
Finite Element Analysis to Investigate the Vibration Characteristics of a Delaminated Composite Plate

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Abstract: - Composite structures are extensively used in various applications, including aerospace, automotive, and marine industries, due to their favorable mechanical properties, such as high strength-to-weight ratios. However, manufacturing composite structures requires meticulous care, and working conditions must be thoroughly assessed before installation. One significant defect in composite structures is delamination. Finite element analysis (FEA) is among the most powerful computational tools used to investigate such structural defects. This study investigates the effect of delamination on the natural frequencies of carbon-fiber-reinforced polymer (CFRP) composite plates using the commercial finite element analysis (FEA) software ABAQUS. Complementary analytical results were obtained using a Rayleigh–Ritz-based MATLAB code. Different stacking sequences and boundary conditions were considered in both the analytical formulation and finite element analysis. The finite element results were compared with the analytical results to validate the composite plates. The natural frequency of the composite plate decreased as the delamination size increased. Additionally, composite plates clamped on all sides exhibited higher natural frequencies in lower modes for symmetrical laminates compared to other constraints. For cross-ply laminates, simply supported composite plates showed higher natural frequencies. The comparison revealed that the results from both finite element analysis and analytical analysis were in good agreement. The novelty of this work lies in the systematic ABAQUS-based finite element investigation of mid-plane delamination effects across 48 CFRP plate configurations, encompassing four boundary conditions, three delamination areas (6.25%, 25%, and 56.25%), and three stacking sequences, validated against analytical Rayleigh–Ritz solutions. The findings have direct practical significance for structural health monitoring, damage assessment, and design of CFRP components in aerospace and automotive industries.

Keywords: vibration characteristics, composite material, delamination, finite element analysis, Abaqus simulation, natural frequency.

1. INTRODUCTION

The application of fiber-reinforced composite structures has significantly increased across various sectors, from bridges and marine structures to aerospace and daily life equipment, owing to their attractive properties and low manufacturing costs [1]. Particularly, carbon-fiber-reinforced polymers (CFRP) have seen a substantial rise in usage due to their lightweight and high-strength carbon fibers. CFRP are renowned for their high strength-to-weight ratios, making them essential in aerospace engineering, automotive engineering, civil engineering, and other high-strength applications [2]. However, cracks or delamination in composite plates are inevitable during service. Several factors, including service conditions and variations in temperature or pressure, can impact performance. Experimental evidence shows that specific delaminations affect the dynamic performance of the entire structure. Additionally, resonance or crack propagation can induce significant displacements or dislocations, leading to structural failure [3]. Given their critical applications, unique properties, and

widespread use, the linear or non-linear behavior of cracked or delaminated structures warrants thorough investigation.

Freed et al. [4] conducted finite element analysis of composite piezoelectric structures using Nastran software. Zhu et al. [5] performed finite element analysis to determine the free vibration properties of carbon nanotube-reinforced composite plates, comparing the results with those from the ANSYS software package. Fantuzzi et al. [6] compared analytical results with finite element methods for vibration properties of functionally graded carbon nanotube-reinforced plates.

Shu et al. [7] analyzed the vibrations of composite beams with two non-overlapping delaminations. Rout et al. [8] used finite element analysis to examine the impact of delamination, fiber orientation, and twist angle on the vibration characteristics of pre-twisted laminated cylindrical shells. Thornburgh et al. [9, 10] analyzed the vibration characteristics of delaminated composite laminates using finite elements and third-order shear deformation theory. Sahoo et al. [11] conducted finite element method analysis using MATLAB

code, while Ganesh et al. [12] used first-order shear deformation theory and computational methods to analyze the vibration characteristics of delaminated composite plates.

Nagesh et al. [13] performed finite element analysis to determine the effect of delamination on natural frequencies. Shankar et al. [14] developed MATLAB code to find the vibration properties of delaminated composite plates. Amit et al. [15] investigated the effect of crack length on the natural frequencies of graphite epoxy composite pre-twisted shells using finite element methods. Hu et al. [16] studied the effect of delamination on composite beams and plates using finite element-based higher-order shear deformation theory. Saravanos and Hopkins [17] explored delaminated laminates and beams using generalized laminate theory.

