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Dynamic Effect of Ply Angle and Fiber Orientation on Composite Plates

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ABSTRACT

Composite materials have revolutionized industries such as aerospace and automotive with their impressive strength-to-weight ratios and customizable properties. Ply angle and fiber orientation are critical factors that significantly impact the dynamic behavior of composite structures, influencing stiffness, strength, and vibrational characteristics. This research delves into the dynamic characteristics of composite plates, explicitly examining how ply angle and fiber orientation affect vibrational behavior. Through finite element analysis (FEA), composite plates with varying ply angles and fiber orientations were modeled to understand their influence on natural frequencies, mode shapes, and dynamic responses under various loading conditions. The study reveals that cross-ply [0/0/0/0] exhibits the highest stiffness and superior stress handling, while the cross-ply balanced laminate [90/0/0/90] demonstrates better vibrational characteristics. The findings highlight the intricate relationships between design parameters and structural vibrational behavior, offering opportunities for optimizing composite structures. Additionally, harmonic analysis showed that a cut-out increases the natural frequency. The results underscore the importance of optimizing composite plate configurations to enhance vibrational characteristics and align natural frequencies with operational requirements, thereby mitigating resonance-related issues.

1. Introduction

Composite materials have revolutionized industries such as aerospace and automotive with their impressive strength-to-weight ratios and customizable properties [1-3]. The ply angle and fiber orientation, both critical factors, play an essential role in determining the performance of composite plates [4,5]. These factors significantly impact the dynamic behavior of composite structures, influencing their stiffness, strength, and vibrational characteristics [6,7]. Carbon fiber, also known as carbon fiber reinforced polymer (CFRP), is a type of composite material with a high strength-to-weight ratio, making it lightweight, strong, stiff, and durable [8,9]. It is widely used in aerospace, automotive, civil engineering, marine, and construction industries due to its exceptional properties

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[10,11]. Composite plates made of metal and CFRPs behave intricately due to the materials' anisotropic elastic properties and elastoplastic material behavior [12]. Techniques like numerical homogenization and refined plate theories such as the Carrera unified formulation and third-order shear deformation plate theory are used to model the mechanical behavior of composite plates [13,14].

Analytical developments for approximating structural components as plates are based on classical plate theories, such as Kirchhoff or Reissner-Mindlin plate theories [15,16]. The First-Order Shear Deformation Theory (FSDT) is a crucial concept in structural mechanics, with specific assumptions, distinctions from classical plate theory, and practical applications that make it highly relevant in the field [17,18]. Bojović and Rakočević [19] analyzed the natural vibration traits of laminated composite plates with different thicknesses. Their research revealed that the orientation angles influence the plates' mechanical properties, such as the flexural modulus. Özben and Şen [20] found the mechanical properties of composite plates are significantly affected by the stacking sequence of plies, which includes symmetric or antisymmetric arrangements with different orientation angles. Marques et al. [21] have proven that optimizing fiber paths and characteristic angles to create variable stiffness composites can improve fundamental frequencies and critical buckling loads. Sebaey et al. [22] discovered that the impact of the bending stiffness coefficients is negligible when creating a laminate with equivalent bending stiffness. The arrangement of layers impacts the mechanical characteristics of laminates, including their tensile strength. Balasubramani et al. [23] found that a specific layering order (60/30/60/30) exhibited the most resistance to shearing between layers and the highest rate of retained strength after degradation. Cameron et al. research [24] reveals that including thin plies in the stack results in a corresponding rise in bearing stiffness, strength at the beginning of damage, and ultimate bearing stress. Switching to a 100% thin-ply laminate significantly enhances stability at the start of damage. Karsh et al. [25] studied the initial ply failure strength of laminated composite plates, focusing on how spatial variation affects the loading location.

The failure strength of composite laminates is affected by factors such as stacking sequence, ply orientation, number of layers, degree of orthotropy, and ply thickness. The statistical analysis of failure strengths considers the influence of stacking sequence and ply orientation [25]. Setyabudi et al. [26] studied the impact of orientation angle lay-up on the uniaxial tensile test specimens of carbon fiber composite. They manufactured the composite using resin transfer molding with vacuum bagging. The tensile strength of the composite plates varied depending on the lay-up orientation angle. The study observed the highest tensile strength in specimens with a specific orientation angle lay-up, highlighting the significant influence of ply orientation on this mechanical property. Wu et al. [27] experimental findings show that ply thickness impacts the mechanical behavior of carbon fiber-reinforced composites, with research into cross-sectional microstructures and tensile behaviors. Bullock et al. [28] examined how the orientation of surface ply affects the open-hole shear strength of composite plates under shear loading. Based on findings from Balasubramani et al. [23], the stacking sequence affects the mechanical behavior of angle-ply laminates, including interlaminar shear strength and impact damage resistance. Two distinct research investigations, one carried out by Zenkour [29] and the other by Draiche et al. [30], have validated the importance of considering shear deformation effects when examining the bending behavior of angle-ply composite plates. Both studies utilized higher-order shear deformation theories to highlight the significance of these effects in such analyses. Yang et al. [31-33], developed semi-analytical methods based on large deflection theory and FSDT. These methods were designed to estimate the ultimate strength of composite plates, considering the impact of ply degradation and displacement fields. Javed [34] has applied numerical analysis using higher-order shear deformation theory to examine the vibration of symmetric angle-ply composite plates, highlighting the parametric effects of plate aspect ratio, layer alignment, and number of layers on plate frequency. Fazilati [35] investigated the dynamic behavior of variable stiffness composite laminated plates with curvilinear fiber orientation, illustrating the influence of fiber orientation on the structural stability and dynamic behavior of the plates. Zhu and Yang [36] studied the vibration characteristics of cross-ply and angle-ply laminated composite plates under harmonic excitation. They found that altering the lamination patterns could shift the resonant frequencies and change the corresponding peak resonance values, demonstrating the impact of fiber orientations on vibration behavior. Research conducted by Senthilkumar et al. [37] examined how the orientation of fibers affects the static and dynamic properties of sisal/polyester composites. The static and dynamic characteristics were notably affected by the orientation of fibers between the layers, impacting the flexural strength, impact strength, natural frequencies, and damping properties. Niu and Pan [38] examined the collapse of a composite plate with a hole in the middle to improve the fiber orientations on variable stiffness plies. Their investigation showed a significant 197% boost in initial damage capability and a 97% improvement in ultimate load capability due to the optimization, showcasing improved mechanical characteristics. Cakiroglu and Bekdaş [39] studied laminated composite plates using simulations. They found that changes in the order of ply thicknesses and fiber orientation angles significantly impacted the plates' ability to bear loads, highlighting the importance of optimizing these factors. Infante et al.'s research [40] into optimizing the ply fiber orientations in hybrid carbon-glass composite plates when subjected to bending and torsion loads, resulted in a reduction of over 30% in the maximum out-of-plane displacement. This suggests tangible benefits in minimizing displacement when experiencing various loads. Li et al. [41] devised a novel approach to optimize discrete fiber angles using the Archimedean spiral function. The utilization of this method resulted in a remarkable enhancement in structural stiffness of up to 20% at the maximum, effectively addressing the issue of heightened computational expense associated with optimizing fiber angles with multiple layers.

Research so far has mainly concentrated on the impact of the nonlinear behavior of materials on composite plates with different fiber-orientation angles [42]. However, our understanding has significant gaps, particularly regarding the dynamic effects of ply angle and fiber orientation, which still need to be thoroughly addressed [43]. Although some studies cover the dynamic behavior of composite plates with varying fiber orientations, they primarily focus on static and failure analyses, with minimal attention given to dynamic effects [44-46]. Previous research mentions manufacturing limitations about fiber curvatures but does not explore the dynamic consequences of these constraints [47]. Further exploration in these areas is necessary.

This research delves into the dynamic characteristics of composite plates, explicitly examining how ply angle and fiber orientation affect vibrational behavior. Through finite element analysis (FEA), the study models composite plates with varying ply angles and fiber orientations to understand their influence on natural frequencies, mode shapes, and dynamic responses. The investigation encompasses dynamic effects under various loading conditions, such as harmonic excitations and transient forces.

2. Geometry and Meshing

A simple rectangular shape was created as a surface on CAD software, depicted in Figure 1. The meshing process for a composite plate involves dividing the plate's geometry into a grid of finite elements to facilitate accurate structural analysis. Shell 181 was used. Moreover, shell elements are well-suited for modeling thin-walled structures, such as composite plates, shells, or laminates, where the bending and membrane behaviors are significant. The layers of different materials and orientations within the laminate were considered. A set of elements with specific material properties and fiber orientations typically represents each layer. The mesh density is a critical aspect, as it influences the precision of the simulation. Therefore, a fine mesh was used to capture detailed behaviors, but it demands more computational resources, Shell 181 was used for this analysis, moreover, shell 181 is a finite element available in ANSYS Mechanical software. It is specifically designed to analyze the behavior of shell structures in simulations. Shell elements are used to model thin-walled structures, such as plates and shells, where bending and membrane effects dominate the structural behavior as shown in Figure 1.

