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Combined Effect of Stacking Sequence, Mid-Plane Circular Delamination, Fibre Orientation and Boundary Conditions on the Modal Parameters of Four-ply Composite Plate

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ABSTRACT

A three-dimensional finite element (FE) model of a four-ply fiber-reinforced composite plate, with and without delamination, is developed using ABAQUS software to investigate its vibration characteristics. Initially, modal analysis is conducted on the undamaged (healthy) composite plate to examine the influence of stacking sequence, boundary conditions (BCs), and fiber orientation angle on the fundamental natural frequency. Four different stacking sequences are analyzed, comprising two symmetric layups—[ϴ/ϴ/ϴ/ϴ] and [ϴ/-ϴ/-ϴ/ϴ]—and two anti-symmetric layups—[ϴ/-ϴ/ϴ/-ϴ] and [ϴ/ϴ/-ϴ/-ϴ]. The boundary conditions considered include Clamped-Free (CF), Clamped-Clamped (CC), Clamped-Simply Supported (CS), and Simply Supported-Simply Supported (SS). The fiber orientation angle (ϴ) is varied from 0° to 90° in 15° increments. The simulation outcomes are validated by comparing them with existing numerical and experimental results from the literature.

Subsequently, the developed plate model is employed to investigate the effect of mid-plane circular delamination on the modal natural frequencies of the composite structure. Delaminations of varying diameters—2 cm, 4 cm, and 8 cm—are introduced at the mid-plane to assess their influence under different stacking sequences and fiber orientation angles, consistent with the configurations used in the healthy beam model. However, in this phase, the boundary condition is limited to a single case: one edge clamped and the remaining edges free. The results reveal that delamination size has a pronounced impact on the fundamental frequency, with larger delaminations causing greater reductions. These findings highlight that changes in modal parameters, particularly natural frequency, can serve as effective indicators for detecting delamination in composite plates.

Keywords: Natural frequency, Finite element model, Composite plate, Delamination, Fibre orientation

1. INTRODUCTION

Fiber-reinforced composite structures are widely used in various industries like automobiles, aerospace, defense, manufacturing units, etc. due to their excellent specific stiffness and strength. Debonding also known as delamination or separation of plies of the laminate, occurs frequently during manufacturing or in service. Repeated cyclic stresses, impact, shocks, or loadings cause lamina to separate resulting in a significant reduction in mechanical stiffness. The delamination within interfaces may not be visible to us. However, their presence affects the vibration characteristics of the structure [1, 2]. Natural frequency plays a vital in understanding the dynamic characteristics of a healthy and unhealthy structure [3]. If the excitation frequency matches with the natural frequency of a structure then the structure undergoes large deflection and hence internal stresses build-up due to the resonance. As a result, the structure may collapse. Various researchers have worked for the past many years to understand the dynamic behaviour of the composite structure.

Structural strength and stiffness are reduced in the presence of delamination [4, 5]. Various factors affecting the vibration aspect of the composite structure are reviewed by Della and Shu [6]. Lee [7] explored the effect of the lay-up sequence on the first vibration mode of a delaminated composite cantilever beam made of T300/5208 graphite epoxy. An increased effect on the natural frequency with a lay-up angle was observed in the presence of delamination. A similar observation was made by Zhu et al. [8]. Other studies also showed that change in stacking sequence affects the natural frequency of delaminated [9, 10] and un-delaminated structure [11].

To detect damage experimentally in composite materials, Jian [12] used piezoelectric patches. Results of piezoelectric patches showed the expected reduction in the frequency with an increase in damage. Jun [13] predicted accurately the vibration attribute of a generally layered composite beam by using a dynamic finite element method. Results were obtained by changing lay-up angle and boundary conditions and discussing the change in the natural frequency of composite material. Sultan et al. [14] simulated a 3D FE model to find dynamic results of composite laminated plates with and without delamination experimentally and numerically to extract their natural frequencies. A 3D FE model was also developed by Alnefaie [15] to analyze the dynamics of the delaminated fiber-reinforced composite plate.

Callioglu et al. [16] conducted an analytical, numerical, and experimental investigation to find the effects of multiple delaminations, locations, sizes, orientation angles, boundary conditions, and stacking sequences on the free vibration dynamics of a laminated composite beam. Yang and Oyadiji [17] presented a novel approach to detect damage using modal frequency surface (MFS) by a point mass attaching at different locations. The FEM technique is employed to simulate the modal natural frequency. The frequency variation shows a quasi-exponential decrease with an increase in delamination depth. Zou et al. [18] developed a method that used a vibration-based model with piezoelectric sensors

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and actuators incorporated into composite structures to monitor the health and detect damage. FE analysis techniques along with experimental results are used to detect damage [19]. So, it is very important to study the modal characteristic of the composite structure under the combined effect of stacking sequence, lay-up angle, boundary condition, and presence of delamination.

The present study modeled a four-layer composite beam and plate for carrying out simulations for modal analysis. The two symmetrical and two anti-symmetrical stacking sequences, four different boundary conditions, and three different delamination sizes are used for simulation to know their effect on the natural frequency. A 3D FE model is developed and simulations are performed using ABAQUS software to compare and validate the results with numerical and experimental results for the healthy composite beam from the literature. The results produced by the models are then discussed and plotted to get a clear understanding of the combined effects of all these parameters on modal natural frequencies.