Ju et al. [18] examined delaminated composite plates using finite element methods with 8-node, 40-degree-of-freedom isoparametric plate elements and Mindlin theory for analytical solutions. Shen et al. [19] conducted vibration analysis to assess the impact of delamination on composite beams using Timoshenko Beam Theory and the local Rayleigh-Ritz method, finding that fundamental resonant frequencies decrease with increasing delamination size. Ju et al. [20] explored the effect of multiple delaminations using composite beams and first-order shear deformation Timoshenko Beam Theory, concluding that the impact of the first three delaminations is uniform in lower modes but significant in higher modes.

Kitipornchai et al. [21] investigated the effect of crack depth on functionally graded materials using the Ritz Method, noting that crack depth significantly influences linear frequencies but has no significant impact on non-linear frequencies. Qu et al. [22] studied piezoelectric composite plates with cracks using classical laminate theory, observing a systematic reduction in natural frequencies in the presence of cracks. Chang et al. [23] examined the influence of delamination size on delaminated composite plates subjected to axial loads using classical plate theory, concluding that fundamental natural frequency values decrease with increasing delamination size, as corroborated by other studies [24-26].

Talookolaei et al. [27] investigated composite beams with single delaminations using Hamilton's principle, finding that increased delamination length significantly reduces natural frequencies, which increase with rising rotational speed. Kulkarni and Frederick [28] studied clamped circular cylindrical shells with circumferential central cracks using linear thin shell theory and Kirchhoff-Love's theorem but did not draw specific conclusions

despite their comprehensive theoretical framework. Thuc et al. [29] conducted free vibration analysis using ANSYS and ABAQUS, comparing results with numerical outcomes from shear and normal deformation theory on axially loaded composite beams. Arthur et al. [30] analyzed the dynamic response of bio-based composite beams through experimental and finite element analysis software packages.

The review indicates a scarcity of finite element work using software packages like ANSYS or ABAQUS to investigate the influence of delamination on the vibration characteristics of carbon fiber-reinforced polymer composite rectangular plates. Existing literature has not extensively focused on this area. This study aims to address this gap by conducting a free vibration analysis of delaminated carbon fiber-reinforced polymer composite plates using finite element methods and analytical techniques to determine natural frequencies. The effects of delamination size, ply orientation, and boundary conditions on the natural frequencies of carbon fiber-reinforced polymers are thoroughly examined. The specific novelty of this work over existing literature is threefold: (i) a comprehensive parametric sweep of 48 distinct CFRP plate configurations is modelled using the commercial FEA software ABAQUS, whereas most prior studies are restricted to a limited set of delamination sizes or boundary conditions; (ii) the FEA results are rigorously validated against closed-form Rayleigh-Ritz analytical solutions for non-delaminated plates, establishing a reliable benchmark; and (iii) the study provides quantitative guidance on optimal stacking sequences and boundary restraints for delamination-tolerant CFRP plate design, directly supporting structural integrity assessment in aerospace and automotive engineering. This work builds upon and extends the authors' prior experimental and analytical studies on delamination behaviour in CFRP structures [35, 36, 37].

2. ANALYTICAL APPROACH

The differential equation for the transverse bending of a plate having rectangular orthotropic plate is depicted in equation (1)

$$D_x \frac{\partial^4 \omega}{\partial x^4} + 2D_{xy} \frac{\partial^4 \omega}{\partial x^2 \partial y^2} + D_y \frac{\partial^4 \omega}{\partial y^4} + \rho \frac{\partial^2 \omega}{\partial t^2} = 0 \quad (1)$$

where D_x , D_y , D_{xy} are the stiffness terms computed for homogenous plate. Because they are computed for such a plate, we must change them with the terms which describe a laminate composite plate.

Replacing D_x , D_y and D_{xy} with α_{11} , α_{12} and α_{22} respectively. So, we can write as

$$D_{11} = \alpha_{11} \quad (2)$$

$$D_{12} = \alpha_{12} \quad (3)$$

$$D_{13} = \alpha_{13} \quad (4)$$

The terms D_{11} , D_{12} , and D_{66} are computed using the equations presented below.

