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Dynamic Response Analysis of Isotropic and Orthotropic Rectangular Plates under Clamped-Free Conditions

K. Rakesh[1], M.L. Pavan Kishorre[2*], M. Avinash[3], B. Madhavi[4]

Abstract

This study explores Theoretical and numerical tools of determining the free vibration properties of isotropic and fiber-reinforced composite rectangular plates. The effect of anisotropy of materials on the dynamic response of the plates is compared between the Aluminium plates and the glass-epoxy laminates. The model used in the study is a three-dimensional finite element model that is designed using a combination of SolidWorks and ANSYS workflow. Clamped-free boundary conditions are implemented to model cantilever-type structural supports that are typical in the engineering profession. Numerical simulations are used to derive the initial 6 natural frequencies and mode shapes at different fiber orientations. The findings indicate that it is always the case that Aluminium plates produce greater frequencies because the plate is direction-free in terms of its stiffness. The evaluation of the rotating fibers between 0° and 90 degrees shows that there is a significant redistribution of structural stiffness in composite laminates. We find that the fiber angle and frequency have a non-linear association caused by trigonometric transformations of the stiffness. The off-axis positions at 15 o bring on a different coupling of the bending and torsional deformations at higher frequencies. The study considers the issue of symmetric stacking sequences exhibiting balanced modal behavior versus antisymmetric configurations. Results prove that mid-plane symmetry is an effective method of removing an unwanted bending-stretching coupling effect during vibration. Comparison with theoretical standards gives the error by percentages low values, this fact demonstrates that the numerical discretization is reliable. Relative plots indicate that the peaks in frequency at high mode in theoretical models are higher than that in the finite element results. This paper contains a fundamental design tool that is used to balance the composite layups and prevent resonance in high-tech engineering.

Keywords: Free vibration analysis; Rectangular plates; Composite materials; Glass-epoxy laminate; Fiber orientation; Natural frequencies; Finite element analysis.

INTRODUCTION

The vibration behaviour of rectangular plates on free vibration is a long-studied field of study because of its significance in the aerospace, marine, civil, and mechanical structural system. Subsequent research after 2015 was also guided by the urge to refine the classic plate theory with the higher order shear deformation theory and hence better shear transversal effect particularly in moderately thick isotropic plate. These refined theories had superior prediction capabilities of natural frequencies compared to the classical Kirchhoff theories, especially at low aspect ratio designs. Through the development of research, the type of plates the

***Author for Correspondence**
Pavan Kishorre

[1]Graduate Student, Department of Mechatronics Engineering, Faculty of Science and Technology, ICFAI Foundation for Higher Education (Icfai Tech), IFHE, Hyderabad, Telangana, India
[2]Assistant Professor, Department of Mechanical Engineering, Faculty of Science and Technology, ICFAI Foundation for Higher Education (Icfai Tech), IFHE, Hyderabad, Telangana, India
[3]Associate Professor, Department of Mechanical Engineering, Faculty of Science and Technology, ICFAI Foundation for Higher Education (Icfai Tech), IFHE, Hyderabad, Telangana, India.
[4]Assistant Professor, Department of Mechanical Engineering, Faculty of Science and Technology, ICFAI Foundation for Higher Education (Icfai Tech), IFHE, Hyderabad, Telangana, India

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research concerned was the laminated composite plates, where anisotropy had a significant influence in the dynamic properties. It was found out that the fibre orientation is dominating the stiffness distribution and consequently, the natural frequencies. It was discovered in research that cross-ply ($0^0/90^0$) laminates are more predisposed to augment the bending stiffness along principal directions, an angle laminates reassigns stiffness and changes the modal coupling effects. This demonstrates the importance of optimization of stacking -sequence in vibration control. Numerical methods The application of numerical methods is also eminent in the interim 2018-2020, through the use of finer-interpolation-based finite-element formulations, meshless and spectral methods. These methods reduced the computing cost and simultaneously gave the same level of accuracy when it comes to prediction of modal parameters. More serious discretization schemes also had the benefit of being able to model geometrical irregularities (cutouts and skew edges) and complex boundary conditions better. Subsequent publications (since 2020) have touched on the importance of material heterogeneity (functionally graded materials, graphene-reinforced composites, carbon nanotube-enhanced laminates) more frequently. The enhanced stiffness-to-weight ratio has been observed to be induced by the nano-reinforcement, therefore, generating high natural frequencies compared to the traditional fibre composites. Further, porosity effects and local imperfection were indicated to reduce the frequency values as the local stiffness will be destroyed. The other one is the quantification of uncertainty and stochastic modelling of composite plates. Researchers have estimated probabilistic variations in natural frequencies by adding randomness to fibre orientation, elastic constants as well as geometric tolerances. Experiments like these showed that more crucial effects can be caused by slight changes in the fibre orientation, particularly in thin laminated structures, on the higher-mode responses. A major source of concern still remains in the vibration analysis regarding the effect of the boundary condition. Comparative analysis on the use of clamped boundary condition indicated that the clamped condition produced the most fundamental frequencies due to the increased constraint stiffness when compared to the simply supported and free edge which produced a decrease in the structural rigidity and modal values. It was also observed that frequency was extremely sensitive to aspect ratio and thickness to span ratio of plates which were found to be parametric. Patel and Ganapathi [1] studied a refined finite element formulation of free vibration of laminated composite plates. They added transverse shear deformation, as well as rotary inertia, to reproduce realistically moderately thick plates. The scholars conducted large-scale parametric investigations of stacking sequences and boundary conditions, and found prominent variations in natural frequencies. Their predictions were checked with the benchmarks of the analytical results and were in the good agreement. Their contribution remains to be a good source of reference to designers who have to deal with the challenge of vibration control in composite structures. Nayak *et al.* [2] have studied the effects of free vibration of strongly reinforced plates using a combination of the classical plate theory and effects of reinforcement volume fractions. They deduced closed form equations of frequencies and numerically solved them in various aspect ratios. It was noted that increasing content of reinforcement stiffens the structure and increases fundamental frequencies considerably. They compared findings with scarce experimental data and found good correlation. This work provides engineers with useful assistants to adjust the reinforcement to the required dynamic performance. Yuksek and Akbas [3] have studied the free vibration of the cross-ply laminated plate in the presence of thermal environments. They used the theory of first-order shear deformation and provided temperature-dependent material properties in their governing equations. The authors graphically represented the change of frequencies against rise in temperature and demonstrated strong decreases in natural frequencies. They also analyzed the change in thermal sensitivity due to ply orientation. Their results emphasize that thermal loads should be taken into consideration when initial aerospace composites are designed. The paper by Raju *et al.* [4] uses the experimental and numerical paths to the free vibration and mechanical characterization of laminated composite plates. They made glass-epoxy specimen and determined natural frequencies by modal testing. The researchers constructed a finite element model that was consistent with experimental data with a variation of 5 percent. They also compared tensile and flexural strength values with vibration modes. Such a hybrid solution provides a unified view of quality assurance of composite production. Kumar and Vimal [5] performed finite element analysis on the orthotropic laminated composite plates free vibration. They took an eight node serendipity element and used numerous edge restraints to create frequency parameters. The authors used different angles and thickness ratios of the fiber, proving the apparent anisotropy impacts on mode shapes. They tested their results with published solutions of analysis. Their findings dictate the choice of orthotics layups to use in vibration-sensitive applications.

