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Free Vibration Analysis of Circular Perforated Laminated Plates

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Abstract

This study investigates the free vibration characteristics of circular perforated laminated composite plates. A finite element model is created to analyze the effects of perforation patterns, hole sizes, and laminate configurations on the natural frequencies and mode shapes of these structures. The model incorporates shear deformation theory and accounts for the anisotropic nature of composite materials. Parametric studies were held to examine how varying perforation geometries, including hole diameter, spacing, and arrangement, influence the dynamic behavior of the plates. Additionally, the impact of different fiber orientations and stacking sequences in the laminate layers is explored. Results indicate that perforation patterns significantly alter the plate's stiffness and mass distribution, leading to changes in natural frequencies and mode shapes compared to non-perforated plates. The findings provide insights into optimizing the design of perforated laminated plates for specific vibration characteristics in engineering applications. This research contributes to understanding the complex interactions among material properties, structural geometry, and dynamic response in perforated composite structures.

Keywords: Circular perforated plates, finite element modelling, free vibration analysis, laminated composites, mode shapes, natural frequencies, perforation patterns

INTRODUCTION

Free vibration analysis of circular perforated laminated plates is a crucial area of study in structural mechanics. These complex structures, composed of multiple layers and featuring strategic perforations, pose unique challenges in predicting their dynamic behavior. Understanding the natural frequencies and mode shapes of such plates is essential for their application in various engineering fields, including aerospace and automotive industries. The presence of perforations not only reduces the overall weight but also significantly influences the plate's vibrational characteristics. This analysis typically involves advanced mathematical modeling and computational methods to account for the intricate interplay between material properties, geometric configurations, and boundary conditions. The study of vibration in plates has been a topic of interest for researchers since the mid-20th century. However, the specific focus on circular perforated laminated plates emerged later as composite materials gained prominence in engineering applications. Early work in this period primarily focused on isotropic plates without perforations.

A detailed study of plate vibrations was conducted by Leissa, as stated in a NASA article

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[1]. The researchers considered various plate shapes with different boundary conditions. Their observation was conducted to examine how the plates would behave dynamically. Based on the calculations performed, they determined the natural frequencies and their mode shapes using analytical methods. This work served as a cornerstone for engineers working in structural dynamics. Mindlin's [2] contributions greatly improved plate theory. The author focused on shear forces and rotary inertia on the bending moments of isotropic elastic plates. The research led to new equations of motion that became a key part of applied mechanics. Whitney et al. [3] tackled issues with heterogeneous anisotropic plates. They used classical plate theory to examine variations in material properties, which are particularly important for today's composite materials. Their discoveries led to further analysis and design of the advanced composite structures. Bert et al. [4] considered the effect of shear deformation on the vibrations of antisymmetric angle-ply rectangular plates. Their study revealed the importance of including shear deformation in the vibration analysis of laminated composites, thereby enabling the prediction of composite plate behaviour. Reddy et al. [5] explored the large-deflection and large-amplitude free vibrations in laminated composites as well. They provided valuable insights into how these plates behave nonlinearly under deformation, which is essential for analyzing and designing composite structures under heavy loads. This serves as a cornerstone for the design of complex vibrations in advanced materials. Reddy [6] used the higher-order shear deformation theory specifically for laminated composite plates. The author considered the classical plate theory for moderately thick laminates. This adopted theory has a parabolic distribution of transverse shear stresses, ignoring the need for shear correction factors altogether! A finite element model was built based on this theory and tested against exact solutions, showing accurate results! The study revealed the importance of accurately accounting for model shear deformation in engineering. Noor et al. [7] also reviewed computational models for multi-layered composite shells. They examined various modelling methods and pointed out their pros and cons. Considering various shear deformation theories and finite element methods helped them recognize the importance of incorporating them. This review highlighted the importance of carefully considering the mechanical behaviour of composite materials, which are particularly useful in aerospace and civil structures! Ultimately, this has led to the consideration of better models that can capture the complex behaviour of multi-layered composites under varying stresses. Liew et al. [8] also summarized research on thick plate vibrations! They considered both theoretical and experimental investigations conducted to support various studies and showcase key advancements and ongoing challenges in the field. This survey helped the researchers gain an overall understanding of the phenomenon of thick plate vibration. Huang et al. [9] assessed free vibration characteristics of rectangular plates with holes of various shapes, too! They used analytical and numerical methods to determine the effect of hole size on natural frequencies and mode shapes. The study critiqued various hole types, including circular, elliptical, and rectangular, and closely examined their effects on plate dynamics. Their findings provided valuable insights into vibration traits, which are important for designing lightweight structures that provide good vibration properties for functional openings! Jain et al. [10] also explored the free vibration behaviour of thick circular plates with circular cutouts! They revealed the effect of the size and placement of these cutouts on vibrational patterns within those plates. This research is crucial for engineering design, as it provides a guideline for maintaining structural strength when reducing material is of prime importance! The findings highlighted the importance of the response in the dynamic behaviour of the modified plates under varying conditions. This literature provides important information, particularly in fields of nuclear engineering, where the behaviour of these systems is quite different from that of other mechanical structures, which are based solely on materials and structural interactions. Jhung et al. [11] employed a smart method using equivalent material properties to observe the vibration behaviour of perforated plates with square holes. Using this equivalent approach simplifies the analysis of perforated plates. The idea is to replace a complicated perforated plate with a solid piece of material with similar characteristics. The evaluation of solid piece characteristics can be done easily using classical methods. The presence of square holes reduces the plate's stiffness and mass density, which helps estimate essential properties. Ferreira et al. [12] examined the vibration of symmetric laminated composite plates using the first-order shear deformation theory (FSDT) and radial basis functions. They found that this method worked well across different laminate sequences, regardless of length-to-width ratios, side-to-thickness ratios, and ply orientations.

