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Research Article

Effect of Delamination on the Natural Frequency of Fiber Metal Laminate under Various Conditions

Nikhil Prakash Raut [a]*, Manzoorahamad Mirza [b], Vivek Vishnu Kulkarni [c], Shrinivas Gombi [c]

[a] *Department of Technology, Shivaji University, Kolhapur 416004, Maharashtra, India*

[b] *KSE Rajarambapu Institute of Technology, Rajaramnagar, 415414, Maharashtra, India*

[c] *KLs Gogte Institute of Technology, Belagavi, 590008, Karnataka, India*

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ABSTRACT

Multi-layered composite materials with improved capabilities are fiber metal laminates (FMLs). Damage to the composites, such as delamination, decreases their stiffness and modifies the dynamic behaviour of the structures. Vibration analysis can be a good way to forecast delamination since the loss of stiffness affects the natural frequencies, mode shapes, and other structural features. In this research, vibrational analysis of aluminum and mild steel-based carbon fiber metal laminates is considered with delamination. A total of thirty-six fiber metal laminate specimens of 3/2 configuration with various delamination areas and situated at various interfaces were considered for vibrational analysis, which was carried out experimentally and by FEA software. The analysis is done on healthy and delaminated specimens under clamped-free and clamped-clamped conditions. The results demonstrate that the proposed method indicates that delamination reduces the natural frequency of the FML. The decrease in natural frequency can be used for damage detection, which will act as a base for an inverse problem.

1. Introduction

Fiber-metal laminates (FML), which are composed of thin metal sheets with carbon or glass fiber soaked with epoxy, have several benefits over monolithic metal. Reducing the disadvantages of traditional fiber-reinforced composite materials. Because aligned fibers are included, the density of the FML materials is around 15% to 20% lower, and they are stronger than metal alone. They also exhibit enhanced fatigue behaviour, fire resistance, damage tolerance, and reduced susceptibility to impact damage. [1, 2] Like other traditional composite materials, FMLs can sustain various types of damage, including corrosion, delamination, and cracking. On the other hand, these structures may collapse suddenly due to degradation propagating within them. Finding damage in these structures is crucial for avoiding property damage and human casualties.

Thus, the structural health monitoring (SHM) of FMLs is the main topic of this work. It is essential to monitor the health of these composites in real-time in order to determine their suitability and guard against future failure. Traditional non-destructive examination (NDT) methods, such as C-scan, X-ray, and ultrasonic,

* **Corresponding author.**
E-mail address: nikhilraut44@gmail.com

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are widely used to assess structural damage in fiber metal laminates (FMLs) [2, 3, 4, 5, 6]. This method's benefits include its non-destructive nature, ease of use, and capacity to record worldwide reactions. Several studies have tried to use long-term measurement data to assess how variations in natural frequencies affect structural conditions. These techniques, however, are complex, expensive, time-consuming, and need longer maintenance intervals.

Vibration-based damage identification and classification are crucial for condition monitoring of beams since a defect-like delamination in a beam can grow over time and cause catastrophic collapse of the beam. Structural damage detection (SDD) techniques are vibration-based techniques using the dynamic features like natural frequency, mode shape, etc. Hence study of the natural frequency of the fiber metal laminate structure is important. For a single crack at different depths and locations, the analysis demonstrates a link between fracture depth and modal natural frequency [7]. Using the vibroacoustic approach and the finite element method (FEM), the author performed a computational assessment of fiber metal laminate (FML) with mid-plane center delamination [8]. Nonlinear acoustics for the detection of damage in composite laminates. Instrumented low-profile piezoceramic transducers were used to calibrate the level of damage caused by the low-velocity impact on the laminate plates [9]. Mechanical analysis and vibration testing of jute-based SS 304 laminate are carried out. Damping is affected by the stacking sequence; a conclusion is drawn through vibrational analysis [10]. A researcher studied a typical delamination damage in fiber metal laminate using vibrational analysis and coupled it with a machine learning algorithm to find the severity and location [11]. The researchers studied the vibrational behaviour of woven glass fiber metal laminate, considering different parameters like side-to-thickness ratio, ply orientation, aspect ratio, and boundary conditions. Analysis is done using Finite Element formulation, and experimental method shows that as side to thickness ratio increases, the natural frequency of the laminate decreases [12]. Parametric analysis of woven glass fiber metal laminate subjected to in-plane static and harmonic loading, considering various parameters like static load factor, aspect ratio, ply orientation, length to thickness ratio, number of plies, and boundary condition, was carried out. The study showed that these parameters have an influence on the dynamic stability and behaviour of FML [13]. Vibrational analysis of FML and hybrid structure made of aluminium, carbon, glass, or aramid fiber is carried out experimentally and numerically by ANSYS, and the results were compared. The boundary condition is a clamped-free condition, and it is suggested that various parameters like the number of layers, aluminium thickness, and fiber orientation affect the in-plane vibration [14]. The buckling behaviour of GFML is studied considering the various parameters such as aspect ratio, side-to-thickness ratio, boundary condition, and ply orientation. The study showed that an increase in aspect ratio reduces the buckling load, while an increase in side-to-thickness ratio also reduces the buckling load [15]. An experimental and numerical study of a new FML material is carried out. The results show a good arrangement. In the study, the influence of boundary conditions and aspect ratio on dynamic characteristics is studied [16]. Free vibration study on carbon/epoxy (CARALL), glass/epoxy (GLARE), or aramid/epoxy (ARALL) with aluminium sheets. Using numerical analysis and results are compared with experimental [17]. Fiber metal laminate under cantilever conditions is analysed using a theoretical model based on the mechanics of composites and classical laminated plate theory. Natural characteristics were obtained using the energy method and the orthogonal polynomial method. TA2/TC500 fiber metal laminates, thin plate, were analysed for natural frequency [18]. Under free vibration analysis, a numerical comparison of Glass-Aluminium-reinforced Laminates (GLARE) and Carbon-Aluminium-reinforced Laminates (CARALL) with and without cracks of lengths of 5 mm, 10 mm, 15 mm, and 20 mm is carried out; the effect of boundary conditions on natural frequency is also examined. It is evident from the results that, in comparison to GLARE, CARALL displayed greater natural frequency values. The carbon fiber's great strength and stiffness could be the reason [19]. This study examines the impact of delamination under free vibration analysis of fiber metal laminates based on magnesium (Mg AZ31) alloys and correlates the numerical validation of mode I delamination with previously published experimental data. The numerical values for the model that was provided demonstrated good agreement with the DCB test experimental data. Additionally, it was noted that the fiber metal laminates' delamination significantly lowers the natural frequency [20]. The temperature and contact effects, along with the nonlinear dynamic response of a delaminated FML Timoshenko beam [21]. Delamination in a 2/3 fiber metal laminate results in a reduction in stiffness as well as natural frequency. The stiffness of mild steel and aluminium fiber metal laminate was calibrated numerically and theoretically. The following procedure will help in accurately predicting damage location and depth of delamination [23].

