Numerical Analysis of 3/2 Aluminium Carbon Fiber Laminate with Delamination to Study the Effect on Natural Frequency and Stiffness

Nikhil RAUT *
Department of Technology, Shivaji University, Kolhapur, Maharashtra, India, nikhilraut44@gmail.com

Vivek KULKARNI
KLS Gogte Institute of Technology, Belagavi, Karnataka, India, vvkulkarni@git.edu

Shrinivas GOMBI
KLS Gogte Institute of Technology, Belagavi, Karnataka, India, slgombi@git.edu

* Author to whom correspondence should be addressed

Abstract: - Delamination is a common problem in fiber-metal laminate composite structures, which often go undetected and can reduce structural stiffness. Delamination is definitely a significant issue since it affects the functionality of Fiber Metal Laminates (FMLs) structures in use. In an industry such as aviation, identifying and evaluating delamination severity is crucial for both financial and safety reasons. The natural frequency, mode shapes, stiffness, and other vibration properties of composites are affected by the presence of delamination. As a result, the location and amount of delamination may be accurately determined using this signal. This paper uses a 3/2 aluminium carbon fiber laminate made up of three layers of aluminium and two layers of unidirectional carbon fiber. The current study utilises finite element analysis to examine the effect of delamination on the natural frequency and stiffness of 3/2 aluminium carbon fiber laminate beams using free vibration characteristics. The first six modes of natural frequency are obtained using finite element analysis. The stiffness is calculated and compared using two methods: vibration methods and deflection methods. Finite element analysis is done for both undamaged and damaged aluminium carbon fiber laminate. From the study, the natural frequency and stiffness are affected by the delamination.

Keywords: - fiber metal laminates, natural frequency, stiffness, delamination.

1. INTRODUCTION

Fiber-metal laminates, or FMLs, are natural extensions of traditional composites and stacked metal materials. Since they have superior fatigue qualities and weigh less than regularly used aluminium alloys, they were developed at TU Delft as a material that may be employed in aerospace applications (Roebroeks and Laminates 1994, Singh et al. 2019). The most well-known example of a Fiber metal laminate is GLARE, which comprises glass Fiber-reinforced epoxy and aluminum layers. Further, there is an increasing interest in Fiber metal laminates from other industries, such as the automobile sector. The configuration, thickness, and other factors may all be changed, which adds to the experimental testing period and is time-consuming as well as expensive.

The orientation of the fiber, the metal volume percent, the fiber volume fraction in the composite, and the order in which the metal and composite layers are stacked all affect the characteristics of the fiber-metal laminate. Because Fiber metal laminates (FML) have so many desirable features, including low weight density, a high strength-to-weight ratio, and high fatigue strength, they are specifically created for aerospace applications. By adjusting various factors such as the angle of fiber orientation, relative fracture depth, and delamination position, vibration characteristics are investigated in the current study both with and without delamination for free vibrations. Some researchers could determine the position and location of delamination by analysing natural frequency behaviour and mode shape (Singh et al., Kuiry et al, Wei et al., Magalhães et al., Monazami et al).

Vibration analysis is necessary for every structure to be used practically and operate better. Additionally, every system has a maximum allowable natural frequency. Catastrophic failure occurs when the allowable limit is approached or crossed by frequency brought on by external factors. Understanding the natural frequency of any construction with mass and elasticity qualities is crucial to avoiding these situations. It's critical to identify natural frequencies to avoid the resonance state and prevent any construction collapse brought on by unwanted vibrations.

Delamination reduces stiffness under dynamic stress, which might result in a larger deflection magnitude for the total structure. Foreign object impact is also a common cause of fiber-reinforced polymer delamination (Liu et al. 2020). The vibrational behaviour of the beam was examined by experiments and the use of ANSYS FEM software.