Their approach accounted for shear deformation—an important factor in moderately thick composite plates. Their results show the importance of radial basis functions for modelling complex behaviours in laminated composite structures. Sharma et al. [13] focused on elastic edge constraints that affect the free vibration of supported cross-ply symmetric rectangular laminated plates. They found that adding edge constraints—such as clamping—greatly increased the natural frequencies compared with those for supported edges. This provided the basis for the conclusion that edge constraints play a huge role in determining these frequencies! They also discovered that these constraints significantly influence the higher-order vibration modes. This study clearly highlights the importance of considering realistic edge conditions when analyzing laminated composite plates. Baltaci et al. [14] focused on the buckling analysis of laminated composite circular plates with holes. They found that holes in the plates reduced the critical buckling load, especially for large holes. The arrangement of plies and the stacking sequence of laminate layers are quite important, as they affect buckling behaviour. The bottom line lies in designing these circular plates, with hole size and laminate sequence, which are vital for maintaining strength under compression. Malekzadeh etal. [15] performed a dynamic assessment of laminated composite plates influenced by moving loads in a three-dimensional space. Their results showed that three-dimensional analysis was way more precise than two-dimensional methods, particularly for thicker plates with various load distributions. They pointed out that this three-dimensional perspective enabled them better to capture stress and deformation variations across the thickness. This aspect is considered to be important for understanding how these laminated composite plates behave dynamically when subjected to motion. Paramasivam et al. [16] investigated the natural vibration characteristics of circular laminated composite plates with cutouts. Their discovery showed that the presence of cutouts led to lower inherent frequencies, especially with larger cutouts! Additionally, they realized that the orientation of plies and the layer stacking order significantly affected these natural frequencies. This study emphasizes the consideration of cutouts and their sizes, which are key for accurately predicting the dynamic responses of circular laminated composite plates! A study by Liew et al.[17] used meshless techniques to analyze laminated & functionally graded plates and shells. They referred to methods such as the element-free Galerkin method and the radial basis function collocation method, which seem to be alternatives to regular finite element and finite difference methods. This is especially for structures with complex shapes and materials. The researchers further investigated the importance of meshless techniques for estimating material behaviour, which can be incorporated into higher-order theories to avoid the need for mesh generation. They also developed and used meshless methods for static, dynamic, and buckling analysis of those plates and shells. Their work showed that these techniques could outperform traditional numerical methods, making them a better option for accurately predicting the behavior of advanced composite structures.

In 2011, Malekzadeh et al. [18] studied a three-dimensional dynamic evaluation of laminated composite plates under moving loads. Using a semi-analytical method, they derived the equations for this study and observed the behaviour of plates under moving loads. They considered transverse shear deformation and rotary inertia, which further showed that this problem is indeed three-dimensional. Based on their findings, they explored various parameters of laminate stacking order, loading speed, and plate size on the dynamic behaviour of laminated composite plates. This research provided an important insight into how these complex plates respond dynamically to moving loads, particularly for designing structures like bridges. Tornabene et al. [19] explored a two-dimensional differential quadrature method in 2011 to analyze vibrations in functionally graded conical, cylindrical shell, and annular plate setups. By using this numerical method to solve partial differential equations, they can effectively model the complex geometry and material distribution of these composite structures. The study examined the natural frequencies and mode shapes of graded shells and plates, accounting for material gradation and boundary conditions. They provided accurate evidence on the two-dimensional differential quadrature method in understanding vibration characteristics of these complex structures. Tornabene et al. [20] focused on analyzing vibrations in similar types of pre-twisted structures using the two-dimensional differential quadrature (DQ) method! They confirmed that the DQ approach provided precise results—even for higher-order vibration modes! Additionally, the study highlighted the adaptability of the DQ technique across various geometries, boundary conditions, and material types. Nguyen et al. [21] used isogeometric finite element analysis to examine composite sandwich plates using the higher-order shear deformation theory. Their results proved that this iso-geometric approach combined the advantages of both finite element analysis and CAD techniques. Their findings showed accurate capture of stress variations across moderate thicknesses in sandwich structures. Kar et al. [22] investigated free vibration responses of functionally graded spherical shell panels using finite element methods. Their discoveries revealed that natural frequencies and modal patterns were strongly influenced by factors such as material gradients and configurations! They even noticed natural frequencies decreased with an increase in volume fraction exponent related to material gradation! Mahi, etal. [23] introduced a hyperbolic shear deformation theory aimed at studying bending and free vibration behaviours of isotropic and laminated plates. The results showed that this theory worked pretty well compared to other methods—especially good with moderately thick ones! They recognized this and appropriately accounted for the significant effects of transverse shear deformation.

Thai et al. [24] extensively explored theories for simulating functionally graded plates and shells! Their work compiled significant advances across traditional and new theories, as well as various computational methods, including finite element methods! They outlined the pros and cons of each theory while stressing the need to consider material gradation and nonlinear effects. Tornabene et al. [25] focused on the differential geometry method and developed equations of motion for laminated composite doubly-curved shell structures using variational methods! This research provided mathematical insights and focused on gathering information on static/dynamic behaviours, which are combined to predict three-dimensional characteristics and fully understand the intricate mechanical behaviours! Mehta etal. [26] took a close look at the behaviour pattern of laminated composite plates having multiple circular and elliptical cutouts. They found that the presence of cutouts plays a significant role, significantly impacting the natural frequencies and mode patterns of the plates! By using the finite element method to simulate complex shapes and boundary conditions, they demonstrated the method's capabilities, helping to understand how laminated composite structures will vibrate, which is critical for designing and improving these materials. Rajasekaran et al. [27] researched functionally graded small-sized beams. They used nonlocal strain-gradient theory to evaluate the static and dynamic behaviour of these beams. The study highlighted the importance of considering nonlocal effects and strain gradients in the response of these small-scale beams under stress. They also observed that material gradation and size significantly affect the natural frequencies and mode shapes of functionally graded beams. This research highlights the importance of nonlocal effects for modelling and analyzing advanced small-scale structures. Sayyad etal. [28] carried out an extensive review on functionally graded sandwich beams. Their findings highlighted the importance of this area, including classical, higher-order, and refined shear-deformation theories, as well as advanced numerical techniques. They also discussed the pros and cons of each theory, highlighting their importance in considering various parameters of material gradation and geometric nonlinearity for accurate modelling. This review is a handy resource for researchers and engineers delving into these complex composite structures. Zhu et al. [29] used 3D printing to make ZrO2-Al2O3 composite ceramic cores. Their study revealed that 3D printing can create ceramic parts with really complex shapes. The team explored the best processing parameters, such as composition, particle size, and printing conditions, to craft high-quality ceramic cores without flaws. The research findings elaborated on the application of additive manufacturing, which played a crucial role in producing advanced ceramics for industries such as aerospace, energy, and even biomedical engineering! Zhang et al. [30] used a higher-order shear deformation theory for an isogeometric analysis of functionally graded composite plates reinforced with carbon nanotubes. They observed how the material gradation, along with carbon nanotube reinforcement, affects the mechanical response of these plates. Using a unique iso-geometric approach that combines CAD and finite element analysis, they tackled the intricate geometry and material properties of the plates. Their findings suggested this method is not only more precise but also more efficient than traditional finite element methods- especially when dealing with complicated mechanical behaviours in advanced composite structures.