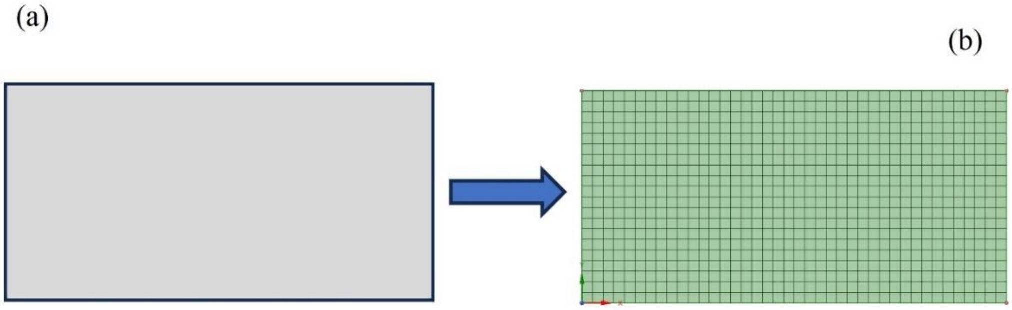

Fig. 1. (a) Geometry of composite plate; (b) Meshing of laminated composite plate

Additionally, mesh transitions between layers represented abrupt changes in material properties. Advanced meshing techniques like mapped or swept meshing were used to ensure accurate and efficient analysis of composite plates. A well-constructed mesh was created to ensure a smooth transition and maintain computational efficiency. The mesh statistics of the lamina are listed in Table 1.

Table 1
Mesh statistics

Nodes	Elements	Element Type	Computational time	CPU
19936	19644	SHELL 181	55 minutes	cores (2.5GHz)

2.1 Material Properties

This research used Epoxy Carbon UD (230 GPa) Prepreg. However, unidirectional carbon fiber fabric is a form of carbon reinforcement characterized by a non-woven structure where all the fibers align in a single direction. In this fabric style, fibers are closely packed without any gaps, lying flat and devoid of a cross-sectional weave that would compromise strength by dividing it in another direction. This design ensures a concentrated fiber density, offering unparalleled longitudinal tensile strength, surpassing fabric weave. In addition to the stacking sequence of the laminate, the material properties of the composite material are defined in Table 2 as selected from ANSYS library, which are mechanical elasticity (E_x, E_y, E_z, G_{xy}, and υ_{xy}).

Table 2
Material properties of the composite

Material	Ex (MPa)	Ey (MPa)	Ez (MPa)	υxy	Gxy
Epoxy Carbon UD (230 GPa) Prepreg	121000	8600	8600	0.27	4700

2.2 Simulation Process

Simulating the natural frequency of a laminated composite plate involves employing FEA techniques to predict the plate's vibrational behavior. Initially, the composite material's mechanical properties, such as modulus of elasticity, Poisson's ratio, and density, are defined. The plate geometry is modeled in the ANSYS ACP, and an appropriate mesh is generated to discretize the structure. Boundary conditions are then applied to simulate the physical constraints, and material orientation is specified for each ply layer within the composite. However, Figure 2 illustrates the flow chart of the analysis process. An appropriate solver and analysis type were employed, such as modal analysis, and the simulation was executed to determine the plate's natural frequencies and mode shapes.

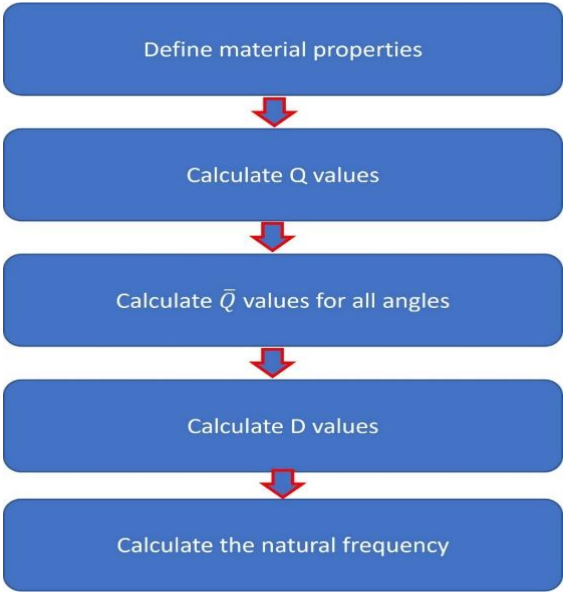

Fig. 2. Flow chart of the analysis process

2.3 Laminated Composite Plate Theory

Assumptions:

i. The plane section remains plane before and after bending (displacements are linear through the thickness).
ii. Transverse fibers are stretchable/infinitely rigid (No strain in thickness direction, No Poisson's effect).
iii. The thickness of the plate is much less than the other two dimensions (Plane stress conditions).
iv. The plane section remains perpendicular to the mid-surface before and after bending (No shear deformations).

3. Analytical Solution of composite laminated modelling method

Classical Lamination Theory (CLT) is applied to predict the vibrational behavior of composite laminates. According to Shokrieh's hypothesis [48] for orthotropic materials, the strain-stress relationships of a composite lamina in its fundamental material coordinate system can be formulated as [49]:

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{bmatrix} \tag{1}$$

where the terms Qi,j which constitute the [Q] reduced stiffness matrix are specified by the following equations:

$$Q_{11} = \frac{E_1}{1-v_{12}v_{21}},\ Q_{12} = \frac{v_{12}E_2}{1-v_{12}v_{21}} = \frac{v_{21}E_1}{1-v_{12}v_{21}},\ Q_{22} = \frac{E_2}{1-v_{12}v_{21}},\ Q_{66} = G_{12}. \tag{2}$$

The constitutive relations of each lamina must be transformed to the laminate's coordinate system, given that laminated composite plates consist of orthotropic layers oriented in various directions. The stress–strain relations in the x–y coordinates for each layer are provided as [49]:

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} \bar{Q}_{11} & \bar{Q}_{12} & \bar{Q}_{16} \\ \bar{Q}_{12} & Q_{22} & \bar{Q}_{26} \\ \bar{Q}_{16} & \bar{Q}_{26} & \bar{Q}_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} \tag{3}$$

In which

$$\bar{Q}_{11} = Q_{11}\cos^4\ \theta + 2(Q_{12} + 2Q_{66})\sin^2\ \theta\cos^2\ \theta + Q_{22}\sin^4\ \theta \tag{4}$$

$$\bar{Q}_{12} = (Q_{11} + Q_{22} - 4Q_{66})\sin^2\ \theta\cos^2\ \theta + Q_{12}(\sin^4\ \theta\cos^4\ \theta) \tag{5}$$

$$\bar{Q}_{22} = Q_{11}\sin^4\theta + 2(Q_{12} + 2Q_{66})\sin^2\theta\cos^2\theta + Q_{22}\cos^4\theta \tag{6}$$

$$\bar{Q}_{16} = (Q_{11} - Q_{12} - 2Q_{66})\sin\theta\cos^3\theta + (Q_{12} - Q_{22} + 2Q_{66})\sin^3\theta\cos\theta \tag{7}$$

$$\bar{Q}_{26} = (Q_{11} - Q_{12} - 2Q_{66})\sin^3\theta\cos\theta + (Q_{12} - Q_{22} + 2Q_{66})\sin\theta\cos^3\theta \tag{8}$$

$$\bar{Q}_{66} = (Q_{11} + Q_{22} - 2Q_{12} - 2Q_{66})\sin^2\theta\cos^2\theta + Q_{66}(\sin^4\theta\cos^4\theta) \tag{9}$$

The elements Q_{ij} that comprise the transformed reduced stiffness matrix $(\bar{Q})$ are functions of the reduced stiffness matrix terms Q_{ij} and the lamina angle θ. Consequently, they also depend on the four elastic constants and the angle θ of the lamina. As our analysis pertains to symmetric laminates, only the $[D]$ matrix is pertinent for the calculation of bending vibrations. Hence, the subsequent step involves assembling the $[D]$ matrix, referred to as the bending stiffness, which is the aggregate sum of the elements Q_{ij} and their corresponding thicknesses.

$$D_{ij} = \frac{1}{3}\sum_{k=1}^{N} \left(\bar{Q}_{ij}\right)_k (h_k^3 - h_{k-1}^3) \tag{10}$$