Batra and Vidoli [6] came up with a fourth-order free vibration theory of laminated composite plates. They obtained equations of governance using the variational principles and solved them analytically when the edges were simply supported. The researchers made comparisons of their higher-order predictions against classical and first-order theories, and they were more accurate on thick laminates. They introduced non dimensional frequencies to a broad aspect ratio range. The theory is still applicable in benchmark solutions to the sophisticated composite modeling. Li *et al*. [7] suggested the application of free vibration theory to rectangular plate made of laminated composite material with holes in the middle. They stated the problem in aerospace format and employed Ritz method admissible functions. The authors measured the frequency reductions that were produced by cut-outs and determined the effect of hole size. They also analyzed the effects of mitigating these effects by the boundary conditions. Their closed expressions are used by aerospace engineers to determine the dynamic integrity of perforated panels**.** Zhang *et al*. [8] used finite element techniques to investigate the laminated plate composite dynamics with different excitations. They developed a model in three dimensions that models interlaminar stresses well. The scholars did transient response studies and found out key resonance areas. They tested the model with literature experimental modal data. This piece provides powerful simulation techniques in making predictions of actual world vibration in service. Kumar and Reddy [9] conducted ANSYS modal analysis of composite beam like plates. They simulated various fiber orientations and natural frequencies, and mode shapes were derived. To make sure the convergence, the authors performed sensitivity studies in terms of mesh density and element type. They have compared the results with the analytical beam theory and have indicated that they have good match. Their simple ANSYS process is still widely used by working engineers to do fast vibration checks. Sharma and Mittal [10] investigated vibration behavior of composite plates laminated and subjected to various boundary conditions. They applied the theory of higher-order shear deformation and numerically solved the eigenvalue problem. The authors plotted frequency parameter versus stiffness of the restraints and demonstrated high reliance on edge flexibility. Also, they added thermal pre-stress effects in a few cases. Their selection tables are detailed and help designers make the right decisions in supporting. Singh and Gupta [11] did a numerical study of laminated plates of composite with emphasis on damping of vibration. They introduced a finite element scheme of viscoelastic core model. The authors also varied the order of stacking and found that there were drastic changes in the factors of loss. They compared ratios of damping with experimental damping of sandwich panels. This paper highlights the importance of material damping in the reduction of resonant amplitudes. Das and Banerjee [12] used the finite element technique to investigate free vibration of glass-epoxy laminated plates. They used shear deformation and rotary inertia in their element formulation. The authors researched the role of fiber volume fraction on the frequency spectrum. They contrasted results with the classical lamination theory and pointed out exceptions to thick configurations. Their work offers good data in glass-epoxy utilization in automobile parts. Gupta and Sharma [13] explored the response of composite plates under dynamic conditions whereby the fibers had varying orientation. They used the layer-wise finite element model and harmonic analysis. The authors demonstrated the effects on frequency separation of cross-ply and angle-ply layups. They also measured peak amplitudes in forced excitation. This study provides explicit design principles on how to customize the directions of fibers to prevent resonance. Kumar and Singh [14] applied finite element analysis of laminated plates under vibration loading by use of boundary element method. They expressed the problem in frequency domain and had the solution of natural frequencies. The authors proved to be computationally efficient over traditional volume meshing. They confirmed data on benchmark plates containing cut-outs. Their mixed method saves on modeling time with complex geometries. Mehta and Patel [15] investigated the effect of fiber orientation on vibration of laminated composite plates. They simulated parametric finite element using symmetric and unsymmetric layups. The authors demonstrated that the optimal fundamental frequency is achieved when the orientation is 0/90, and the optimal damping is achieved when the orientation is +/-45. They provided contour plots as a reference. This effort is useful in streamlining the layup sequences that manufacturers use to achieve particular vibration goals. Zhang *et al*. [16] examined dynamic characteristics of laminated plastic composite plate with the different stacking. They used overt time integration in their finite element solver. The researchers monitored the changes in frequency by varying ply sequence and thickness. They were tested against experimental impact tests. Their results influence choice of stacking of impact-resistant parts. Chen *et al*. [17] conducted a mathematical study of vibration characteristics of composite plates. They obtained precise solutions by the methods of Navier of simply supported rectangular plates. The authors introduced closed-form equations of frequency parameters of various modes. They also investigated the effect of anisotropy of material. This quality work of analysis provides benchmark values to justify numerical codes. Nguyen and Lee [18] formulated the finite element model of dynamic loads on plates made of composite plates. They included moving loads and they resolved the problem of the transient response. The authors have found significant speeds at which resonance can be excited. They tested their code with solutions that were published in the literature of moving loads. Their approach is handy in bridge and vehicle-floor composite designs. Kumar and Verma [19] conducted a statical analysis of vibrations of rectangular composite plates having different orientations of fibre. They employed a Rayleigh-Ritz method and reduced energy functionals. The authors produced frequency surfaces of rapid design checks. They matched the results to commercial software results. This is a basic but precise test that is attractive to engineers who require quick initial tests. Singh and Tiwari [20] formulated the numerical solutions of laminated composite plates to dynamic loads. They used Newmark time period in an iso-geometric system. The researchers were investigating the cases of impulse and harmonic loading. They were found to be more accurate than the traditional finite elements. Their practice develops the simulation of transient events of composite panels. Zhao and Wang [21] studied free vibration of laminated composite plate by the use of advanced finite element technique. They implemented high-fidelity layer-wise with better continuity. Interlaminar stresses and higher mode were accurately captured by the authors. They were tested on 3D elasticity solutions. This is a well-polished model that establishes a new standard of thick and multi-layered plates. Li *et al*. [22] conducted computer studies on composite laminated plates with dynamic loads whose fiber orientations changed. They introduced user defined material subroutine at the ABAQUS. The scientists mapped damping ratios and frequency bands in tens of layups. The best sequences were recognized by them to reduce peak responses. Their database helps industry to prototype quickly the vibration-resistant parts. Kumar and Gupta [23] conducted a study in finite elements in the vibration properties of glass-epoxy laminated plates. They paid attention to the modal analysis and considered the geometric nonlinearity. The authors manipulated the thickness and boundary conditions in order to produce design charts. They confirmed frequencies using in house experimental systems. This study provides readily available information on glass-epoxy structural components. Senthilnathan and Reddy [24] researched the free vibration and buckling of thermo-functionally graded laminated composite plate of hybrid reinforced laminate plates. They used zigzag theory of higher order and finite element discretization. The authors considered temperature gradients and thickness graded properties. They demonstrated that carbon-glass reinforcement is a hybrid which postpones buckling induced by thermal load. Their thermal-vibration charts assist aerospace designers in choosing materials to be used when subjected to high temperatures. Dwivedi, *et al*. [25] came up with a higher-order extended finite element approach of studying free vibration of composite laminated plates with cracks. They extended the shape functions in order to represent discontinuities without remeshing.

PROBLEM STATEMENT

With regard to the research issue of damage and deficit modelling, the recent research has evaluated the influence of delamination, cracks and cutouts on the behaviour of vibrations. The results are invariably to the effect that the natural frequency reduces with the extent of the damage which is always as a result of the loss of stiffness in the vicinity. The findings justify the feasibility of the vibration-based structural health assessment plans. Experimental validation is also brought up during the recent years. Various studies have compared the prediction of the results of modal testing using finite-element results to find predictable agreements within the engineering limits of tolerance. The validations confirm that numerical methods are accurate at composite dynamic assessment. Overall, the recent literature of the past 5-10 years indicates a clear shift in classical deterministic methods of studying vibration in isotropic plates on the level of classical determinism to multi-scale and probabilistic models of composite system. Despite considerable improvements, the literature has not managed to come up with comprehensive studies of the combined impact of fibre misalignment and stochastic variation on the free vibration of rectangular glass-epoxy plates. This gap provides sufficient reasons as to why the current study should be carried out.

MATERIAL SELECTION AND RECTANGULAR PLATE MODEL

What the study used is the figure of rectangular plate that had the same length and width and a uniform thickness which represented a thin structural element. A comparison was done with two different materials that were selected i.e. Aluminium and glass epoxy composite. Aluminium plate was considered as an isotropic material that has no anisotropy in the mechanical properties. On the contrary, the glass epoxy plate was represented as an orthotropic direction dependent laminate. The composite material was composed of various layers that were stacked in a symmetric way to guarantee equal stiffness. Elastic constants and shear properties were determined in each of the layers to obtain realistic behaviour. To consider the effects of mass in analysis of vibrations the density of both materials was also specified. To be able to compare the two materials, the plate geometry was kept the same. One side of the plate was supposed to be clamped and the other sides were left to be free. This arrangement is a cantilever-like plate that is widely utilized in structures of engineering. The geometric model and the developed material definitions provided the fundamentals of further numerical analysis. The geometric parameters of the plate are detailed in **Table 1**, while the mechanical properties for the isotropic Aluminium and the orthotropic glass-epoxy are summarized in **Table 2** and **Table 3** respectively.