$$D_{11} = \frac{E_x h^3}{12(1-\nu_{xy}\nu_{yx})} \quad (5)$$

$$D_{12} = D_{21} = \frac{\nu_{yx}E_x h^3}{12(1-\nu_{xy}\nu_{yx})} = \frac{\nu_{xy}E_y h^3}{12(1-\nu_{xy}\nu_{yx})} \quad (6)$$

$$D_{22} = \frac{E_y h^3}{12(1-\nu_{xy}\nu_{yx})} \quad (7)$$

$$D_{66} = \frac{G_{xy} h^3}{6} \quad (8)$$

The moment curvature relations are used for the governing equations;

$$M_x = -D_x \left(\frac{\partial^2 \omega}{\partial x^2} + \nu_y \frac{\partial^2 \omega}{\partial y^2} \right) \quad (9)$$

$$M_y = -D_y \left(\frac{\partial^2 \omega}{\partial y^2} + \nu_x \frac{\partial^2 \omega}{\partial x^2} \right) \quad (10)$$

$$M_{xy} = -2D_{xy} \frac{\partial^2 \omega}{\partial x \partial y} \quad (11)$$

From the above equations, the Rayleigh-Ritz method [31-34] is used to find the frequencies as in equation (12)

$$\omega^2 = \frac{1}{\rho} \left(\frac{A^4 D_x}{a^4} + \frac{B^4 D_y}{b^4} + \frac{2CD_{xy}}{a^2 b^2} \right) \quad (12)$$

where A, B, C, and D are frequency coefficients and depend upon the boundary conditions applied and are determined from equations (13, 14) in the case of a simply supported plate.

$$A = \gamma_0 \quad (13)$$

$$B = \epsilon_0 \quad (14)$$

After putting the values of all side-clamped boundary conditions in equation (15), we will solve this in the MATLAB tool to fetch the frequencies.

$$\omega_{m,n} = \frac{\pi^2}{a^2 \sqrt{\rho}} \sqrt{D_x m^4 + 2D_{x,y} m^2 n^2 \left(\frac{a}{b} \right)^2 + D_y n^4 \left(\frac{a}{b} \right)^4} \quad (15)$$

where, a, b, and ρ are the width of the plate, height of the plate, and density, respectively.

The following equations are used to find the values of the constants.

$$\gamma_1 = \left(m + \frac{1}{4} \right) \pi \quad (16)$$

$$\gamma_2 = \left(m + \frac{1}{2} \right) \pi \quad (17)$$

$$\epsilon_1 = \left(n + \frac{1}{4} \right) \pi \quad (18)$$

$$\epsilon_2 = \left(n + \frac{1}{2} \right) \pi \quad (19)$$

Next, using the MATLAB file provided, we will compute the values of D_{11} , D_{12} , and D_{66} . For the case considered, the values for D_{11} , D_{12} , and D_{66} are:

$$D_{11} = 4.35e+04 \text{ N/mm}^2$$

$$D_{12} = 8.34e+03 \text{ N/mm}^2$$

$$D_{66} = 6.96e+03 \text{ N/mm}^2$$

At this point, we have all the data needed to compute the first natural frequency for the CCCC, no-delamination (0/90) plate. Substituting the values for D_{11} , D_{12} , and D_{66} , A, B, and C into equation 12, we get: $\omega_1 = 5571.89 \text{ rad/s}$, and from this, we can compute the natural frequency from equation (15) and get $f_1 = 886.7943 \text{ Hz}$. All natural frequencies are computed for 12 modes using the MATLAB tool.

3. FINITE ELEMENT ANALYSIS USING ABAQUS

Pre-processing was done in Ansa V_16.2.3, Processing in Abaqus V13, and Post-processing in Meta V_16.2.3. All delamination surfaces are located in the mid-plane of the composite laminated plate, as shown in Figure 1

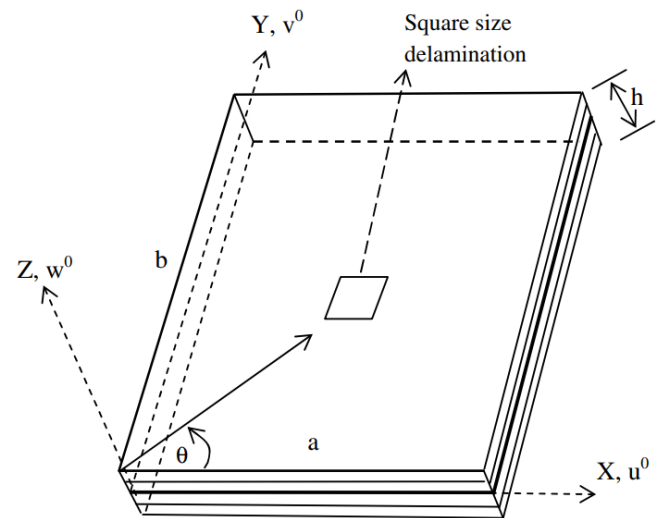


Figure 1. Schematic diagram of delamination location

The orientation of the layers has been defined using coordinate systems as shown in Figure 2.

