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Parametric Stability and Instability of Woven Fibre Composite Plates For Different Structures a Review

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ABSTRACT: This study focuses on exploring the behaviour of laminated woven fibre 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 fibre 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 fibre orientation angle and lamination sequence on buckling behaviour 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 fibre 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 behaviour of woven fibre 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.

KEYWORDS: 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 analysing 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 behaviour of dynamic systems in engineering applications. A detailed examination of the vibration and buckling behaviour 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. RELATED WORK

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 fibre 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 fibre 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 modelling strategies are reviewed recently by Mahmood et al. [2011].

Laila [2008] presented aero elastic 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 aero elastic 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 in plane 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. METHODOLOGY

The mathematical framework for analysing 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 analyse 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.

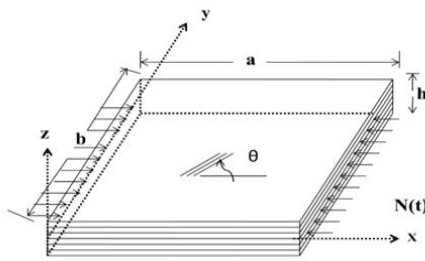


Figure 3.1: Laminated Composite Plate under in-plane harmonic Loading

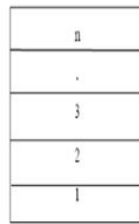


Figure 3.2: Lamination sequence

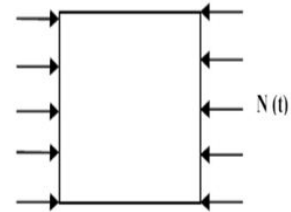


Figure 3.3: Plan-form subjected to in-plane load N (t)

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.

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

3.2 CONSTITUTIVE RELATIONS

A macro-mechanical analysis was carried out to establish the relationship between the forces and general strains of a laminate. The elastic behaviour 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

v12 = Major Poisson's ratio

v21 = Minor Poisson's ratio

The stress strain relation for the Kth lamina is,

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

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

$$[Q_{ij}]_k = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \text{ For } i, j = 1, 2, 6 \quad [Q_{ij}]_k = \begin{bmatrix} Q_{44} & 0 \\ 0 & Q_{55} \end{bmatrix} \text{ For } i, j = 4, 5$$

3.3 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

3.4 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,

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

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

3.5 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

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

3.6 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 discretised structure. The program features and flow charts, used in this study are presented in the Appendix..

IV. EXPERIMENTAL RESULTS

4.1 FREE VIBRATION OF WOVEN FIBER LAMINATED COMPOSITE PLATES

4.1.1 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 fibre 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 analysing 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.

4.1.2 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 fibre 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 behaviour.

4.1.3 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 fibre 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 4.1. 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.

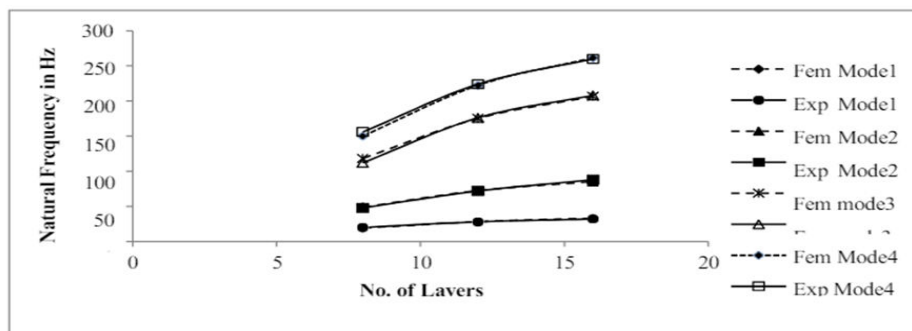


Figure 4.1: Variation of natural frequency with different no. of layers of woven fibre composite plates.

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 expected. 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.

4.1.4 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 fibre 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 4.2: This figure presents the variation of natural frequencies for each fiber orientation, showing how they influence the plate's vibrational behaviour.

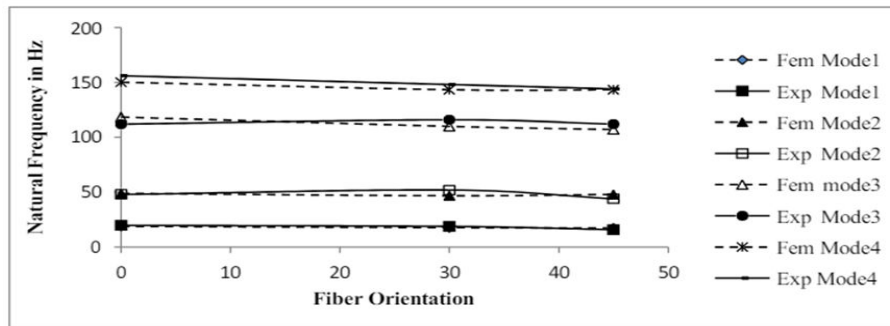


Figure 4.2: Variation of natural frequency with different fibre orientations of woven fibre composite plates

As observed from Figure 4.2, 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.

4.1.5 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 behaviours of the composite plates.

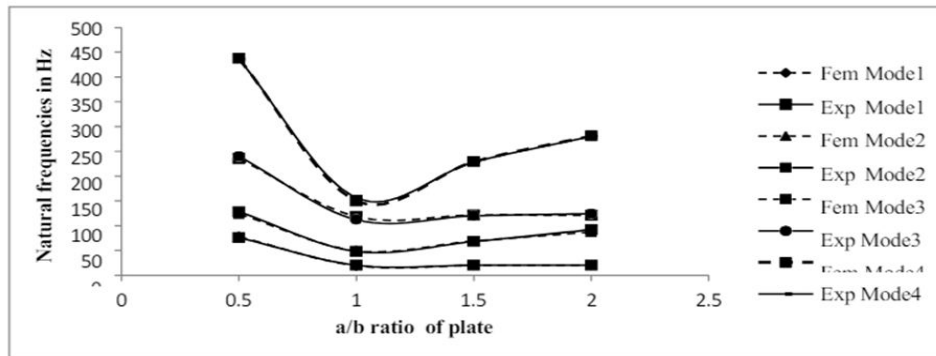


Figure 4.3: Variation of natural frequency with different aspect ratio of woven fiber composite plates.

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.

V. CONCLUSION

5.1 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.

5.2. 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.

5.3 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..

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