Where $i, j = 1,2,6$, the total sum is taken over all N layers of the composite laminate, and h_3, h_4 are the upper layer, while h_0, h_1 are lower layer in z coordinate, the schematic of the layer used is depicted in Figure 3. The coefficients of the bending stiffness matrix $[D]$ can be expressed as:

$$[D] = \begin{bmatrix} D_{11} & D_{12} & D_{16} \\ D_{12} & D_{22} & D_{26} \\ D_{16} & D_{26} & D_{66} \end{bmatrix} \tag{11}$$

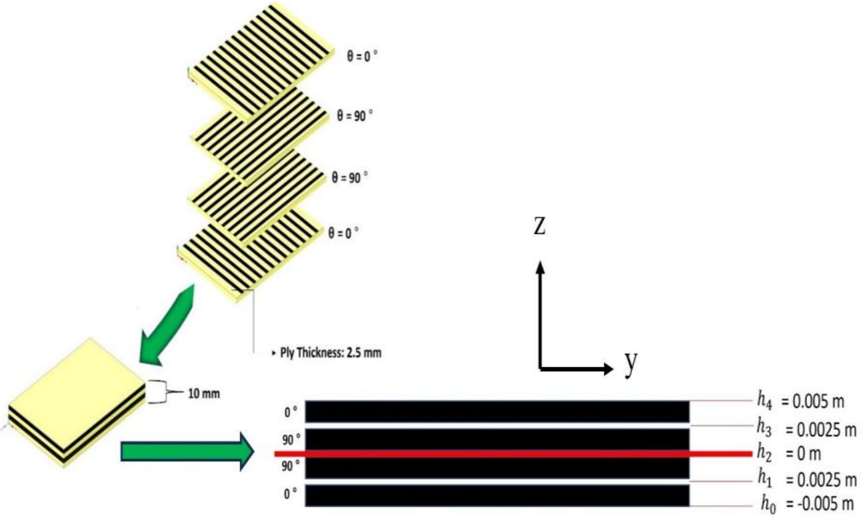

Fig. 3. Laminated composite plate layouts

3.1 Theoretical analysis of natural vibration

The differential equation governing the natural vibration of a specially orthotropic, midplane-symmetric composite plate is expressed as follows [50]:

$$D_1 \frac{\partial^4 w}{\partial x^4} + 2D_3 \frac{\partial^4 w}{\partial x^2 \, \partial y^2} + D_2 \frac{\partial^4 w}{\partial y^4} = -\rho h \frac{\partial^2 w}{\partial t^2} \tag{12}$$

For a composite plate with all four edges simply supported, the natural circular frequency in radians per second is defined as follows:

$$\omega_n = \frac{\pi^2}{\sqrt{\rho_m h}} \left[D_1 \left(\frac{m}{a}\right)^4 + 2D_3 \left(\frac{m}{a}\right)^2 \left(\frac{n}{b}\right)^2 + D_2 \left(\frac{n}{b}\right)^4 \right]^{1/2} \tag{13}$$

where ω_n denotes the cyclic frequency, ρ_m represents the density, h is the plate thickness, and a and b signify the planar dimensions of the plate. For various values of m and n, each combination yields a distinct frequency ω_n and an associated mode shape. In plates supported on all four sides, m and n correspond to the number of half sine waves in the a and b directions, respectively. $D_1 = D_{11}, D_2 = D_{22}$, and $D_3 = D_{12} + 2D_{66}$ are coefficients of the bending stiffness matrix $[D]$.

The natural frequencies of vibration in cycles per second (Hz) are given by [50]:

$$f_{mn} = \frac{\omega_n}{2\pi}. \tag{14}$$

The dimensionless frequency can be specified as [51]:

$$\bar{\omega} = \left(\frac{\omega \alpha^2}{h}\right) \sqrt{\frac{\rho}{E_2}} \tag{15}$$

This study focuses on a rectangular plate that is simply supported along all four edges. The natural frequency of an especially orthotropic single-layer plate is influenced by various parameters, such as the plate aspect ratio (a/b), the modulus ratio (E_1/E_2), and the side-to-thickness ratio (a/h). In this context, a and b refer to the in-plane dimensions along the x- and y-coordinate directions of the rectangular laminate, while E_1 and E_2 denote the moduli of elasticity in these respective directions. The geometry and coordinate system for a simply supported rectangular plate are depicted in Figure 4.

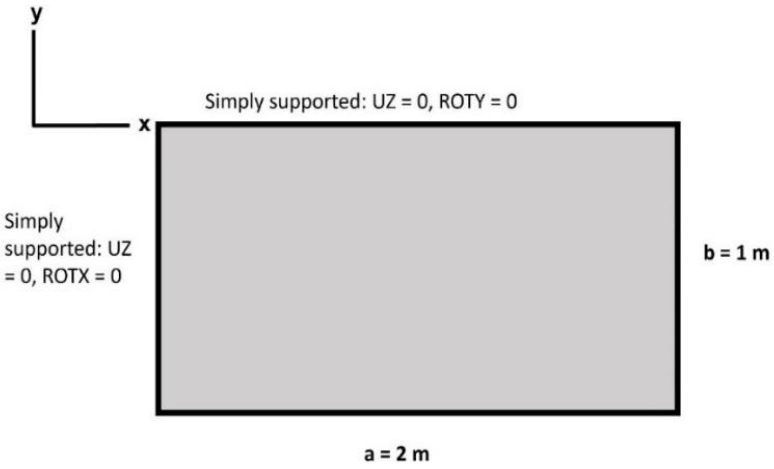

Fig. 4. Geometry and simply supported boundary condition.

4. Validation and convergence of present results

The validation process aims to confirm that the model appropriately captures the system's underlying physics, behaviors, and interactions. In this section, the numerical model was compared with the analytical results. As a result, there was a good correlation with less than 1%. Table 3 shows the modeling validation of the analytical and numerical composite plate of [0/90/90/0] laminate stack up; *m* means the number of half waves in the long axis, while *n* means the number of half waves in the short axis as evaluated in MATLAB software. Figure 5 shows the mode shapes of the laminated composite plate.

Table 3
Analytical and FEA comparison of the composite plate of [0/90/90/0] laminate stack-up

	Half waves (m,n)	Analytical (Matlab)	FEA (Ansys)
mode1	(1,1)	22.088	22.057
mode2	(2,1)	46.061	45.888
mode3	(1,2)	73.780	73.502
mode4	(2,2)	88.352	88.138
mode5	(3,1)	92.485	92.157

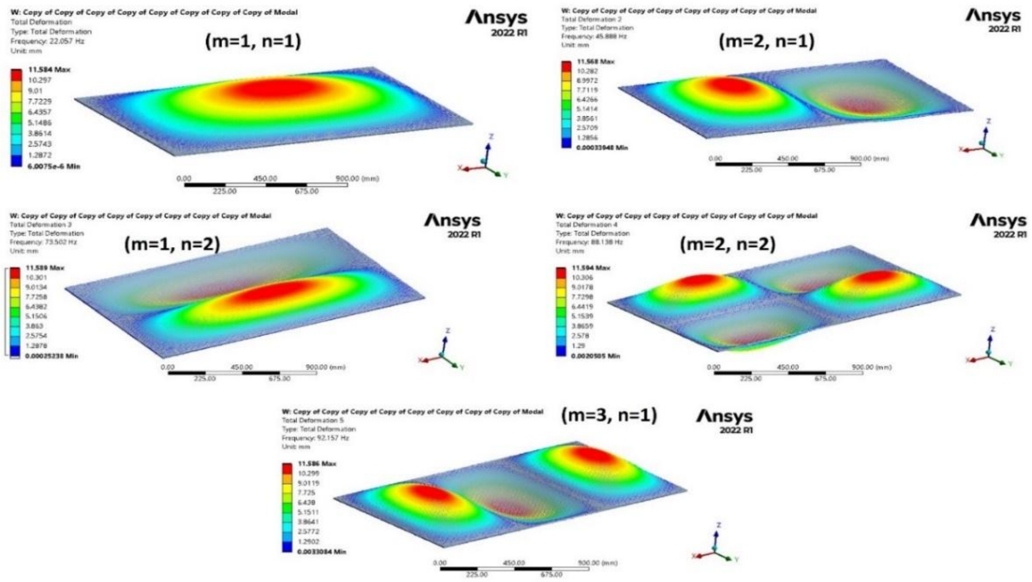

Fig. 5. Mode shapes of laminated composite plate

4.1 The Natural Frequency of Composite Plates with Varying Ply Angle Orientation

The natural frequency analysis of composite plates with varying ply angle orientations involves studying the plate's vibrational behavior under specific loading conditions. Ply angle orientation significantly influences the plate's mechanical properties and natural frequencies, as depicted in Figure 6. In this simulation, the composite plate is modeled using ANSYS Workbench, with each layer characterized by distinct material properties and ply angles. The boundary conditions are typically set to simulate the plate's physical constraints, such as all edges being simply supported. The software calculates the plate's natural frequencies and corresponding mode shapes using a modal analysis approach. As a result, the ply angle orientation of [90/0/0/90] was observed to have a much higher frequency. However, all investigated stacking sequence orientations in mode two tend to have approximately the same natural frequency. The simulation results provide valuable insights into optimizing the design for specific applications, ensuring that the natural frequencies align with operational requirements and avoiding resonance-related issues in practice. In addition, Figures 7 and 8 show the contour plot of mode 1, and mode 2 respectively, depicting the vectorize directional deformation.