The literature provides investigations on the natural frequency reduction of FMLs for the 2/1 configuration, but not for the 3/2 configuration. The application of 3/2 fiber metal laminate could be in the aerospace and automotive industries due to the high strength-to-weight ratio, fatigue resistance, damage tolerance, and impact resistance. The application of mild steel fiber laminate is in the automotive sector, were light weight and impact-resistant components are needed, while aluminium fiber laminate finds application in the aerospace sector. On the basis of the above literature, it is indicated that there is not much research on the effect of delamination on the natural frequency of FMLs. The primary goal of this paper is to examine the vibration response of fiber-metal laminates in various delaminations according to location and areas at various interfaces under various boundary conditions by numerical and experimental methods.

2. Materials and Method

2.1. Materials

2.1.1. Specimen Configuration

A fiber metal laminate plate specimen, which was made utilizing the hand layup method, the weight fraction of reinforcement was reduced to 70:30 in order to create a matrix made of mild steel, aluminium, and epoxy resin, with reinforcement as the fiber layer. Mechanical properties of Mild Steel, Aluminium, and unidirectional carbon fiber are presented in Tables 1 and 2.

Table 1. Mild Steel and Aluminium Mechanical Characteristics

Property	Values	
	Mild Steel	Aluminium
Density (kg/m3)	7860	2660
Modulus of Elasticity (GPa)	200	71.00
Poisson's Ratio	0.3	0.33
Shear Modulus (GPa)	76.923	26.692

Table 2. Unidirectional carbon fiber mechanical properties

Material	Properties									
	E_x (GPa)	E_y (GPa)	E_z (GPa)	μ_{xy}	μ_{yz}	μ_{xz}	G_{xy} (GPa)	G_{yz} (GPa)	G_{xz} (GPa)	ρ (kg/m^3)
Carbon Fiber	123.34	7.78	7.78	0.27	0.42	0.27	5	3.08	5	1518

The unidirectional carbon fiber, and Mild Steel, and Aluminium sheets were cut to predefined dimensions for the test specimen preparation. The stacking order described in Table 3 was used to construct the FML.

Table 3. Fiber Metal Laminate (FML) Composite Stacking Order

Code	Stacking Sequence	Configuration
A1	Al/0/0/0/Al/0/0/0/Al	3/2
M1	Ml/0/0/0/Ml/0/0/0/Ml	3/2

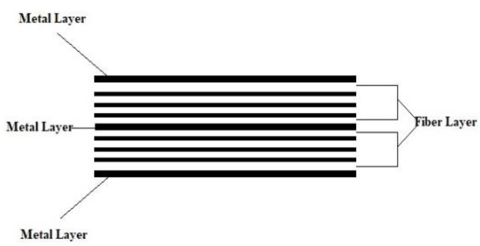


Fig. 1. Schematic sketch of Fiber Metal Laminate showing Fiber and Metal layers for the 3/2 configuration

In Table 3, A1 and M1 are the metal layers, which is Aluminium and mild steel, respectively. The specimen's mean thickness was measured using digital sliding calipers, which is 3.5 mm for experimental modal testing with dimensions of 250 mm by 50 mm. The square-shaped telfon tape is used for artificial delamination. The measurements for delamination specimens are as follows: 4 mm x 4 mm, 7 mm x 7 mm, 8 mm x 8 mm, 9 mm x 9 mm, 10 mm x 10 mm, 11 mm x 11 mm, and 12 mm x 12 mm, respectively. Teflon tape was positioned in the interface layers of the fiber laminates after being cut to the appropriate dimensions for the delamination. Following production, the whole assembly was allowed to cure. An additional 25 mm is provided for clamping on both sides.

