

A STUDY ON THE INFLUENCE OF NANOFILLERS ON THE VIBRATIONAL CHARACTERISTICS OF FIBER METAL LAMINATES

Omkar Jarali¹, Kamaraj Logesh¹, Vikas Khalkar^{2,*}, and Arul Moshi³

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Abstract

In recent years, there has been a significant increase in research focused on developing innovative composite materials, particularly Fiber Metal Laminates (FMLs), which are widely used in the aerospace industry due to their superior mechanical properties. When designing structures, their free vibration behavior, especially natural frequencies, plays a vital role. This study uses numerical and experimental methods to investigate the vibration behavior of a fiber-metal-laminate (FML) composite cantilever beam reinforced with multi-walled carbon nanotubes (MWCNTs). The FML composite beams were fabricated with varying weight percentages of MWCNT (3%, 4%, and 5%) and different beam lengths (200 mm, 225 mm, 250 mm, and 275 mm). The experimental setup involved free vibration tests to determine the natural frequencies of the beams, while Finite Element Analysis (FEA) using ANSYS software was employed to simulate the vibration characteristics. The inclusion of MWCNT at percentages of 3, 4, and 5 resulted in the proposed composites' first natural frequencies as 42 Hz, 46 Hz, and 52 Hz, showing a considerable improvement in the outcomes. The results showed that the natural frequencies of the FML composite beams increased with higher MWCNT content, indicating enhanced stiffness. Additionally, the natural frequencies decreased with increasing beam length. The experimental and numerical results were in good agreement, validating the accuracy of the Finite Element model. This study provides valuable insights into the dynamic behavior of FML composite beams. It highlights the potential of nanoparticle reinforcement in improving the mechanical properties of composite materials for aerospace applications.

Keywords: Fast Fourier Transform; Fiber Metal Laminates; Finite Element Analysis; MWCNT; Nano-particles

¹ Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, Chennai, India. Email: omkarjarali@gmail.com; klogesh7@gmail.com

² Gharda Institute of Technology, Lavel, Khed, Ratnagiri, Maharashtra, India. Email: vrkhalkar@git-india.edu.in*

³ JKKN College of Engineering and Technology, Vattamalai, Komarapalayam, Tamil Nadu, India. Email: moshibeo2010@gmail.com

* Corresponding author

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Introduction

A complex family of materials known as laminated composites is created by combining one or more components with different chemical and physical characteristics. With different orientations, the material characteristics of every layer are maintained, enabling customization. In contrast, fiber-metal-laminated (FML) composites have alternating metal and fiber-reinforced polymer (FRP) layers. It offers better mechanical qualities than traditional high-strength unified metals and polymer composite laminates. FMLs have superior specific strengths, stiffness, and fatigue properties compared to metals. These are the main advantages they offer. Owing to their improved qualities, fiber metal laminates, or FMLs, have recently seen an increase in application across a range of industries. FMLs are a hybrid material composed of thin metal layers and fiber-reinforced composites. Qianjin *et al.* (2023) found that further research is necessary to fully understand how nanoparticles affect the vibrational properties of FMLs, even though their reinforcing effects on polymeric composites have been well established. Materials containing nanoparticles impact the modern world. Enhancing the dynamic and free vibration characterization of fiber metal laminates (FMLs) is still challenging, even though FMLs have much potential as light structural components. Merzuki *et al.* (2021) investigated the vibrational characteristics of FML plates in fixed-free and fixed-fixed boundary configurations. By contrasting the results with those from the ABAQUS finite element analysis, the accuracy of the findings was validated. The results demonstrated that composite layers like aluminum alloy plates have elevated natural frequencies. Structures can be made more visually appealing by adding discontinuities, with or without fractures, or by fixing design flaws that result in a loss of stiffness and stress concentration. Saini *et al.* (2019) described a laminate's behavior. A structure's inherent frequency is lowered when resonance processes reduce stiffness, which can have disastrous consequences. The present work evaluated the fiber orientation angle, relative fracture depth, and relative crack position of a cantilever beam made of a fiber-metal laminate in detail. Danu *et al.* (2021) investigated a hybrid laminated composite beam made of boron-epoxy, aramid-epoxy, and s-glass-epoxy. The finite element approach was applied to quantitatively evaluate the free transverse vibration behavior of a composite beam. Hanten *et al.* (2018) investigated free vibration on laminated fiber-metal beams. Apart from classical models such as Timoshenko