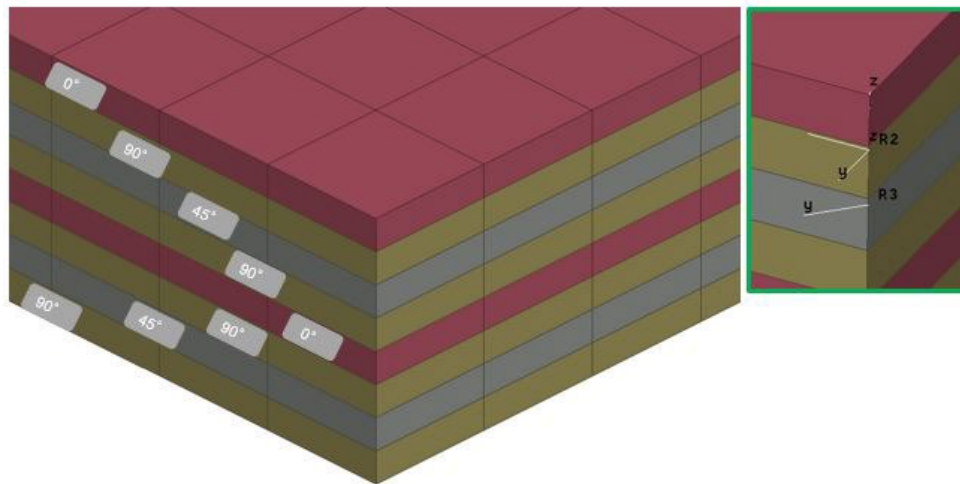


Figure 2. R2 is rotated 90° around z global axis and R3 is rotated 45° around z global axis

The delamination effect was modeled as a disconnected area between the two adjacent mid-plane layers, as shown in Figure 3

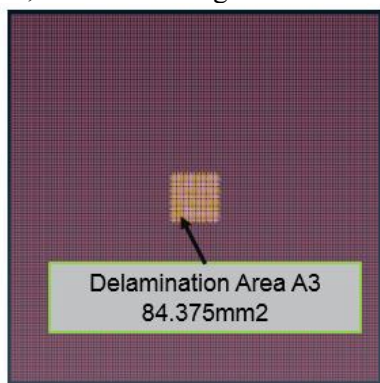


Figure 3. Top view of delamination incorporated

A total of 48 finite element models were analyzed, each yielding 12 natural frequencies and their corresponding mode shapes. The 48 configurations arise from the combination of: 4 boundary conditions (CCCC, SSSS, CFFF, FFFF) $\times$ 3 stacking sequences (0/90, 0/45, 0/90/45/90) $\times$ 4 delamination states (no delamination, 6.25%, 25%, 56.25%) = 48 models. Each model was solved using ABAQUS/Standard Lanczos eigen solver to extract the first 12 eigenvalues.

4. COMPARISON OF FINITE ELEMENT AND ANALYTICAL RESULTS

For comparison, non-delaminated plates with all-sides clamped (CCCC) and all-sides simply supported (SSSS) boundary conditions were analyzed. The results, presented in Table 1, show good agreement between the analytical and FEA methods for both boundary conditions. The relative

error between the two sets of results increases with mode frequency but does not exceed 6%. This strong correlation allows the analytical method to be used to validate the FEA model in the absence of experimental results. The SSSS model showed better correlation with the analytical results, with the largest relative error being -3%.

The no-delamination plates with all stacking sequences are considered. The results listed in Table 1 show that the analytical results and the Finite element results are in better agreement for both types of boundary conditions.

The relative error between the 2 results shows an increase with the mode's frequency but does not exceed 6% (regardless of the stacking type or boundary condition). One can conclude that the analytical method, in the absence of experimental results, can be used to validate the FEA model.

As for the boundary condition, the SSSS model correlates better with the analytical results (biggest relative error: -3%).