2. COMPOSITE PLATE FE MODELING

A three translational DOF at each node along the global coordinate axes X, Y, and Z are used in the FE model of the eight-node element. The element thickness is selected as the thickness of an individual lamina. The fiber direction is coincident with the first axis. X_1, X_2, and X_3 are arranged as a local element coordinate system. All the elements are assumed to have identical elemental physical parameters. So, the elemental displacement field is given by

$$\{\delta\} = (u, v, w)^T = \sum_{i=1}^{8}[N_i]\{\delta i\} \quad (1)$$

Where, $\{\delta\} = (u_i, v_i, w_i)^T$ is the nodal displacement vector at node i and N_i is the shape function. Then the elemental strain vector expressed in terms of global coordinate displacement as

$$\{\varepsilon^e\} = (\varepsilon_{11}^e, \varepsilon_{22}^e, \varepsilon_{33}^e, \varepsilon_{12}^e, \varepsilon_{13}^e, \varepsilon_{23}^e)^T = \sum_{i=1}^{8}[B_i]\{\delta i\} \quad (2)$$

$$\text{Where,} [Bi] = [\Delta][Ni] \quad (3)$$

And

$$[\Delta] = \begin{bmatrix} \frac{\partial}{\partial x} & 0 & 0 \\ 0 & \frac{\partial}{\partial y} & 0 \\ 0 & 0 & \frac{\partial}{\partial z} \\ \frac{\partial}{2\partial y} & \frac{\partial}{2\partial x} & 0 \\ 0 & \frac{\partial}{2\partial z} & \frac{\partial}{2\partial y} \\ \frac{\partial}{2\partial z} & 0 & \frac{\partial}{2\partial z} \end{bmatrix} \quad (4)$$

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Thus, the elemental strain vector can be expressed in terms of nodal displacements as $\{\varepsilon^e\} = [B]\{\delta^e\}$

With$[B] = [[B_1], [B_2], \dots, [B_8]]and\{\delta^e\} = (\{\delta_1\}^T, \dots, \{\delta_8\}^T)^T$ (5)

Therefore, the global coordinate system elemental stresses expressed in term of nodal displacement as

$$\{\sigma^e\} = \{\sigma_{11}^e, \sigma_{22}^e, \sigma_{33}^e, \sigma_{12}^e, \sigma_{13}^e, \sigma_{23}^e\} = \sum_{i=1}^{8}[K^e]\{\delta^e\} \quad (6)$$

Where $[K^e]$is the elemental stiffness matrix,

$$[K^e] = \int_{v_e}[B]^T[A][C][A]^{-1}[B]dV \quad (7)$$

Where

$$[C] = \begin{bmatrix} \frac{1}{E_1} & \frac{-\vartheta_{12}}{E_1} & \frac{-\vartheta_{13}}{E_1} & 0 & 0 & 0 \\ \frac{-\vartheta_{12}}{E_1} & \frac{1}{E_2} & \frac{-\vartheta_{23}}{E_2} & 0 & 0 & 0 \\ \frac{-\vartheta_{13}}{E_1} & \frac{-\vartheta_{23}}{E_2} & \frac{1}{E_3} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{12}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{13}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{23}} \end{bmatrix}^{-1} \quad (8)$$

is material constants matrix, where $E_1, E_2, E_3, G_{12}, G_{13}, G_{23}, \vartheta_{12}, \vartheta_{13}, \vartheta_{23}$being the individual lamina orthotropic elastic constants, and

$$[A] = \begin{bmatrix} cos^2\theta & sin^2\theta & 0 & 0 & 0 & -sin2\theta \\ sin^2\theta & cos^2\theta & 0 & 0 & 0 & sin2\theta \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & cos\theta & sin\theta & 0 \\ 0 & 0 & 0 & -sin\theta & cos\theta & 0 \\ sin\theta cos\theta & -sin\theta cos\theta & 0 & 0 & 0 & cos2\theta \end{bmatrix} \quad (9)$$

is the local and global coordinate transformation matrix. Then, kth elemental strain energy is given by

$$U_k^e = \frac{1}{2}\int_{v_k}\{\varepsilon^e\}^T\{\sigma^e\}dV = \frac{1}{2}\{\delta_k^e\}^T[K_k^e]\{\delta_k^e\} \quad (10)$$

Where $[K_k^e]$ and $\{\delta_k^e\}$ represents kth elemental stiffness matrix and the displacement vector, respectively.

For a composite plate comprising N elements, the total strain energy is as

$$U = \sum_{k=1}^{N} U_k^e = \frac{1}{2}\sum_{k=1}^{N}\{\delta_k^e\}^T\ [K_k^e]\{\delta_k^e\}$$
(11)

Therefore, after assembling all the elemental nodal displacements, the total strain energy of a multi-plies composite plate is written as

$$U = \frac{1}{2}\{\delta\}^T[K]\{\delta\} \tag{12}$$

Where $[K]$ and $\{\delta\}$ are the global nodal stiffness matrix and displacement vector, respectively. Similarly, the kth elemental kinetic energy is

$$T_k^e = \frac{1}{2}\int_{v_k}\rho\{\dot{\delta}_k^e\}^T dV = \frac{1}{2}\{\dot{\delta}_k^e\}^T[M_k^e]\{\dot{\delta}_k^e\} \tag{13}$$

Where $[M_k^e]$ and $\{\dot{\delta}_k^e\}$ represents kth elemental mass matrix and the velocity vector, respectively.