and Euler-Bernoulli, there exist other higher-order displacement-based theories. Through the displacement field approximation, the governing differential equations and boundary conditions are produced in a generic form similar to a generic term. The outcomes showed that the suggested method for three-dimensional finite element methods (FEM) solutions generated by a commercial finite element program employing three-dimensional components was accurate and computationally efficient. Using the modified couple stress theory (MCST), Ghasemi and Mohandas (2018) computed the frequency of cylindrical FML (fiber-metal laminate) micro- and nanoshells. The thin cylindrical shell and beam modal function model was utilized to fulfill the governing equations of motion under various boundary conditions, and Love's first approximation shell theory was applied to it. Research on the vibration of micro and nano FML cylindrical shells with respect to composites of aluminum/epoxy, glass/epoxy, aramid/epoxy, and carbon/epoxy has been done. Liu *et al.* examined the fundamental characteristics (Liu *et al.*, 2020) of the thin, fiber-metal laminated plates situated beneath a cantilever boundary, both conceptually and physically. The authors used composite material mechanics and conventional laminated plate theory to create their theoretical model. When the test frequencies and the outcomes were compared, the errors ranged from 3.4% to 4.5%. Using a beam model function and Love's first approximation shell theory, Mohandes and Ghasemi (2019) examined the fluctuations in the free vibration of composite cylindrical shells reinforced by carbon nanotubes (CNTs) and fiber-metal laminates (FML). For example, the stiffness-to-weight and strength-to-weight ratios of FMLs are notable and robust. The dynamic character of FMLs has not been extensively studied. The dynamic behavior of glass fiber/epoxy and fiber metal laminates was studied by Merzuki *et al.* (2019a). Two state-of-the-art production techniques-compression moulding and vacuum bagging-were used to create the specimens. A free vibration test ascertained the specimen's dynamical properties by hammering a cantilever plate (El-Mahdy and Gadelrab, 2000; Zhang *et al.*, 2001; Kim *et al.*, 2014; Treviso *et al.*, 2015). The stiffness of the material is directly proportional to an increase in natural frequency. FML is currently the material most commonly utilized in this business, and it makes up the majority of structural components for the aircraft. These components include engine cowlings, seamless tubes, and cargo flooring. There is a dynamic load for each

frequency-based structural service. As such, understanding and experimenting with FMLs to accurately predict dynamic behavior is more difficult. By observing free vibrations, one can determine the natural frequency and mode form. Static and dynamic loads are common for many active structures, including those used in the automotive and aviation sectors. To properly comprehend the deformation and vibration (Prasad and Sahu, 2018) of FML structures, one must comprehend the implications of the scenario. FMLs are a family of hybrid composite materials composed of metal layers and fiber-reinforced polymers. Aghamohammadi *et al.* (2020) investigated the effects of multi-walled carbon nanotubes (MWCNTs) on the flexural and high-velocity impact behaviour of basalt fibers/epoxy layers and aluminium 2024-T3-based FMLs. Scanning electron microscopy, or SEM, was used to study the fracture surfaces of the sample. The results showed that the addition of nanofillers substantially affected the adherence of composite plies and the interfaces between basalt fibers and epoxy layers. It should be noted that how nanoparticles on polymeric composites support one another is generally understood. However, it is yet unclear how nanoparticles affect the mechanical characteristics of FMLs and adhesively bonded junctions between polymeric composites and metal sheets. The Studies of (Eslami-Farsani *et al.*, 2022) have shown that nanoparticles can maintain FML properties. Khurram *et al.* (2018) tried using multi-walled carbon nanotubes (MWCNT) to strengthen the bonding of fiber metal laminates. To improve the bonding of the FML junction, MWCNT was added in weights of 1.0, 2.0, and 3.0% to the epoxy matrix of the E-glass fiber composite. The outcomes showed that the interfaces between aluminium and E-glass/epoxy were enhanced by the addition of MWCNT. The effects of the transverse shear deformation on the vibrational properties of the beam were investigated using the Rayleigh-Ritz method (Kolar, 2002). The relationship between vibrational behavior, sheet thickness, fiber orientation, and plate aspect ratio was the main focus of this study. The dynamic behavior needs to be considered (Merzuki *et al.*, 2019b) to achieve the best possible balance between improved performance and material qualities. Yathish *et al.* (2021) experiment's findings demonstrated that hybrid designs and loading conditions significantly impacted hybrid fiber metal laminates' buckling and vibration characteristics. Dadej *et al.* (2019) used analytical, theoretical, and experimental techniques to demonstrate that enhanced carbon fiber failure strain occurs in fiber metal laminates.