I. Effect of Delamination Area

This study examined three mid-plane delamination areas: 6.25%, 25%, and 56.25%. We selected the mid-plane position because it corresponds to the most commonly manufactured and experimentally characterized delamination configuration in CFRP plates, facilitating direct comparison with the existing literature [7, 16, 18]. Furthermore, mid-plane delamination produces symmetric delaminated sub-laminates, enabling a cleaner isolation of delamination-size effects without the confounding influence of asymmetric bending-extension coupling that arises from off-center delamination positions. The authors acknowledge that inter-ply delamination between the first and

second layers would produce larger reductions in natural frequency due to the pronounced asymmetry of the sub-laminates; this configuration is recommended for future investigation. As the delaminated area increases, the natural frequencies

consistently decrease, regardless of the boundary condition or stacking order. This is because delamination reduces the overall stiffness of the composite plate, which in turn lowers its natural frequencies, as shown in Figure 4.

Table 1. Comparison of natural frequencies for finite element and analytical analysis subjected to different boundary conditions

Boundary condition	Stacking	Method	Mode 1, Hz	Mode 2, Hz	Mode 3, Hz	Mode 4, Hz
CCCC	0/90/45/90	FEA	883.41	1804.1	1804.1	2538
		Analytical	886.7904	1822.9	1822.9	2522.2
		Error,%	0.4	1.0	1.0	-0.6
	0/45	FEA	876.31	1776.6	1776.6	2601.4
		Analytical	882.4113	1802	1802	2659.03
		Error,%	0.7	1.4	1.4	2.2
	0/90	FEA	887.42	1820	1820	2489.8
		Analytical	886.7943	1837.03	1837.03	2522.2
		Error,%	0.1	0.9	0.9	1.3
SSSS	0/90/45/90	FEA	444.78	1175.8	1175.8	1769.6
		Analytical	447.6413	1182.3	1182.3	1790.6
		Error,%	0.6	0.5	0.5	1.2
	0/45	FEA	475.96	1191.9	1191.9	1892.9
		Analytical	482.4101	1206.02	1206.02	1929.6
		Error,%	1.3	1.2	1.2	1.9
	0/90	FEA	421.66	1163.1	1163.1	1678.2
		Analytical	422.2056	1165.8	1165.8	1688.8
		Error,%	0.1	0.2	0.2	0.6

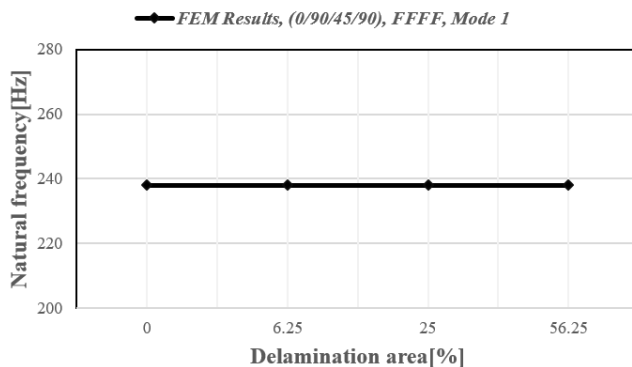


Figure 4. First natural frequency versus delamination area of an all-edges-free composite plate

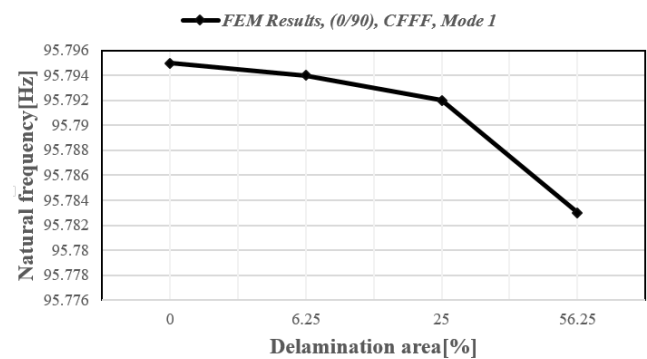


Figure 6. Trends of 1st natural frequency subjected to variation in delamination area of a one side clamped composite plate