For a composite plate comprising N elements, the total kinetic energy is as

$$T = \sum_{k=1}^{N} T_k^e = \frac{1}{2}\sum_{k=1}^{N}\{\dot{\delta}_k^e\}^T[M_k^e]\{\dot{\delta}_k^e\} \tag{14}$$

Therefore, after assembling all the elemental nodal velocities, the total kinetic energy of a multi-plies composite plate is written as

$$T = \frac{1}{2}\{\dot{\delta}\}^T[M]\{\dot{\delta}\} \tag{15}$$

Where $[M]$ and $\{\dot{\delta}\}$ are the global nodal mass matrix and velocity vector, respectively.

The kinetic energy of the composite laminate in the case, if plate experiences ω angular frequency harmonic motion is

$$T = \frac{1}{2}\omega^2\{\delta\}^T[M]\{\delta\} \tag{16}$$

Then, for the free vibration of the plate, the equation of motion by Lagrange's principle is converted to the eigen-value problem

$$([K] - \omega^2[M])\{\delta\} = 0 \tag{17}$$

Therefore, natural frequenciesω_i, modal strains, mode shape and all the other modal parameters are obtained.

To ensure the material continuity to an arbitrary intact laminated plate, for each pair of coincident nodes, the displacements and their variations on the lower and theupper adjacent lamina have to be equal in the computing process. For the delaminated region, pairs of nodes are modelled where delamination is to be induced. Within the delamination region,the pairs of nodes are not attached and their lower and upper surface displacements are not to be connected.

3. RESULT AND DISCUSSION

3.1 FE Model Validation

To validate the FE model with the results available in the reference [13], the geometrical and mechanical properties of the four plies composite laminated cantilever beam of a square cross-section taken are as below

E_1= 144.8 GPa, E_2 = E_3= 9.65 GPa, G_{12}= G_{13} = 4.14 GPa, G_{23} = 3.45 GPa, υ_{12} = 0.3, ρ = 1389.23kg/m^3, Length of beam L = 0.381 m, width b = 25.4 × 10^{-3} m and thickness h = 25.4 × 10^{-3} m.

Four different stacking sequences were considered in the simulation for modal analysis, comprising two symmetric lay-ups—[Ө/Ө/Ө/Ө] and [Ө/-Ө/-Ө/Ө]—and two anti-symmetric lay-ups—[Ө/-Ө/Ө/-Ө] and [Ө/Ө/-Ө/-Ө]. Table 1 presents the numerically obtained fundamental natural frequencies (in Hz) for a cantilever composite beam as the fiber orientation angle (Ө) varies from 0° to 90° in increments of 15°. The simulation results closely match the reference data, with an error margin of less than 5%, confirming the validity and accuracy of the developed finite element model. However, the data reported in Ref [20] show significant deviation from other sources, suggesting the possibility of a typographical error. Additionally, it is observed that for all stacking configurations, beyond a lay-up angle of 60°, the fundamental natural frequency exhibits minimal variation, indicating a frequency saturation trend with increasing fiber orientation.

Table 1 Fundamental natural frequency in (Hz) for four-ply composite cantilever beam

Stacking sequence		**Lay-up angle Ө (degree)**						
		0	**15**	**30**	**45**	**60**	**75**	**90**
[Ө/-Ө/-Ө/Ө]	Present	264.41	202.53	134.99	87.498	71.275	69.941	70.29
	Ref [13]	278.4	207.2	137.9	89.3	74.7	73.7	74.2
	Ref [21]	NA	NA	NA	87.8	NA	NA	NA
	Ref [22]	NA	NA	NA	89.3	NA	NA	NA
	Ref [23]	NA	NA	NA	84.3	NA	NA	NA
	Ref [20]	279.2	263.0	217.5	156.7	NA	NA	NA
[Ө/Ө/Ө/Ө]	Present	264.41	158.83	100.15	77.369	70.625	69.844	70.29
[Ө/-Ө/Ө/-Ө]	Present	264.41	224.48	147.51	69.885	71.216	69.921	70.290
[Ө/Ө/-Ө/-Ө]	Present	264.41	165.84	113.04	82.655	70.913	69.855	70.29

Figure 1 clearly illustrates that the fundamental natural frequencies obtained for various fiber lay-up angles using the stacking sequence [Ө/-Ө/-Ө/Ө] are in close agreement across different references, with the exception of Ref [20], which shows a noticeable deviation likely due to a typographical or computational error. Additionally, it is evident that the natural frequency tends to converge and stabilize for lay-up angles of 60° and above, indicating reduced sensitivity to further changes in fiber orientation beyond this point. Moreover, the figure demonstrates that the trend of decreasing natural frequency is qualitatively consistent across all

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considered boundary conditions, suggesting that the influence of lay-up angle on modal behavior follows a similar pattern regardless of support configuration.