A relationship between the modal natural frequencies and the depth and position of the fractures was found by finite element analysis of a cantilever beam with cracks. A relationship between depth, damage location, and natural frequency (Vikram et al. 2016). A computational analysis of Fiber metal laminate (FML) with mid-plane centre delamination using the vibro-acoustic methodology and the finite element method (FEM) (Balakrishnan et al. 2016). Nonlinear acoustics for composite laminate damage detection. To measure the degree of damage inflicted on the laminate plates by the low-velocity impact, instrumented low-profile piezo ceramic transducers were employed (Aymerich and Staszewski 2010). The damaged area of a composite structure undergoes a localised flexibility that modifies its vibration characteristics and decreases its stiffness as it delaminates. The most effective method for identifying a decrease is vibration analysis (Kindova-Petrova). In FML, stiffness and damping capacity are inversely correlated; that is, the damping capacity of the FML falls with increasing stiffness (Akkasali and Biswas 2024). This study examines the combined effects of adhered end fractures and delamination in an adhesively bonded single lap joint (SLJ) on strain energy release rate (SERR) values and the natural frequency response in a thermal environment (Karsh et al. 2021). Using the finite element method (FEM), the natural frequencies of delaminated S-glass and E-glass epoxy cantilever composite plates are calculated. In this analysis, transverse shear deformation and rotating inertia are taken into consideration. The first three natural frequencies of the cantilever plates have an impact of variables like the position of delamination along the thickness, length, and ply-orientation angle (Karsh et al. 2021).

A rectangular composite cantilever beam's natural frequencies are affected by delamination at the free end of the beam. Twintex and natural fiber/polypropylene materials are considered the individual phases. During FEA, the contact model is taken into account. The results indicate that the size and presence of delamination significantly affect the natural frequency, causing the natural frequency to decrease and introducing new opening modes of vibration (Gowda et al. 2024). The development of a novel crack model showed that the depth of the fracture influences the natural frequency and stiffness of composite beams (Orhan et al. 2016). In order to identify the locations and degree of delamination in the Fiber Metal laminate cantilever beams, this study employed a machine learning and regression model. Finite Element Analysis was applied to obtain a dataset about delamination's position, severity, and bending natural frequencies (Khalkar et al. 2023). The GLARE-related properties of fatigue fracture propagation and delamination extension under single overloads were studied (Huang et al. 2015). A technique for dynamic analysis that investigates how delamination affects the Eigenvalues and Eigenvectors of the dynamic response. However, the produced natural frequencies of the developed model correspond well with actual data as well as higher-order theoretical predictions (Kim et al. 2003).

The location and size of the delamination were predicted by taking into account and utilising the variations in the vibrational characteristics as inputs. This study examines the delamination of a glass fiber-reinforced composite beam using an artificial neural network (ANN) with the natural frequency as the standard vibration parameter (Srikanth et al. 2021). The authors investigated the transient behaviour of a delaminated composite plate with integrated active Fiber composite (Ganesh Shankar et al. 2019). Through a detailed analysis of the digital image correlation (DIC) findings, the impact of different delamination behaviours during testing on the compressive load capacity could be assessed.

The introduction of local flexibility in the damage area caused by delaminations in composite constructions alters the dynamic behaviour of the material due to a decrease in stiffness (Stawiarskia et al.). The impact of variations in stress on the delamination pattern in fiber-metal laminates was examined. An explanation is provided for forming delamination forms under different amplitude loading (Khan et al. 2009).

The physical and modal characteristics of the beam, such as its natural frequency, damping, stiffness, and mode shapes, are changed by delamination; as a result, the beam's dynamic response is significantly altered. Free vibration-based techniques have been used longer to identify beam delamination. To detect delamination in beams, these techniques employ the influence of natural frequency, stiffness, damping, and mode shapes as input in the inverse vibration problem. This experiment's primary goal is to examine the fiber-metal laminates with various delamination areas. The novelty of this paper studies the change in natural frequency due to delamination for fiber-metal laminate specimens with the objective to investigate the effect of different delamination areas in fiber-metal laminates on natural frequency and stiffness. This research uses the vibration method to study changes in natural frequency caused by delamination and the theoretical method to determine changes in stiffness.

2. MATERIALS AND METHOD:

2.1 Materials:

2.1.1 Specimen configuration:

A 50:50 weight proportion of the Fiber-to-matrix ratio is produced during the fiber layer preparation procedure. On the other hand, the fiber metal laminate plate specimen, composed of aluminium and epoxy resin as reinforcement, was manufactured using the hand layup process using a 70:30 weight fraction of the reinforcement to the matrix.