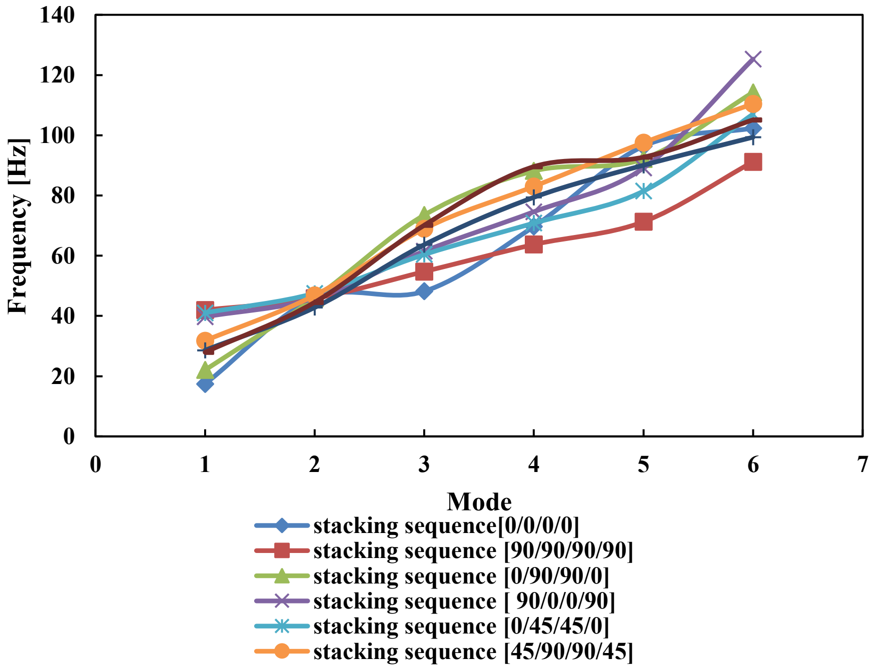

Fig. 6. Natural frequency of composite plates

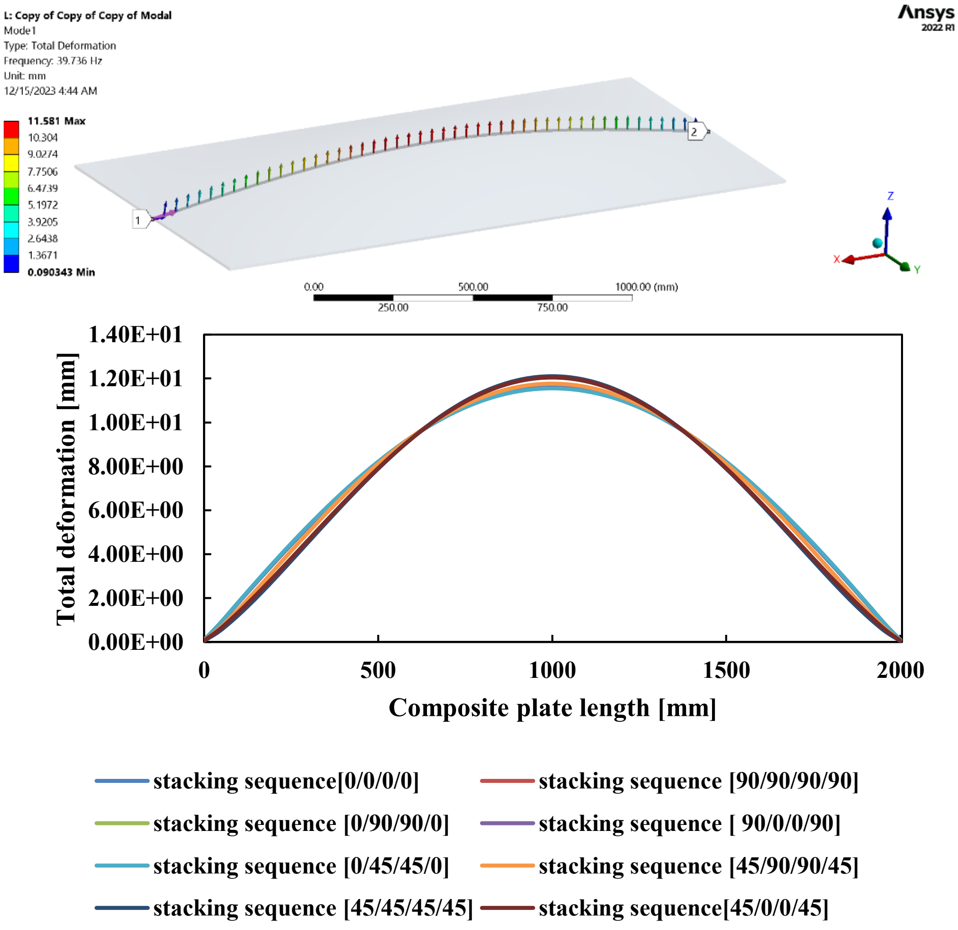

Fig. 7. Contour plot of mode 1

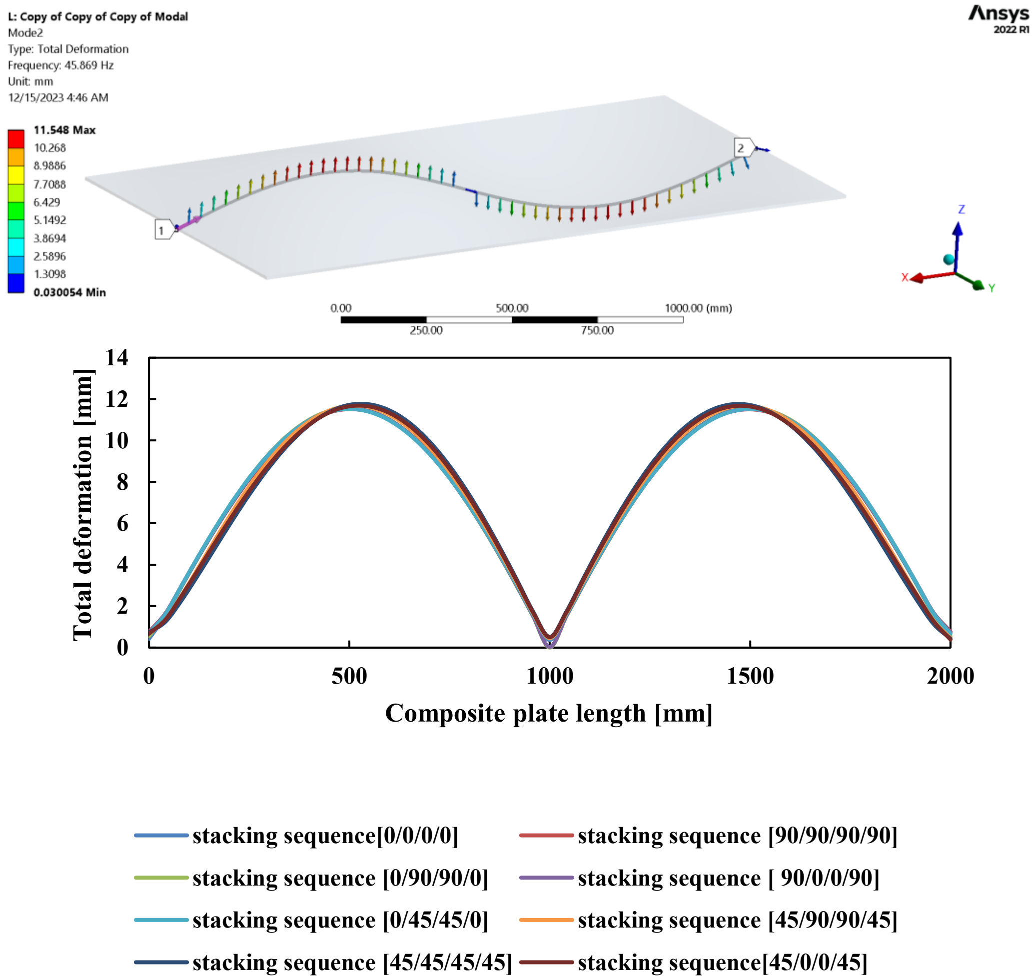

Fig. 8. Contour plot of mode 1

4.2 The natural frequency of composite plates with center cut

The vibrational characteristics of a plate with a central opening were analyzed in the natural frequency analysis of composite plates with a center cut (Figure 9). This scenario is common in structural components where weight reduction or specific design requirements necessitate openings in the material. In this simulation process, FEA was employed, and the composite plate was modeled with distinct material properties for each layer, considering the plies' orientation and the cut-out's presence. Moreover, boundary conditions are applied to replicate same without cut out. Modal analyses were then conducted to determine the plate's natural frequencies and mode shapes. The natural frequency of laminated composite plates' unidirectional carbon fiber fabric with circular cut-out was investigated with an orientation stacking sequence [0/0/0/0], the fiber's most robust direction, as shown in Figure 10. Furthermore, the free vibrational response was compared with the non-cut-out composite plate. As a result, it was observed that the composite plate with a centered cut-out has the same mode shape as the non-cut-out composite plate as depicted in Figure 11, though with slightly lesser natural frequency as superimposed in Figure 12. In general, presence of the cut-out influences the distribution of stress and strain, impacting the plate's stiffness and, consequently, its natural frequencies.