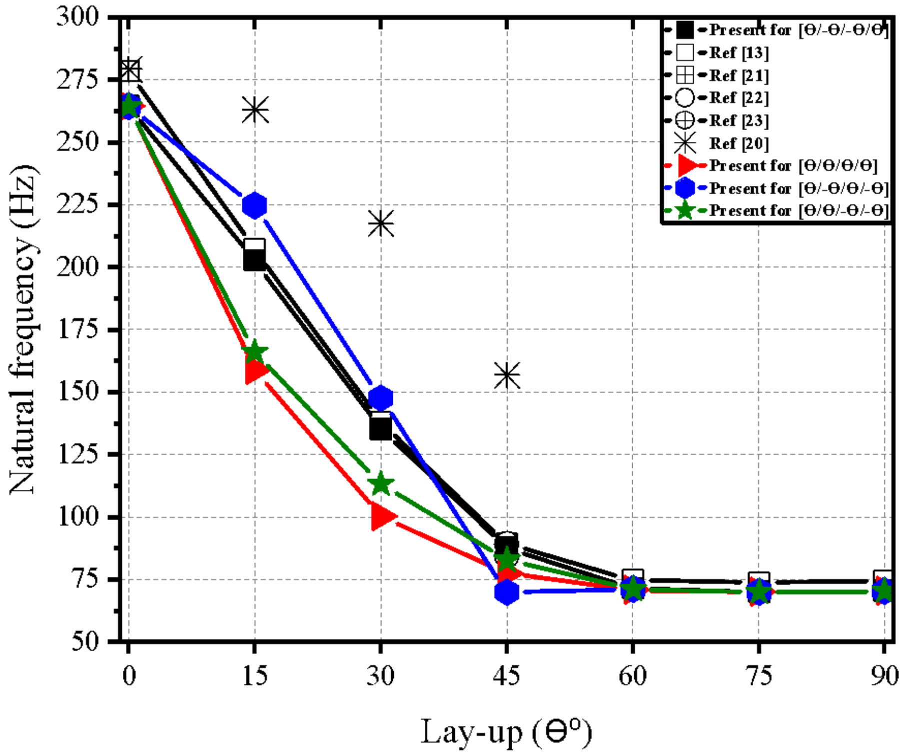

Fig. 1 Comparison of fundamental natural frequency (Hz) with Ref [13, 20-23]

In addition to the Clamped-Free (C-F) condition, three additional boundary conditions—All Clamped (C-C), Clamped-Simply Supported (C-S), and All Simply Supported (S-S)—were employed to determine the fundamental natural frequency of the composite plate. The results obtained from the simulations for all these boundary conditions are summarized in Table 2. These results show strong agreement with the corresponding values reported in the referenced literature, thereby reaffirming the accuracy and reliability of the finite element (FE) model used in the study. This consistency across various support configurations further strengthens confidence in the model's predictive capability for subsequent analyses involving delamination and other structural complexities.

Figure 2 illustrates the variation of natural frequency with respect to fiber lay-up angle for all considered boundary conditions. The plot reveals a consistent trend across all support configurations: as the fiber lay-up angle increases, the natural frequency decreases. This reduction is most pronounced in the range of 0° to 60°, indicating a significant sensitivity of the dynamic response to fiber orientation within this interval. Beyond 60°, however, the rate of decrease in natural frequency becomes minimal, suggesting that changes in lay-up angle have a diminishing influence on vibrational behavior at higher orientations. This trend underscores the importance of optimizing fiber angles, particularly below 60°, to achieve desired dynamic performance.

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Table 2 Fundamental natural frequency (Hz) of composite beam with stacking [Ө/-Ө/-Ө/Ө] for various boundary conditions and lay-up angle.

BC's		Lay-up angle Ө (degree)						
		0	**15**	**30**	**45**	**60**	**75**	**90**
C-C	**Present**	1343.8	1102.9	779.2	543.8	452.6	441.9	438.3
	Ref [13]	1376.4	1125.7	811.2	548.4	462.9	456.4	459.1
	Ref [24]	1384.3	1133.9	818.3	553.6	467.4	460.9	463.7
	Ref [25]	1381.1	1037.3	666.6	522.7	475.1	459.5	461.6
	Ref [26]	1378.7	1326.1	1165.1	905.3	624.9	478.2	460.6
	Ref [20]	1380.9	1327.8	1163.4	901.3	NA	NA	NA
	Ref [23]	NA	NA	NA	525.2	NA	NA	NA
	Ref [22]	NA	NA	NA	550.2	NA	NA	NA
C-S	**Present**	1032.2	815.0	566.7	376.3	313.9	308.0	309.8
	Ref [13]	1058.5	856.1	592.4	368.3	323.2	318.6	320.6
	Ref [24]	1090.9	922.0	629.2	394.6	325.8	321.0	323.0
	Ref [26]	1060.8	1011.9	869.2	654.8	441.0	334.1	321.6
	Ref [20]	1061.6	1012.7	867.2	650.8	NA	NA	NA
	Ref [23]	NA	NA	NA	365.5	NA	NA	NA
	Ref [22]	NA	NA	NA	385.0	NA	NA	NA
S-S	**Present**	730.1	596.2	374.7	241.6	201.8	198.9	200.3
	Ref [13]	753.2	656.6	428.6	256.4	209.2	206.1	207.4
	Ref [20]	755.4	713.9	595.9	433.9	NA	NA	NA
	Ref [23]	NA	NA	NA	235.8	NA	NA	NA
	Ref [22]	NA	NA	NA	249.6	NA	NA	NA