2.2. Methods

2.2.1. Experimental Modal Analysis

The natural frequency is measured using a vibration testing rig. Fig. 2a represents the experimental setup for testing. The experimental setup consists of a computer running LabVIEW software, an impact hammer, a data collecting system (DAQ), and a triaxial accelerometer. The specimens are held in place via cantilever clamping. Following clamping, the specimens' effective dimensions are 250 mm by 50 mm.

The clamping plate was excited by an impact hammer, which resulted in an impulse force being applied to the composite plate. To record the stimulated plate's dynamic behaviour, a tri-axial accelerometer was employed. With the z-axis pointing downwards, the accelerometer was fastened and affixed to the surface using petro wax glue. The accelerometer was connected to a data-gathering device that converted the accelerometer's analog signals into digital signals by amplifying and translating them. LabVIEW software was utilized to interact with the DAQ, which was connected to the PC.

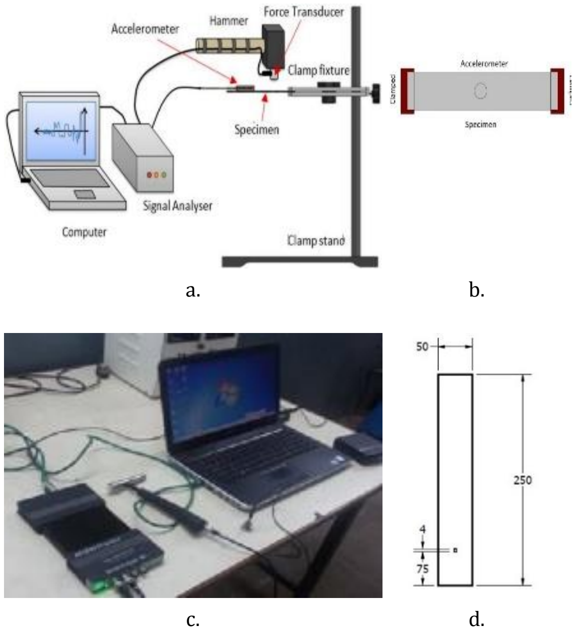


Fig. 2. a: Schematic sketch of experimental setup for vibration testing for Clamped-free condition; b. top view clamped- clamped condition; c Actual Experimental setup; d. dimension of damaged condition Case G (all dimensions in mm)

The vibration test to determine the beam's natural frequency was conducted using the following procedures:

1) Support the beam as a clamped-free (C-F) supported beam or clamped-clamped (C-C) supported beam;
2) Use an impact hammer to impact the C-F beam at the free end;
3) Use a detachable disc to save the vibration signal from the accelerometer;
4) Apply FFT using sig-view software to transfer the vibration signal from time domain to frequency domain to determine the natural frequency.

According to the ISO 3534–3, five repeated tests per specimen of each configuration were conducted, and the average natural frequency is presented [22].

2.2.2. Finite Element Analysis

A finite element model of undamaged and delaminated three-dimensional cantilever fiber metal beams was created using the commercial software ANSYS 19.1. This beam type consisted of a 3/2 configuration fiber metal laminate with two composite layers and three metal layers. Prior research provided the material property of the composite beam, which was used as input for FEA. Moreover, Tables 1 and 2 list each of these properties. Since the composite beam falls within the three-dimensional modelling of solid structures, the solid 186-layered element was utilized to model the beams. Each layer's information is defined by shell components. The details of each layer were provided via a shell element. Furthermore, just one factor was taken into account for each layer's thickness. After doing a mesh sensitivity analysis, the ideal element count was ascertained to strike a compromise between the accuracy of the model parameters and the computing time. Target elements and contact elements make sure that the two surfaces connect and debond perfectly. ANSYS modal analysis was used to determine the delaminated beams' initial six bending natural frequencies.

2.2.3. Delamination Configuration

In this study, a total of 16 delaminated specimens and 2 specimens without delamination of mild steel and aluminum-based fiber metal laminates were considered. To investigate the effect of delamination in different areas on the natural frequency of fiber metal laminate under cantilever conditions. Two separate delamination cases are considered for mild steel and aluminum.

- Case 1

One undamaged specimen of each metal layer is considered for finite element analysis. Two specimens of undamaged Aluminum carbon fiber laminate and Mild Steel carbon fiber laminate

- Case 2

In this case, mild steel fiber metal laminates are considered with a total of 8 specimens with the specified stacking sequence in Table 3. This case is subdivided into eight subcases. The subcases are divided according to the delamination area and the interface of damage.

- Case 3

In this case, aluminum-fiber metal laminates are considered with a total of 8 specimens. This case is subdivided into eight subcases. The subcases are divided according to the delamination area and layer of damage refer Table 4.

Analysis of all three cases was done using experimental and numerical methods under clamped-free and clamped-clamped boundary conditions.