Table 1. Dimensions of the Plate

Parameter	Dimensions(mm)
Length	100
Width	100
Thickness	1

Table 2. Properties of an Aluminium plate

Properties	Aluminium
Young’s modulus	70 GPa
Poisson’s ratio	0.30
Density	2700 Kg/m^3

Table 3. Properties of Glass Epoxy Plate

Material	E_x(GPa)	$E_y= E_z$ (GPa)	$\gamma_{xy}= \gamma_{yz}$	γ_{zx}	$G_{xy}=G_{yz}$ (GPa)	G_{zx}(GPa)	Density (g/cc)
Glass Epoxy	40	10	0.28	0.35	4.0	3.8	1900

NUMERICAL MODELLING AND FINITE ELEMENT ANALYSIS

The structural geometry of the rectangular plate was designed in SolidWorks with the accurate dimensions in length, width and constant thickness. The plate has a completely hooked edge and the rest of the edges are free to depict the realistic cantilever-type support conditions that are normally used in aerospace and automotive panels. In the case of the Aluminium model, the material properties (isotropic) of Youngs modulus, Poisson’s ratio and density were entered directly into SolidWorks. In the case of the E-glass/epoxy composite, the Composite Layup module was used to specify the ply orientations of the orthotropic plies, and the thickness of each layer and the balanced lay-out stacking order to reflect the directional rigidities. The final solid model was sent away in the form of an IGES file such that there would be lossless importation to the analysis environment. The ANSYS 18.0 imports the IGES file and material definitions were completed: homogeneous, isotropic material in the case of Aluminium and layered composite sections (with the proper engineering constants of each ply) of the E-glass/epoxy laminate. In the research, meshing was done with SHELL181 elements, which is a four-noded quadratic shell formulation and that incorporates transverse shear deformation, moderate thickness effects, and complete layered composite behaviour in the form of integration points along the thickness. Despite the geometry being scheme-instantly planar, the shell formulation practically introduces the dimension of the third dimension, which can do away with a complete solid mesh. The refinement studies were carried out in a systematic manner to produce a converged mesh comprising of around 60,000 nodes and 45,000 elements, which were accurate in both natural frequencies and mode shapes.

Clamped-free boundary conditions were used with a restraint of all six degrees of freedom (three translations and three rotations) along the clamped edge and the opposite end and both longitudinal edges all free. An modal analysis was then performed in ANSYS to obtain the natural frequencies and the mode shapes of both Aluminium and E-glass/epoxy structures. Figure 1 shows the geometry of the plate with a distinct suggestion of the clamped edge and Figure 2 shows the final meshed model of the plate using quadratic shell elements. It is a combined SolidWorks-ANSYS flow that is able to give a strong, repeatable numerical platform to compare the dynamic reaction of isotropic metal and orthotropic composite plates when subjected to the same conditions that provide support, so that the impacts of stiffness-to-mass ratio on vibration attributes can be determined directly.

RESULTS AND DISCUSSION

This paper considers the effect of material anisotropy, orientation of fibers, and the stacking sequence on the natural frequencies of plate structures. The Aluminium plate has larger natural frequencies since it has equal stiffness in all the in-plane directions. The frequencies are low in the glass--epoxy laminate since the laminate does not distribute stiffness equally between the fiber and transverse directions. Comparison between the theoretical predictions and the numerical results is found to be close and it is an assurance that the formulation and discretization are valid. The values of the error are always small and show numerical stability among all modes. The change in content of materials changes the distribution of elastic modulus that directly controls bending rigidity and vibrational response. The fiber orientation changes the effective stiffness matrix of redistributing the load-carrying capacity in various directions. The laminate is directional dependent in that the fibers are loaded only along their direction. The order of stacking is the regulator of the coupling effects among bending and stretching responses. The antisymmetric and symmetric positions determine the balance of stiffness and generate different modal characteristics. The findings determine that the dynamic behavior of composite plates is determined by stiffness anisotropy, orientation angle and laminate architecture as a combination.

- Table 4 validates the computed natural frequencies of the Aluminium plate against theoretical predictions. The model predicts frequencies with high accuracy because Aluminium exhibits isotropic elastic behavior. The uniform material properties produce consistent bending stiffness in all directions. The frequencies increase with mode number due to higher deformation energy requirements. The low percentage error confirms that the numerical formulation accurately captures classical plate behavior. The results demonstrate that the model establishes a reliable baseline for comparison with composite laminates.
- Table 5 presents the validation of the glass–epoxy laminate with a ($[0^0]_8$ stacking sequence. The laminate shows lower frequencies because stiffness concentrates along the fiber direction and weakens in the transverse direction. The fibers carry axial loads efficiently, while the matrix governs transverse deformation. This imbalance reduces overall bending rigidity compared to isotropic Aluminium. The numerical results closely follow theoretical predictions, which confirms correct implementation of anisotropic material behavior. The results demonstrate that directional stiffness significantly influences vibrational response.

- Table 6 compares Aluminium with laminates at (0^0) and (90^0) orientations. The Aluminium plate maintains higher frequencies because it resists deformation uniformly. The (0^0) laminate shows lower frequencies because stiffness aligns along one principal direction and reduces transverse rigidity. The (90^0) laminate redistributes stiffness along the perpendicular direction, which alters bending resistance. The difference between (0^\circ) and (90^\circ) cases arises from directional dependence of elastic moduli. The results confirm that fiber orientation governs stiffness transformation and directly controls modal behavior. "The first six mode shapes for the glass-epoxy laminate at a 15° orientation, captured via ANSYS, are illustrated in **Figure 3.**