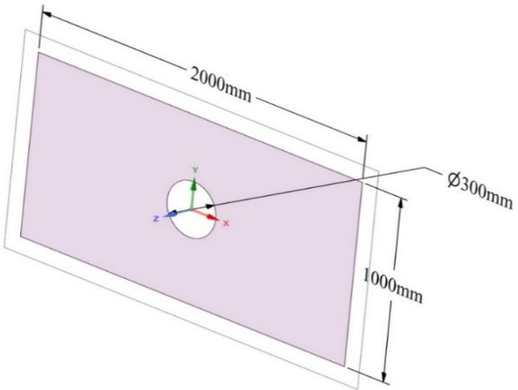

Fig. 9. Composite plates with a center cut

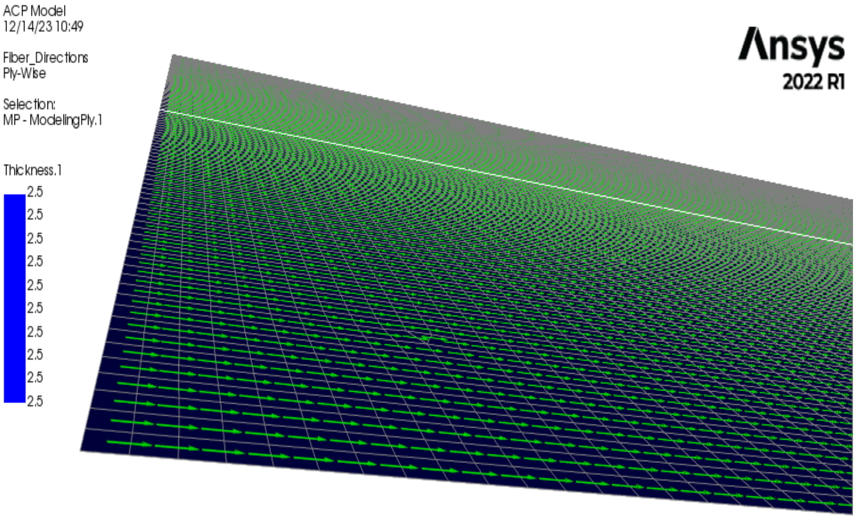

Fig. 10. Unidirectional carbon fiber with orientation stacking sequence [0/0/0/0]

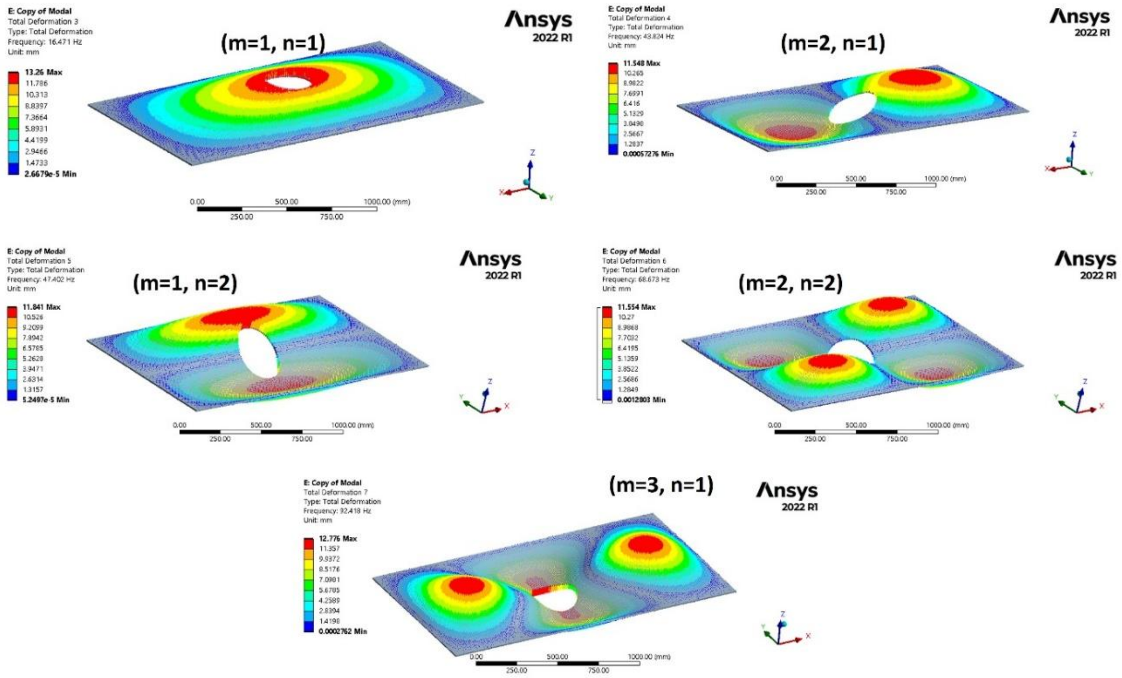

Fig. 11. Mode shapes of laminated composite plates with circular cut-outs

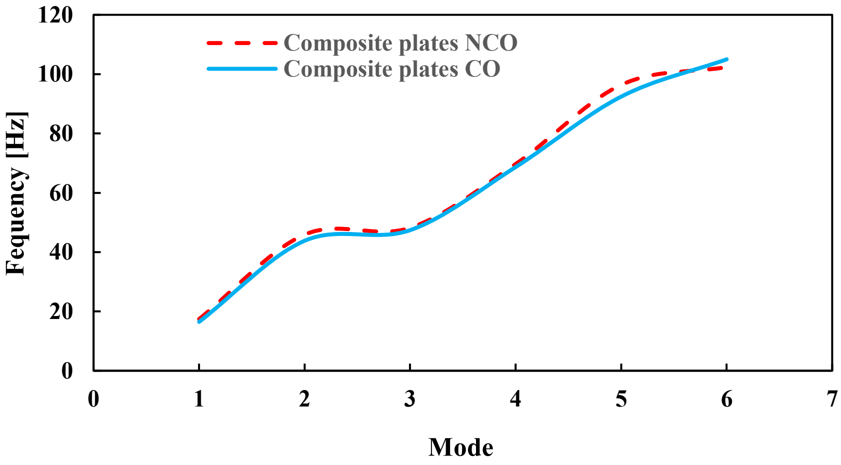

Fig. 12. Superimposed natural frequency of laminated composite plates

4.3 Analysis of axial deformation on the lamina of composite plates with center cut

Analyzing axial deformation on a lamina of composite plates with a center cut and response to axial loading, focusing on the changes in length and deformations along its axis. Utilizing FEA, the lamina is extracted. External axial loads are then applied to the plate, and the resulting deformation were assessed through the FEA results. Figure 13 shows the axial deformation on the laminated composite plate, while Figure 14 illustrates the deformation resistance of different fiber angle orientations. The results show that stacking sequence [0/0/0/0] has the highest stiffness while stacking sequence [90/90/90/90] has the lowest stiffness; this follows that fiber has its highest strength in 0 °, along the fiber direction. This analysis provides insights into how the central cut influences the axial deformations within the lamina, aiding potential stress concentrations and strain distribution. However, a path was created along the circular cut-out for more insight into stress concentration, as shown in Figure 15. Moreover, the total deformation along the stress concentration region was examined for different stacking sequence orientations, as depicted in Figure 16, which shows the stacking sequence of [0/0/0/0] having the most negligible deformation. In general, the stresses along the cut-out edge circular path were analyzed as illustrated in Figure 17, and it was observed that the stacking sequence [0/0/0/0] handled the stresses evenly and well distributed, though it experienced some pick stress at the region of stress concentration.