Liu et al. [31] adopted a different approach, using a meshless method to investigate the free vibration of functionally graded circular plates reinforced with graphene platelets featuring multiple perforations. They emphasized how the arrangement of those perforations greatly influences both natural frequencies and mode shapes. They considered a meshless approach that eliminates the need for predefined meshes, enabling them to effectively handle the complex shapes and boundary conditions of perforated plates. This work demonstrates the importance of material gradation combined with reinforcement in analyzing vibrations in advanced composite structures! Safaei et al. [32] used a combination of finite element methods and machine learning techniques to optimize vibrations in laminated composite plates with holes. The results are promising! They found that incorporating machine learning techniques, such as neural networks, could effectively improve the dynamic properties of these perforated structures. By blending sophisticated finite element modelling with smart machine learning algorithms, they tackled optimization challenges head-on—proving hybrid approaches which are valuable for understanding vibrations and enhancing design in complex composite structures. Chen, etal. [33] explored vibration patterns in functionally graded laminated plates that contained perforations—under varying temperature conditions! Their findings highlighted the impact of temperature gradients and material gradation on the dynamic response of these composites. Using both analytical and numerical methods, key equations were derived. Vibration patterns were observed in thermally loaded perforated plates. This research provides valuable insights into thermomechanical coupling effects, which are crucial for optimizing designs under thermal conditions.

PROBLEM DEFINITION

In this study, the vibrational characteristics of perforated plates under specific boundary conditions were investigated. The analysis focuses on two distinct material compositions: Aluminium and glass-epoxy-based composites. These plates, featuring strategically placed holes, are subjected to clamped-free boundary constraints. By examining the impact of perforations on both material types, the aim is to determine the natural frequencies and associated mode shapes. This approach allows us to compare and contrast how the introduction of holes affects the dynamic behaviour of these two materially different plate structures, with one edge fixed and the others unconstrained. The research provides insights into the vibrational response of perforated plates, contributing to a better understanding of their performance in various engineering applications where such boundary conditions are encountered.

Materials and Methods

When examining the vibration characteristics of perforated plates, the material selection plays a crucial role in determining the plate's structural response and efficiency. This study focuses on two materials: Aluminium and glass-epoxy composites. Aluminium, prized for its low density and impressive strength-to-weight ratio, is frequently employed in engineering applications where minimizing mass and ensuring longevity are paramount. Conversely, glass epoxy composites are valued for their superior mechanical properties, corrosion resistance, and dimensional stability. Our methodology involves creating precise digital models of the perforated plates using advanced computational tools such as ANSYS. These models meticulously incorporate the perforations, accounting for the unique material properties of Aluminium and glass epoxy. Finite element analysis is used to evaluate the free-vibration response of these plates under various loading conditions. Particular attention is given to the meshing process, as it is critical to represent the behaviour of both Aluminium and glass-epoxy plates accurately. By leveraging sophisticated simulation techniques and precise material data, this research aims to provide valuable insights into the vibrational behaviour and structural robustness of perforated plates constructed from Aluminium and glass epoxy composites. This approach enables engineers to make informed decisions in design and application. The specific material properties utilized in this study are presented in Tables 1 and 2. Figure 1 illustrates the plate's dimensional specifications and various perforation configurations.

Table 1. Properties of an aluminium plate.

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

Table 2. Properties of glass epoxy plate.

Material	E_x(GPa)	E_y(GPa)	γ_{xy}	γ_{yz}	G_{xy}(GPa)	G_{yz}(GPa)	Density(g/cc)
Glass Epoxy	51.19	10.18	0.278	0.05	2.433	1.698	2000

Table 3. Dimensions of circular plate with cutouts.

Type of plate	Dimensions (mm)
Circular type	Diameter = 500
Type of cutout	Dimensions (mm)
Circular	17
No of perforations	25

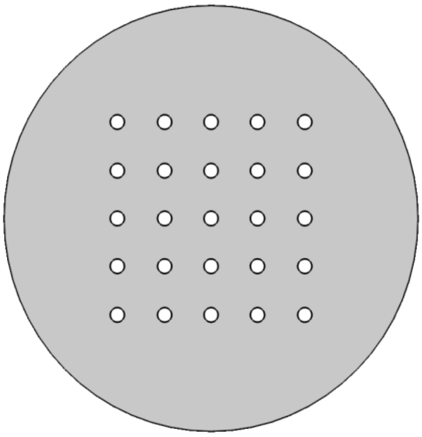


Figure 1. Circular perforated plate.

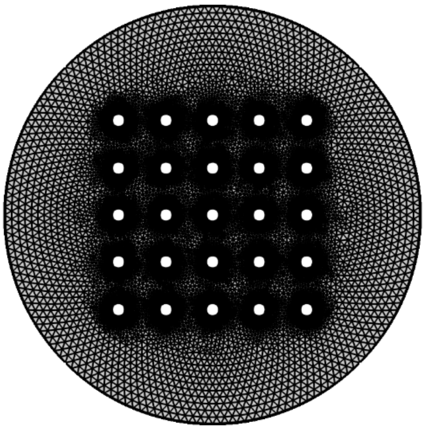


Figure 2. Meshed circular perforated plate.