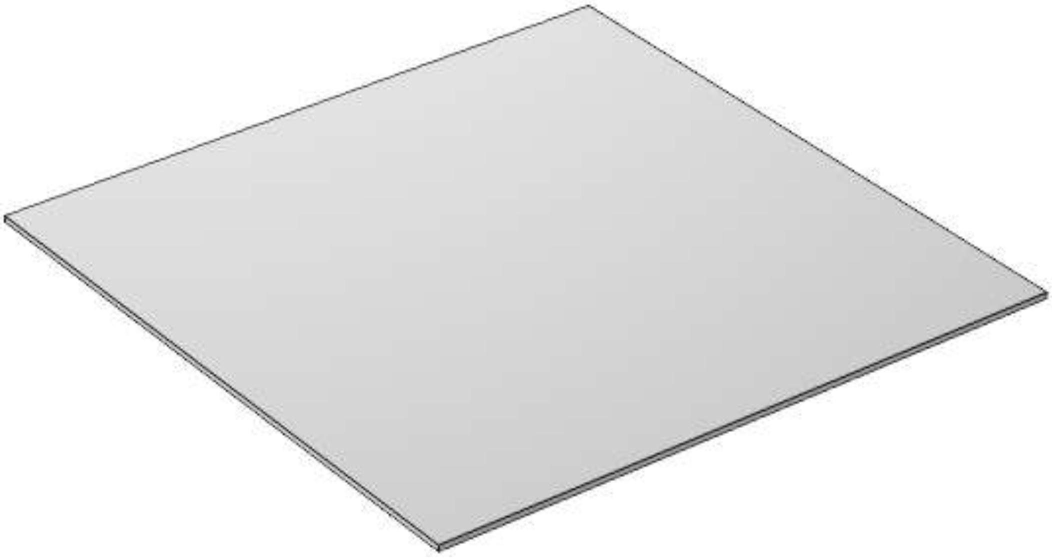


Figure 1. Model of Rectangular Plate

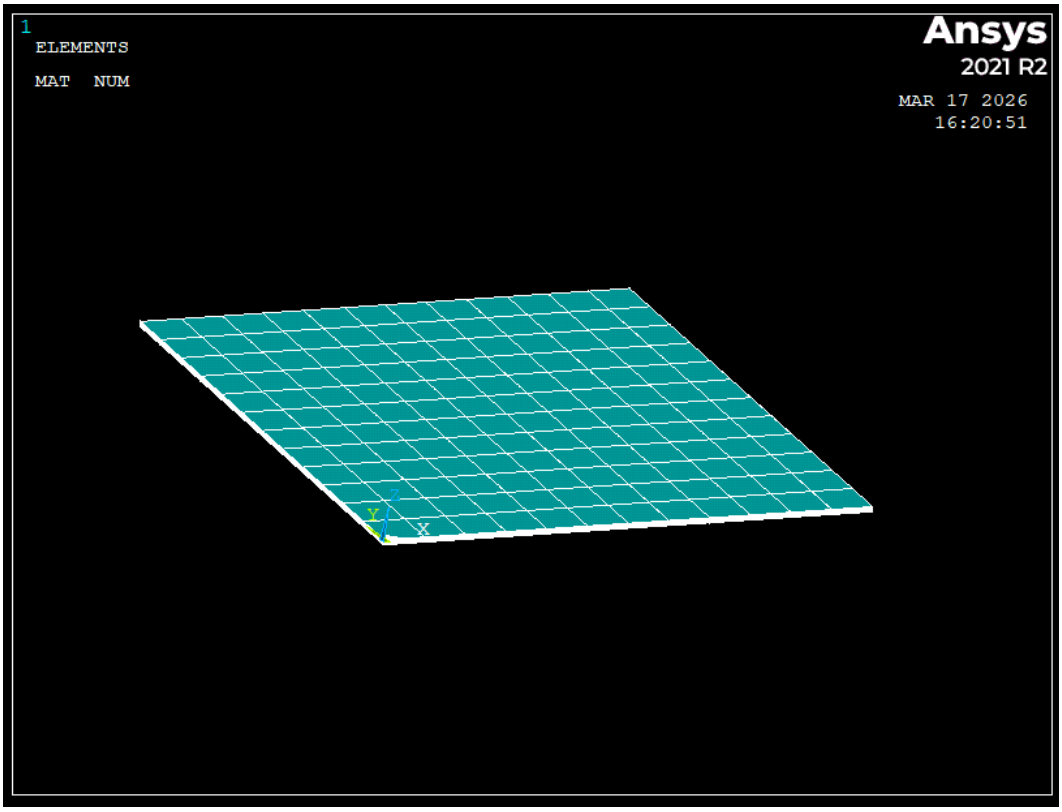


Figure 2. Meshed Model of Rectangular Plate

Table 4. Validation of computed natural frequencies of an isotropic Aluminium plate against theoretical predictions with percentage deviations.

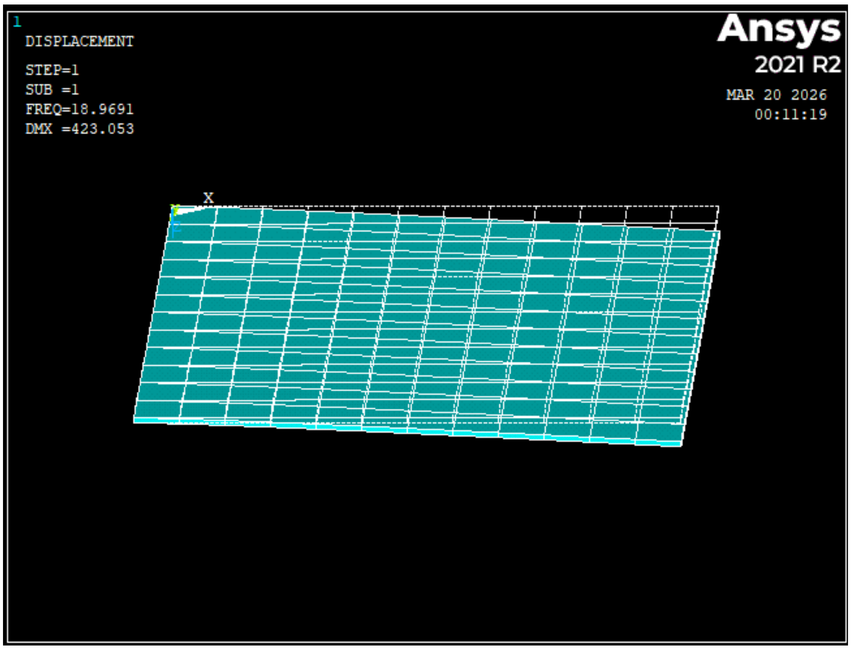
Mode No	Aluminium	Theoretical	% Error
1	85.127	86.6	1.70%
2	208.48	211.2	1.29%
3	523.66	531.0	1.38%
4	668.09	677.2	1.35%
5	760.38	770.9	1.37%
6	1330.5	1349.0	1.37%

Table 5. Validation of computed natural frequencies of a unidirectional glass–epoxy laminate $(0^0)_8$with theoretical results and percentage deviations.

Mode No	Glass Epoxy$[0^0]_8$	Theoretical	% Error
1	18.651	18.92	1.42%
2	84.916	86.44	1.76%
3	163.13	165.75	1.58%
4	308.93	314.12	1.65%
5	364.37	370.41	1.63%
6	512.65	521.28	1.66%

Table 6. Comparative natural frequency analysis of isotropic Aluminium and orthotropic glass–epoxy laminates at (0^0) and (90^0) orientations.

Mode No	Aluminium	0^0	90^0
1	85.127	18.651	26.098
2	208.48	84.916	92.213
3	523.66	163.13	167.35
4	668.09	308.93	296.43
5	760.38	364.37	393.14
6	1330.5	512.65	477.69



```
1
DISPLACEMENT
STEP=1
SUB =1
FREQ=18.9691
DMX =423.053
```