Liao and Liu (2017) studied glass fiber and aluminum laminates under low-velocity impact using FEM to determine their progressive and dynamic failure characteristics. According to Pang *et al.* (2022), specific energy absorption rose as the fiber volume percentage grew and fell as the laminated surface density increased. Kali *et al.* (2020) found that the peak acceleration was much reduced when the aluminum lamination at the core was swapped out for a precisely sized bamboo strip. Stefaniak and Prussak (2019) found that an FML requires at least one layer of metal and one layer of fiber-reinforced polymer (FRP) since material mixing affects the former but not the latter. The main distinction between FML and hybrid or composite constructions is this. Kali *et al.* (2022) studied that, adding nanoparticles to these materials significantly enhanced their mechanical qualities. Hybrid FML exhibits better tensile properties than GLARE. Maraş *et al.* (2018) found that as the Al layer sites move from the surface to the mid-plane, the natural frequencies rise. Jarali *et al.* (2024) studied the fact that intact FML beams give comparatively larger vibration characteristics than damaged ones for the same geometric properties.

The literature review reveals that analytical and numerical techniques have been extensively employed to study the dynamic behavior of fiber-reinforced polymers (FRPs). A significant portion of the existing research has focused on the impact resistance, tensile behavior, and mechanical characterization of fiber metal laminates (FMLs). While several studies have explored the dynamic behavior of FML plates, there is a noticeable scarcity of experimental research explicitly addressing the dynamic properties of FMLs. Furthermore, there is a need for additional investigation to evaluate the performance of already fabricated FML composites, particularly in real-world applications. This gap in the literature highlights the necessity for more comprehensive experimental studies to understand the dynamic behavior of FMLs better, especially when reinforced with nanoparticles such as multi-walled carbon nanotubes (MWCNTs). The primary objective of this study is to investigate the bending natural frequency of a fiber-metal-laminate (FML) composite cantilever beam reinforced with multi-walled carbon nanotubes (MWCNT). The study aims to analyze the influence of nanofiller content (MWCNT) and beam length on the FML composite beam's dynamic behavior using experimental and numerical methods. The research seeks to fill the gap in the literature by providing a comprehensive understanding of how the addition of nanoparticles affects the vibrational properties of FML

composites, which are increasingly used in aerospace and other industries due to their superior mechanical properties. The findings from this study are expected to contribute to the design and optimization of FML structures for improved performance under dynamic loading conditions.

Experimental Program

Multi-walled carbon nanotubes (MWCNT), epoxy glue comprising resin and hardener, 0.5 mm thick aluminium sheet (AA5052-H32), and woven E-glass fiber comprise FML composite beams. One of the fillers utilized to prepare the FML composite beam was MWCNT. MWCNT, aluminium alloy, and epoxy glass fiber structure were used to construct the FML. Araldite AV138, a pure epoxy monomer, was combined with 200 milliliters of ethanol to aid in the dispersion and different amounts of fine MWCNT powder to create the composite. The mixture was stirred for five minutes at room temperature before adding a curing agent (HV998). The hardener to epoxy resin ratio was 10:4. The composite material was left to cure at room temperature for nineteen hours. We cleaned and degreased the 0.5 mm-thick aluminum alloy sheet metal (AA5052-H32). Different weight ratios of MWCNT combined with resin and hardener mixes generated each layer. First, the fibers were sun-dried to lower the moisture content. The layer's skin material was housed inside a wooden foundation. The aluminium sheet was then covered with epoxy, and the precise concentration of MWCNT in the coating was ascertained. After activating the matrix agent, the upper aluminium sheet was filled with epoxy resin nanofiller and connected with woven roving glass fiber. The mixture was distributed uniformly, and the trapped air was released using the roller. Subsequently, an even coating of epoxy resin containing nanofiller was applied to the aluminium alloy upper sheet. There was a ten- to fifteen-minute drying interval following rolling. Before FML composites eventually laminated under stress, they could cure for 19 hours. A continuous load was applied to the three layers for nineteen hours to create the FML composite beam. The specimen was prepared in the rolling direction using water jet machining. The characteristics of the aluminium sheet utilized for the case study are shown in Table 1.