Table 1. Mechanical Characteristics of Aluminium

Property	Values
	Aluminium
Density (kg/m^3)	2660
Modulus of Elasticity (GPa)	71.00
Poisson's Ratio	0.33
Shear Modulus (GPa)	26.692

Table 2. Unidirectional CFRE mechanical properties

Property	Value CFRE
Density (kg/m^3)	1800
Modulus of Elasticity (GPa)	138
Poisson's Ratio	0.28
Shear Modulus (GPa)	17

The unidirectional carbon fiber and aluminium sheets were cut to predefined dimensions for preparing the test specimens. The stack order is described in the Table. 3 was used to construct the FML.

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

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

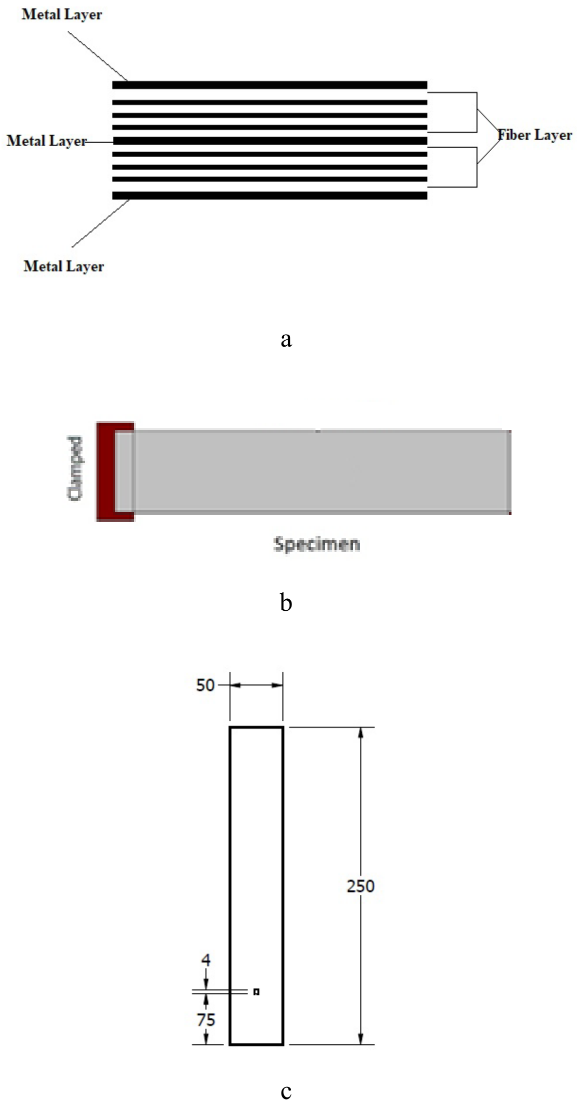

Figure 1. a) Schematic sketch of Fiber Metal Laminate showing the fiber layer and the metal layer,
b) vibration testing for Clamped-free condition
c) effective dimensions of damaged condition sub case G (all dimensions in mm)

In Table 3, A1 is the metal layer, which is Aluminium. The FML specimens are prepared as shown in Figure 1. The specimen's mean thickness was measured using digital sliding calipers and was 3.5 mm for experimental modal testing, with dimensions of 250 mm by 50 mm.

2.2 Methods:

2.2.1 Natural Frequency:

ANSYS 19.1, a commercial program, was used to generate finite element models of undamaged and delaminated three-dimensional cantilever fiber-metal beams. This particular beam type consisted of three metal layers and two composite layers in a 3/2 fiber metal laminate. The composite beam's material properties were determined in earlier research and used as input for FEA. Each of these properties is shown in Tables 1 and 2. Since the composite beam is part of a three-dimensional solid-structure model, the beam was modelled using the solid 185-layered element. Shell components define the data of each layer. A shell element supplied the information for each layer. Moreover, the thickness of each layer was determined by considering only one component. The optimal element count was determined through a mesh sensitivity analysis to balance processing time and model parameter accuracy. Contact and target components ensure a flawless debond and connection between the two surfaces. The first five natural frequencies of bending for the delaminated beams were obtained using ANSYS modal analysis. The first six natural frequencies of the undelaminated FML composite beam are shown in Table 5. The first six natural frequencies of the delaminated FML composite beams are shown in Table 6.