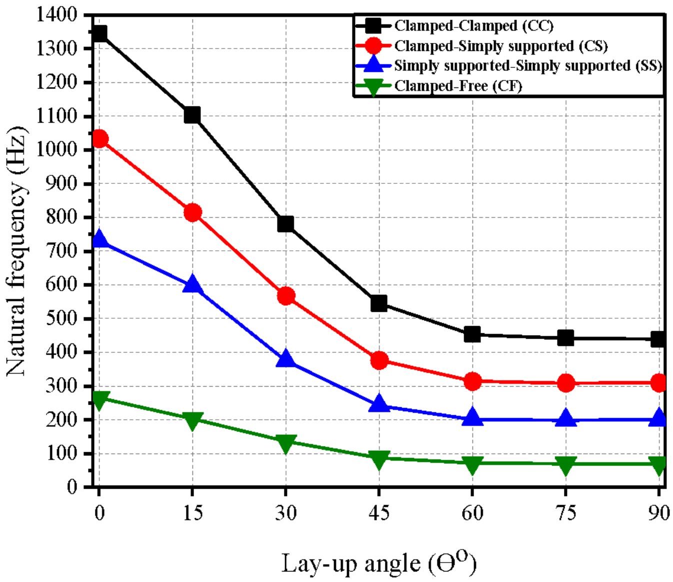

Fig. 2 Fundamental natural frequency (Hz) vs. lay-up angle Ө° for various boundary condition of composite beam [Ө/-Ө/-Ө/ Ө].

It is evident that among all the boundary conditions considered, the clamped-clamped (C-C) configuration consistently yields the highest natural frequencies across the entire range of fiber lay-up angles from 0° to 90°, while the clamped-free (C-F) condition results in the lowest frequencies. This trend highlights the significant influence of boundary restraints on structural stiffness and dynamic behavior. To achieve higher natural frequencies, one can either reduce the fiber orientation angle or enhance edge constraints. As more edges are restrained, the overall stiffness of the structure increases, thereby elevating its natural frequency. Similar observations have been reported in previous studies, including [27], reinforcing the relationship between boundary conditions and vibrational characteristics in composite structures.

3.2 Delamination Effect on Natural Frequency of Composite Plate

To study the effect of delamination of different size on the natural frequency of composite plate, a four-ply square composite plate of side length 15.2 cm and thickness of 0.119 cm, fixed at one edge and other edges are free is shown in Figure 3.

The material considered for the plate is S2 glass fibre/epoxy. The effect of delamination on natural frequency of plate with four different stacking sequences is analyzed. Fibre volume fraction was determined as 0.65 and material properties are taken from ref.[12].

The properties are E_1= 58.8 GPa, E_2 = E_3= 17.5 GPa, G_{12}= G_{13} = 7.28 Gpa, G_{23} = 6.9 GPa, υ_{12} =0.265, ρ = 2042 kg/m^3.

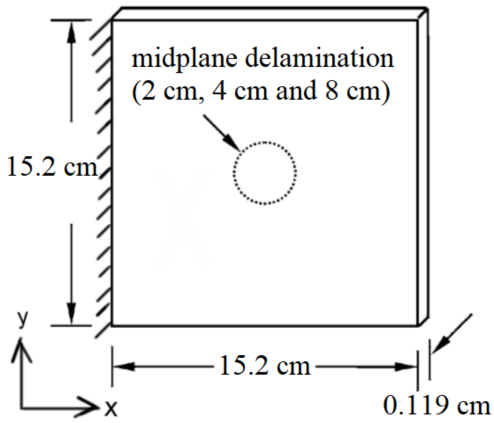

Fig. 3: Composite plate geometry with delamination

The circular delamination of different size 2, 4 and 8 cm diameter is inserted at the centre of interface between second and third ply (mid-plane). Delamination of the desired size can be created while manufacturing by placing a piece of Kapton polyamide release film between the interfaces [12]. As the film thickness is 61µm, the same thickness value is considered in the model for delamination.

Fig. 4 shows the meshed FE model of the four-ply composite plate with delamination of size 8 cm diameter at the mid-plane. The fine mesh is considered for modal analysis of the composite structure. The name of an element in the library of ABAQUS is SC8R: An 8-node quadrilateral in-plane general-purpose continuum shell. The element uses reduced integration with hourglass control. Fine mesh is used to discretise the FE model. The global size of the element is 0.002 cm is used, which comprises 5776 hexahedral elements per ply. Lanczos eigensolver is used to simulate the eigenvalue problem for every value listed in the tables.

Table 3 presents the first seven natural frequencies of the composite plate in the presence of delamination. Figure 6 illustrates how these modal frequencies vary with different delamination sizes across various stacking sequences. The results clearly show that as the size of the delamination increases, the natural frequencies decrease for all stacking configurations. This trend indicates that delamination reduces the overall stiffness of the composite structure, thereby lowering its dynamic response. The findings highlight the sensitivity of modal parameters to damage size, emphasizing the potential of vibration-based techniques for delamination detection and structural health monitoring.

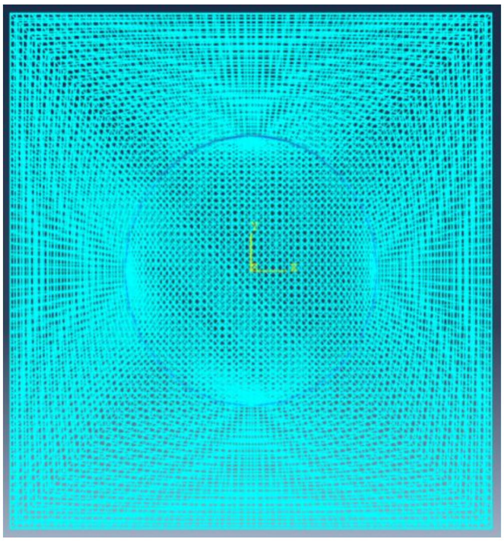

Fig. 4: FE model of composite plate with delamination size of 8 cm diameter.