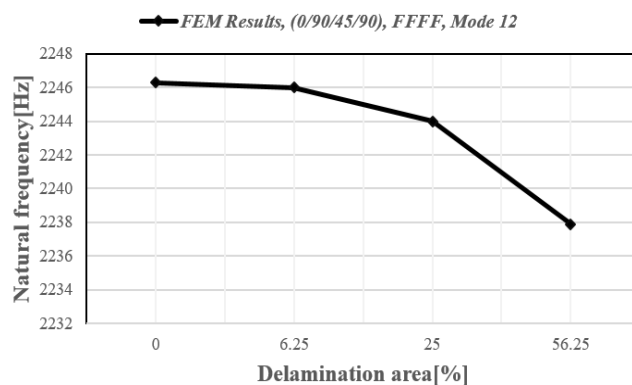


Figure 5. Trends of the 12th natural frequency subjected to variation in delamination area of an all-edges-free composite plate

However, if the delamination areas are small relative to the total plate dimensions, there is no significant impact on the first natural frequency. For instance, the fundamental frequency for a $(0/45/90/0)_2$ plate with all edges free (FFFF) remained unchanged for delamination areas of 6.25%, 25%, and 56.25% compared to the non-delaminated plate. This was consistent across the first three modes for FFFF plates. The influence of delamination size was most noticeable in higher modes, such as mode 12, where frequencies decreased by 0.01%, 0.1%, and 0.3% for the respective delamination areas (Figure 5).

For a CFFF (one-side clamped) (0/90)₄ composite plate, the most significant reduction in the first natural frequency (0.012%) was observed with a 56.25% delamination area (Figure 6). The first natural frequency of a CCCC (0/45)₄ plate also decreased as the delamination area increased (Figure 7).

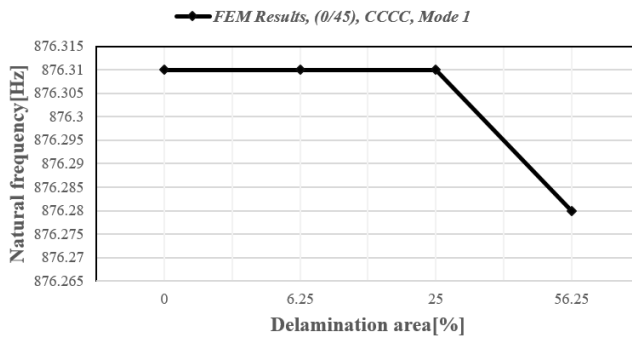


Figure 7. Trends of 1st natural frequency subjected to variation in delamination area of all sides clamped composite plate

As the delaminated area increases, regardless of the boundary condition or stacking order, the first natural frequency consistently decreases. Therefore, if a composite plate were to be manufactured with multiple delamination areas randomly distributed between the layers, the first frequency at which the plate would vibrate would decrease. However, if the delamination areas are small relative to the overall dimensions of the plate, there is no significant impact on the first natural frequency of the composite plate, as demonstrated in Figure 7.

Table 2. Comparison of natural frequencies for a 6.25% delaminated plate under various boundary conditions

Boundary condition	CCCC	SSSS	FFFF	CFFF
Mode 1, Hz	876.31	475.96	309.18	84.583
Mode 2, Hz	1776.4	1191.7	463.92	198.07
Mode 3, Hz	1776.4	1191.7	599.98	511.18
Mode 4, Hz	2601.4	1892.9	811.36	655.37
Mode 5, Hz	3161.1	2381.4	811.36	727.74
Mode 6, Hz	3177.6	2381.8	1482.3	1273.1
Mode 7, Hz	3936.6	3065	1482.3	1483.5
Mode 8, Hz	3936.6	3065	1485.1	1531.4
Mode 9, Hz	5010.2	4029	1617.3	1698.5
Mode 10, Hz	5010.2	4029	1852	2196.1
Mode 11, Hz	5210.7	4216.7	2461.4	2280.7
Mode 12, Hz	5723.9	4694	2461.4	2853.6

II. Effect of Boundary Conditions

Four boundary conditions were investigated:

CCCC, SSSS, CFFF, and FFFF. For a 56.25% delaminated plate with a (0/45)₄ stacking sequence, the smallest natural frequencies were observed for the CFFF condition, while the highest were for the CCCC condition. Specifically, the application of SSSS and CFFF boundary conditions resulted in significant reductions in the first natural frequency compared to the fully clamped plate: 45.68% and 90.34%, respectively. These findings were consistent across other stacking sequences (Table 2-4). This indicates that boundary conditions have a strong influence on the eigenvalues. The best way to constrain a composite plate with delamination areas is by clamping all edges.