2.2.2 Stiffness Analysis

A. Theoretical Approach

The theoretical approach used a fiber-metal laminated cantilever beam with no frequency point load in a healthy state [24]. Based on the deflection curve at zero frequency of a cantilever beam is similar to the curve obtained when the beam vibrates at its original natural frequency. Equation (1) is the natural frequency formula of a Fiber metal laminated cantilever beam.

$$f_n = \frac{1.875^2}{2\pi L^2}\sqrt{\frac{EI}{\rho A}} \tag{1}$$

where

EI = bending stiffness
f_n= natural frequency of nth mode
ρ = density of the material
A = cross-sectional area of Fiber metal laminate = b × h where b is the width, and h is the thickness of the beam.
L = length of the cantilever beam
V_f and V_m are percentage weight fractions of fiber and metal.

For a fiber metal laminate, the natural frequency formula changes to

$$f_n = \frac{1.875^2}{2\pi L^2}\sqrt{\frac{EI}{\rho_{eq} A}}$$

where

$$\rho_{eq} = V_f \cdot \rho_f + V_m \cdot \rho_m \tag{2}$$

Bending stiffness for the first mode is given as

$$EI = \left(\frac{f_1 2\pi L^2}{1.875^2}\right)^2 \rho_{eq} A \tag{3}$$

The spring stiffness of the fiber metal laminate can be found

$$k = \frac{EI}{L^3} \tag{4}$$

Equation 3 applies to the first natural frequency mode. Finite element analysis is used to determine the natural frequency of a healthy fiber-metal-laminated cantilever beam. The rigidity of the delaminated cantilever beam is then calculated using this formula, equation (4), and a technique known as reverse engineering. In this investigation, the mass difference between a healthy and a delaminated beam was predicted to be minimal. As a result, the equivalent density of delaminated beams was assumed in the vibration analysis to be equal to the equivalent density (ρ_{eq}) of a healthy beam. Two approaches were taken in this investigation to determine the impact of delamination on stiffness.

To determine the stiffness of any delaminated case, the vibration approach requires a certain process. The delaminated case's natural frequency of interest is first determined using modal analysis. Next, using the inverse engineering method, this frequency is replaced in equation (4) to get the stiffness of the identical delaminated case.

B. Deflection Method:

Using the deflection method, the stiffness of each delaminated case can be properly determined. The zero frequency deflection of a delaminated cantilever beam, in particular, cannot occur in the direction of the applied load unless 100 N loads are applied at the free end of the beam. Next, the stiffness of the same delaminated case was determined using a conventional formula.

$$\text{Stiffness} = \frac{\text{Load}}{\text{zero frequency deflection}}$$

2.3 Simulated Delamination Configurations:

To investigate the way delamination in various areas affects the natural frequency of the Fiber metal laminate in cantilever condition, eight specimens of aluminium-based Fiber metal laminates with delamination, and one specimen without delamination were considered in this investigation. Two different scenarios are considered for aluminium FML. The delamination considered is a square Teflon patch; the area and location are stated in Table 4.

Case 1:

One undamaged specimen of Aluminium FML is used in the finite element analysis.

Case 2:

This case consists of eight subcases. The subcases are categorized based on the damage interface and the region of delamination.

Table 4. The specifications of the subcases are listed below

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. RESULTS AND DISCUSSION

In this investigation, the natural frequency and stiffness of delaminated and healthy fiber-metal laminated specimens were considered. As shown in Table 4, these cases were further subdivided by delamination and interface area. Using commercial CAD software, nine fiber metal laminate specimens were modelled, both with and without delamination. ANSYS software was used to analyze the specimen up to six natural frequency modes. Every test is performed under a fixed-free end-type boundary condition.

3.1 Healthy Fiber Metal Laminates:

The result of the healthy aluminium carbon Fiber (Al Cf) for the first six mode natural frequencies.

Table 5. Natural frequency for healthy Aluminium Carbon Fiber (Al Cf).