Determination of material constants

The material constants for the glass fiber composite sheets were calculated separately. The universal testing machine performed the uniaxial

Table 1. Material properties of Aluminium sheet (AA5052-H32)

Property	Unit	Value
Young's modulus, E	N/m ²	70.6e9
Density, ρ	kg/m ³	2680
Poisson's ratio, μ	—	0.33

Table 2. Material properties of prepared FML composite beams

Property	Unit	Value
E ₁	N/m ²	7.25e9
E ₂	N/m ²	1.08e9
E ₃	N/m ²	7.25e9
G ₁₂	N/m ²	2.58e9
G ₁₃	N/m ²	1.05e9
G ₂₃	N/m ²	2.58e9
μ_{12}	—	0.22
μ_{13}	—	0.22
μ_{23}	—	0.22
ρ	kg/m ³	2540

tension test on composite beam specimens. One kind of mechanical testing apparatus used to ascertain the mechanical characteristics of different materials, including their tensile, compressive, bending, material modulus, and shear strengths, is the Universal Testing Machine (UTM). The UTM operates by applying a regulated compressive or tensile force to the test specimen and monitoring its reaction. The loading frame and the control panel are the two main parts. The control panel establishes the test parameters and records the test results, while the loading frame is in charge of delivering a load to the specimen. The test findings also showed the composite beam specimens' Young's moduli, shear moduli, and Poisson's ratio. The specifics of the material constants are shown in Table 2.

Details of the prepared specimens

In this study, twelve specimens of 2/1 FML composite beams were examined. The 2/1 configuration composite FML beams were composed of twenty-four aluminium sheets and twelve glass fiber epoxy sheets. The quantity of nanofillers in each of the twelve glass fiber epoxy samples varies. The details of the twelve suggested examples are listed in Table 3. This experiment also used twenty-four sheets of aluminum alloy. Out of twenty-four sheets, the first six sheets have a 200 mm length, the subsequent six sheets have a 225 mm length, again, the subsequent six sheets have a 250 mm length, and the last six sheets have a 275 mm length. Figure 1 displays the resulting 2/1 FML composite beams. Figure 2 shows the concept for the 2/1 FML composite cantilever beam.



Figure 1. The fabricated 2/1 configurations FML (AL/GF-E/AL) composite beams

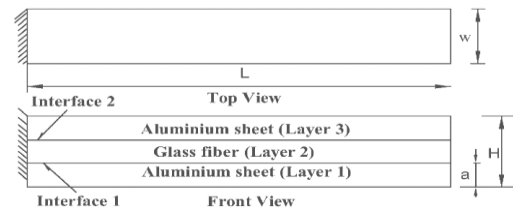


Figure 2. The schematic of the prepared FML composite cantilever beam

Table 3. Dimensions of the proposed glass-fiber epoxy (GF) specimens

Specimen ID	Materials	% of nano-fillers (MWCNT) in glass fibre epoxy	Length (mm)	Width (mm)	Thickness (mm)
H1	GF	3	200	15	1.1
H2	GF	3	225	15	1.1
H3	GF	3	250	15	1.1
H4	GF	3	275	15	1.1
H5	GF	4	200	15	1.5
H6	GF	4	225	15	1.5
H7	GF	4	250	15	1.5
H8	GF	4	275	15	1.5
H9	GF	5	200	15	1.8
H10	GF	5	225	15	1.8
H11	GF	5	250	15	1.8
H12	GF	5	275	15	1.8

Experimental Investigation

The experimental investigation focused on determining the natural frequencies of the FML composite beams under free vibration conditions. Figure 3 shows the experimental vibration setup. The setup included a four-channel vibration analyzer, an accelerometer, an impact hammer, a laptop running pulse software, a fixture, specimens, fasteners, and spanners. A stiff fixture was used to hold the specimens and apply the fixed-free boundary condition. The impact hammer test was employed to excite the beams, and the resulting vibrations were measured using an accelerometer. The Fast Fourier Transform (FFT) was used to convert the time-domain signal into the frequency domain, allowing for the identification of the natural frequencies. The FFT analyzer processed the signals from the accelerometer and impact hammer, and the natural frequencies were obtained from the frequency response function (FRF) generated by the software. The technical details of the instruments are as follows:

- Accelerometer: Bruel and Kjaer 4514, sensitivity of 1 mV/g to 10 mV/g, and frequency range of 0.1 Hz to 26.5 kHz.
- Impact Hammer: Bruel and Kjaer, and a sensitivity of 0.0244 mV/N mV/N.
- Four-channel FFT Analyzer: Bruel and Kjaer 3050-B-040
- Pulse Software: Bruel and Kjaer are used for data acquisition and analysis and are capable of real-time signal processing and FRF generation.