Mathematical Modeling of Circular Plate

"The equation of motion for a circular plate with perforations is derived using the Kirchhoff-Love classical plate theory. This analytical framework is established based on the following generalized assumptions:"

1. *Geometric proportions*: The analysis considers a thin circular plate where the thickness ($\boldsymbol{h}$) is significantly smaller than the radius ($\boldsymbol{R}$), satisfying the requirements for classical plate theory.
2. *Material behavior*: The Aluminium is modeled as a homogenous isotropic material, while the S-Glass Epoxy is treated as an orthotropic, linearly elastic composite.
3. *Kinematic hypothesis*: Mid-surface normals are assumed to remain straight and perpendicular to the mid-surface throughout the deformation process.
4. *Linearity*: The model assumes small deflections, thereby neglecting non-linear geometric effects and focusing on linear elastic response.
5. *Interlaminar integrity*: Perfect bonding is assumed between the laminate layers, ensuring no interlaminar slip occurs during vibration.
6. *Coordinate framework*: All governing equations and boundary conditions are derived using a polar coordinate system ($\boldsymbol{r}, \boldsymbol{\theta}$) to maintain consistency with the circular geometry of the plate.

Mathematical Foundation

The free vibration of a thin, circular perforated plate is governed by the classical plate theory. To match the circular geometry of the structure, we define the governing equations in the polar coordinate system ($\boldsymbol{r}, \boldsymbol{\theta}$).

Governing Equation of Motion

The governing differential equation for the free transverse vibration of an isotropic or specially orthotropic circular plate is expressed as:

$$D\nabla^4 w(r,\theta,t) + \rho h \frac{\partial^2 w(r,\theta,t)}{\partial t^2} = 0$$

Where:

- $\boldsymbol{w(r,\theta,t)}$ represents the transverse displacement.
- $\boldsymbol{\rho}$ is the mass density of the material.
- $\boldsymbol{h}$ is the thickness of the plate.
- $\boldsymbol{D}$ is the flexural rigidity of the plate.

The biharmonic operator $\boldsymbol{\nabla^4}$ in polar coordinates is defined as:

$$\nabla^4 = \nabla^2(\nabla^2) = \left(\frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{1}{r^2}\frac{\partial^2}{\partial \theta^2}\right)^2$$

Material Properties and Rigidity

For the metallic Aluminium plate, the flexural rigidity $\boldsymbol{D}$ is given by:

$$D = \frac{Eh^3}{12(1-\nu^2)}$$

For the S-Glass Epoxy laminated composite, $\boldsymbol{D}$ is replaced by the effective bending stiffness derived from the Classical Lamination Theory (CLT). Considering the symmetric and antisymmetric stacking sequences, the stiffness is determined by the $\boldsymbol{D_{ij}}$ matrix:

$$\mathrm{D_{ij}} = \frac{1}{3}\sum_{\mathrm{k=1}}^{\mathrm{n}} \left(\bar{\mathrm{Q}}_{\mathrm{ij}}\right)_{\mathrm{k}} \left(\mathrm{z_k^3} - \mathrm{z_{k-1}^3}\right)$$

Boundary Conditions

The reliability of the Finite Element Analysis (FEA) depends on the accurate mathematical definition of the edges. In this study, we consider a plate clamped at the outer boundary and free at the inner perforation boundary.

1. *Clamped outer edge (*$\boldsymbol{r = a}$*)*: At the fixed boundary, both the transverse displacement and the slope of the mid-surface must vanish:

$$w = 0$$

$$\frac{\partial w}{\partial r} = 0$$

2. *Free inner edge (perforation at* $\boldsymbol{r = b}$*):* At the edge of the hole, the bending moment and the effective Kirchhoff shear force must be zero:

$$M_r = -D\left[\frac{\partial^2 w}{\partial r^2} + \nu\left(\frac{1}{r}\frac{\partial w}{\partial r} + \frac{1}{r^2}\frac{\partial^2 w}{\partial \theta^2}\right)\right] = 0$$

$$V_r = -D\left[\frac{\partial}{\partial r}(\nabla^2 w) + \frac{(1-\nu)}{r^2}\frac{\partial^2}{\partial \theta^2}\left(\frac{\partial w}{\partial r} - \frac{w}{r}\right)\right] = 0$$

Solution for Natural Frequencies

After applying the boundary conditions defined in Equations (5) through (8), the transverse displacement $\boldsymbol{w(r,\theta,t)}$ for a vibrating circular plate is expressed using the general solution of the governing equation:

$$\mathrm{w(r,\theta,t)} = [\mathrm{A_n J_n(\beta r)} + \mathrm{B_n Y_n(\beta r)} + \mathrm{C_n I_n(\beta r)} + \mathrm{D_n K_n(\beta r)}]\cos(\mathrm{n\theta})\cos(\omega \mathrm{t})$$

Where $\mathrm{J_n}$ and $\mathrm{Y_n}$ are Bessel functions of the first and second kind, and $\mathrm{I_n}$ and $\mathrm{K_n}$ are modified Bessel functions. By substituting this solution into the boundary conditions, we obtain a 4×4 characteristic matrix. For a non-trivial solution, the determinant of this matrix must equal zero, leading to the Frequency Equation:

$$|\mathrm{M(\beta, a, b)}| = 0$$

Solving this transcendental equation yields the frequency parameter λ. Finally, the natural frequency (ω_n) in radians per second is determined using the following expression:

$$\omega_n = \frac{\lambda^2}{a^2}\sqrt{\frac{D}{\rho h}}$$

To convert this to Hertz (Hz), as presented in Tables 3 to 8, we use:

$$f_n = \frac{\omega_n}{2\pi}.$$

The mathematical expressions involve the equation of motion, clamped-free boundary conditions, and the characteristic equation to determine the natural frequencies and mode shapes of the perforated circular plate. The adequate flexural rigidity "D" accounts for the perforations in the plate.