Mode	Natural Frequency Al Cf
1	560.54
2	1236.2
3	2861.5
4	3709.1
5	5197.1
6	6183.2

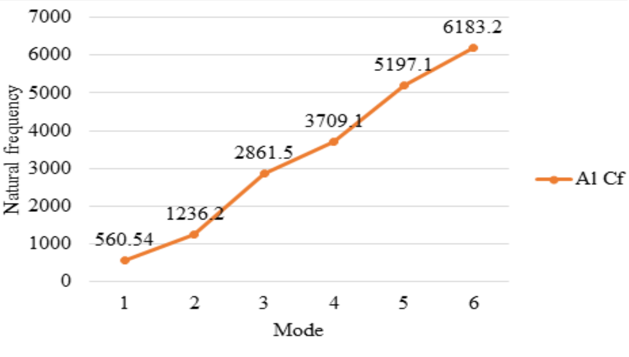

Figure 2. Graphical representation of natural frequencies of Aluminium Carbon Fiber (Al Cf)

3.2 Delaminated Fiber Metal Laminates:

Figure 3. Graphical representation of the mode natural frequencies of Aluminium Carbon Fiber (Al Cf) for different sub-cases.

The graph above shows the natural frequency of a specimen with varying delamination areas located at different interfaces. The graph demonstrates that the frequency drop for modes 1 and 3 is consistent across all subcases. However, there is a sharp drop in the natural frequency for case D in modes 2, 4, 5, and 6. The existence of delamination between the aluminium and Fiber layers is the cause of this. Because of a delamination at the final interface between the metal and Fiber layers, Case H has a lower natural frequency than the other examples.

Table 6. Natural frequency of delaminated Aluminium Carbon Fiber (Al Cf) for various cases.

Mode	**Natural Frequency**							
	Case A	**Case B**	**Case C**	**Case D**	**Case E**	**Case F**	**Case G**	**Case H**
1	558.04	557.94	557.88	556.96	556.89	556.61	556.99	556.97

3.3 Stiffness:

In this study, the effect of delamination on the stiffness of cantilever Fiber metal laminates is investigated using deflection and vibration methods. The delamination in the fiber metal laminate is situated at different lengths and has different areas. The natural frequencies computed by the numerical analysis for aluminium-based fiber metal laminates are presented in Table 6. Only the first mode frequency is used for the vibration analysis. The stiffness results obtained using deflection and vibration methods for the various cases are presented in Table 7.

Table 7: Comparing the equivalent stiffness of cantilever beams with delamination by vibration and deflection method for aluminium Fiber metal laminate

Case	Stiffness 'K' (N/m)		Error
	Vibration Method	Deflection Method	
Undamaged	90136.4	87253.7	3.198
Case A	86249.3	86477.1	-0.264
Case B	85511.7	86446.2	-1.093
Case C	84786.7	86427.6	-1.935
Case D	89733.6	86142.7	4.002
Case E	84858.6	86121.1	-1.488
Case F	89373.5	86034.5	3.736
Case G	88571.6	86152.0	2.732
Case H	89936.9	86145.8	4.215

Because of variations in the stiffness of the delaminated beams, the stiffness calculated from deflection techniques varies considerably from that estimated by vibration methods. In comparison, the vibration approaches yield more dependable findings.

The percentage variations of the stiffness for the aluminium delaminated specimen are less than 10%, as shown in Figure 4. This suggests that the delamination's position and depth can be satisfactorily predicted using a free-vibration-based delamination detection approach, regardless of the delamination region. A significant difference in stiffness between undamaged and damaged materials indicates that delamination alters vibrational characteristics. The influence of stiffness and natural frequencies is a fundamental criterion for predicting structural delamination in the free-vibration-based delamination detection technique.

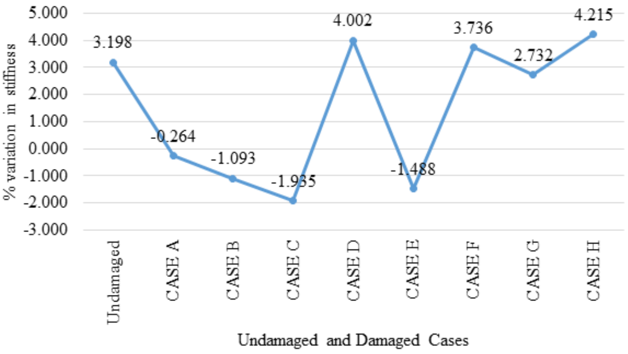

Figure 4: Percentage variance in stiffness for aluminium fiber metal laminate with delamination at various locations