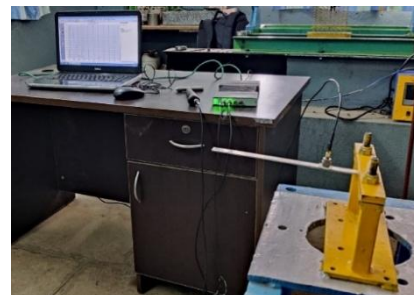


Figure 3. Experimental set-up for the vibration analysis of a FML composite beam

Finite Element Modeling and Analysis

The dynamic properties or structural features of a composite cantilevered beam were evaluated using the FEA software, i.e., ANSYS, such as the vibration characteristics-also referred to as the vectors and eigenvalues-provided by the modal analysis. Modal analysis has applications in design optimization, troubleshooting, prediction, and simulation. Using finite element methods, ANSYS is a multi-purpose engineering software (Khalkar *et al.*, 2022; Jarali *et al.*, 2023; Khalkar *et al.*, 2024) that simulates the interplay of all physics, structural, vibration, fluid dynamics, heat transport, and electromagnetic disciplines. ANSYS generates geometry by importing CAD data and using its “pre-processing” features. Similarly, the same pre-processor produces a finite element model needed for computing. The post-processor shows the results once loadings and analysis have been finished. The version 12.1 of ANSYS was used in this investigation. A solid 186 The layered solids or thick shells are modeled using the Layered function. It works well for modeling irregular meshes, such as those created by different CAD/CAM systems. Any spatial direction can be used to align the element. It

is capable of withstanding a lot of strain. The shifting geometry brought on by this deformation can no longer be disregarded when a material's strains surpass a few percent. Finite-strain or large-strain analyses take this effect into account. In a static or transient study, a major strain analysis is conducted. The SOLID 186 elements were selected for the finite element analysis. Since the composite beam falls within the solid structure category, a three-dimensional solid 186-layered element was used to model it. Three surrounding zones were established when the area command was used for the first time. Using a third extrusion direction for these components may make it easier to create three-dimensional solid models. The glass fibre epoxy layer that was positioned between the two solidified products was made from aluminium sheets. Three-dimensional illustrations of the meshed FML composite beam are shown in Figure 4. The Solid 186 elements could be used to mesh all solids. Figure 4 displays the model's mesh, which was produced using mapped hexahedral components. There was no alternative method to bend or create the left end of the composite beam model. Therefore, cantilevered border conditions were used.

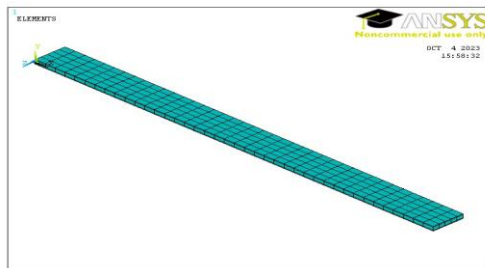


Figure 4. Meshed finite element model of the FML composite cantilever beam

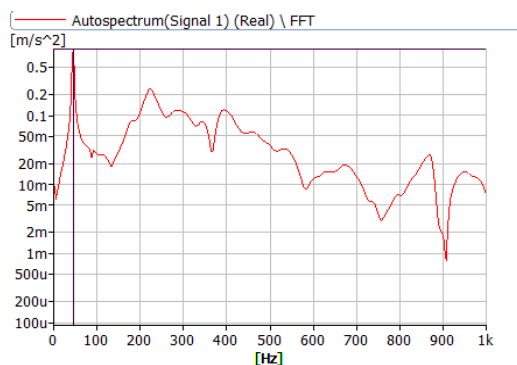


Figure 5. Plot of the experimental first, second and third natural frequencies for the FML beam's H1 configuration

Results and Discussion

Experimental Analysis Results

The experimental natural frequency results of the composite beams under investigation are represented by the peaks shown in the Figure 5.

Numerical Analysis Results

The first, second and third natural frequency plots for the H1 configuration of the composite cantilever beam obtained from the numerical analysis study are shown in Figures 6, 7 and 8 respectively.