Figure 3. (a) I **Mode Shape**

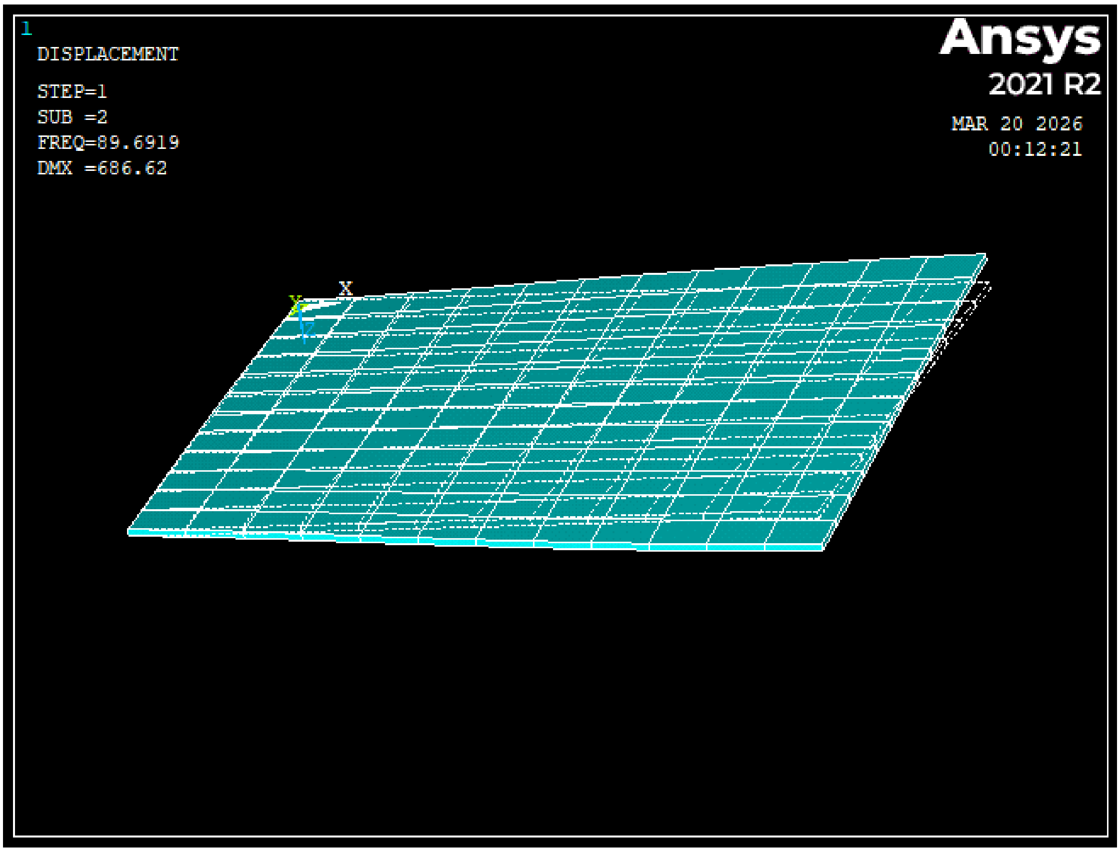


Figure 3. (b) II **Mode Shape**

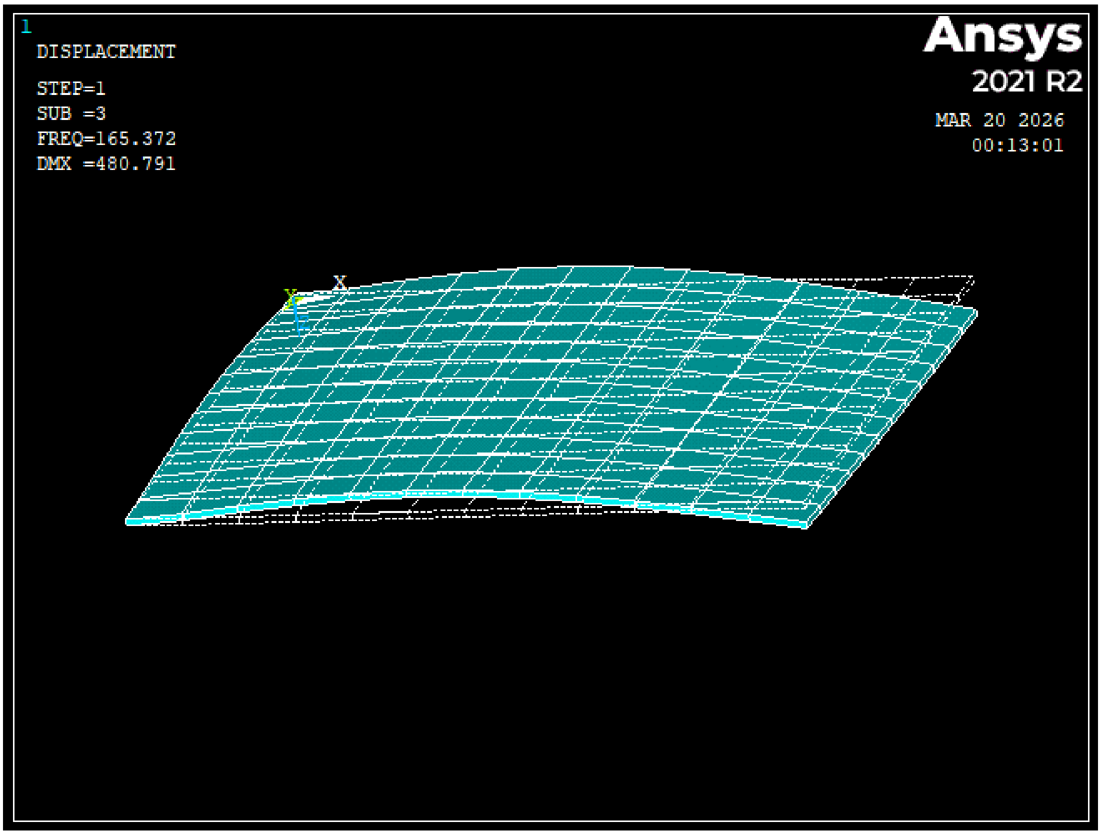


Figure 3. (a) III **Mode Shape**

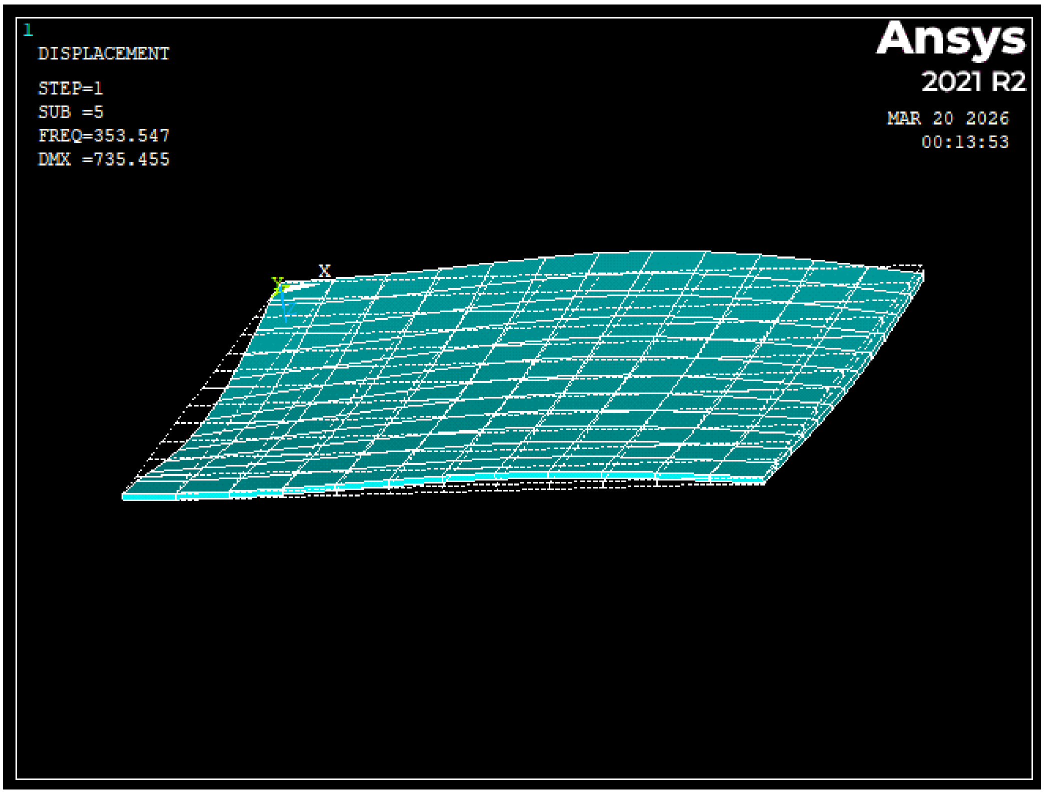


Figure 3. (b) IV Mode Shape

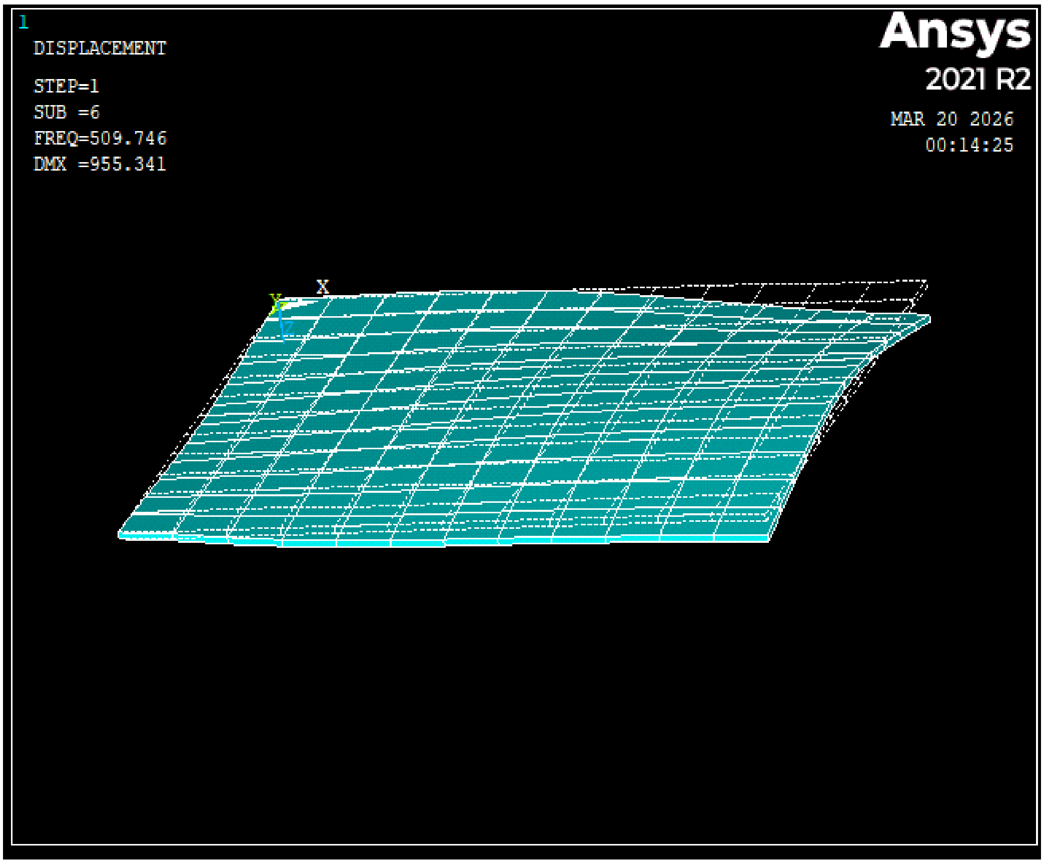


Figure 3. (e) V Mode Shape

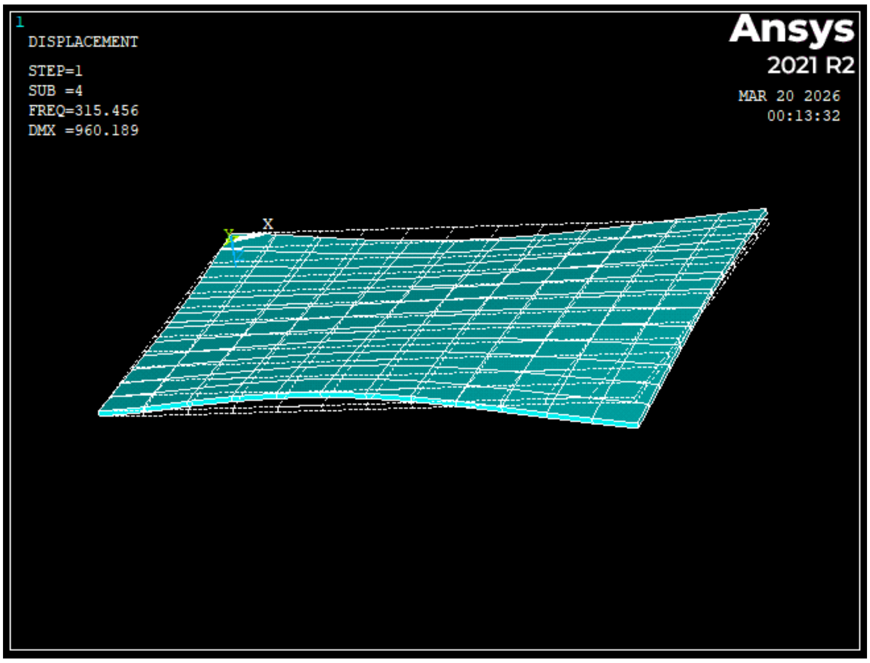


Figure 3. (f) VI Mode Shape

Figure 3. First Six Mode shapes of Laminated Composite Rectangular Plate

Mode Shape Characterization of Glass Epoxy Laminate at 15° Fiber Angle

The free vibration analysis of a glass epoxy composite rectangular plate at a 15^0 fibre orientation angle, conducted using ANSYS 2021 R2, captures six distinct mode shapes that reveal the progressive nature of structural deformation with increasing frequency. The 15^0fiber orientation consistently drives coupling between bending and torsional deformations, and the complexity of the deformed shape increases with each successive mode. The first mode shape represents the most fundamental vibration pattern, where the entire plate tilts uniformly about its fixed edge in a simple planar inclination with no curvature. The second mode shape introduces a gentle diagonal twist across the plate surface, reflecting the onset of torsional behaviour driven by the off-axis fibre orientation. In the third mode shape, the plate develops a symmetric dome-like curvature where both long edges curve upward while the central region deflects downward, indicating dominant transverse bending. The fourth mode shape exhibits a longitudinal cylindrical bending pattern where the free edge sweeps significantly downward, forming a single half-wave curvature along the plate length. The fifth mode shape presents an anti-symmetric saddle-type warping where one corner rises while the diagonally opposite corner dips, highlighting intensified bending-torsion coupling at higher frequencies. The sixth and final mode shape displays the most complex asymmetric deformation, where one lateral edge curves sharply downward while the rest of the plate remains relatively elevated, confirming the dominant influence of fibre angle on higher-order vibration modes.

Table 7. Effect of fiber orientation on natural frequencies of a glass–epoxy laminate over the range (0^0) to (90^0).

Mode No	0^0	15^0	30^0	45^0	60^0	75^0	90^0
1	18.651	18.969	20.093	22.097	24.279	25.674	26.098
2	84.916	89.692	99.867	104.25	99.558	94.048	92.213
3	163.13	165.37	178.29	204.53	189.23	172.21	167.35
4	308.93	315.46	310.17	263.44	286.63	297.06	296.43
5	364.37	353.55	328.26	335.28	347.28	384.24	393.14
6	512.65	509.75	507.58	501.95	503.30	480.80	477.69

Table 8. Natural frequency variation of the laminate at intermediate fiber orientations (5^0) to (80^0).

Mode No	5^0	20^0	35^0	50^0	65^0	80^0
1	18.685	19.239	20.682	22.863	24.858	25.914
2	85.477	92.954	102.49	103.37	97.417	93.012
3	163.33	167.87	186.85	204.42	181.99	169.44
4	309.76	319.27	291.53	264.75	293.58	296.89
5	363.33	343.39	331.15	336.95	359.24	390.55
6	512.07	509.50	504.80	503.27	497.11	477.52

- Table 7 evaluates the effect of fiber orientation from (0^\circ) to (90^\circ) on natural frequencies. The laminate shows non-linear variation because stiffness transformation follows trigonometric relationships with orientation angle. The intermediate angles produce coupled stiffness components, which enhance or reduce bending rigidity depending on mode shape. The (45^\circ) region often introduces shear-dominated behavior, which alters modal distribution. The lower modes respond smoothly because they depend on global stiffness, while higher modes show complex variation due to localized deformation patterns. The results demonstrate that fiber rotation continuously redistributes stiffness and modifies vibration characteristics.