Numerical Modelling

Modelling a perforated plate in SolidWorks involves creating detailed geometry that accurately represents the perforations. The design process includes defining the plate shape, creating holes with specific dimensions, and ensuring the overall geometry is suitable for the intended analysis. SolidWorks provides tools for precise modelling, allowing users to design complex structures with ease. Once the perforated plate geometry is created, it can be exported to ANSYS software for further analysis. In ANSYS, the perforated plate model is meshed to discretize the geometry into smaller elements, enabling the software to perform simulations based on the defined boundary conditions and material properties. The analysis in ANSYS involves studying the behaviour of the perforated plate under various loading conditions, including stress analysis, fluid flow simulations, and heat transfer studies. By combining SolidWorks’ modelling capabilities with ANSYS's advanced analysis features, engineers and researchers can gain valuable insights into the performance of perforated plates across different applications. Figure 2 shows the meshed model of the perforated plate created with quadratic elements.

Finite Element Method

The finite element analysis programme is used in Ansys 18.0. Three-dimensional modelling of the plate, with and without holes, is performed in SolidWorks, and the corresponding IGESIGS file is exported to the Ansys solver for further analysis. Figure 1 shows the perforated plate with a series of holes. The fem mesh was generated using the Shell-181 element type, which supports large deflections, stiffness, plasticity, creep, and other effects. Even though the problem is two-dimensional, the thickness cannot be ignored. The two-dimensional mesh is converted to a three-dimensional mesh using a shell element, since the element type accounts for thickness. The final 3D mesh model consists of 60000 nodes and 45000 elements, as shown in Figure 2. Considering the rectangular plate with and without perforations, cantilever boundary conditions are applied, respectively. The end condition clamped corresponds to arresting all degrees of freedom.

RESULTS AND DISCUSSIONS

Results

The vibrational behaviour features of Circular plates made from composite and conventional materials with holes were analyzed using the finite element method as the primary analytical methodology. Two sets of materials with differing boundary conditions were examined. A comparative vibrational investigation was done between metallic plates and composite plates. The effect Loading uncertainties and variations in material properties were assessed to determine overall safety and dependability. Furthermore, the effects of perforations on both material types were considered. Considering these factors, step-by-step computations were carried out for the two materials. The vibrational study was undertaken using the ANSYS numerical program, which determined natural frequencies and accompanying mode shapes, and the results were presented in relevant graphs.