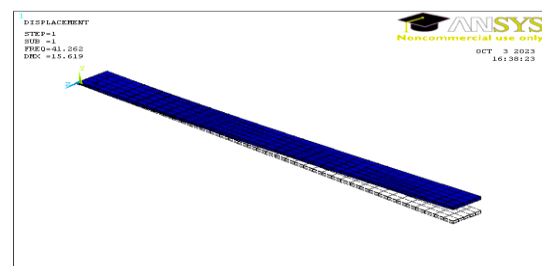


Figure 6. Numerical first natural frequency plot for the H1 configuration of the composite cantilever beam

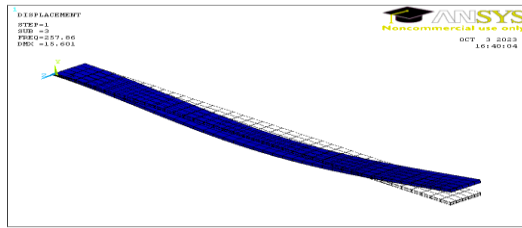


Figure 7. Numerical second natural frequency plot for the H1 configuration of the composite cantilever beam

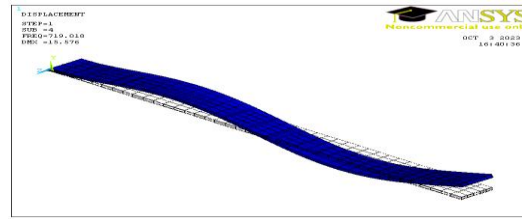


Figure 8. Numerical third natural frequency plot for the H1 configuration of the composite cantilever beam

Table 4. Experimental and numerical natural frequencies for different configurations of the tested FML composite cantilever beams

Wt.% of MWCNT	Size of specimen (L × W)	Natural frequency 1 (Hz)			Natural frequency 2 (Hz)			Natural frequency 3 (Hz)		
		Numerical	Experimental	% of Deviation	Numerical	Experimental	% of Deviation	Numerical	Experimental	% of Deviation
3	200 × 15	41.26	45	-9.06	257.86	222.5	13.71	719.018	675	6.12
4	200 × 15	47.334	55	-16.20	295.489	317.5	-7.45	822.504	777.5	5.47
5	200 × 15	51.572	56	-8.59	321.68	362.5	-12.69	894.22	862.5	3.55
3	225 × 15	32.59	32.5	0.28	203.78	165	19.03	568.73	572.5	-0.66
4	225 × 15	37.389	37.5	-0.30	233.59	230	1.54	651.01	697.5	-7.14
5	225 × 15	40.74	40	1.82	254.37	275	-8.11	708.15	715	-0.97
3	250 × 15	26.391	27.5	-4.20	165.09	160	3.08	461.03	432.5	6.19
4	250 × 15	30.278	30	0.92	189.28	177.5	6.22	527.98	542.5	-2.75
5	250 × 15	32.993	32.5	1.49	206.14	180	12.68	574.52	557.5	2.96
3	275 × 15	21.806	20	8.28	136.45	117.5	13.89	381.22	425	-11.48
4	275 × 15	25.019	26	-3.92	156.47	140.8	10.01	436.74	450	-3.04
5	275 × 15	27.263	32.5	-19.21	170.43	167.5	1.72	475.37	542.5	-14.12

Table 4 displays the predicted and measured natural frequencies for FML composite cantilever beams. Experimental and numerical methods were used to study the vibration parameters of a sandwich beam formed of fiber metal laminates containing nanopowders, specifically multi-walled carbon nanotubes (MWCNT). The experimental natural frequency results were broadly consistent with the calculated results. The stiffness of the composite beam increased with the thickness of the specimen. Table 4 demonstrates that the natural frequency increases proportionately to the fraction of nanoparticles in the FML composite beam.