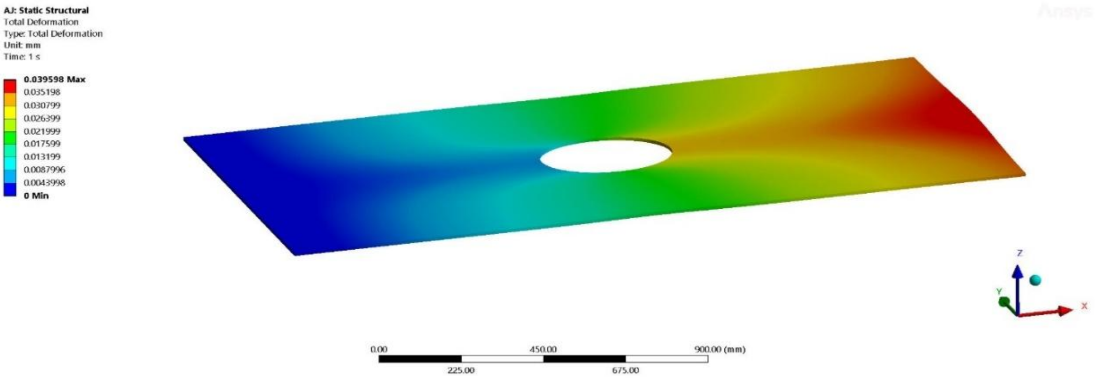

Fig. 13. Axial deformation of laminated composite plate

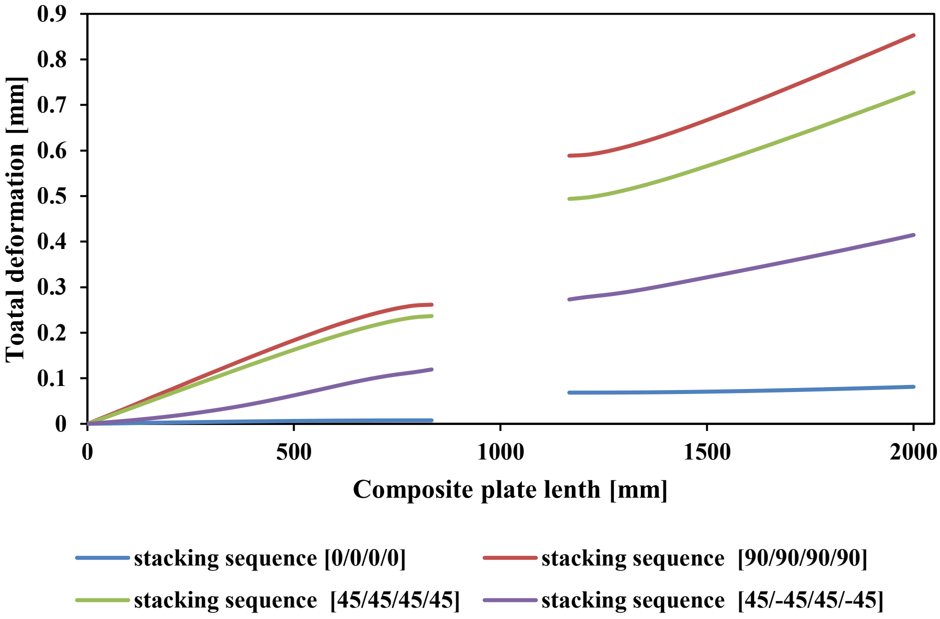

Fig. 14. Axial deformation resistance of different stacking sequence

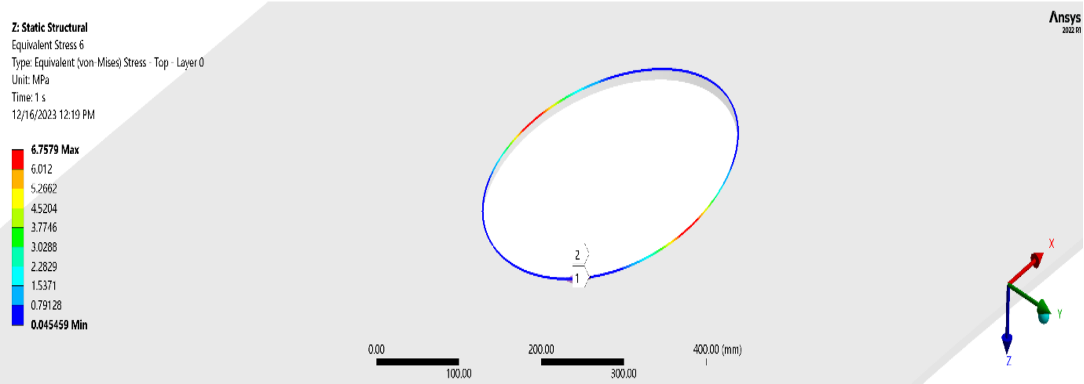

Fig. 15. Cut-out edge circular path

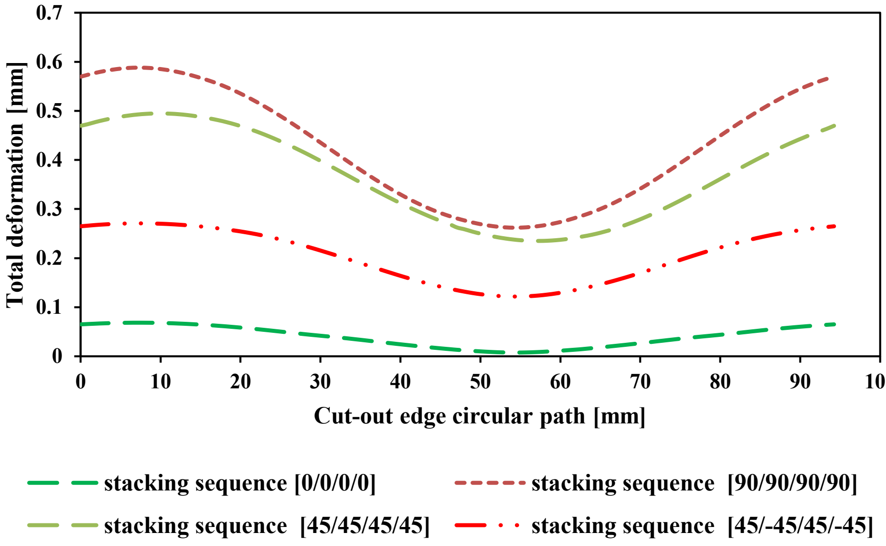

Fig. 16. Laminated composite plate total deformation along the cut-out edge

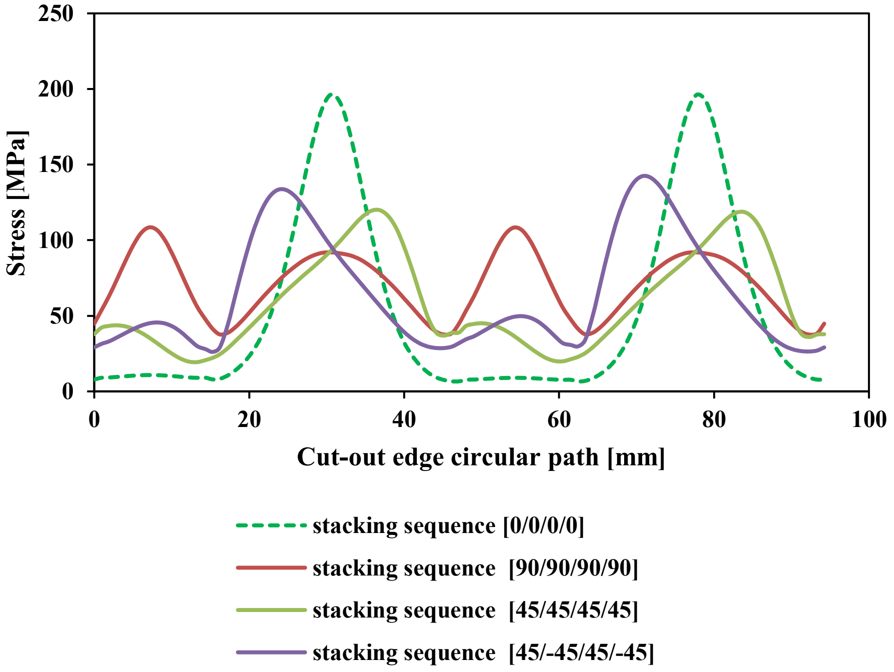

Fig. 17. Laminated composite plate stresses along the cut-out edge

4.4 Analysis of stress on the lamina of composite plates with center cut

This section examined the analysis of stresses on a lamina of composite plates with a center cut having a stacking sequence [0/90/90/0], and the distribution of internal forces and deformations within individual layers of the composite material were equally investigated. The simulation accounts for stresses on each of the four layers of the composite plate, as shown in Figure 18 along the lamina stack up (Figure 19), thereby identifying regions of higher or critical stress within the lamina. A tensile axial load of 10000 N was applied, as shown in Figure 20. As a result, the lamina of the first layer and fourth layer having stacking sequence of [0] were examined, as illustrated in Figure 21, showing more stresses in the outer layer. Similarly, Figure 22 shows the lamina of the second layer and third layer having a stacking sequence of [90]; stresses are much less than when the stacking sequence is [0], as there are almost at the neutral axis, and it is observed that the second layer has more stress than the third layer.