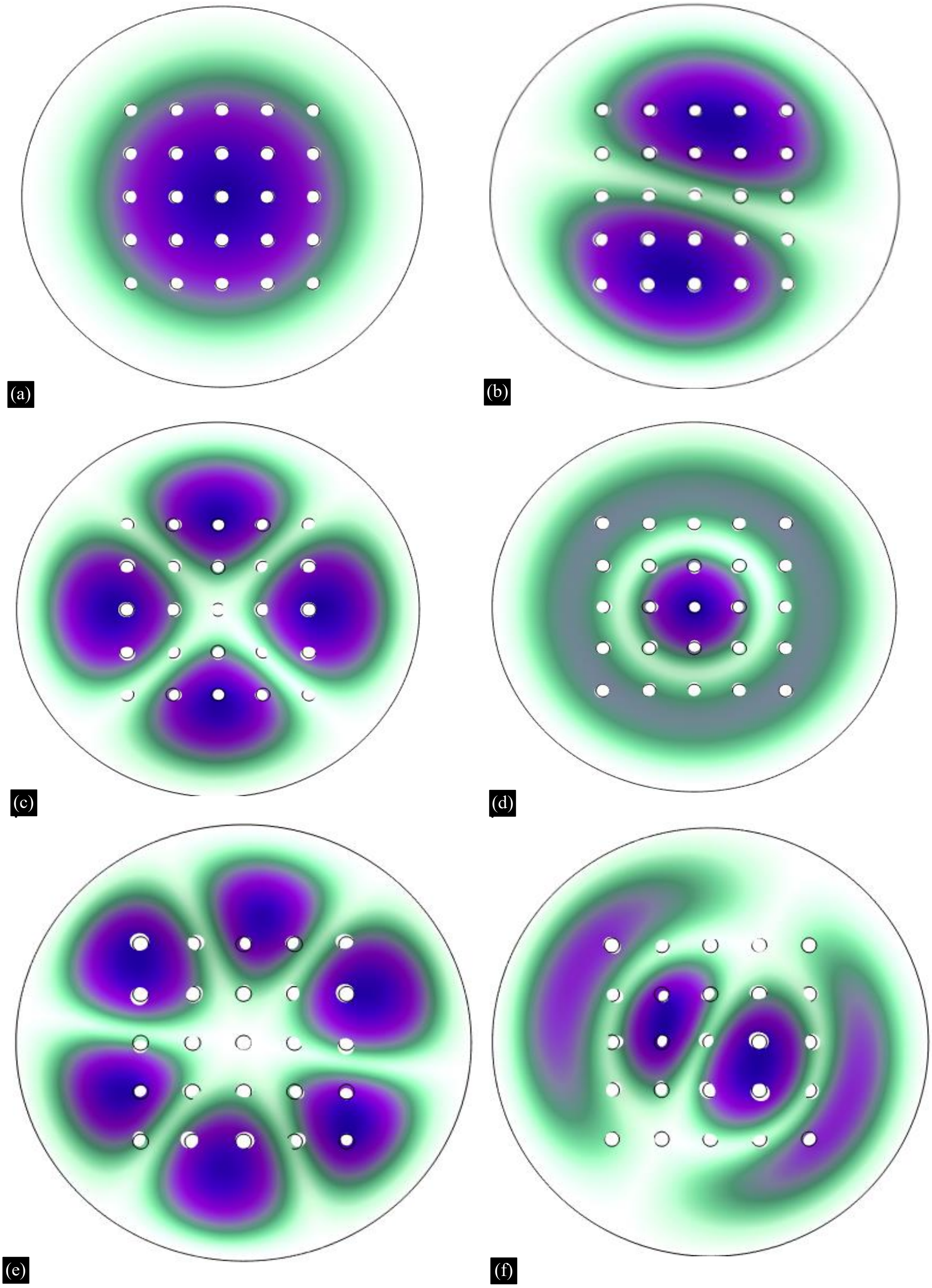
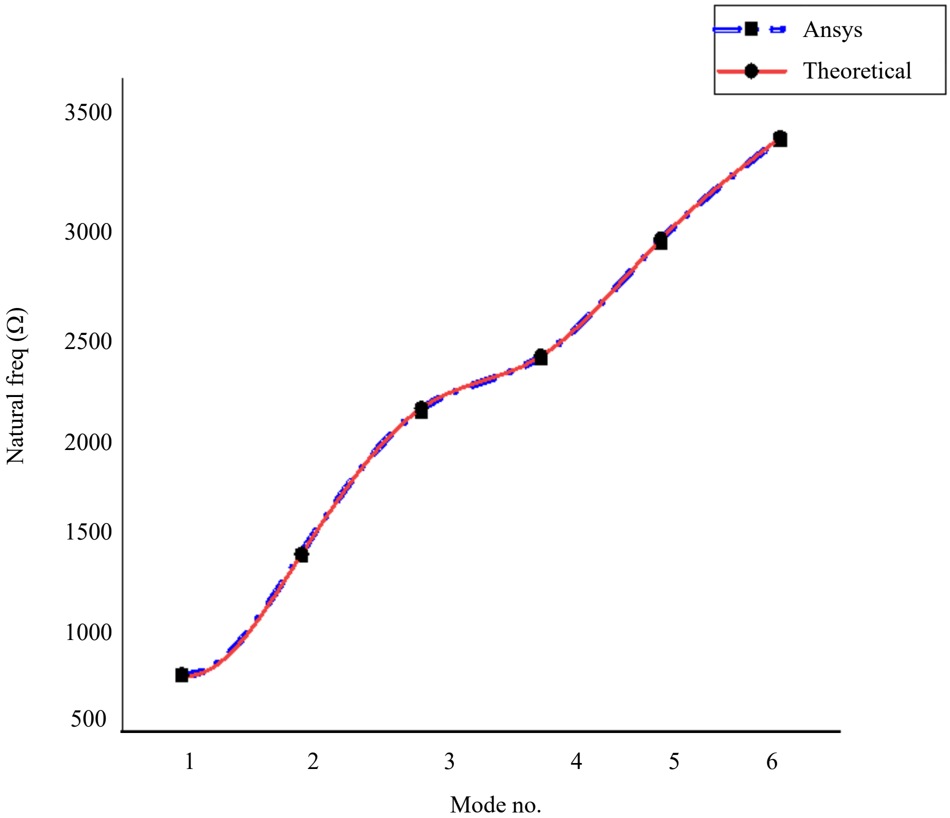
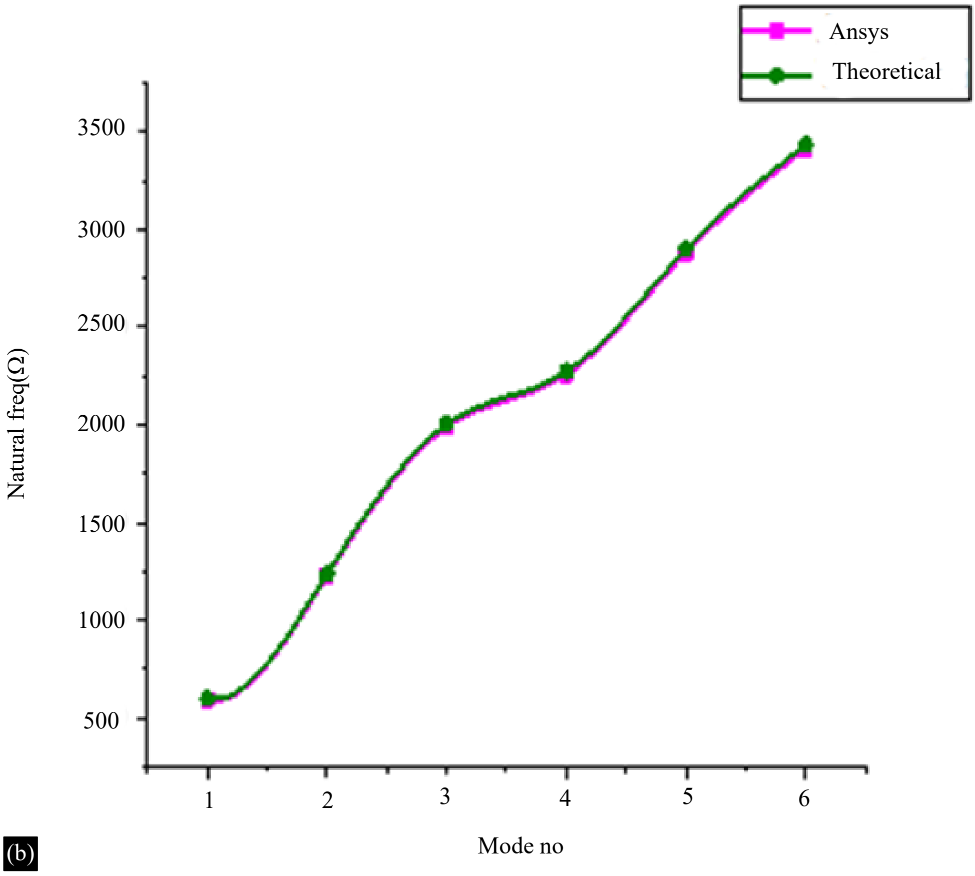