Comparison of Experimental and Numerical Results

The experimental results were compared with the numerical results obtained from the finite element analysis (FEA) using ANSYS. The comparison shows a reasonable agreement between the two, with deviations ranging from -19.21% to 19.03% across different configurations. The deviations are within acceptable limits, indicating that the FEA model accurately captures the dynamic behavior of the FML composite beams. For instance, in the H1 configuration, the first natural frequency obtained from FEA was 41.26 Hz, while the experimental result was 45 Hz, resulting in a deviation of -9.06%. This close agreement validates the accuracy of the numerical model and confirms

that the FEA approach is suitable for predicting the dynamic behavior of FML composite beams. The peak of natural frequency was observed at 400 Hz in the experimental spectrum of the fiber metal laminate composite cantilever beam. The FEA analysis was conducted to capture the first six natural frequencies of a composite cantilever beam. As per the FEA analysis, there were six modes, i.e., bending mode at 41.262 Hz, longitudinal mode at 228.901 Hz, bending mode at 257.06 Hz, bending mode at 719.01 Hz, torsional mode at 919.332 Hz, and longitudinal mode at 1398 Hz natural frequency. This research study mainly deals with determining the first three bending natural frequencies. The mode shapes plot for these bending frequencies are shown in Figures 6 to 8. From the FEA analysis, it was found that there was no vibration mode at or near the 400 Hz frequency. Hence, the experimental peak corresponding to 400 Hz is not considered the third bending natural frequency.

Effect of MWCNT Content on Natural Frequencies

The results indicate that adding MWCNT influences the natural frequencies of the FML composite beams. As the weight percentage of MWCNT increases from 3% to 5%, the natural frequencies of the beams also increase. This is attributed to the enhanced stiffness of the composite

material due to the reinforcing effect of MWCNT. The nanoparticles improve the interfacial bonding between the glass fiber and epoxy matrix, leading to a more rigid structure that resists deformation under dynamic loading.

For instance, the first natural frequency of the H1 configuration (3% MWCNT) was experimentally measured at 45 Hz, while for the H9 configuration (5% MWCNT), it increased to 56 Hz. This trend is consistent across all three bending modes, as shown in Figures 9 to 11, where the natural frequencies increase with higher MWCNT content. This suggests that the addition of nanoparticles enhances the stiffness and improves the overall dynamic performance of the FML composite beams.

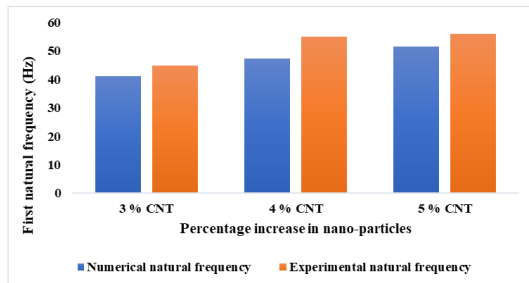


Figure 9. The MWCNT percentage and natural frequency for H1, H5 and H9 configurations

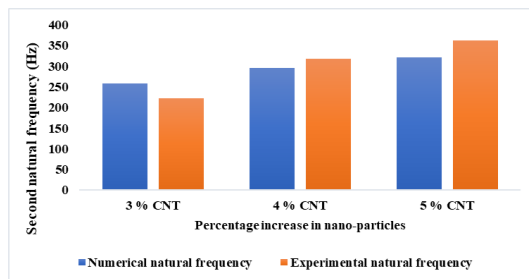


Figure 10. The MWCNT percentage and natural frequency for H1, H5 and H9 configurations

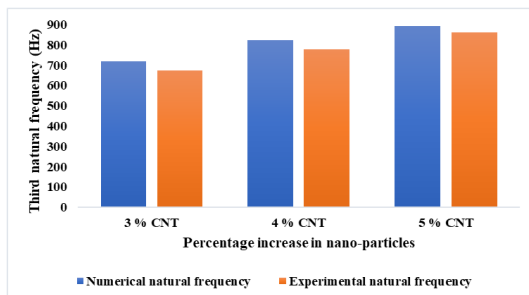


Figure 11. The MWCNT percentage and natural frequency for H1, H5 and H9 configurations

Effect of Beam Length on Natural Frequencies

Figure 12-14 depicts how natural frequencies vary with the length of FML composite beams under cantilever boundary conditions. The study also investigated the effect of beam length on the natural frequencies. It was observed that as the beam length increases from 200 mm to 275 mm, the natural frequencies decrease. This is due to the increased bending moment at the cantilevered end of the beam, which reduces the overall stiffness of the structure. Longer beams are more flexible, leading to lower natural frequencies.

