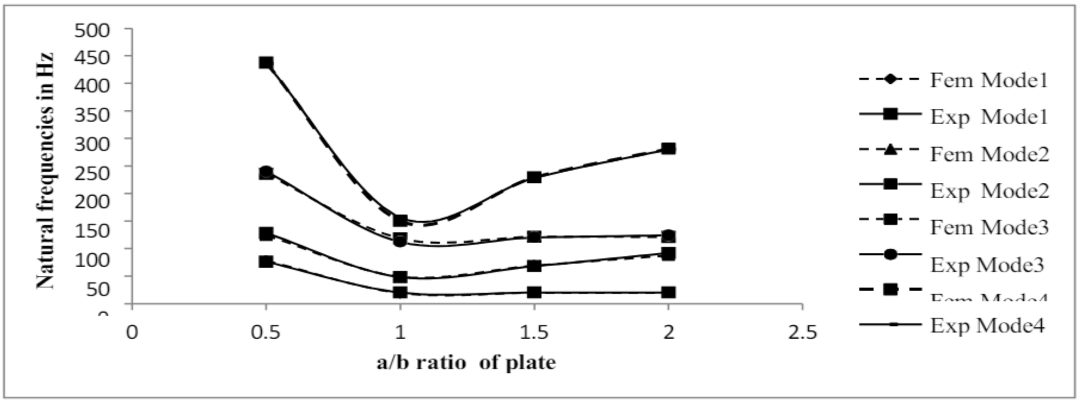

Figure 5.6: Variation of natural frequency with different aspect ratio of woven fiber composite plates.

As observed from Figure 5.3, there is decrease in fundamental natural frequency from 76 Hz to 20 Hz, with increasing value of a/b ratio from 0.5 to 2 experimentally. However, the frequencies of vibration of higher modes decrease significantly from aspect ratio a/b=0.5 to 1 and then the variation is not much significant except fourth lowest mode for both experimental and numerical result.

VI. Conclusion

6.1 Vibration of Composite Plates

The results of the experimental and numerical studies of vibration of laminated plates can be summarized as follows:

- The Effect of Different Parameters: We analyzed how the number of layers, aspect ratio (shape), fiber orientation, and boundary conditions (like free-free, cantilever, simply supported, and fully clamped) affect vibration. We found that our numerical predictions closely matched experimental tests, especially for cantilever and free-free conditions.
- Natural Frequency: Plates supported in a cantilever configuration have lower natural frequencies compared to simply supported and fully clamped plates. As the aspect ratio (a/b ratio) increases, the fundamental natural frequency decreases. Additionally, higher vibration modes decrease significantly as the aspect ratio moves from 0.5 to 1.
- Dependency on Fiber Orientations: The natural frequencies of the plates are strongly influenced by the orientation of the fibers. This finding indicates that designers have significant control over how these laminated composite structures respond dynamically. Specifically, for cantilever setups, increasing the orientation angle of the fibers leads to a decrease in natural frequency.

6.2. Buckling of Composite Plates

- Experimental Study: We conducted a detailed experiment to understand how woven fiber composite plates behave under static conditions, specifically focusing on plates with a C-F-C-F (clamped-free-clamped-free) boundary condition. Our experimental results closely matched the predictions from numerical simulations, showing good agreement.
- Test Frame Design: We designed and built a specialized compressive test frame to perform buckling experiments under both static and dynamic conditions.
- Effect of Boundary Conditions: Plates with fully clamped boundaries (restrained edges) exhibited the highest buckling load compared to plates with clamped-free or simply supported boundaries. This aligns with expectations, as edge restraint increases the stability of the plates.
- Impact of Fiber Orientation: Changing the orientation angle of the fibers significantly affected the critical buckling load. Increasing the ply orientation angle from 0 to [30/-30] or [45/-45] led to lower buckling load values, both in numerical simulations and experiments. Plates with a [0]8 layup (fiber orientation) showed the highest buckling load, while those with a [45/-45]2s layup exhibited the lowest.
- Influence of Plate Dimensions: Buckling loads decreased notably with changes in side-to-thickness ratios and aspect ratios (plate shape). Thicker plates and those with higher aspect ratios were less resistant to buckling.
- Effect of Layering: Increasing the number of layers in the composite plates enhanced stability resistance due to the bending-stretching coupling effect.

6.3. Parametric Instability of Composite Plates

The parametric instability study of woven fiber laminated composite plates in subjected to periodic in- plane loads is examined. From the detailed experimental and numerical study, the following observation can be made:

- Effect of Number of Layers: Plates with more layers exhibit higher excitation frequencies, indicating greater dynamic stability. Increasing the number of layers enhances the plates' ability to resist dynamic loads.
- Influence of Lamination Angle: The angle at which the layers are arranged (lamination angle) affects the instability region of the plates.
- Impact of Static Load Factor: Excitation frequencies decrease as the static load factor increases. Higher static loads lead to lower excitation frequencies.
- Role of Boundary Conditions: Different boundary conditions (like fully clamped, clamped-free-clamped-free, simply supported) play a crucial role in determining the instability region and response of square woven fiber laminated composite plates. Fully clamped plates exhibit the highest excitation frequencies compared to other boundary conditions.
- Effect of Plate Thickness: Plates with greater thickness are more dynamically stable, exhibiting higher excitation frequencies. Thicker plates are less prone to parametric instability compared to thin plates.
- Side-to-Thickness Ratio: Increasing the side-to-thickness ratio widens the instability region. Excitation frequencies generally decrease with an increase in side-to-thickness ratio, although not uniformly.
- Degree of Orthotropy: Plates with higher degrees of orthotropy (higher ratio of stiffness in one direction to another) experience instability at higher excitation frequencies due to increased stiffness. Conversely, excitation frequencies decrease with a decrease in the degree of orthotropy.

From the above discussions, it is clear that the instability behavior of composite plates is influenced by the geometry, material, ply lay-up, ply orientation, boundary conditions. So the designer has to be careful while dealing with structures subjected to harmonic loading. This can be used to the advantage of tailoring during design of composite structures. The study can also be used for structural health monitoring of composite structures.

VII. Scope for further work

Though in this research topic, some studies have been attempted for dynamic stability behavior of composites but still many areas are left which require further investigation. The possible extensions to the present study are as presented below.

- Dynamic Stability under Hygrothermal Conditions: The study can be expanded to investigate how woven fiber composite plates behave under varying temperature and moisture conditions, known as hygrothermal conditions.
- Delaminated Composite Plates: The focus can shift to studying delaminated composite plates, where layers of the composite separate under certain conditions, and how they respond to hygrothermal effects.
- Incorporating Damping Effects: Future research could explore the impact of damping on the instability regions of laminated woven fiber panels. Damping affects how vibrations and dynamic loads are absorbed within the composite structure.
- Material Nonlinearity: Including material nonlinearity in the formulation would extend the analysis to account for how materials behave beyond linear relationships, providing a more comprehensive understanding of dynamic stability.
- Experimental Investigations on Stiffened Plates and Shells: Beyond composite plates, there is a significant opportunity to conduct experimental studies on the dynamic stability of stiffened plates and shells. This involves exploring how structural reinforcements (stiffeners) affect stability under dynamic loads.

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