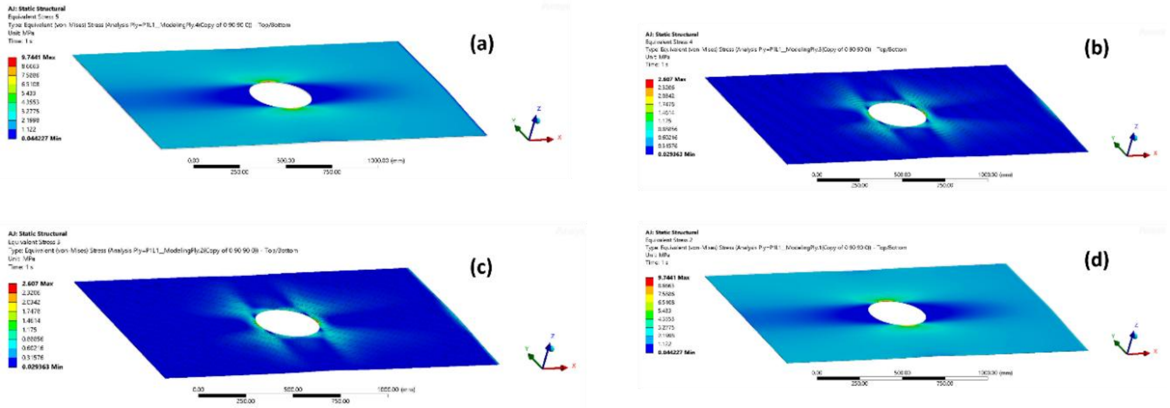

Fig. 18. laminated composite plate; (a) Layer 1 stacking sequence [0]; (b) Layer 2 stacking sequence [90] (c) Layer 3 stacking sequence [90] (d) Layer 4 stacking sequence [0]

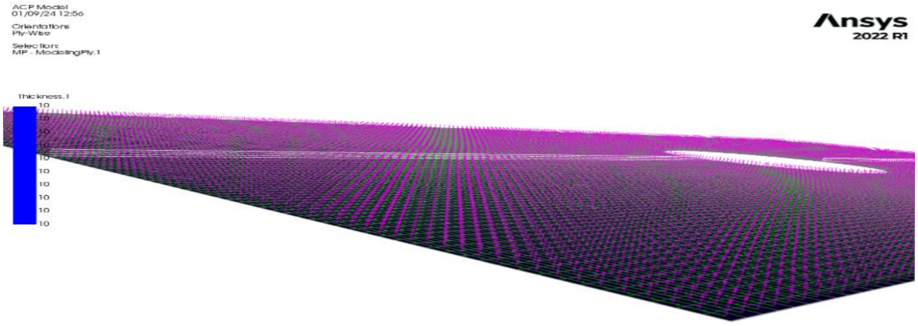

Fig. 19. Direction of lamina stack-up orientation

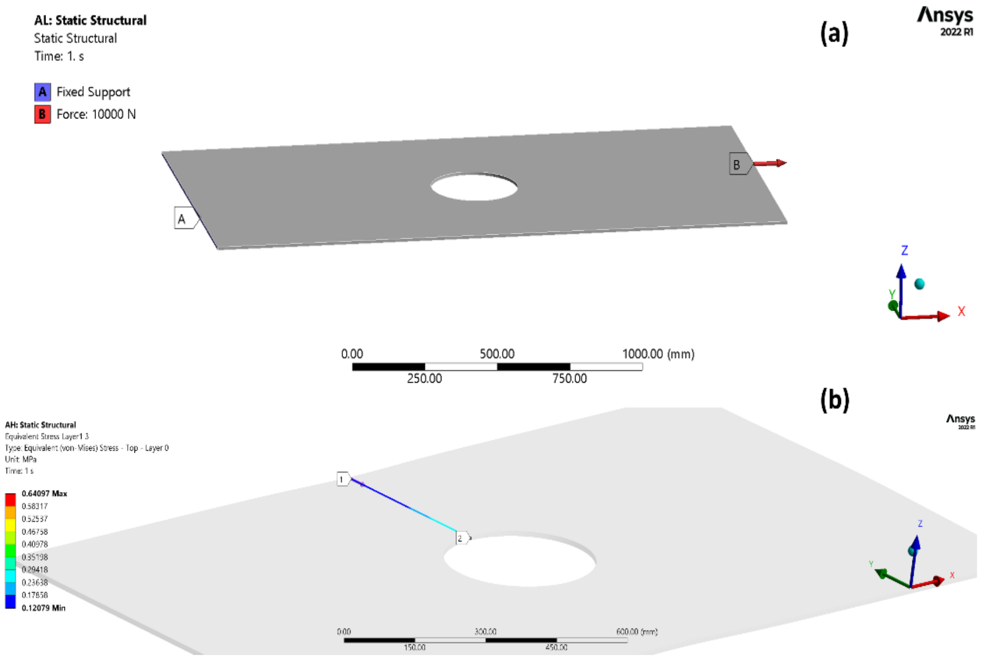

Fig. 20. Laminated composite plate (a) Tensile axial load of 10000 N (b) stresses concentration path

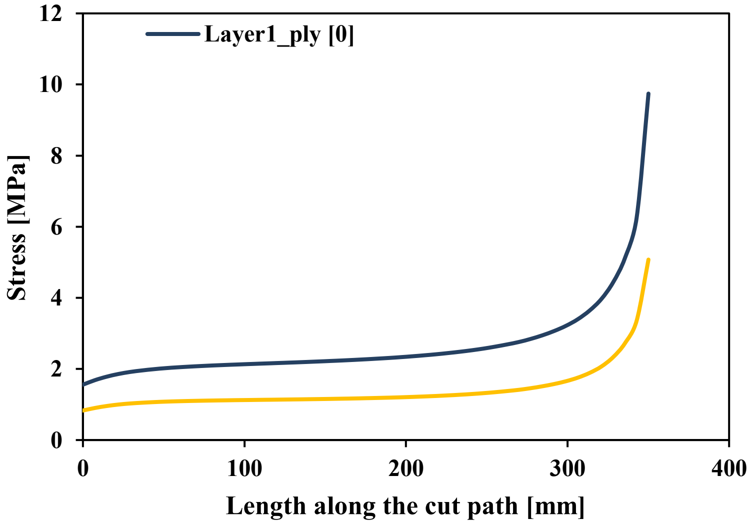

Fig. 21. Stresses from the long axis center to the cut-out edge (layer 1 and layer 4)

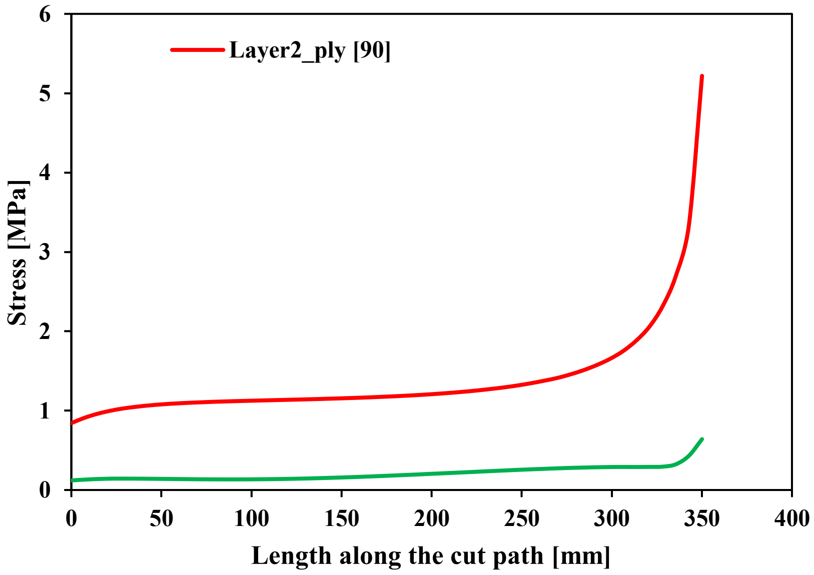

Fig. 22. Stresses from the long axis center to the cut-out edge (layer 2 and layer 3)

4.5 Harmonic response on composite plates with center cut

The harmonic response analysis of composite plates of stacking sequence [0/90/90/0] with a center cut involves examining how they respond to sinusoidal excitations. However, the composite plate is modeled with distinct material properties for each layer, incorporating the orientation of plies and considering the presence of the central cut-out, Figure 23 and Figure 24 depicts the first 2 modes. The harmonic load of 10 N was applied on the composite plate top face, and specified frequency ranges of 0 to 50 Hz were set, with a global damping ratio of 2%, and the response of the plate were observed, revealing how its amplitude and phase vary across different locations as depicted in Figure 25 for non-cut-out and cut-out composite plate. It is worth to mention that the cut-out increased the pick frequency and adjusted the natural frequency slightly lower as compared with non-cut-out composite plate. In addition, Figure 26 and Figure 27 shows the total deformation of mode 1 and mode 2 of laminated composite plates respectively. It was observed that composite plates with circular cut-outs have slightly higher deformation than laminated composite plates without circular cut-outs, mainly along the cut-out region.