Table 2. Comparison of natural frequencies for a 25% delaminated plate for various boundary conditions

Boundary condition	CCCC	SSSS	FFFF	CFFF
Mode 1 , Hz	876.31	475.96	309.18	84.581
Mode2 , Hz	1774.5	1191	463.92	198.07
Mode3 , Hz	1774.5	1191	599.98	511.18
Mode4 , Hz	2601.3	1892.8	811.31	655.36
Mode5 , Hz	3160.9	2381.3	811.31	727.69
Mode6 , Hz	3177.3	2381.7	1481.6	1273.1
Mode7 , Hz	3933.5	3063.3	1481.6	1482.8
Mode8 , Hz	3933.5	3063.3	1485.1	1531
Mode9 , Hz	4995	4020	1617.3	1698.2
Mode10 , Hz	4995	4020	1852	2194.6
Mode11 , Hz	5210.1	4216.5	2459.4	2279
Mode12 , Hz	5723.9	4694	2459.4	2853.6

Table 3. Comparison of natural frequencies for a 56.25% delaminated plate for various boundary conditions

Boundary condition	CCCC	SSSS	FFFF	CFFF
Mode 1 , Hz	876.28	475.95	309.18	84.575
Mode2 , Hz	1768.7	1188.7	463.92	198.07
Mode3 , Hz	1768.7	1188.7	599.97	511.18
Mode4 , Hz	2600.8	1892.7	811.15	655.31
Mode5 , Hz	3159.8	2380.9	811.15	727.54
Mode6 , Hz	3175.5	2381	1479.2	1272.9
Mode7 , Hz	3923.7	3057.7	1479.2	1480.6
Mode8 , Hz	3923.7	3057.7	1485	1529.6
Mode9 , Hz	4950.5	3993.3	1617.3	1697.3
Mode10 , Hz	4950.5	3993.3	1851.8	2189.8
Mode11 , Hz	5206.5	4214.7	2453.3	2273.6
Mode12 , Hz	5723.9	4691.6	2453.3	2853.1

III. Effect of Stacking Sequence

The effect of stacking sequence on natural frequencies was analyzed for a one-side clamped (CFFF) composite plate with 6.25%, 25%, and 56.25% delamination areas. For a cantilever

composite plate, the highest natural frequency was obtained for the (0/90) stacking sequence. Figure 8 shows that for a 56.25% delaminated CFFF plate, the (0/90) stacking sequence provides the most advantageous performance in terms of the first natural frequency. While the stacking sequence influences the amplitude of vibration, it does not affect the first modal shape. It is important to note that the free vibration analysis in ABAQUS yields natural frequencies and mode shapes, not specific vibration amplitudes, which depend on an external excitation force not considered in this study. The qualitative observation regarding amplitude is a general conclusion based on the change in system stiffness.

In order to show the effect of the stacking sequence on the natural frequencies, the 6.25%, 25% and 56.25% delaminated plates, one side clamped, for all stacking sequences, composite plates are presented in Table 5, Table 6 and Table 7. The results corresponding to the first mode from Table 5 are represented in Figure 8.

Table 5. The natural frequency for a 6.25% delaminated plate with various stacking sequences

Stacking	0/90/45/90	0/45	0/90
Mode1 , Hz	91.647	84.583	95.794
Mode2 , Hz	168.4	198.07	140.23
Mode3 , Hz	564.2	511.18	594.62
Mode4 , Hz	654.7	655.37	649.57
Mode5 , Hz	691.05	727.74	658.57
Mode6 , Hz	1142.4	1273.1	1027.7
Mode7 , Hz	1596.2	1483.5	1665.2
Mode8 , Hz	1628	1531.4	1682.8
Mode9 , Hz	1722	1698.5	1730.8
Mode10 , Hz	2074.3	2196.1	1970.4
Mode11 , Hz	2120.5	2280.7	1988.9
Mode12 , Hz	2965.4	2853.6	2603.6

Table 6. The natural frequency for a 25% delaminated plate with various stacking sequences

