

FEA Simulation for Optimization of Laminated Composite Plate with Cutout in Free Vibrations

Manuraj^{1*}, Anadi Misra²

Abstract

Laminated composites have a large application in engineering. The work done in this study is to see the free vibration response of graphite epoxy composite square plate subjected to different boundary conditions. Finite element analysis has been done on the software ANSYS. The results obtained by the simulation have been compared with those obtained from a published data obtained by semi-analytical solution. It is observed that the solutions through ANSYS and that obtained through analytic solution are in good agreement and hence we see that this can be a valid method for simulating the problem. The analytic solution to this problem is complex and time consuming, so we suggest this approach which gives faster and reasonably accurate solution to the problem. The boundary conditions taken from the reference data are SSCC, SSCS, SSSS and SSCF and the ply taken is a cross ply with 0/90 lay. Further we see how the 1st mode natural frequency depends upon the area of the cutout. For a relative study we take readings for square, pentagonal, hexagonal, and circular shape cutout. For this we investigate different standard ply types with one of the above boundary conditions. Boundary condition taken is SSCS and the ply-types SP, QI, CP, and AP. Optimization has been carried out by selection of appropriate interpolation function for the data points as shown in the graphs. Then Genetic Algorithm is used to determine corresponding area to minimum and maximum frequency. Mode shapes can be extracted to see the deformation associated with particular modes. It can be utilized for placement of constraints on the structure.

Keywords: FEA, laminated composite plate, ANSYS, deformation theory, modal Analysis

INTRODUCTION

Simulating a process on computer can save a lot of time and money. Simulation can be especially useful when point of application is difficult to reach. Examples are maintenance of satellites and offshore plants. Computers have evolved in recent times and the capabilities for large computations have increased. Here it is utilized to analyze the problem of composite plates which has lot of computation requirement as it is a layered structure. This can be understood as an extended part of isotropic plates which has been the field of extensive research.

***Author for Correspondence**
Manuraj

¹M.Tech., Department of Mechanical Engineering, Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, Uttarakhand, India

²Professor, Department of Mechanical Engineering, Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, Uttarakhand, India

Received Date: April 12, 2021
Accepted Date: April 20, 2021
Published Date: April 26, 2021

Citation: Manuraj, Anadi Misra. FEA Simulation for Optimization of Laminated Composite Plate with Cutout in Free Vibrations. Journal of Experimental & Applied Mechanics. 2021; 12(1): 6–17p.

Composite laminated plate is modeled as a lay of orthotropic lamina stacked one over the other and the angle between the material axes of layers is one of the key parameters in determining its characteristics. The orthotropic material properties are used in the modeling. A composite is a material made by two or more materials having distinct characteristics which are merged at microscopic level, however in the final product each component can be identified separately as either reinforcement or matrix. The reinforcement phase is the member which sustains load in the member. The interface

offers a prevalent contact surface between matrix and reinforcement, while the matrix phase offers a well-binding strengthening medium. The reinforcement can be fiber/particle/metal and matrix can be plastic/ceramic. These days, composites are replacing all the major alloys and metallic parts due to their enhanced mechanical properties such as large strength to weight ratio. For example, steel is very strong but it is heavy. Wherever weight is a key design parameter, the utilization of composites finds application which are both light and strong but are significantly costly.

The review of the recent literature suggests many studies of successful simulations carried out for composite structure through software. ANSYS is one of the prominent software. Dong *et al.* presented a formulation based on theory for non-homogeneous and anisotropic plates and shells [1]. Civelok has used Discrete Singular Convolution (DSC) method for discretization of special derivatives to analyze the free vibration of laminated composite plates [2]. Kumar and Singh studied effect of boundary condition on buckling and post buckling analysis of composite laminated plate with various shape cutouts [3]. Isanaka has studied geometries like circular, square, rectangular with above aspect ratio of 1.25, 1.50 and 1.75, respectively and skew square (with 70, 76.67 and 83.33° skew angles, respectively) [4]. Fan and Cheung performed a study, and the results related to analysis for plates with mixed boundary conditions or with point support such as column-supported slabs and riveted plates are reported [5]. Boscolo have worked with the dynamic stiffness method which works with higher degree of accuracy for the analysis of laminated composite plates [6]. Pandit *et al.* discussed a nine-node iso-parametric plate-bending element for the analysis of free un-damped vibration of isotropic and fiber reinforced laminated composite plates [7]. Kant *et al.* have worked for dynamic analysis of beams [8]. Ramkrishna *et al.* have developed a computer program to obtain natural frequencies of the plate problem [9]. Number of elements for the solution have been obtained by hit and trial method. The material modeled can be molded in various shapes as plates, shells, beams etc. In many other applications we require to make openings in the planar shapes for wiring fitment or manholes. Monica S Swamy *et al.* [13] studied the plates of homogeneous and orthotropic property. They studied the buckling loads for various types of plates. This is done to access the stability aspect of the structure. Bhardwaj *et al.* [10] studied effects of different geometric parameters (aspect ratio, thickness ratio, boundary conditions, number of layers, and angle of lamina, some geometry of cut-out, cut-out side to plate side ratio and distance between cut-outs) and material properties on the free vibration responses.