Table 4. Specification of subcase for Case 2

Sub case	Interface	Area of Delamination (mm^2)	Distance from the fixed end (mm)
A	The metal layer and the first carbon fiber layers	100	150
B	First and Second carbon fiber layers	49	175
C	Second and third carbon fiber layers	144	200
D	The third carbon fiber layer and the metal layer	81	125
E	Metal layer and fourth carbon fiber layer	64	200
F	fourth and fifth carbon fiber layers	121	50
G	Fifth and sixth carbon fiber layers	16	75
H	Sixth carbon fiber and metal layer	100	100

3. Result and Discussion

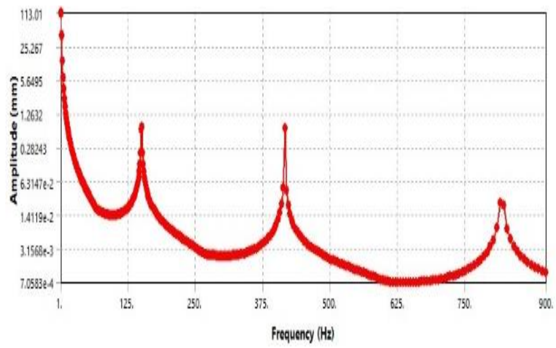
Numerical simulations were performed on the considered FML under various boundary conditions utilizing ANSYS software to validate the analysis results. The selected specimens were created in the software, and boundary and loading conditions were implemented. Mild steel and Aluminium are utilized in the simulations, with their properties remaining unchanged throughout the analysis. The material characteristics, such as Young's modulus (E), shear modulus (G), and Poisson's ratio, are presented in Table 1. Similarly, the values of epoxy carbon fiber are presented in Table 2 and remain the same throughout the analysis. The mesh sensitivity analysis of the FML was carried out, and it suggested that although processing time was much increased, there were no notable differences from using a refined mesh with pieces smaller than 30 mm.

3.1. Comparing Experimental and FE Frequencies

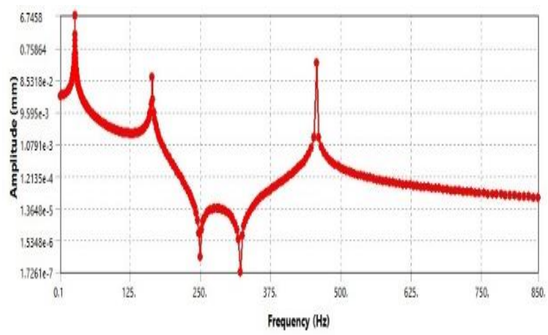
In this investigation, the natural frequency of three different cases with delaminated and undelaminated fiber metal laminated specimens was considered with clamped-free and clamped-clamped boundary conditions. The second and third cases consist of mild steel and aluminum, respectively. These cases were divided into subcases based on the area of delamination and the presence of delamination along the interface. The analysis of the specimen was carried out using an experimental method and ANSYS software for six modes of natural frequency. All the tests are carried out for clamped-free end and clamped -clamped boundary conditions.

3.2. Undamaged Fiber Metal Laminate

Table 5 compares the measured frequencies of the undamaged fiber metal laminate under clamped free conditions with those predicted by the FE model. As may be observed, there are typically fewer than 9% differences between the numerical forecasts and the measured frequencies for the undamaged beams. This is to be expected as the material properties employed in the FE models were determined through an examination of the measured frequencies of the undamaged beams with the model predictions.



a.



b.

Fig. 2. b: Amplitude vs frequency graphs for undamaged specimen under Clamped Free conditions a. AL FML specimens, b. MS FML specimen

The results in the above table show that due to the high stiffness of mild steel as compared to aluminium, the natural frequency of the MS Carbon fiber laminate is higher than that of the Al Carbon fiber laminate. This trend continues for all the modes under consideration.

The standard deviation graph indicates positive correlation. The increasing trend of standard deviation with mode indicates that as the mode increases, the variability of the data also increases. Thus, indicating that the higher mode is associated with higher standard deviations.

Table 6 shows the comparison of the measured frequencies of the undamaged fiber metal laminate under clamped clamped condition with those predicted by the FE model. The difference between the experimental and numerical models is less than 8%.

Table 5. Result of undamaged FML composite beam for clamped free condition.

Mode	Aluminium			MS Cf			Al Cf		
	Natural Frequency (Hz)		Error %	Natural Frequency (Hz)		Error %	Natural Frequency (Hz)		Error %
	Numerical	Experimental		Numerical	Experimental		Numerical	Experimental	
1.	46.04	44.09	4.23	26.19	25.55	2.42	23.79	23.22	2.43
2.	287.94	271.50	5.71	163.45	158.37	3.11	148.94	144.90	2.71
3.	442.57	409.02	7.58	291.37	266.55	8.52	277.99	256.92	7.58
4.	627.10	585.77	6.59	414.28	391.25	5.56	417.41	398.25	4.59
5.	807.03	778.14	3.58	455.40	439.10	3.58	437.66	426.37	2.58
6.	1354.57	1278.30	5.64	884.74	869.26	1.75	819.48	773.34	5.63

Table 6. Result of undamaged FML composite beam for clamped-clamped condition.