Stacking	0/90/45/90	0/45	0/90
Mode1 , Hz	91.645	84.581	95.792
Mode2 , Hz	168.4	198.07	140.23
Mode3 , Hz	564.2	511.18	594.61
Mode4 , Hz	654.69	655.36	649.57
Mode5 , Hz	691.03	727.69	658.56
Mode6 , Hz	1142.4	1273.1	1027.7
Mode7 , Hz	1595.5	1482.8	1664.2
Mode8 , Hz	1627.6	1531	1682.3
Mode9 , Hz	1721.7	1698.2	1730.5
Mode10 , Hz	2072.6	2194.6	1968.4
Mode11 , Hz	2118.7	2279	1987.2
Mode12 , Hz	2965.2	2853.6	2603.6

Table 4. The natural frequency for a 56.25% delaminated plate with various stacking sequences

Stacking	0/90/45/90	0/45	0/90
Mode1 , Hz	91.638	84.575	95.783
Mode2 , Hz	168.4	198.07	140.23
Mode3 , Hz	564.2	511.18	594.61
Mode4 , Hz	654.65	655.31	649.55
Mode5 , Hz	690.96	727.54	658.54
Mode6 , Hz	1142.3	1272.9	1027.6
Mode7 , Hz	1593.1	1480.6	1661.2
Mode8 , Hz	1626	1529.6	1680.7
Mode9 , Hz	1720.8	1697.3	1729.3
Mode10 , Hz	2067.3	2189.8	1962.4
Mode11 , Hz	2113.3	2273.6	1981.8
Mode12 , Hz	2964	2853.1	2603.6

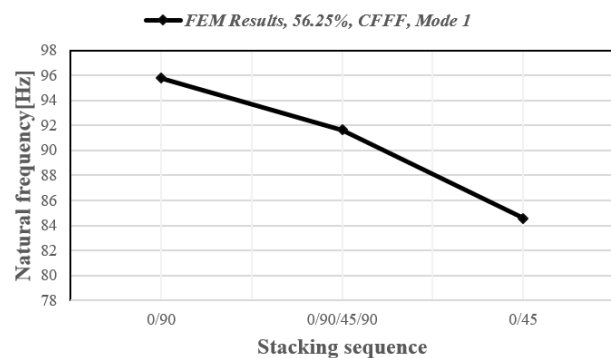


Figure 8. Trends of natural frequency for different stacking sequences subjected to a cantilever composite plate with delamination

From Figure 8, it can be concluded that the most advantageous stacking sequence, in the case of a delaminated composite plate, is (0/90)4. Also, the stacking sequence does not influence the first modal shape but it has an effect on the amplitude of the vibration. The same conclusions can be extended to the other boundary condition composite plates.

4. CONCLUSIONS

This study successfully used a finite element model in ABAQUS to analyze a delaminated composite plate. The effects of delamination area, boundary conditions, and stacking orientation on the natural frequencies were investigated.

Key findings include:

- The existence of delamination areas causes a decrease in the natural frequencies of a composite plate.

- A good correlation was observed between the analytical and finite element analysis results for non-delaminated plates, which served to validate the FEA model.

- The natural frequencies of the plate are highly dependent on the boundary conditions.

- Clamping all edges is the best way to constrain a composite plate with delamination, as it results in the highest natural frequencies.

- For a cantilever plate, the (0/90) stacking sequence yielded the highest natural frequency.

- The stacking sequence influences the amplitude of vibration but not the modal shapes. The principal novelty of this work consists in providing a comprehensive and validated finite element database of 48 CFRP plate configurations — covering four boundary conditions, three stacking sequences, and four delamination states — that can serve as a benchmark for future experimental validation campaigns and structural health monitoring algorithm development. From an engineering standpoint, the results demonstrate that: (i) delamination of 56.25% area reduces the first natural frequency of a CCCC plate by only 0.003% for mid-plane delamination, indicating that mid-plane damage has limited effect on the fundamental eigenvalue and that higher-mode monitoring is required for reliable damage detection; (ii) for a CFFF cantilever beam-plate — representative of rotor blades and wing skins — the (0/90) stacking sequence consistently provides the highest fundamental frequency, offering a clear design guideline for delamination-tolerant structural design; and (iii) boundary condition governs eigenvalue magnitude far more strongly than delamination size, with CCCC plates yielding natural frequencies approximately 10× higher than CFFF plates for the same configuration. These findings are directly applicable to the structural integrity assessment and maintenance scheduling of CFRP components in aerospace, automotive, and marine structures, and the validated FE modelling framework is extensible to impact-induced or thermally induced delamination scenarios.

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