As validation, a more general case of rectangular section is analyzed with various boundary conditions. The results are compared with the existing literature. Then we compare the results obtained for different types of cutout for different types of standard ply.

The parameters like boundary condition, aspect ratio and orientation of the fibers are the variables which are studied in this study.

MATERIALS AND METHODS

Materials and Procedures for Flat Plate

First order shear deformation theory, utilized by ANSYS, for plate has following assumptions:

1. Straight line perpendiculars to the mid-plane remain straight during deformation.
2. Transverse normal do not experience elongation ($\epsilon_{zz}=0$).
3. The theory takes into account the gross transverse shear strain in the formulation. As a result, the transverse normal does not remain normal to the mid-surface. The slope changes to some other value ϕ_x and ϕ_y .

The strains can be expressed in the following form:

$$\begin{Bmatrix} \epsilon_{xx} \\ \epsilon_{yy} \\ \gamma_{yz} \\ \gamma_{xz} \\ \gamma_{xy} \end{Bmatrix} = \begin{Bmatrix} \epsilon_{yy}^{(0)} \\ \epsilon_{yy}^{(0)} \\ \gamma_{yz}^{(0)} \\ \gamma_{xz}^{(0)} \\ \gamma_{xy}^{(0)} \end{Bmatrix} + z \begin{Bmatrix} \epsilon_{yy}^{(1)} \\ \epsilon_{yy}^{(1)} \\ \gamma_{yz}^{(1)} \\ \gamma_{xz}^{(1)} \\ \gamma_{xy}^{(1)} \end{Bmatrix} \quad (1)$$

Where,

$$\begin{Bmatrix} \epsilon_{yy}^{(0)} \\ \epsilon_{yy}^{(0)} \\ \gamma_{yz}^{(0)} \\ \gamma_{xz}^{(0)} \\ \gamma_{xy}^{(0)} \end{Bmatrix} = \begin{Bmatrix} \frac{\partial u_0}{\partial x} + \frac{1}{2} \left(\frac{\partial w_0}{\partial x} \right)^2 \\ \frac{\partial v_0}{\partial y} + \frac{1}{2} \left(\frac{\partial w_0}{\partial y} \right)^2 \\ \frac{\partial w_0}{\partial y} + \phi_y \\ \frac{\partial w_0}{\partial x} + \phi_x \\ \left(\frac{\partial u_0}{\partial y} \right) + \left(\frac{\partial v_0}{\partial x} \right) + \left(\frac{\partial w_0}{\partial y} \right) \left(\frac{\partial w_0}{\partial x} \right) \end{Bmatrix} \quad (2)$$

And,

$$\begin{Bmatrix} \epsilon_{yy}^{(1)} \\ \epsilon_{yy}^{(1)} \\ \gamma_{yz}^{(1)} \\ \gamma_{xz}^{(1)} \\ \gamma_{xy}^{(1)} \end{Bmatrix} = \begin{Bmatrix} \frac{\partial \phi_x}{\partial x} \\ \frac{\partial \phi_y}{\partial y} \\ 0 \\ 0 \\ \frac{\partial \phi_y}{\partial x} + \frac{\partial \phi_x}{\partial y} \end{Bmatrix} \quad (3)$$

The relation between the force and moment resultants and the corresponding deformation and curvature can be given as:

$$\begin{bmatrix} N_x \\ N_y \\ N_z \\ M_x \\ M_y \\ M_z \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{bmatrix} \epsilon_x^0 \\ \epsilon_y^0 \\ \gamma_{xy}^0 \\ \kappa_x^0 \\ \kappa_y^0 \\ \kappa_{xy}^0 \end{bmatrix} \quad (4)$$

The survey of the literature shows that many researchers have tried to solve problem of determining natural frequency of composite plates using analytic mathematical modelling.

Major work on the subject has been done by A.A. Khider, J.N. Reddy where they found the nonlinear equations to determine the natural frequency of the composite plate. They have utilized the concept to obtain the solution corresponding to various boundary conditions for thick and moderately thick plates [9–11].

The schematic of the sample used in the problem is given in Figure 1.

The displacement fields are assumed as:

$$u_1 = u + x_3 \phi_1 + x_3^2 \phi_2 \quad (5)$$

$$u_2 = v + x_3 \psi_1 + x_3^2 \psi_2 \quad (6)$$

$$u_3 = w \quad (7)$$

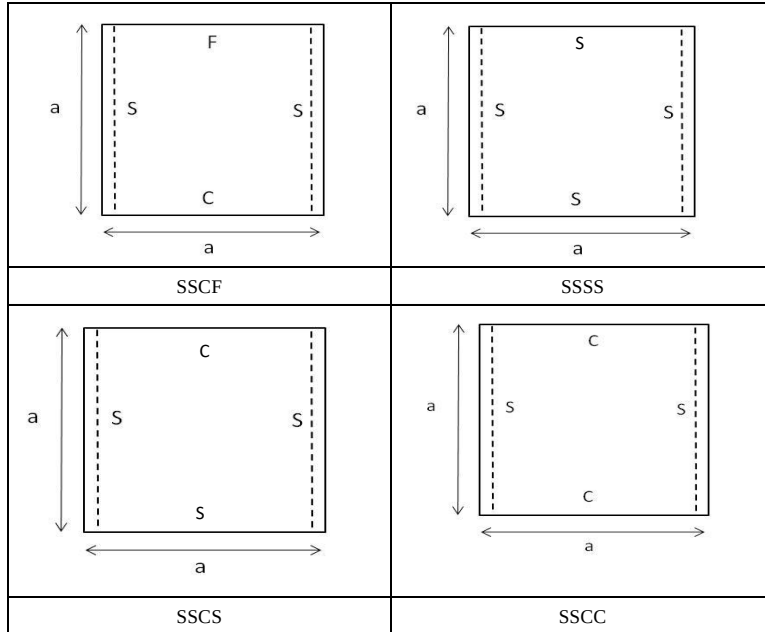


Figure 1. Geometry of model 1.

The two simply supported edges at $x_1=0$, a where $a=1$ are simply supported and hence follow the boundary condition:

$$u=w=\psi_1=\phi_2=M_1=N_6=L_6=0 \quad (8)$$

The displacement in the x_1 and x_2 direction can be modelled as:

$$u(x_1, x_2, t) = U_m(x_2, t) \sin \alpha x_1 \quad (9)$$

$$v(x_1, x_2, t) = V_m(x_2, t) \cos \alpha x_1 \quad (10)$$

$$w(x_1, x_2, t) = W_m(x_2, t) \sin \alpha x_1 \quad (11)$$

$$\phi_1(x_1, x_2, t) = \Phi_{1m}(x_2, t) \cos \alpha x_1 \quad (12)$$

$$\phi_2(x_1, x_2, t) = \Phi_{2m}(x_2, t) \sin \alpha x_1 \quad (13)$$

$$\psi_1(x_1, x_2, t) = \Psi_{1m}(x_2, t) \sin \alpha x_1 \quad (14)$$

$$\psi_2(x_1, x_2, t) = \Psi_{2m}(x_2, t) \cos \alpha x_1 \quad (15)$$

The equation of motion can be expressed in the form:

$$[y'] = [M]\{\ddot{y}\} + [K]\{y\} \quad (16)$$

The vector $\{y\}$ can be expressed as:

$$\{y\} = \{Y_m(x_2)\} T_m(t) \quad (17)$$

The general equation can be expressed as:

$$\ddot{T}_m + \omega_m^2 T_m = 0 \quad (18)$$

And,
 $[Y'] = [A][Y]$ (19)

Where,

$[A] = [k] - \omega_n^2 [M]$ (20)
 ω_n is the natural frequency regarding to the mth mode.

A similar model has been developed in ANSYS to determine the natural frequency of the laminated composite plate. A 1 m×1 m square plate has been modelled. A cross ply with (0/90) angle orientation has been investigated in the present study. The analysis has been done on ANSYS workbench and meshing is carried out. Then after applying appropriate boundary condition, the solution is done. The properties of material used are given in the Table 1.

Table 1. Material Properties for Graphite Epoxy.

E ₁ (GPa)	E ₂ (GPa)	G ₁₂ (GPa)	G ₁₃ (GPa)	G ₂₃ (GPa)	V ₁₂
100	4	2	2	0.8	0.25

Materials and Procedures for Flat Plate with Cutout

The model of plate with opening can be given as shown in Figure 2.