4. CONCLUSIONS

The modelling of Fiber metal laminates was performed using commercial CAD software, and the finite element method was solved in ANSYS. Free vibration analysis can be used to detect structural damage over time. Each damaged and undamaged specimen of a Fiber metal laminate beam is subjected to both deflection and vibration methods to determine its stiffness; the stiffness estimated from the vibration approach and the deflection approach agrees. Free vibration of a delaminated Fiber metal laminate was investigated under cantilever conditions, with variations in the delaminated area and position. A free vibration analysis of a cantilever condition with delamination can lead to the following conclusions:

a. Aluminium fiber metal laminates are prone to variations in the delamination area when it comes to vibration characteristics. Since the phenomenon of delamination changes with vibration modes, the location of delamination may be identified by observing its variable influence on natural frequency.

b. The position and size of delamination in an aluminium fiber-metal laminate may be more precisely predicted using a free vibration-based approach.

c. Natural frequency for 1st mode in the un-delaminated case for aluminium-based Fiber metal laminate, 560.54 Hz, and stiffness 4 N/m by vibration method. This is due to the presence of three metal layers in the fiber metal laminate.

d. Delamination reduces the natural frequencies of aluminium carbon fibre metal laminate plates. The delamination area affects the higher natural frequency modes significantly, while it has a negligible influence on the first mode.

e. Delamination substantially decreases natural frequencies. The natural frequencies of the second, fourth, fifth, and sixth modes in aluminium carbon fibre metal laminate deteriorate significantly more than those of the first and third modes.

f. The deflection technique and the finite element free vibration approach can be used to assess the extent of structural damage. The rigidity of aluminium carbon fiber laminates are more susceptible to delamination. The stiffness of the FML beam decreases as the delamination area and distance vary.

g. When compared to the deflection approach, the vibration method yields more precise delamination results. Its stiffness reduces as the delamination area increases with increasing distance.

h. The percentage variation in stiffness found for damaged aluminium FML is 4.002%, whereas the percentage variation in stiffness of undamaged aluminium FML is 3.198%. The fibre metal laminate exhibits a significant reduction in stiffness for the deflection technique at a distance greater than 125 mm from the free end as a result of delamination.

ACKNOWLEDGMENTS

The author would like to acknowledge Shivaji University, Kolhapur, and KLS Gogte Institute of Technology, Belagavi

REFERENCES

[1] G. H. J. J. Roebroeks, Fiber-Metal Laminates, Fatigue 1994, 18, 33 (1994).

[2] N.P. Singh, V.K. Gupta, A.P. Singh, Graphene and carbon nanotube reinforced epoxy nanocomposites: a review. Polymer 180, 121724 (2019)

[3] M. Kuiry, S. Karati, T. Kumar Roy, Determination of Marshall parameters of bituminous mix by using non-destructive testing method. Mater. Today (2023). https:// doi. org/ 10. 1016/j. matpr. 2023. 03. 575

[4] Z. Wei, W. Jie, P. Zhi-bo, L. Jia, M. Lian-hua, J.-y Zhou, S. Yi-fan, Review on optimization design, failure analysis and non-destructive testing of composite hydrogen storage vessel. Int. J. Hydrogen energy 47(91), 38862–38883 (2022)

[5] C.D. Magalhães, P. André, Z.L. Basei, B.M. Briguet, I.N. Bastos, Da. Silva, Non-destructive testing of high-tenacity polyester subropes for mooring systems. Appl. Ocean Res. 134, 103513 (2023)

[6] M. Monazami, A. Sharma, R. Gupta, Evaluating performance of carbon fiber-reinforced pavement with embedded sensors using destructive and non-destructive testing. Case Stud. Constr. Mater. 17, e01460 (2022)

[7] Liu, Y.J., Jiang, Z., Wen, H.M. (2020) Predicting impact induced delamination of FRP laminates. Int. J. Impact Eng. DOI: 10.1016/j.ijimpeng.2019.103436

[8] Vikram S. Yendhe, V.L. Kadlag, R.S. Shelke, Vibration analysis of cracked cantilever beam for varying crack size and location, Int. Res. J. Eng. Technol. 3 (8) (2016) 1913–1919.