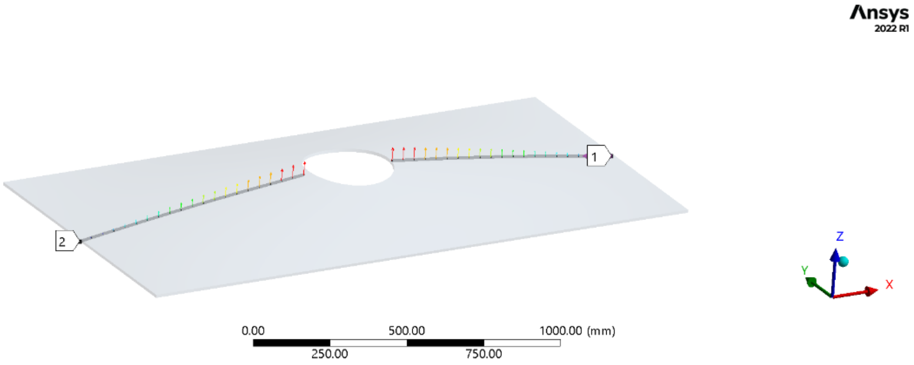

Fig. 23. Cut-out laminated composite plate deformational path of mode 1

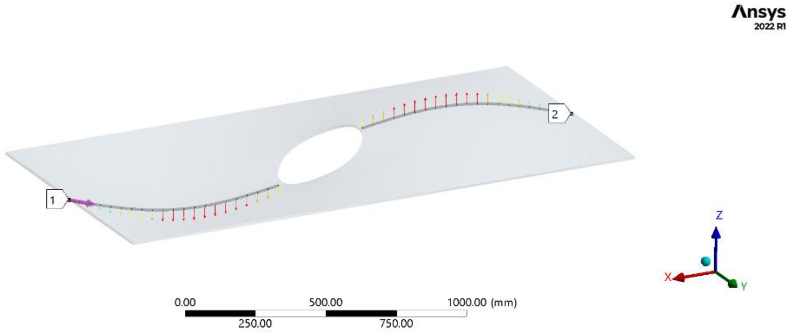

Fig. 24. Cut-out laminated composite plate deformational path of mode 2

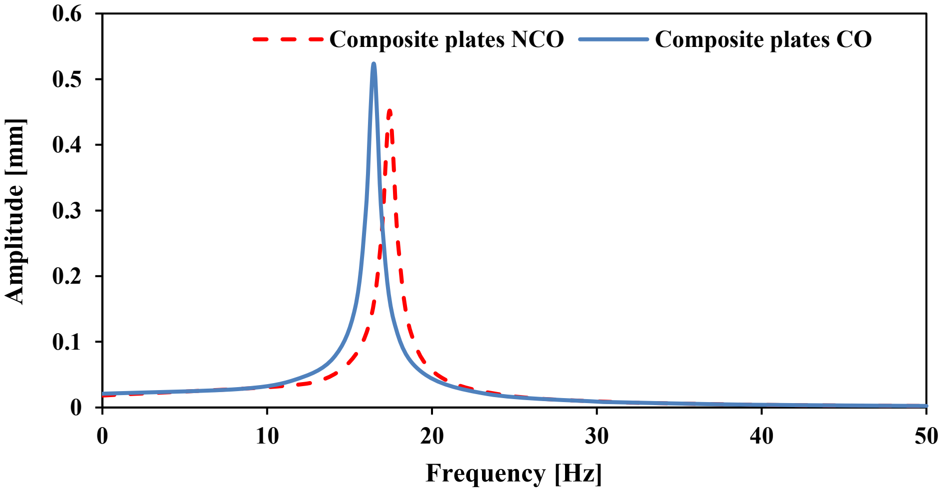

Fig. 25. Harmonic response plot of laminated composite plate

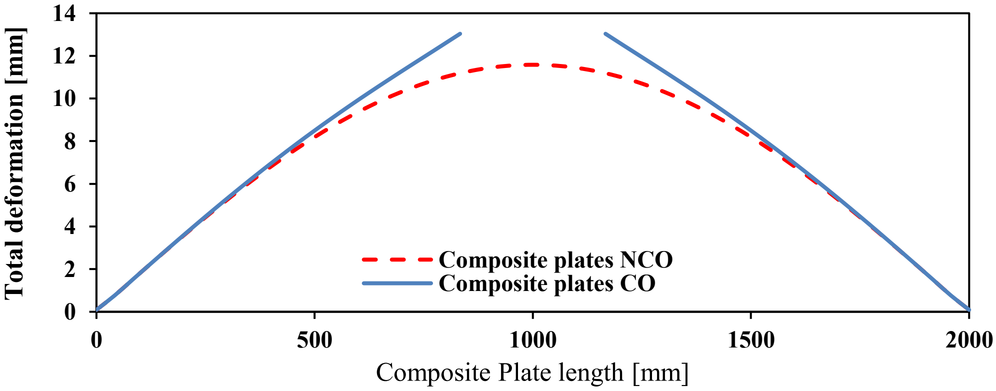

Fig. 26. Superimposed total deformation of mode 1 of laminated composite plate.

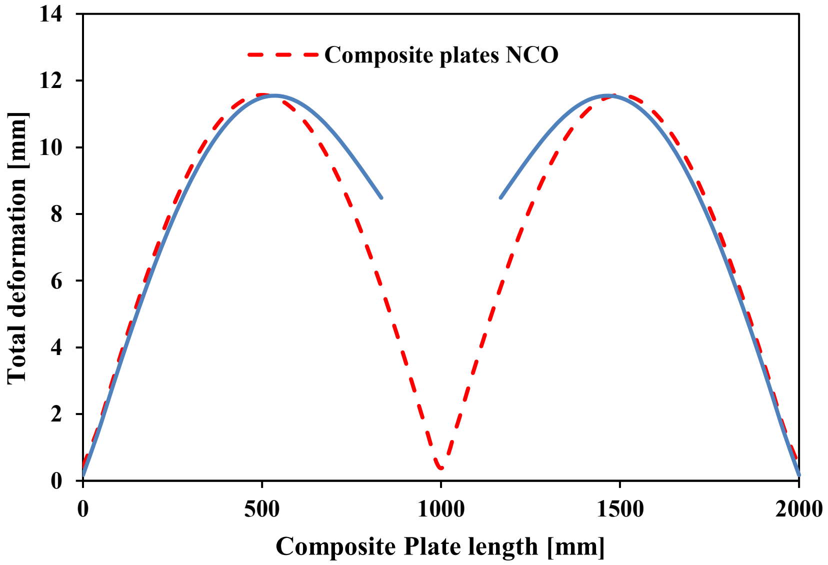

Fig. 27. Superimposed total deformation of mode 2 of laminated composite plate.

5. Conclusion

This study employs FEA to investigate the dynamic effects of ply angle and fiber orientation on composite plates. The research reveals that cross-ply [0/0/0/0] exhibits the highest stiffness and superior stress handling compared to other orientations, it is worth to mention that all configurations have the same mass. The cross-ply balanced laminate [90/0/0/90] demonstrates better vibrational characteristics regarding dynamic response than other laminate configurations. The findings illuminate the intricate relationships between design parameters and structural vibrational behavior, providing opportunities for optimizing composite structures. Furthermore, stresses at each lamina were investigated, it was observed that stacking sequence [0/0/0/0] handled the stresses evenly and well distributed. The results contribute to a deeper understanding of the interplay between material composition and dynamic performance, in tailoring composite plate configurations for enhanced vibrational characteristics. Moreover, harmonic analysis captures the effect of cut-out on composite plate, which increases the natural frequency. The study emphasizes optimizing designs based on simulation and theoretical results, aligning composite plate natural frequencies with operational requirements, and mitigating resonance-related issues

Author Contributions

Conceptualization, A.M., E.C.O., M.A., and B.S.; methodology, E.C.O., M.A., and B.S.; software, M.A., and B.S.; validation, A.M., E.C.O., M.A., and B.S.; formal analysis, investigation, writing—original draft preparation, writing—review and editing, A.M., E.C.O., M.A., and B.S.; visualization, M.A., and B.S. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

The study did not report any additional data.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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