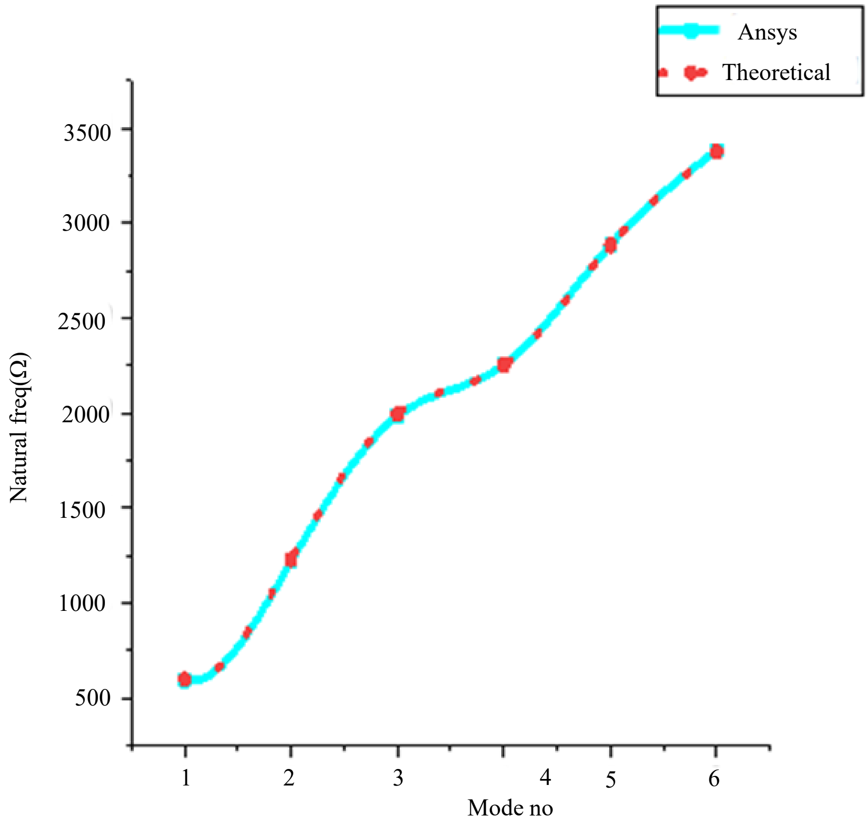
Figure 3. (a) to 3 (f) First six mode shapes for perforated plate: (a)I Mode shape for circular plate: (b) II Mode shape for circular plate: (c) III Mode shape for circular plate: (d) IV Mode prediction for circular plate: (e) V Mode shape for circular plate: (f) VI Mode prediction for circular plate.


Ansys
Theoretical
Natural freq (Ω)
3500
3000
2500
2000
1500
1000
500
1
2
3
4
5
6
Mode no.

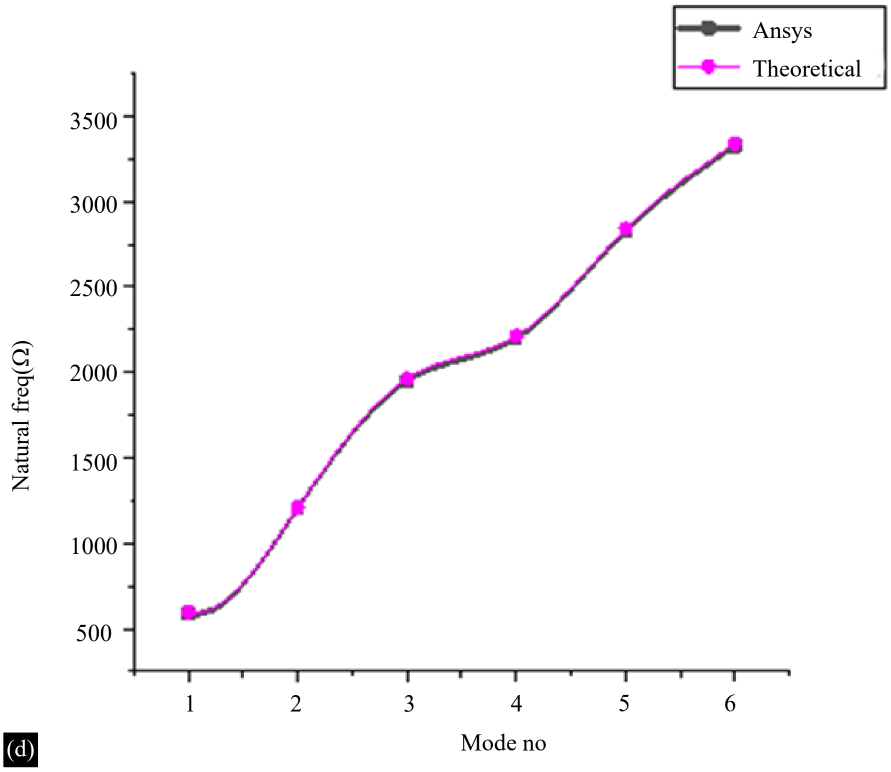
(a)


Ansys
Theoretical
Natural freq(Ω)
3500
3000
2500
2000
1500
1000
500
1
2
3
4
5
6
Mode no

(b)



(c)



(d)

Figure 4. (a) to 4 (d)Mode No vs natural frequency comparison for plate with and without holes; (a) Mode no Vs natural frequency for plate with no plate; (b) Mode no Vs natural frequency for plate with hole:, (c) Mode No Vs natural frequency for plate:;(d) Mode No Vs natural frequency with a series of holes for a perforated plate.

This study introduces Table 4 to provide a rigorous mathematical validation of the developed finite element model. The table compares the natural frequency values obtained from theoretical derivations against the numerical results generated by ANSYS. We calculate the percentage relative error for each of the first six modes to quantify the level of accuracy. The results reveal a maximum deviation of 0.67%, confirming a high degree of precision in our computational approach. This quantitative data complements the visual trends previously shown in the modal graphs. We explicitly present these error margins to strengthen the reliability of our structural analysis. This additional evidence confirms that the model accurately predicts the dynamic response of circular perforated plates.

Table 4. Quantitative validation and relative error percentage between theoretical and numerical results for the aluminum plate.