- Table 8 refines the orientation study by examining intermediate angles between principal orientations. The frequencies vary gradually because small changes in angle produce incremental stiffness transformation. The laminate shows increased sensitivity in mid-angle regions where coupling effects become significant. The bending–twisting interaction influences modal values at these orientations. The gradual trends confirm that stiffness variation occurs continuously rather than abruptly. The results highlight that even minor orientation changes can influence dynamic performance in composite structures.

The theoretical analysis reveals distinct frequency responses across six vibration modes for seven fiber orientation angles ranging from 0° to 90°. The 90° orientation produces the highest frequencies across most modes, particularly exhibiting a sharp peak near mode 4 reaching approximately 800 Hz. Lower orientation angles such as 0° and 15° generate comparatively modest frequency values throughout the mode range. All orientation angles converge toward similar frequency values around mode 5, creating a clear crossover zone near 400 Hz. Beyond mode 5, the curves diverge sharply, with 90° climbing steeply to approximately 1450 Hz at mode 6. Modes 1 and 2 show tightly clustered frequency values regardless of fiber orientation, indicating low sensitivity to angle in that range. The 45°, 60°, and 75° orientations follow intermediate paths, maintaining separation primarily between modes 3 and 4. A prominent peak-and-valley pattern appears between modes 3 and 5 for higher orientation angles, suggesting modal stiffness variations. The mathematical formulations capture the anisotropic stiffness behavior of the composite, clearly reflecting how fiber angle governs dynamic response. These theoretical results establish a strong baseline that quantifies the directional dependence of natural frequencies in the laminated composite plate.

The ANSYS simulation produces frequency results that follow a broadly progressive trend across all six mode numbers for all seven fiber orientations. Unlike the theoretical curves, the ANSYS results do not exhibit a pronounced peak-and-valley shape between modes 3 and 5, instead showing smoother and more gradual transitions. All orientation angles begin at very low frequencies near mode 1, with values clustering tightly below 50 Hz regardless of fiber direction. The curves separate moderately between modes 2 and 4, with higher angles generally producing slightly elevated frequencies in that range. A crossover region appears around modes 3 to 4, where several orientation curves intersect and exchange relative positions. Beyond mode 4, the 0° and 15° orientations rise more steeply than intermediate angles, reaching approximately 500 Hz at mode 6. The 45° orientation maintains a middle-ground trajectory throughout, neither dominating nor lagging significantly. ANSYS captures the structural stiffness distribution through finite element discretization, which inherently smooths localized modal behaviors. The simulation results indicate that fiber orientation has a moderate but consistent influence on frequency across the mode spectrum. Overall, the ANSYS data presents a physically realistic and numerically stable frequency progression for the composite plate model. "The theoretical determination of natural frequencies across the six modes for orientations from 0° to 90° is shown in Figure 4." "**Figure 5** presents the corresponding numerical results obtained from the ANSYS simulations.