Mode	MS Cf			Al Cf		
	Natural Frequency (Hz)		Error %	Natural Frequency (Hz)		Error %
	Numerical	Experimental		Numerical	Experimental	
1.	166.54	164.03	1.51	152.49	150.64	1.21
2.	455.65	445.72	2.18	419.92	406.65	3.16
3.	608.80	596.50	2.02	584.07	558.31	4.41
4.	885.13	816.44	7.76	823.54	809.79	1.67
5.	1241.90	1202.41	3.18	1195.30	1182.87	1.04
6.	1448.00	1446.26	0.12	1363.00	1324.29	2.84

Mild steel CF has a higher natural frequency than the Aluminium CF for all modes under consideration. For Mode 1, by 8.5%, 7.8% for Mode 2, to 5.9% for Mode 6. The standard deviation graphs are plotted for mild steel and aluminium FML, error bars in the standard deviation graph indicate uncertainty in the measurement for each mode. The graph shows a positive relationship between mode and standard deviation, with higher modes corresponding to higher standard deviation.

3.3. Delaminated Fiber Metal Laminate

Delaminated carbon fiber metal laminate was tested in clamped-free and clamped-clamped boundary conditions. The results were obtained by experimental method and predicted numerically using FE.

3.3.1. Aluminum Fiber Metal Laminate

To study the effect of delamination area on natural frequencies of the FML, various boundary conditions are considered.

The natural frequency of the specimen with different delamination areas situated at different interfaces is represented in the above figure. The figure shows a comparison of the natural frequency obtained by experimental and numerical simulation. The error in the numerically simulated and experimental values is represented in the figure below.

The maximum error obtained in the experimental and numerical values is below 14%. The correlation coefficient for numerical and experimental natural frequency ranges from 0.99843 to 0.99989 for Cases A to H. The highest correlation coefficient is for Case H, i.e., 0.99989, and the lowest for Case E, i.e., 0.99843.

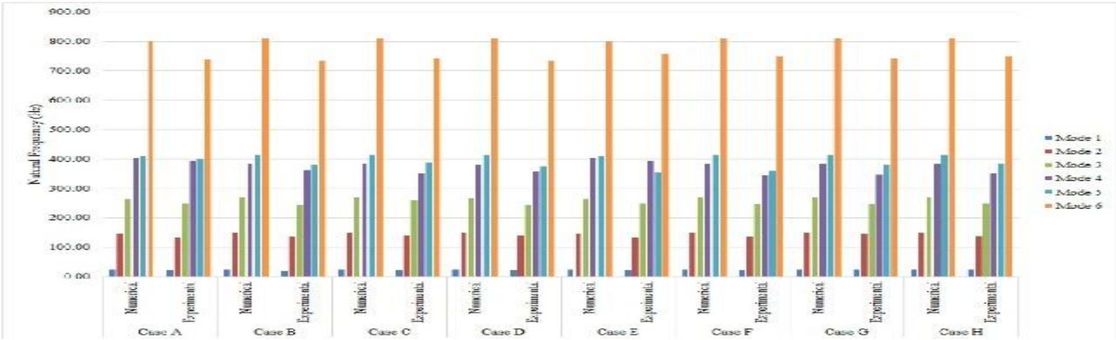


Fig. 3. Result of Damaged Aluminium Carbon fiber (Al Cf) under clamped free condition.

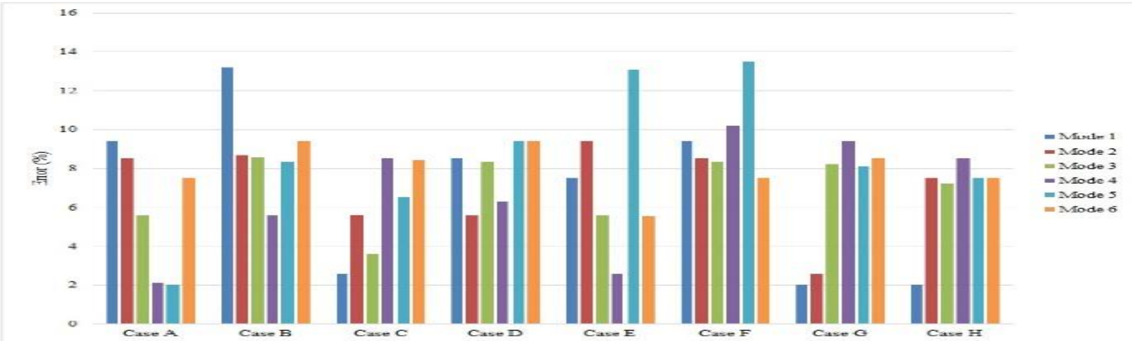


Fig. 4. Error in natural frequency of delaminated Aluminium Carbon fiber (Al Cf) under clamped free condition.