The natural frequencies of higher vibration modes are found to be more sensitive to increases in delamination size compared to the lower modes, across all stacking sequences. While small delaminations have a negligible impact on the fundamental and lower-order natural frequencies, their influence becomes more pronounced in the higher modes. This behavior is observed consistently in both composite beams and plates, suggesting that higher modes are more effective indicators of internal damage. Similar observations have been reported in the literature, including references [2, 27–29], reinforcing the importance of analyzing higher-order modes for early delamination detection and structural assessment.

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Table 3 First seven modal natural frequencies of composite plate of various stacking sequences with delamination size 2, 4 and 8 cm diameter.

Stacking sequence	Delamination dia. (cm)	Modal natural frequency (Hz)						
		1	2	3	4	5	6	7
[Θ/-Θ/-Θ/Θ]	2	25.16	64.60	153.26	223.01	235.50	421.29	451.06
	4	23.23	64.46	144.85	221.17	231.52	413.23	426.39
	8	22.43	62.27	137.61	210.43	214.25	365.80	390.88
[Θ/Θ/Θ/Θ]	2	25.21	64.61	154.24	222.40	234.22	421.63	449.90
	4	23.47	64.49	144.64	221.10	231.10	413.73	426.59
	8	22.43	62.34	138.14	210.68	213.46	365.24	390.87
[Θ/-Θ/Θ/-Θ]	2	25.21	64.61	154.24	222.40	234.22	421.63	449.90
	4	23.47	64.49	144.64	221.10	231.10	413.73	426.59
	8	22.43	62.34	138.14	210.68	213.46	365.24	390.87
[Θ/Θ/-Θ/-Θ]	2	25.01	64.36	152.66	222.19	233.72	421.79	445.93
	4	23.43	64.49	144.63	221.09	231.83	413.63	426.61
	8	22.44	62.32	138.11	210.42	213.30	365.42	390.89

Figure 5 illustrates the delamination region corresponding to the tenth mode shape of a 0° unidirectional, four-ply composite cantilever plate with a mid-plane delamination of 8 cm diameter. The figure clearly shows that the modal displacement becomes increasingly sensitive with the growth in delamination size. As the delamination diameter increases, the local stiffness of the structure decreases, leading to higher modal displacements. This highlights the significant impact of delamination on the dynamic behavior of composite plates, especially in higher-order modes, where displacement variations become more pronounced and serve as useful indicators for damage assessment.

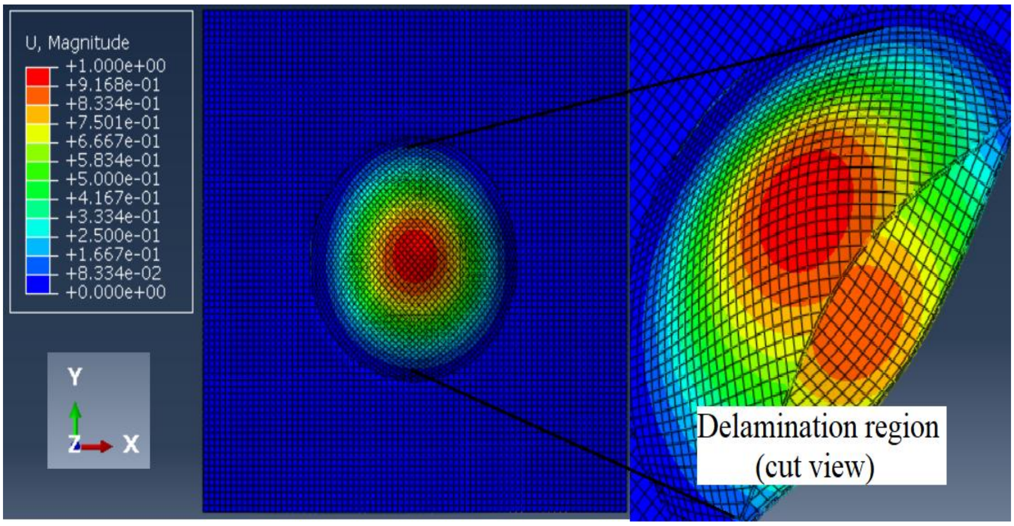

Fig. 5: The tenth mode shape of four plies composite cantilever plate [0/0/0/0] with size of delamination of 8 cm (557.37 Hz).