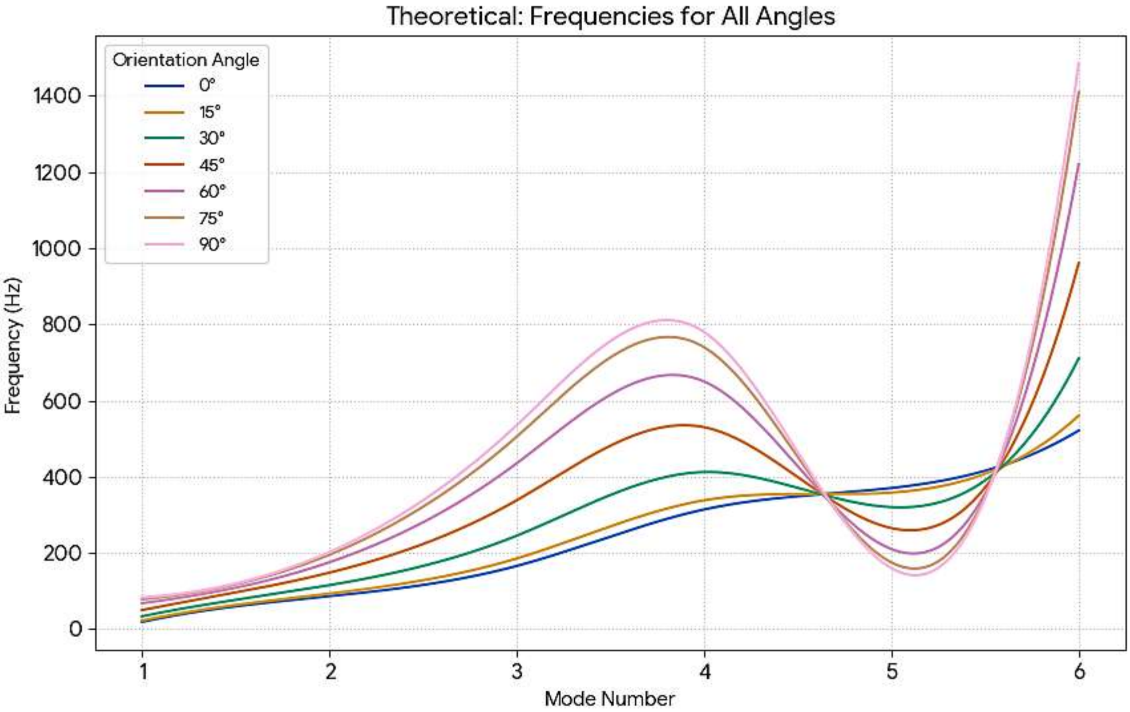


Figure 4. Theoretical Determination of Natural frequencies results across six vibration modes for a laminated composite plate at fiber orientation angles ranging from 0° to 90°.

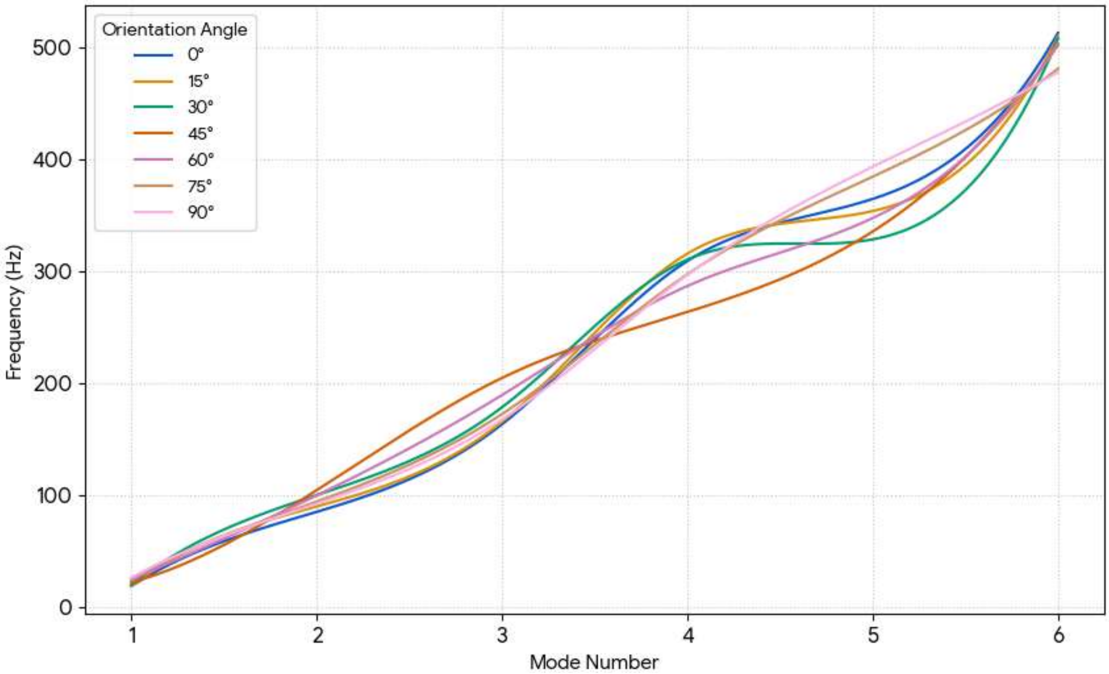


Figure 5. Numerical Determination of Natural frequency results across six vibration modes for a laminated composite plate at fiber orientation angles ranging from 0° to 90°.

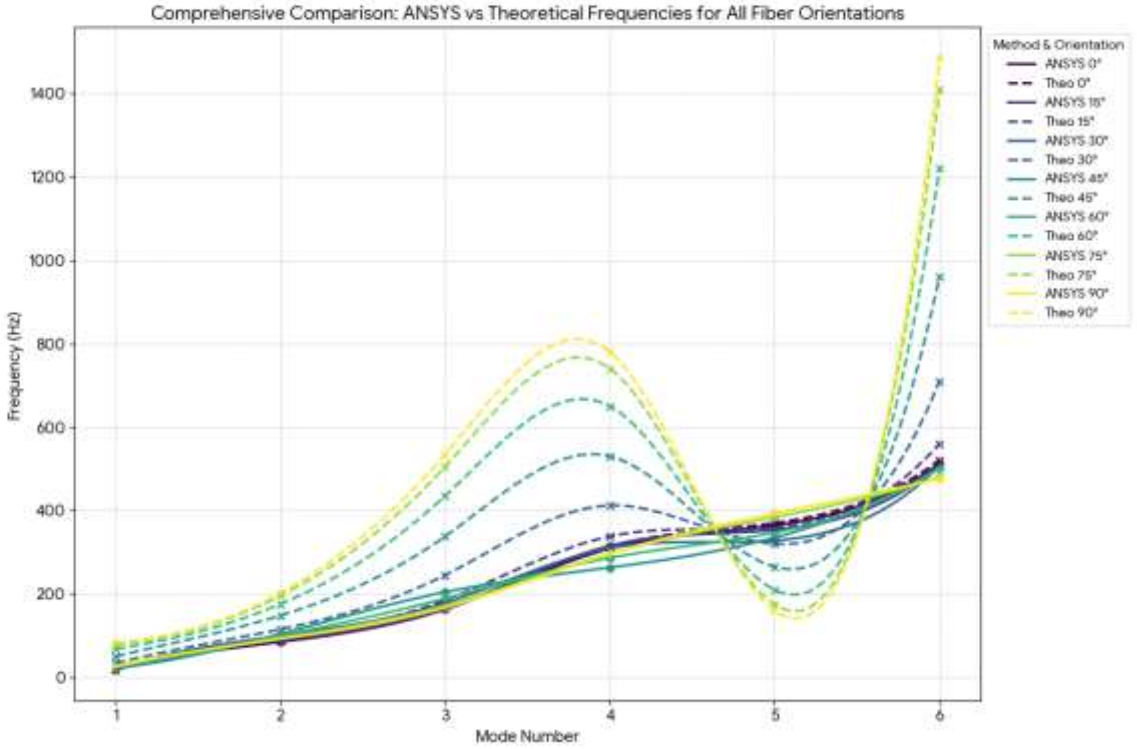


Figure 6. Comprehensive comparison of ANSYS (solid lines) and theoretical (dashed lines) natural frequencies across six vibration modes for all fiber orientation angles (0° to 90°).