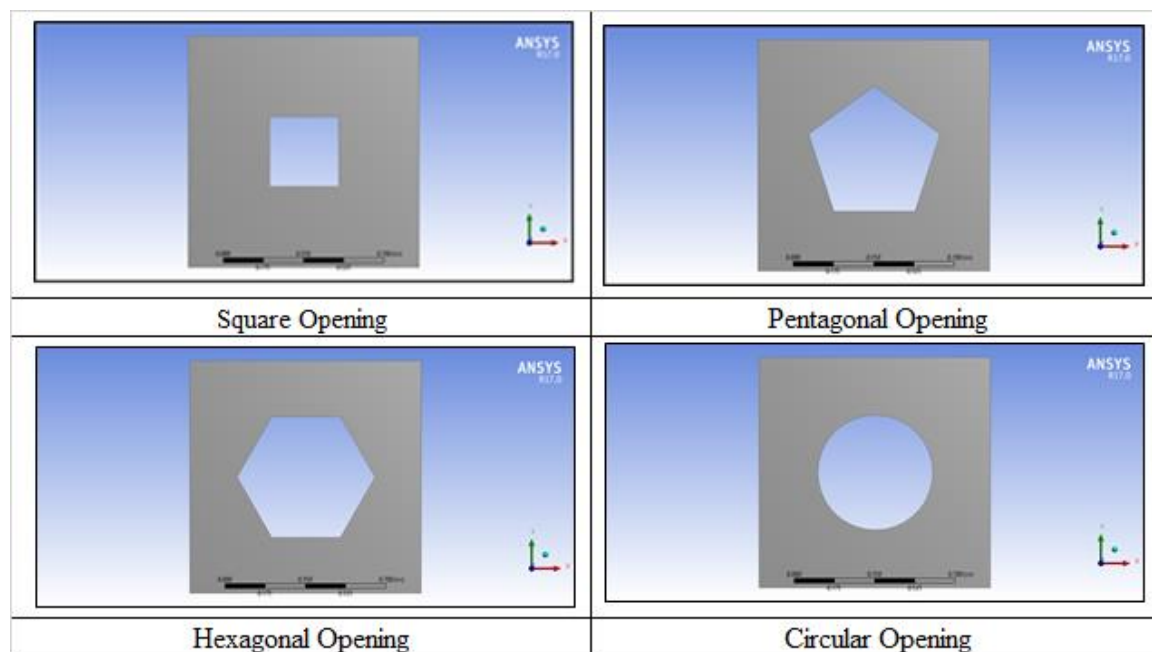


Figure 2. Geometry of plate with different openings.

The area of the opening has been increased gradually, starting with a small-size opening. Opening types taken are circular, square, hexagonal, and pentagonal openings. A symmetric ply [0/30/60/30/0], Quasi Isotropic ply [0/36/72/-18-54], Angle ply [45/-45/45/-45/45] and Cross ply [0/90/90/0/90] orientation has been investigated in the present study. The analysis has been done on ANSYS workbench and meshing is carried out. Then after applying boundary condition SSCS, the solution is done.

RESULTS AND DISCUSSION

Comparative Results of Theory and ANSYS

The result is obtained when the plate is subjected to various boundary conditions and the error

percentage is calculated as given in Table 2.

Table 2. Response of plate subjected to different boundary conditions.

S.N.	Boundary Condition	Aspect Ratio	η_{ANSYS}	η_{th}	Error (%)
		(a/h)	(Hz)	(Hz)	
1	SSSS	5	407.75	395.51	3.09
		10	252.63	233.83	8.04
		20	137.37	123.50	11.23
		50	56.679	50.24	12.82
2	SSSC	5	440.85	439.44	0.32
		10	294.92	280.77	5.04
		20	167.63	154.28	8.66
		50	70.301	63.66	10.43
3	SSCC	5	487.41	485.44	0.40
		10	358.57	336.80	6.46
		20	210.4	195.12	7.26
		50	89.529	82.31	8.06
4	SSFC	5	316.41	294.98	7.26
		10	196.89	171.61	14.73
		20	106.99	90.13	18.70
		50	44.188	43.48	1.63

The graphical representation comparative for SSSS boundary condition is given in Figure 3. For SSSC boundary condition, the comparative data is given in Figure 4. For SSCC boundary condition, the comparative data is given in Figure 5. For SSCF boundary condition, the comparative data is given in Figure 6.

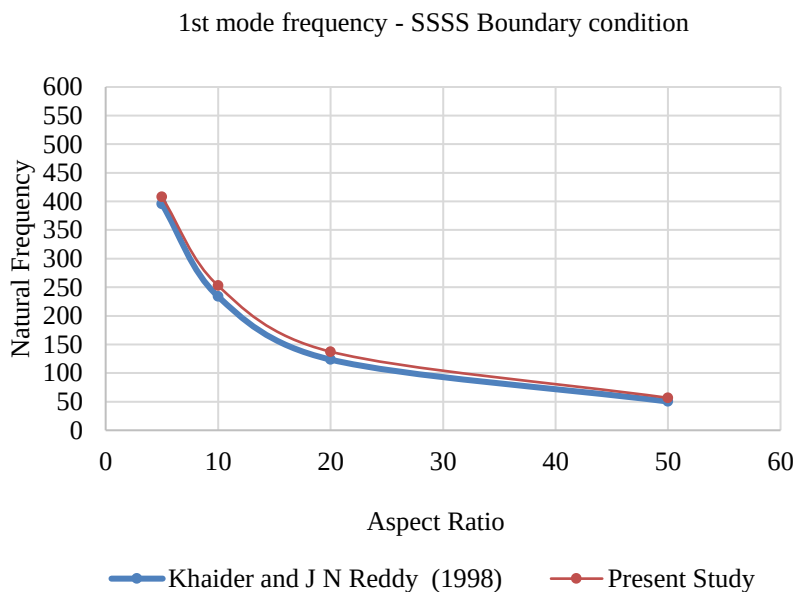


Figure 3. Response of SSSS B.C. for different aspect ratio.

The graph clearly shows that the present data is in close agreement with the Khaider and J N Reddy (1998) [9] as both the graphs give the same pattern and values corresponding to the given aspect ratio. Different mode shapes for all edges simply supported are given in Figure 7.

Response of the Plate with Opening

The boundary condition under consideration is SSCS. For the SY ply type, trend observed for different types of opening is given in Figure 8.