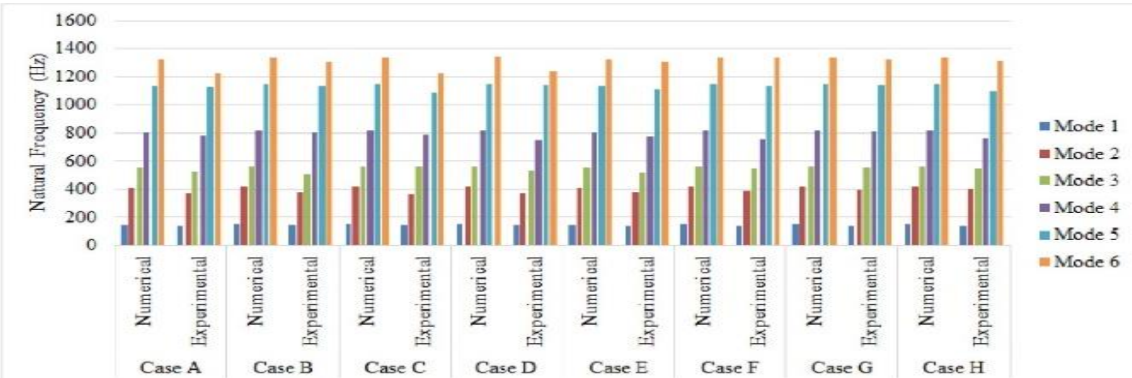


Fig. 5. Result of delaminated Aluminium Carbon fiber (Al Cf) under clamped - clamped condition

The figure shows a comparison of the natural frequency obtained by experimental and numerical simulation.

The error in the numerically simulated and experimental values is represented in Figure 5. The maximum error obtained in the experimental and numerical values is below 12.5%. The correlation coefficient for numerical and experimental natural frequency ranges from 0.99719 to 0.99989 for Cases A to H. The highest correlation coefficient is for Case G, i.e., 0.99989, and the lowest for Case D, i.e., 0.99719.

The error in the numerically simulated and experimental values is represented in the figure above. The maximum error obtained in the experimental and numerical values is below 13%.

Figure 4 shows that for mode 1, the decrease in frequency is steady for all the sub-cases. But for modes 2, 4, mode 5, and mode 6, there is a sudden decrease in natural frequency for case E. This is due to the presence of delamination between the fiber layer and aluminium layer. The natural frequency of Case A is lower than for all the other cases; this is due to the presence of delamination at the last interface between the fiber layer and the metal layer.

3.3.2. Delaminated Mild Steel Fiber Laminate

The natural frequency of the specimen with different delamination areas situated at different interfaces is represented in the above figure. The figure shows a comparison of the natural frequency obtained by experimental and numerical simulation. The error in the numerically simulated and experimental values is represented in the figure below. The maximum error obtained in the experimental and numerical values is below 12%. The natural frequency of the mild steel specimen under clamped-free conditions with different delamination areas and situated at different interfaces is represented in the above figure. The graph shows that for modes 1, 3, 4, mode 5, and mode 6, the decrease in frequency is steady for all the sub-cases. But for modes 3 and 5, there is a sudden decrease in natural frequency for case E. This is due to the presence of delamination between the fiber layer and mild steel layer. The correlation coefficient for numerical and experimental natural frequency ranges from 0.99672 to 0.99987 for Case A to Case H. The highest correlation coefficient is for Case A, i.e., 0.99987, and the lowest for Case D, i.e., 0.99672.

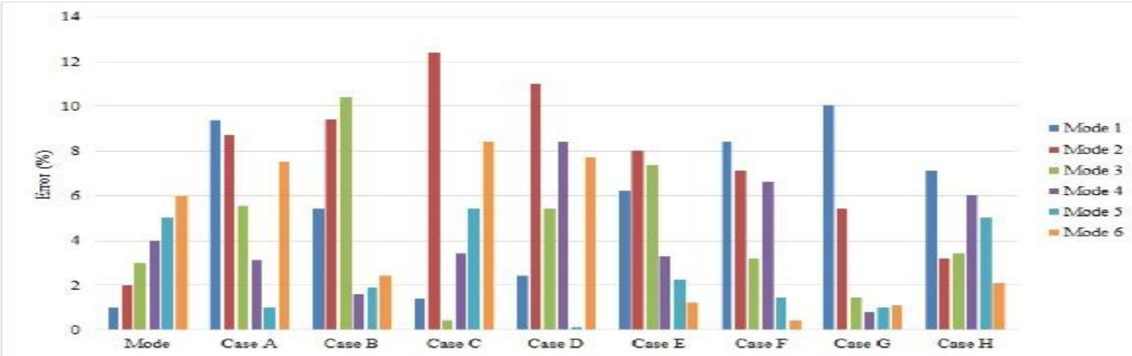


Fig. 6. Error in natural frequency of delaminated Aluminium Carbon fiber (Al Cf) under clamped-clamped condition