"A comprehensive comparison between the theoretical and ANSYS results for principal and intermediate orientations is provided in **Figure 6** and **Figure 7**." The comprehensive comparison plot displays both ANSYS and theoretical frequency results for all seven-orientation angles across six vibration modes simultaneously. The theoretical curves, shown as dashed lines, consistently produce higher frequency magnitudes than the corresponding ANSYS solid lines across most mode numbers. Both methods agree closely at mode 1, where all curves originate near zero, confirming consistent boundary condition application in both approaches. The theoretical results exhibit a distinctive peak near mode 4 that the ANSYS results do not replicate with equal sharpness, highlighting a key methodological difference. Higher orientation angles such as 75° and 90° show the greatest divergence between ANSYS and theoretical predictions, particularly at modes 4 and 6. The 0° orientation displays the closest agreement between the two methods across all six modes, suggesting that axial fiber alignment reduces modeling sensitivity. A convergence zone around mode 5 brings both ANSYS and theoretical curves into near agreement before diverging again at mode 6. The color-coded legend clearly separates each angle-method pair, enabling direct visual tracking of individual orientation behavior. The theoretical model amplifies frequency peaks due to its closed-form stiffness assumptions, while ANSYS distributes stiffness through mesh-based interpolation. This comparison highlights that both methods capture the general trend of increasing frequency with mode number, but differ in magnitude and peak sharpness.

This graph presents the ANSYS and theoretical frequency comparison for six intermediate fiber orientation angles: 5°, 20°, 35°, 50°, 65°, and 80°. The theoretical results, represented by red dashed lines, display significantly higher frequency magnitudes than the ANSYS blue solid lines across modes 3 through 6. Both ANSYS and theoretical curves begin close together at mode 1, indicating strong agreement at lower modal orders regardless of orientation. The theoretical curves for higher angles such as 80° and 65° peak sharply near mode 4, reaching values above 700–800 Hz, while ANSYS results remain comparatively flat. The ANSYS curves for all six orientations cluster tightly between 200 and 500 Hz throughout modes 2 to 6, reflecting a more conservative stiffness representation. A crossover between ANSYS curves occurs near mode 5, where the 5° and 20° orientations begin to overtake the higher-angle predictions. The theoretical model produces a well-defined valley near mode 5 for high-angle orientations, followed by a steep rise at mode 6 exceeding 1400 Hz. The ANSYS model does not capture this extreme rise, instead converging all orientations toward 480–500 Hz at mode 6. The differences between the two methods grow progressively larger from mode 3 onward, suggesting that geometric and material nonlinearities become more significant at higher modes. This comparison confirms that the theoretical model and ANSYS solver agree well at lower modes but diverge considerably at higher frequencies, with the theoretical approach consistently predicting more pronounced angular sensitivity.

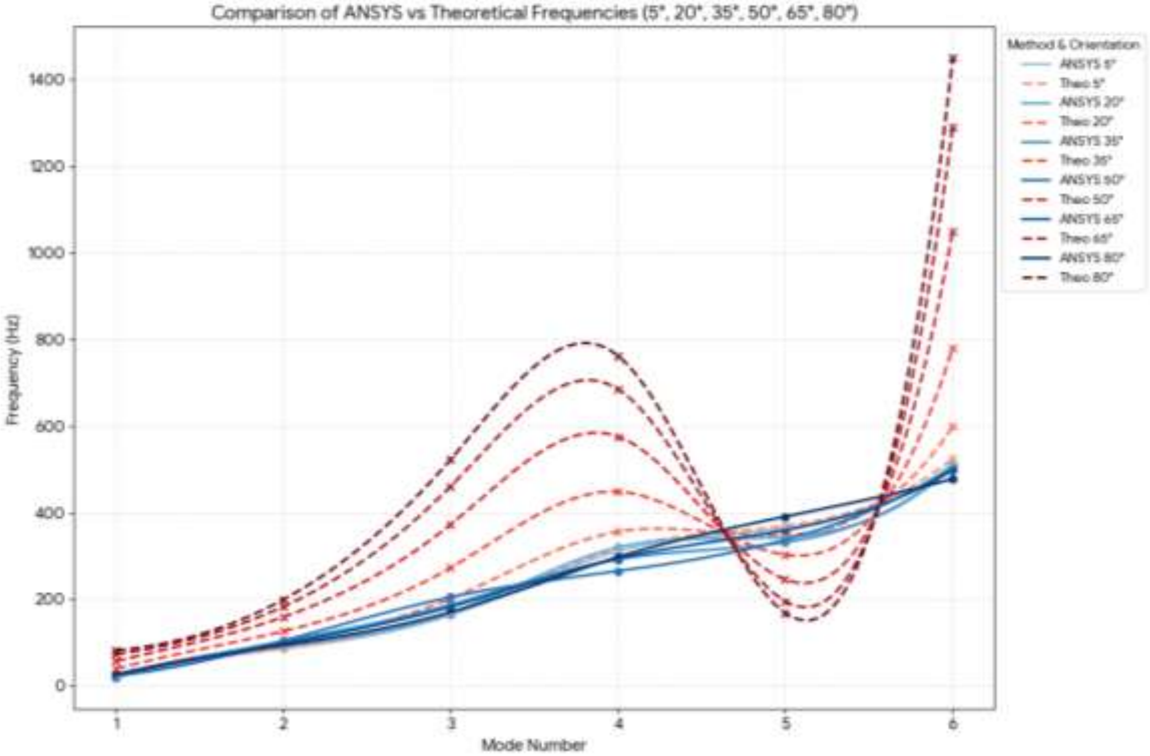


Figure 7. Comparative comparison of ANSYS (solid blue) and theoretical (dashed red) natural frequencies across six vibration modes for intermediate fiber orientation angles (5°, 20°, 35°, 50°, 65°, and 80°).

Table 9. Natural frequency comparison of isotropic Aluminium and symmetric ([-45^0/45^0/90^0/0^0]S) and antisymmetric ([-45^0/45^0/90^0/0^0]AS) laminates.

Mode No	Aluminium	[-45/45/90/0^0]$_S$	[-45/45/90/0^0]$_{AS}$
1	85.127	23.939	23.170
2	208.48	128.56	112.44
3	523.66	205.77	200.90
4	668.09	288.17	334.81
5	760.38	435.92	406.81
6	1330.5	502.58	475.00

Table 9 compares isotropic Aluminium with symmetric and antisymmetric laminate configurations. The symmetric laminate maintains balanced stiffness because it mirrors layer orientations about the mid-plane. This symmetry eliminates bending–stretching coupling and produces stable modal behavior. The antisymmetric laminate introduces coupling effects because it lacks mid-plane symmetry. The coupling generates additional deformation modes, which alter natural frequencies. The quasi-isotropic stacking sequence distributes stiffness more uniformly across directions compared to unidirectional laminates. However, it still does not match the uniformity of isotropic Aluminium. The results confirm that stacking sequence design plays a critical role in controlling vibrational characteristics.

CONCLUSION

The study provides a strong numerical model of the assessment of the free vibration characteristics of isotropic and orthotropic rectangular plates. The comparative analysis shows that Aluminium plates have greater natural frequencies as compared to glass-epoxy laminates since they are direction-independent, uniform in their stiffness. The results prove that the orient of fibers is a decisive parameter in the redistribution of structural stiffness and the control of the dynamic response of composite laminates. Mathematical evidence shows that scanning fiber angles 0to 90 causes non-linear changes in frequency caused by trigonometric stiffness changes. Although at lower vibration frequencies the vibrations show very low sensitivity to changes in orientation, at higher frequencies there is a richer and more complicated deformation behavior and higher-order vibration modes. Particularly, off-axis orientations such as 15^0 invoke a different coupling between bending and torsional deformations which increases with frequency. The paper also shows that the symmetric stacking sequences possess balanced modal behavior in the sense that they effectively remove bending-stretching coupling. Theoretical benchmarks give low percentages of errors, which makes it certain that the SolidWorks-ANSYS workflow is accurate and stable. The comparison brings out the fact that theoretical models tend to forecast stronger frequency peaks compared to higher modes with the finite element simulations. These findings indicate that to minimize resonance, designers can maximize structural performance by a choice of fiber direction and laminate architectures. The given work manages to fill the research gap concerning the combined effect of material anisotropy and orientation on the plate dynamics. These lessons eventually form a critical basis of the engineering design and vibration control of high technology composite structures.

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