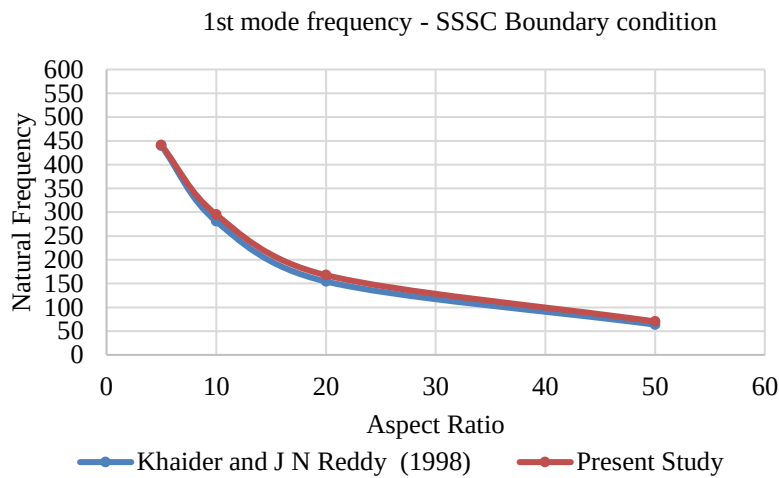


Figure 4. Response of SSSC B.C. for different aspect ratio.

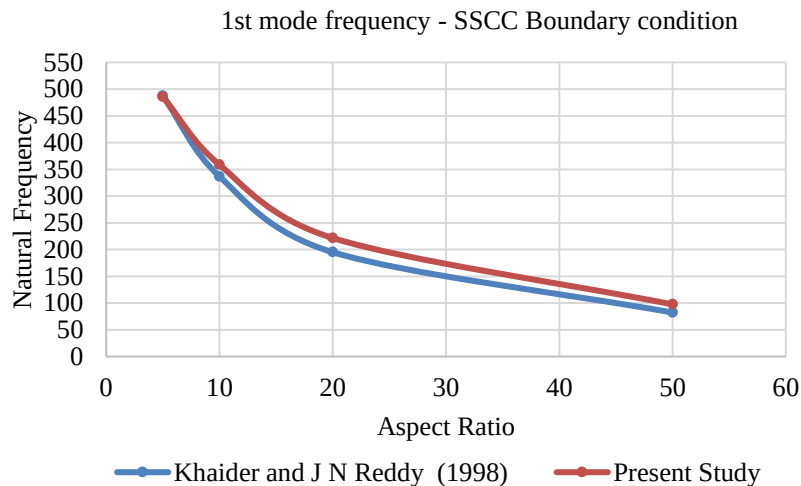


Figure 5. Response of SSCC B.C. for different aspect ratio.

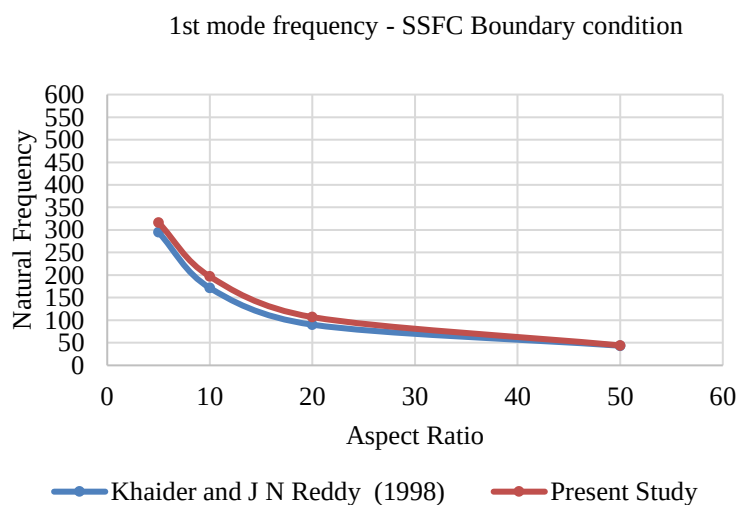


Figure 6. Response of SSFC B.C. for different aspect ratio.