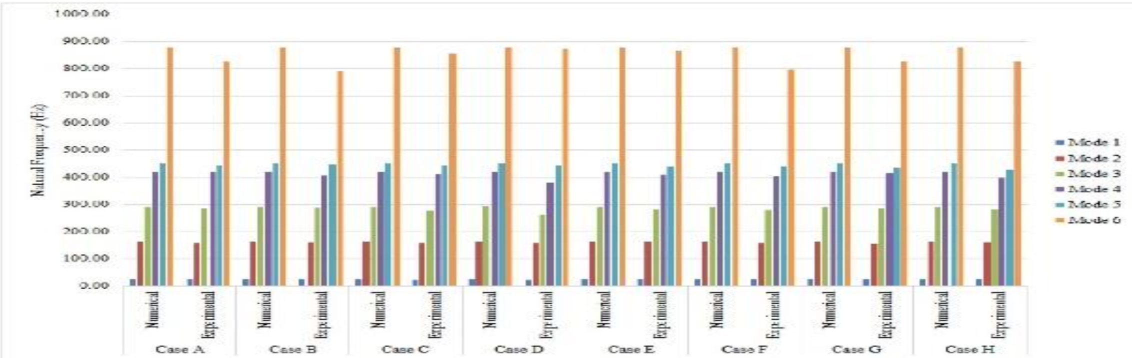


Fig. 7. Result of delaminated Mild Steel Carbon Fiber (MS Cf) under clamped free condition

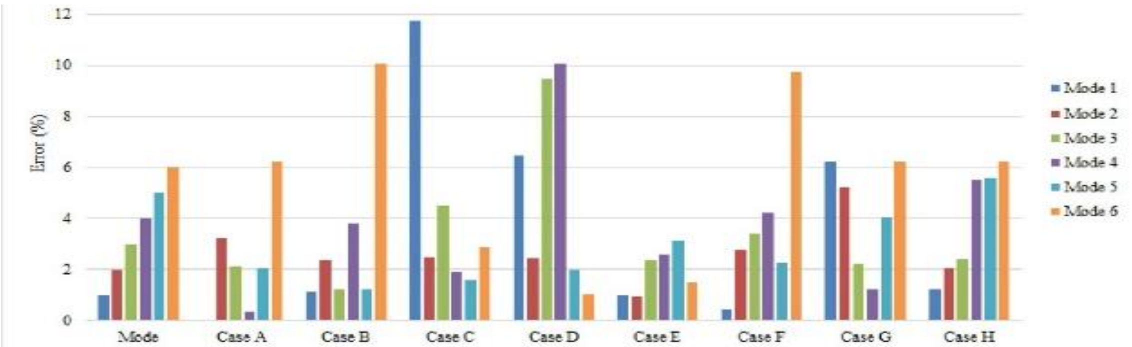


Fig. 8. Error in natural frequency of delaminated mild steel carbon fiber (Al Cf) under clamped-free condition

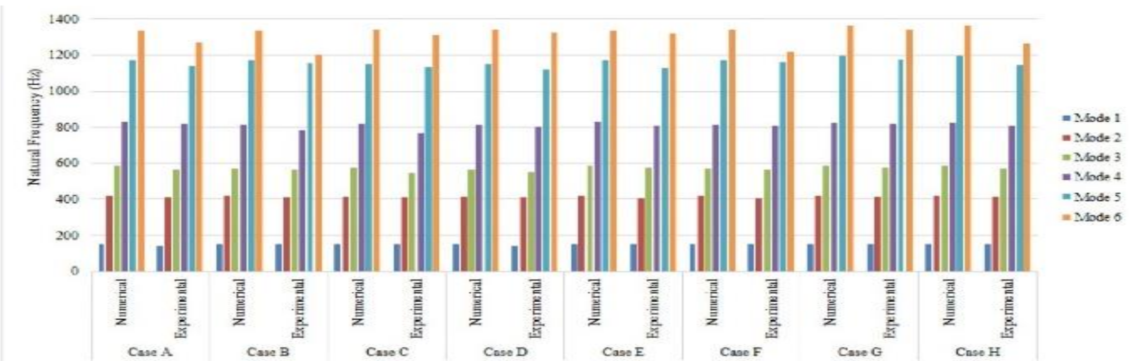


Fig. 9. Result of delaminated Mild Steel Carbon Fiber (MS Cf) under clamped – clamped condition

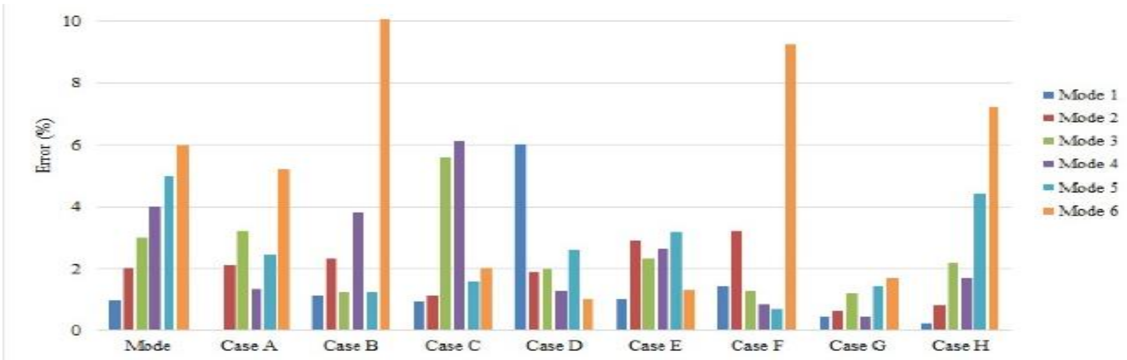


Fig. 10. Error in natural frequency of delaminated mild steel carbon fiber (Al Cf) under clamped-clamped condition

The natural frequency of the specimen with different delamination areas situated at different interfaces is represented in the above figure. The figure shows a comparison of the natural frequency obtained by experimental and numerical simulation. The error in the numerically simulated and experimental values is represented in the figure below. The maximum error obtained in the experimental and numerical values is below 10.5%. The correlation coefficient for numerical and experimental natural frequency ranges from 0.99894 to 0.99999 for Cases A to H. The highest correlation coefficient is for Case E, i.e., 0.99999, and the lowest for Case C, i.e., 0.99894.