[9] B. Balakrishnan, S. Raja, D. Dwarakanathan and Amirtham Rajagopal (2016) Vibroacoustic performance of fiber metal laminates with delamination, Mechanics of Advanced Materials and Structures, 23:12, 1369-1378, DOI: 10.1080/15376494.2015.1091523

[10] Aymerich, F., and Staszewski, W. J. (2010). Impact damage detection in composite laminates using nonlinear acoustics. Composites Part A: Applied Science and Manufacturing, 41(9), 1084 -1092. doi:10.1016 /j.compositesa.2009.09.004

[11] Kindova-Petrova D. Vibration-based methods for detecting a crack in a simply supported beam. Journal of Theoretical and Applied Mechanics; Vol. 44, No. 4,2014, pp. 69–82. 10.2478/jtam-2014-0023

[12] Abhijeet Pidge, Aniket Salve, Ashok Mache, Aparna Kulkarni, and Yashwant Munde Effect on Vibration Characteristics of Fiber Metal Laminates Reinforced with Jute/glass Fibers R. K. Tyagi et al. (eds.), Advances in Engineering Materials, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-981-99-4758-4_11

[13] Akkasali, N.K., Biswas, S. Effects of Combined Delamination and Crack Damage on Natural Frequency and Strain Energy Release Rate in Adhesively Bonded Joints Under Thermal Condition: FEA and Experimental Validation. J. Vib. Eng. Technol. (2024). https://doi.org/ 10.1007/s42417-024-01341-z

[14] Karsh, P. K., Thakkar, B., Kumar, R. R., Kumar, A., & Dey, S. (2021). Effect of Delamination on Natural Frequencies of E-glass and S-glass Epoxy Composite Plates. European Journal of Computational Mechanics, 29(4-6), 437–458. https://doi.org/10.13052/ ejcm1779-7179.29466

[15] Gowda, C.V., Yogesha, K.B., Manjunath, H.R. et al. Effect of Delamination Size on the Natural Frequency of Twintex and Natural Fiber/Poly-Propylene Hybrid Composite Cantilever Beam. J. Inst. Eng. India Ser. D (2024). https://doi.org/10.1007/s40033-023-00622-3

[16] Orhan, Sadettin & Lüy, Murat & Dirikolu, M. Husnu & Zorlu, Gazi. (2016). The Effect of Crack Geometry on the Non-destructive Fault Detection in a Composite Beam. International Journal of Acoustics and Vibrations. 21. 271-273.

[17] Vikas Ramnath Khalkar, Pon Hariharasakthi sudhan, Kamaraj Logesh, Arul Moshi, Jyoti Borade, Rohan Kalamkar, Some Studies Verify the Applicability of the Free Vibration Method of Crack Detection in Composite Beams for Different Crack Geometries , Romanian Journal of Acoustics and Vibration: Vol. 20 No. 1 (2023)

[18] Huang, Y., Liu, J., Huang, X., Zhang, J., Yue, G., Delamination and fatigue crack growth behavior in Fiber Metal Laminates (Glare) under single overloads, International Journal of Fatigue, Vol. 78, 2015, pp. 53 – 60.

[19] Heung Soo Kim, Aditi Chattopadhyay, Anindya Ghoshal, Characterization of delamination effect on composite laminates using a new generalized layerwise approach, Computers and Structures, Vol. 81, 2003, pp. 1555–1566.

[20] T.G. Srikanth, M. Senthikumar, and S. M. Reddy, Vibration-based delamination evaluation in GFRP composite beam using ANN, Polymer and polymer composites, Vol. 29, 2021, pp. 5317 – 5324.

[21] Ganesh Shankar, Jayant Prakash Varuna, P.K. Mahato, Effect of delamination on vibration characteristic of smart laminated composite Plate, Journal of Aerospace System Engineering, Vol. 13, No. 4,2019, pp.10–17.

[22] A. Stawiarskia, A. Muca, and M. Barskia, Experimental and numerical studies of laminated plates with delamination subjected to compressive loads, Latin American Journal of Solids and Structures, Vol. 17, No. 5,2020, pp. 1–12.

[23] S.U. Khan, R.C. Alderliesten, R. Benedictus, Delamination growth in Fiber Metal Laminates under variable amplitude Loading, Composites Science and Technology, Vol. 69, No.15/16, 2009, pp. 2604–2615.

[24] Gilbert-Rainer Gillich, Marius Tufoi, Zoltan-Iosif Korka, Emilian Stanciu, Adrian Petrica, The Relations between Deflection, Stored Energy and Natural Frequencies, with Application in Damage Detection, RJAV, vol. 13, issue 2, 2016, pp. 87-93.