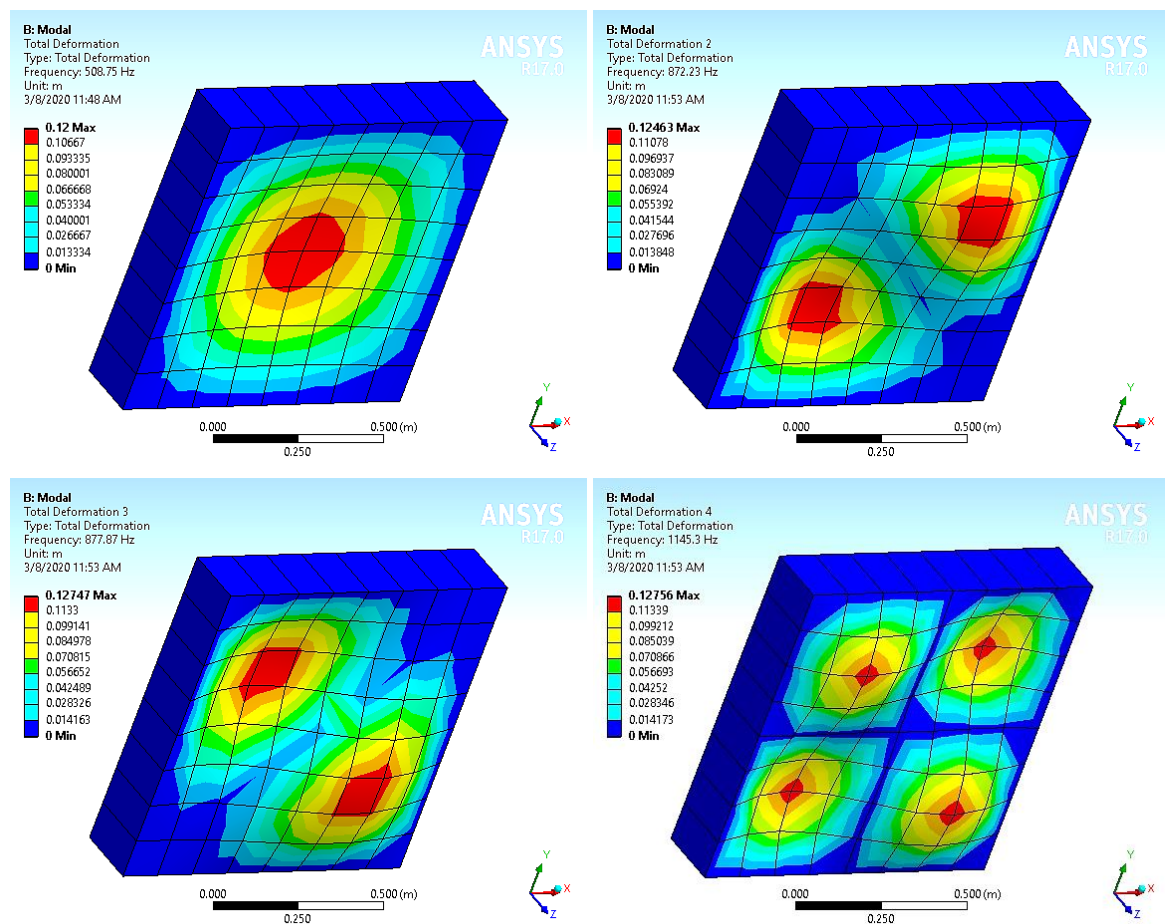


Figure 7. Plot for different thickness and boundary conditions.

The area corresponding to minimum and maximum frequency for symmetric ply is given in Table 3.

Table 3. Frequency, Min/Max.

	Frequency		A_F	
	Min	Max	Min	Max
Circular	83.58	148.57	0.13	0.65
Hexagonal	82.69	137.54	0.15	0.65
Pentagonal	81.67	109.60	0.16	0.60
Square	73.07	86.74	0.50	0.00

For the QI ply type, trend observed for different types of opening is given in Figure 9.

The area corresponding to minimum and maximum frequency for QI Ply is given in Table 4.

For the CP ply type, trend observed for different types of opening is given in Figure 10.

The area corresponding to minimum and maximum frequency for CP Ply is given in Table 5.

For the AP ply type, trend observed for different types of opening is given in Figure 11.

The area corresponding to minimum and maximum frequency for AP Ply is given in Table 6.

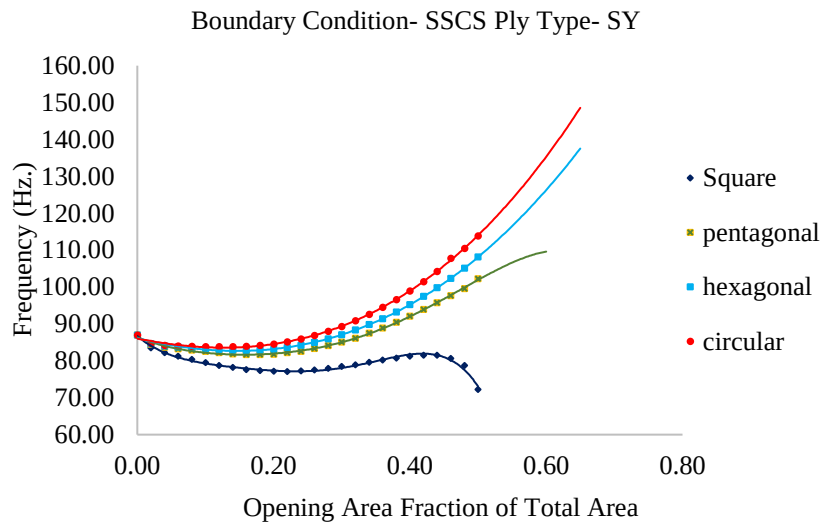


Figure 8. Changes in frequency for Symmetric Ply type.