The natural frequency of the mild steel specimen with different delamination areas and situated at different interfaces is represented in the above graph with clamped-clamped boundary conditions. The graph shows that for modes 1, mode 2, and mode 6, the decrease in frequency is steady for all the sub-cases. But for Cases D, mode 4, and mode 5, there is a sudden decrease in natural frequency. This is due to the presence of delamination between the fiber layer and fiber layer.

Based on Tables 5, 6, and Figures 3, 4, 5, 6, 7, 8, 9, 10 following conclusions can be drawn for all boundary conditions. For Aluminium Carbon Fiber Laminate, 1st, 2nd, and 3rd natural frequency observed for clamped-free condition are 23.794, 148.94, 277.99, and clamped-clamped condition is 152.49, 419.92, and 584.07. The natural frequency of the FML plate for clamped-free and clamped–clamped is increased by 84.39% at the 1st mode, 64.53% at the 2nd mode, and 52.40% at the 3rd mode. For Mild Steel Carbon Fiber laminate, 1st, 2nd, and 3rd natural frequency observed for clamped-free condition are 26.185, 163.45, 291.37, and that for clamped-clamped condition 166.54, 455.65, 608.8. The natural frequency of the FML plate for clamped-free and clamped-clamped is increased by 84.28% at 1st mode, 64.13% at 2nd mode, and 52.14% at 3rd mode. In the damaged condition of the Aluminium Carbon Fiber laminate for Case A, the 1st,2nd, and 3rd natural frequency observed to be 23.416, 146.4, 264.37 clamped-free boundary condition and 149.4, 410.48, 554.55 clamped–clamped boundary condition. The natural frequency of the FML plate for clamped-free and clamped–clamped is increased by 84.32% at the 1st mode, 64.33% at the 2nd mode, and 52.32% at the 3rd mode. Similar trends occur for the remaining cases of Aluminium Carbon Fiber Laminate. In the damaged condition of Mild Steel Carbon Fiber laminate for Case A, the 1st,2nd, and 3rd natural frequency observed to be 25.982, 162.17, 289.43 clamped-free boundary condition and 151.32, 418.38, 585.86 clamped–clamped boundary condition. The natural frequency of the FML plate for clamped-free and clamped–clamped is increased by 82.83% at the 1st mode, 61.23% at the 2nd mode, and 50.59% at the 3rd mode. Similar trends occur for the remaining cases of Mild Steel Carbon Fiber Laminate.

The results obtained from numerical studies show that the natural frequency is higher in a clamped–clamped boundary condition than in a clamped-free boundary condition. The FML plates are significantly dependent on the boundary conditions.

4. Conclusions

The study aimed to investigate the vibrational characteristics of the performance of Aluminium and Mild Steel carbon fiber laminate under clamped-free and clamped-clamped boundary conditions under the influence of delamination. Specifically, it focused on analysing how different delamination areas at various layers impacted the natural frequency of the beam sections under clamped-free and clamped-clamped boundary conditions. The experimental modal analysis of aluminium and mild steel fiber metal laminates was also carried out. The following results were obtained from the investigation:

1. The natural frequency for 1st mode in the undamaged case for mild steel-based fiber metal laminate (26.185 Hz) is more than

Aluminium laminate (23.794 Hz). This is due to the presence of three metal layers in the fiber metal laminate for clamped-free conditions, and similarly, for clamped-clamped boundary condition it is 166.54 Hz for Mild steel and 152.49 Hz for Aluminium FML.

2. For both types of fiber metal laminate plates, the natural frequencies are reduced by delamination, and the first mode has little effect considering the delamination area, but the delamination area has a considerable impact on the higher natural frequency modes.
3. Natural frequencies are considerably reduced by delamination in fiber metal laminate cantilever beams. As the area of delamination changes, for aluminium-based fiber metal laminate, the second, fourth, fifth, and sixth mode natural frequencies degrade considerably more than the first and third mode natural frequencies. Similarly, for mild steel-based fiber metal laminate second, third, and fifth modes' natural frequencies degrade more than the first, fourth, and sixth modes' natural frequencies.
4. The error in the natural frequency obtained by experimental and simulated FE method is below 15% for all cases of clamped-free and clamped-clamped boundary conditions.
5. The correlation coefficient shows that a perfect positive linear relationship exists between experimental and numerical values.
6. The delamination area and location of delamination have considerable effects on the natural frequency of both the fiber metal laminates, because of which these vibration modes can be used for delamination detection.

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Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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