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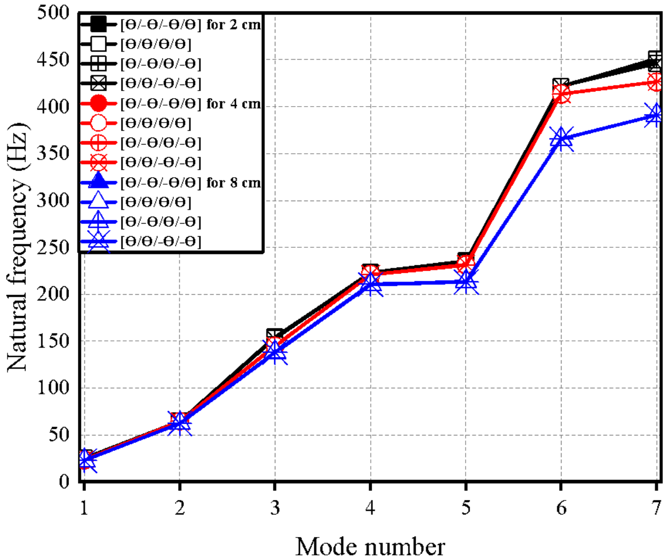

Fig. 6 First seven modal natural frequencies of composite plate of various stacking sequences with delamination size 2, 4 and 8 cm diameter.

The simulation is carried out to study the effect of fibre orientation angle along with the above parameters, on the fundamental natural frequency of the composite plate. Table 4 lists the results of this simulation for different stacking sequences for each of the fibre orientation angles varied from 0^o to 90^o in the interval of 15^o in the presence of delamination of different size.

Table 4 Fundamental modal natural frequencies of composite plate of various stacking sequences with delamination size 2, 4 and 8 cm diameter for different fibre lay-up angle.

Delamination size	Stacking sequence	Lay-up angle Θ (degree)						
		0	15	30	45	60	75	90
2 cm	[Θ/-Θ/-Θ/Θ]	25.82	25.16	23.74	22.31	21.30	20.83	20.72
	[Θ/Θ/Θ/Θ]	25.82	25.21	23.78	22.31	21.30	20.83	20.72
	[Θ/-Θ/Θ/-Θ]	25.82	24.96	23.38	22.08	21.24	20.82	20.72
	[Θ/Θ/-Θ/-Θ]	25.82	25.01	23.49	22.15	21.26	20.83	20.72
4 cm	[Θ/-Θ/-Θ/Θ]	23.60	23.23	22.68	22.14	21.56	20.03	20.82
	[Θ/Θ/Θ/Θ]	23.60	23.47	22.95	22.34	21.66	21.07	20.82
	[Θ/-Θ/Θ/-Θ]	23.60	23.24	22.69	22.15	21.56	20.06	20.82
	[Θ/Θ/-Θ/-Θ]	23.60	23.43	22.95	22.34	21.65	20.06	20.82
8 cm	[Θ/-Θ/-Θ/Θ]	22.86	22.43	21.61	20.85	20.28	19.92	19.75
	[Θ/Θ/Θ/Θ]	22.86	22.43	21.56	20.74	20.14	19.81	19.76
	[Θ/-Θ/Θ/-Θ]	22.86	22.43	21.60	20.86	20.29	19.92	19.76
	[Θ/Θ/-Θ/-Θ]	22.86	22.44	21.57	20.74	20.13	19.81	19.76

It is observed that for 2 and 4 cm delamination size, the change in natural frequency for different stacking sequence is comparatively small for fibre lay-up angle of 60^o and above. However, for delamination size of 8 cm, the changes in natural frequency for different stacking sequence are comparatively small for fibre lay-up angle of 30^o and less.

The stacking sequences also cause a change in the natural frequency and hence mode shape. Out of the two symmetric stacking sequences i.e. [Ɵ/Ɵ/Ɵ/Ɵ] and [Ɵ/-Ɵ/-Ɵ/Ɵ], in the former stacking sequence, the drop in fundamental natural frequency is more than in the latter stacking sequence for delamination size 2 cm and 4 cm. However, opposite behaviour occurs for 8 cm delamination size. Similarly, for the two anti-symmetric stacking sequences, the plate with stacking sequence [Ɵ/Ɵ/-Ɵ/-Ɵ] has a smaller drop in fundamental natural frequency than [Ɵ/-Ɵ/Ɵ/-Ɵ] for 2 cm and 4 cm delamination size and the opposite for 8 cm delamination.

Figures 7(a) to 7(c) show fundamental natural frequency (Hz) versus fibre angle for cantilever plate with circular delamination of size 2 cm, 4 cm and 8 cm. It is seen that delamination size affect the natural frequency of the plate with different fibre lay-up angle and stacking sequence. Natural frequency drop with increasing lay-up angle is observed in delaminated plate similar to the healthy plate qualitatively [11]. However, for smaller delamination size, the rate at which drop in natural frequency occurs is faster compared to the rate for larger delamination size for all the stacking sequence.

It is also observed that for delamination size 2 and 4 cm, the change in natural frequency for different stacking sequence is comparatively high for fibre lay-up angle up to 45^o and becomes low for fibre lay-up angle of 60^o and above. However, for larger delamination size of 8 cm, the changes in natural frequency for different stacking sequence are comparatively low for fibre lay-up angle of 30^o and below and becomes relatively high for fibre lay-up angle of 60^o and above.

Unlike natural frequency of healthy plate which does not change for fibre lay-up angle 60^o and above for all stacking sequence, the natural frequency of delaminated plate changes.