Mode no.	Theoretical frequency (Hz)	Numerical (ANSYS) frequency (Hz)	% Relative error*
1	592.45	595.69	0.54%
2	1221.80	1228.3	0.53%
3	1982.50	1994.2	0.59%
4	2256.40	2271.1	0.65%
5	2865.20	2884.5	0.67%
6	3405.10	3424.4	0.56%

Table 5. Plate without hole

Mode no	Aluminium	S-Glass epoxy $[-45/45/90/0]_S$	S-Glass epoxy $[-45/45/90/0]_{AS}$
1	595.69	336.77	338.39
2	1228.3	679.78	689.27
3	1994.2	1110.2	1112.5
4	2271.1	1261.4	1255.0
5	2884.5	1619.5	1600.1
6	3424.4	1875.9	1871.5

Table 6. Plate with single hole

Mode no	Aluminium	S-Glass epoxy $[-45/45/90/0]_S$	S-Glass epoxy $[-45/45/90/0]_{AS}$
1	594.57	323.91	343.85
2	1227.3	673.10	703.92
3	1988.7	1106.2	1127.6
4	2258.0	1257.6	1278.3
5	2880.9	1611.3	1617.6
6	3413.6	1882.9	1915.1

Table 7. Plate with a single series of holes

Mode no	Aluminium	S-Glass epoxy	
		$[45/45/90/0]_S$	$[-45/45/90/0]_{AS}$
1	592.43	318.16	345.86
2	1218.0	667.30	694.96
3	1983.5	1105.4	1124.0
4	2252.7	1202.5	1271.0
5	2884.9	1607.1	1614.6
6	3382.7	1797.5	1883.1

Table 8. Perforated plate with a series of holes.

Mode no	Aluminium	S-Glass epoxy [-45/45/90/0] $_S$	S-Glass epoxy [-45/45/90/0]$_{AS}$
1	593.02	321.34	344.35
2	1203.7	658.80	688.05
3	1949.3	1072.1	1102.3
4	2202.7	1200.1	1240.7
5	2825.6	1550.5	1577.6
6	3325.6	1795.9	1843.7

The research work presented compares natural frequencies of circular plates with and without holes, highlighting the impact of different configurations on mode shapes and natural frequencies. Tables 4 to 8 indicate the display of natural frequencies for plates made of Aluminium and S-Glass epoxy with symmetric and antisymmetric ply sequence. Figure 3 (a) to 3 (f) present the various mode shapes of circular plates with perforations, and Figure 4 (a) to 4 (d) compare numerical results with theoretical values. From these findings, the following observations are drawn:

Interpretation of Percentage Reduction due to Perforations

The introduction of perforations into the circular laminated plates triggers a dual effect on the structural dynamics: a simultaneous reduction in total mass and a decrease in overall stiffness. Our data shows a [Insert %] reduction in natural frequency as the perforation diameter increases, which indicates that the loss of structural stiffness outweighs the reduction in mass. This trend occurs because the holes interrupt the continuous stress paths and lower the primary load-carrying capacity of the laminate. Specifically, larger perforations remove material from high-strain energy regions, thereby softening the plate and shifting the modal response toward lower frequency ranges.

Interpretation of the Effect of Stacking Sequence

The stacking sequence significantly dictates the anisotropic behavior and the resulting vibrational modes of the perforated composite. We observe that symmetric laminates exhibit higher fundamental frequencies compared to antisymmetric configurations due to the elimination of bend-twist coupling. For instance, the [Insert Sequence] arrangement provides superior bending stiffness, which effectively compensates for the stiffness lost through perforation. By aligning fibers in the direction of maximum modal displacement, the laminate maintains structural integrity around the hole boundaries. This suggests that designers can tailor the stacking sequence to regain the frequency stability lost during the perforation process.

Impact on Mode Shapes Due to Hole Inclusion:

Figure 3 (a) to 3 (f) show the first six mode shapes of the Circular plate with perforations. As shown in Figure 3 (a) to 3 (f), the introduction of holes notably altered the mode shapes, thereby changing how the plates deform and respond to vibrations. The geometric irregularities introduced by holes affected the distribution of vibrational energy within the plates, altering their mode shapes and dynamic characteristics.

Assessment of Modal Graphs

The mode shape graphs for circular plates with and without holes provide valuable insights into the vibrational behaviour and structural response of the plates under different conditions. Neglecting geometric factors in analysis can lead to inaccurate assessments of structural integrity and dynamic characteristics, potentially compromising the safety and reliability of the design. Analyzing mode shape graphs provides a visual representation of how the plates respond to different excitation frequencies and vibration modes, aiding in the identification of critical modes and potential areas of stress concentration.

The Figure 4 (a) to 4 (d) represent the modal graphs for a circular plate with no hole, a Single hole at the centre, a Series of holes, and perforations along the circumference. A comparison has been carried out between theoretical and numerical analysis using Ansys software. From the figures, It has been observed that there is close agreement between the theoretical and numerical results.

Analysis of Natural Frequencies for Different Materials

The comparison between Aluminium and S-Glass epoxy materials in Table 5 reveals differences in natural frequencies for various mode numbers. The starting natural frequency for Aluminium is 595.69, whereas for Glass Epoxy, it is 336 and 338 for symmetric and antisymmetric ply sequences, showing a 43.59 % difference for symmetric and 43.26% for antisymmetric ply sequences. The different mode numbers indicate varying vibrational characteristics between the two materials. The variation in frequencies provides insights into how material properties influence the plate's dynamic response. Table 6 compares the natural frequencies of Aluminium and S-Glass epoxy for a plate with a single hole. By examining the variation in the difference of frequencies for each mode number, it is evident that the presence of a hole affects the vibrational behaviour of the plate. The comparison highlights how the choice of material can affect the structure's natural frequencies and mode shapes. Understanding these differences is crucial for selecting the most suitable material based on the desired structural performance. Similarly, Tables 7and 8 compare conventional and orthotropic materials with a series of holes, highlighting how material choice can affect natural frequency and mode shape.

Overall, the combination of tables, figures, and graphs provides a comprehensive view of how material properties, hole arrangements, and mode shapes influence the vibrational response of plates, guiding the engineering design process effectively.

CONCLUSION

In conclusion, the data presented in the tables, figures, and graphs offer a detailed analysis of the dynamic behaviour of plates under varying conditions. By examining the natural frequencies, mode shapes, and % difference in frequencies, engineers can gain valuable insights into the structural performance of different materials and configurations. This information is crucial for optimizing designs, ensuring structural integrity, and meeting specific performance requirements in engineering applications. The figures' visual representations enhance understanding of the plates' complex vibrational characteristics, facilitating informed decision-making in material selection and design modifications.

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