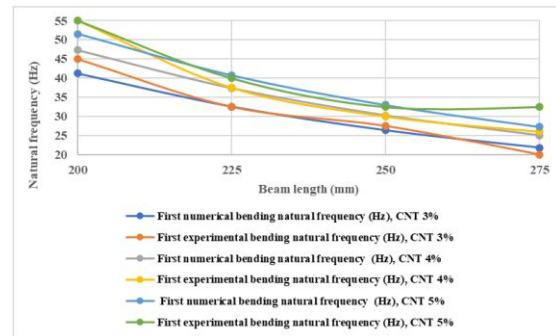


Figure 12. Beam length and first natural frequency variation

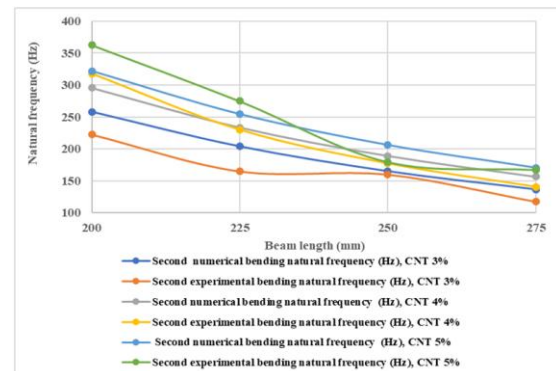


Figure 13. Beam length and first natural frequency variation

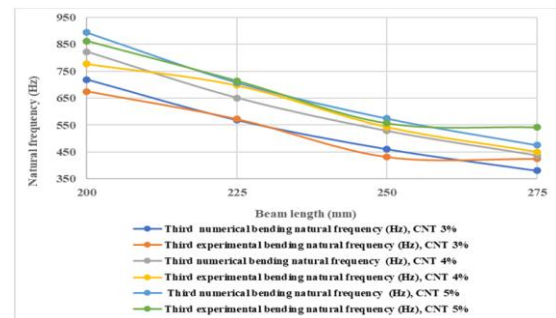


Figure 14. Beam length and first natural frequency variation

For example, in the H1 configuration (3% MWCNT), the first natural frequency decreased from 45 Hz for a 200 mm beam to 20 Hz for a 275 mm beam. This inverse relationship between beam length and natural frequency is consistent with classical beam theory, which predicts that longer beams have lower natural frequencies due to reduced stiffness.

Implications for Practical Applications

The findings of this study have significant implications for the design and optimization of FML composite structures, particularly in industries such as aerospace, automotive, and marine, where lightweight and high-strength materials are crucial. Adding MWCNT nanoparticles enhances the stiffness and natural frequencies of the FML beams, making them more suitable for applications requiring high dynamic performance. However, it is important to note that the agglomeration of nanoparticles beyond a certain threshold (e.g., 5%) could reduce mechanical properties. Therefore, future studies should explore the optimal concentration of nanoparticles to achieve the best balance between stiffness and dynamic performance.

Conclusions

This study investigated the free vibration behavior of fiber-metal-laminate (FML) composite cantilever beams reinforced with multi-walled carbon nanotubes (MWCNT) using both experimental and numerical methods. The effects of MWCNT content and beam length on the natural frequencies were analyzed, and the results were validated through finite element analysis. The following key findings were drawn from the research:

- The natural frequencies of the FML beams increased with the proportion of MWCNT nanoparticles, ranging from 3% to 5%. For example, the first natural frequency increased from 45 Hz (3% MWCNT) to 56 Hz (5% MWCNT) for a 200 mm beam.
- The natural frequencies decreased as the beam length increased from 200 mm to 275 mm. For instance, the first natural frequency dropped from 45 Hz (200 mm) to 20 Hz (275 mm) for the 3% MWCNT configuration.
- Experimental results showed reasonable agreement with numerical predictions, with deviations ranging from -19.21% to 19.03%. For example, the first natural frequency for the 3% MWCNT, 200 mm beam was 41.26 Hz (numerical) and 45 Hz (experimental), with a deviation of -9.06%.

- The study examined the first three bending modes, showing that natural frequencies increased with higher mode numbers. For the 3% MWCNT, 200 mm beam, the frequencies were 45 Hz (1st mode), 222.5 Hz (2nd mode), and 675 Hz (3rd mode).
- FML composites with MWCNT reinforcement are suitable for applications requiring high dynamic performance, such as in aerospace and automotive industries, with the 5% MWCNT beam showing the highest natural frequencies (56 Hz for the first mode).
- Agglomeration of nanoparticles beyond 5% may reduce mechanical properties, indicating the need for further optimization of nanoparticle concentration.
- Future studies should explore higher concentrations of MWCNT (e.g., 6% and 7%) and the use of hybrid nanoparticles to further enhance the dynamic properties of FML composites.

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