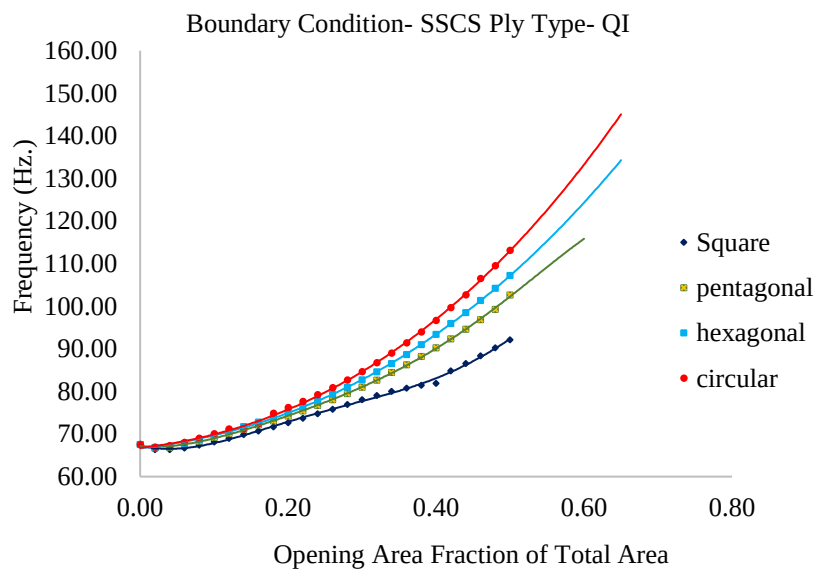


Figure 9. Changes in frequency for Quasi Isotropic ply type.

Table 4. Frequency, Min/Max.

	Frequency		A_F	
	Min	Max	Min	Max
Circular	66.75	145.07	0.00	0.65
Hexagonal	66.65	134.30	0.00	0.65
Pentagonal	67.00	115.85	0.02	0.60
Square	66.52	92.30	0.04	0.50

Table 5. Frequency, Min/Max.

	Frequency		A_F	
	Min	Max	Min	Max
Circular	78.48	108.84	0.16	0.65
Hexagonal	76.47	99.82	0.25	0.65
Pentagonal	76.33	83.24	0.28	0.54
Square	56.67	81.66	0.50	0.00

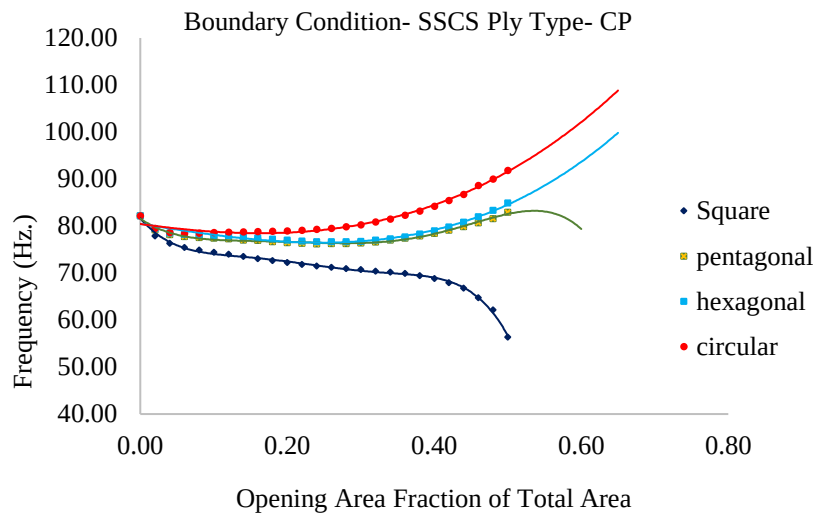


Figure 10. Changes in frequency for Cross ply type.

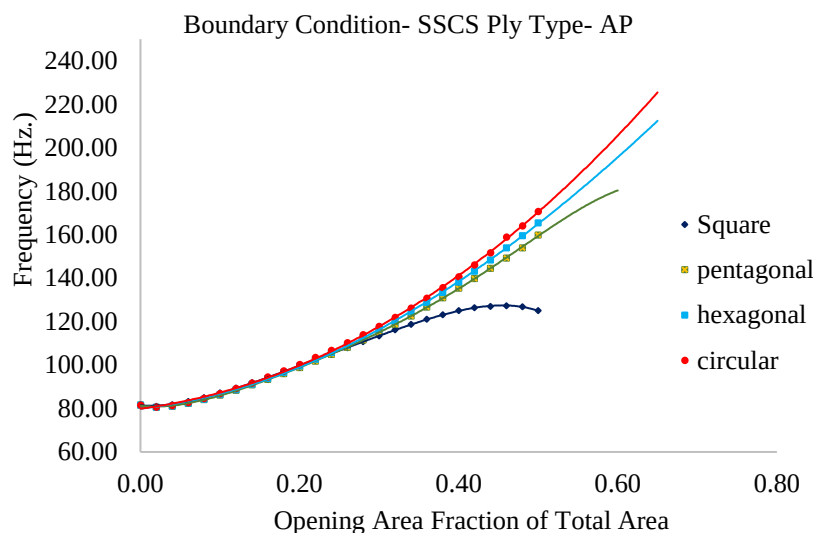


Figure 11. Changes in frequency for Angle ply type.