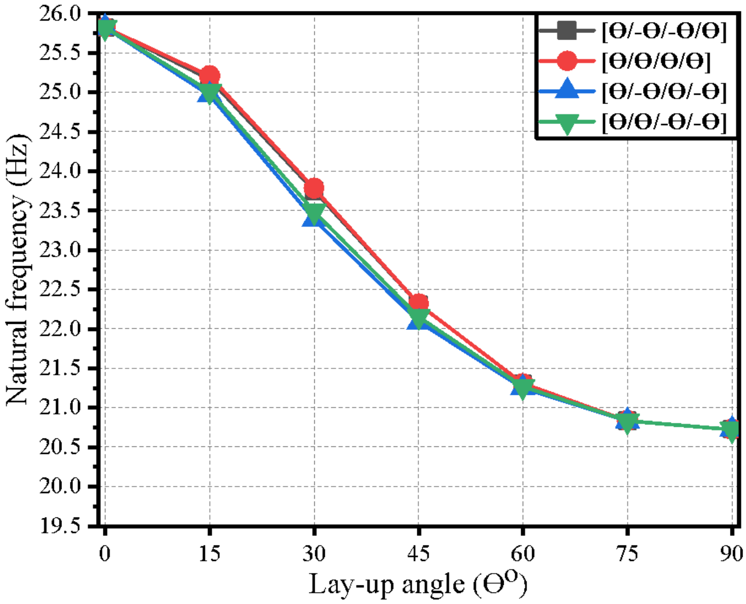

Fig. 7a 2 cm delamination

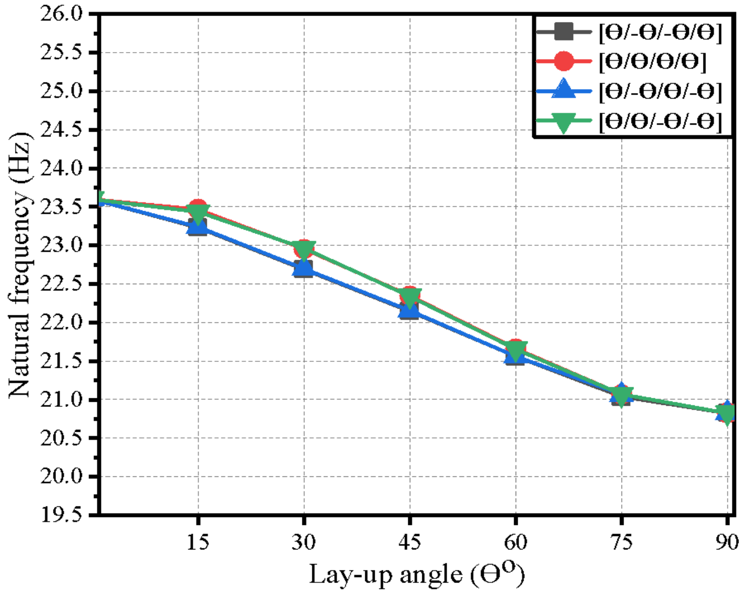

Fig. 7b 4 cm delamination

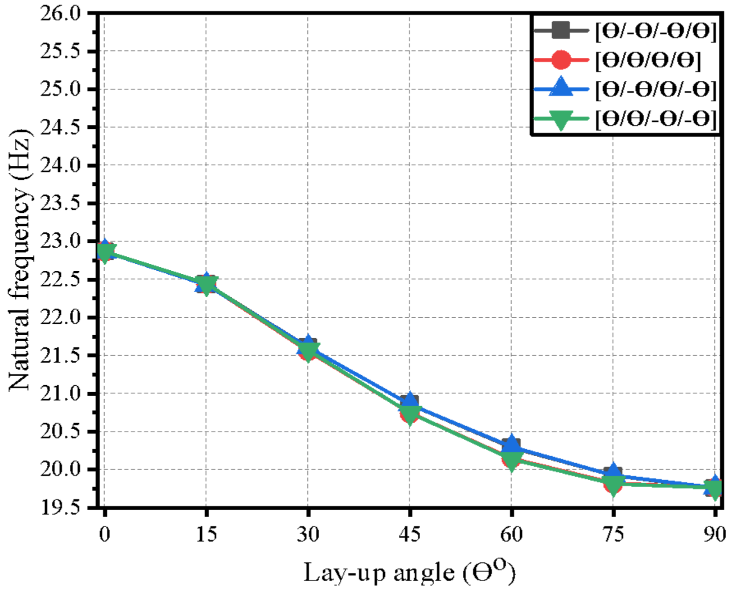

Fig. 7c 8 cm delamination

Fig. 7 Fundamental natural frequencies vs. fibre lay-up angle of composite plate of various stacking sequences with delamination size 2, 4 and 8 cm diameter

4. CONCLUSIONS

A detailed finite element (FE) model of composite beams and plates has been developed and analyzed to study their free vibration characteristics. To ensure computational accuracy, a relatively fine mesh is employed, which enhances the precision of the results. The FE model effectively captures the dynamic behavior of multi-ply composite plates both in healthy conditions and in the presence of delamination. It is observed that modes of vibration with high modal displacement are particularly sensitive to delamination occurring in those regions, resulting in significant shifts in natural frequency. The study comprehensively examines the combined influence of fiber lay-up angles, stacking sequences (both symmetric and anti-symmetric), various boundary conditions, and mid-plane circular delamination on the vibrational performance of the composite plate. Notably, as the size of mid-plane delamination increases, a more pronounced reduction in the natural frequency is seen across all stacking sequences and fiber orientations. This emphasizes the critical role of delamination severity and location. Furthermore, numerical displacement results on the plate surface can be effectively compared with experimental modal analysis data, offering a practical method for detecting delamination and assessing structural integrity through dynamic response analysis.

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