Table 6. Frequency, Min/Max.

	Frequency		A_F	
	Min	Max	Min	Max
Circular	66.75	145.07	0.00	0.65
Hexagonal	66.65	134.30	0.00	0.65
Pentagonal	67.00	115.85	0.02	0.60
Square	66.52	92.30	0.04	0.50

CONCLUSION

In the present investigation, an orthotropic epoxy material is analyzed and the laminate is subjected to SSCS boundary condition with four types of openings. It is observed that the results are in good agreement with the results given in literature. So, it is a valid method for simulating the problem. As expected, the frequency is highest for the constrained structure. Again, the modal analysis shows the location at which the maximum deformation occurs and the node points where there is no deformation. Also constraints must be located at that location for the design purpose.

Regarding the plate with opening:

1. When we require a square opening for symmetric or cross plies, we need a thorough study of the design by modal analysis, as frequency is strong function of area. The frequency drops continuously as the area increases. There is a sharp drop in frequency beyond a particular area. This situation should be avoided.
2. When using a pentagonal opening, it can be used for symmetric ply. When using for cross ply type, a study must be carried out based on the application.
3. There is no significant drop observed as the area of the opening for any type of opening for angle ply. So, this ply has high suitability for applications where openings are requirement in a structure.
4. For application of quasi-isotropic ply, we can expect that making an opening will not reduce frequency of the structure. This type of ply has a low natural frequency.
5. For symmetric or cross ply, circular or hexagonal openings must be used strictly. As, although there is a noticeable but small drop in frequency as the size of opening increases before reaching a particular area, beyond that, the frequency increases.

Acknowledgement

The authors acknowledge the ANSYS software and related technical help provided by Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, without which this study might not have been possible.

Abbreviation

ε	Linear total strains
[M]	Mass Matrix
[K]	Stiffness Matrix
κ	Curvature
σ	Stress
u, v, w	Displacement Components in x, y, z
ω_n	Natural Frequency of nth mode
N, M, L	Force, Moment resultants
A, B, D	Plate Stiffness
SP	Symmetric Ply
QI	Quasi Isotropic Ply
CP	Cross Ply
AP	Angle Ply
SSCC	Boundary Condition with two edges simply supported, two edge clamped
SSCS	Boundary Condition with three edges simply supported, one edge clamped
SSSS	Boundary Condition with four edges simply supported
SSCF	Boundary Condition with two edges simply supported, one edge clamped, one edge free

REFERENCES

1. Bhardwaj H, Vimal J, Sharma A. Study of free vibration analysis of laminated composite plates with triangular cutouts. Eng Solid Mech. 2015; 3(1): 43–50.
2. Boscolo M, Banerjee JR. Layer-wise dynamic stiffness solution for free vibration analysis of laminated composite plates. J Sound Vibr. 2014; 333(1): 200–27.
3. Isanaka BR, Akbar MA, Mishra BP, et al. Free vibration analysis of thin plates: Bare versus Stiffened. Engineering Research Express (ERX). 2020; 2(1): 015014.
4. Civalek Ö. Free vibration analysis of symmetrically laminated composite plates with first-order shear deformation theory (FSDT) by discrete singular convolution method. Finite Elem Anal Des. 2008; 44(12–13): 725–31.
5. Kumar D, Singh SB. Effects of boundary conditions on buckling and postbuckling responses of composite laminate with various shaped cutouts. Compos Struct. 2010; 92(3): 769–79.

-
6. Dong SB, Pister KS, Taylor RL. On the theory of laminated anisotropic shells and plates. *Journal of the Aerospace Sciences*. 1962; 29(8): 969–75.
 7. Fan SC, Cheung YK. Flexural free vibrations of rectangular plates with complex support conditions. *J Sound Vibr*. 1984; 93(1): 81–94.
 8. Kant T, Marur SR, Rao GS. Analytical solution to the dynamic analysis of laminated beams using higher order refined theory. *Compos Struct*. 1997; 40(1): 1–9.
 9. Khdeir AA, Reddy JN. Free vibrations of laminated composite plates using second-order shear deformation theory. *Comput Struct*. 1999; 71(6): 617–26.
 10. Mallika A, Rao RN. Topology optimization of cylindrical shells for various support conditions. *International Journal of Civil and Structural Engineering*. 2011; 2(1): 11–22.
 11. Swamy Monica S, et al. Buckling Analysis of Plate Element Subjected to In Plane Loading Using ANSYS. *International journal of Scientific and Engineering Research (IJSER)*. 2012; 9: 70–79
 12. Pandit MK, Haldar S, Mukhopadhyay M. Free vibration analysis of laminated composite rectangular plate using finite element method. *J Reinf Plast Compos*. 2007; 26(1): 69–80.
 13. Ramakrishna S, Rao KM, Rao NS. Free vibration analysis of laminates with circular cutout by hybrid-stress finite element. *Compos Struct*. 1992; 21(3): 177–85.