Sound & Vibration 2025, 59(6), 3799.
doi: https://doi.org/10.59400/sv3799

Article

Vibrational behaviour of MWCNT-reinforced single and cross overlap adhesive joints: Experimental and FEA analysis

Vikram Hanmantrao Londhe[1], **Madan Mohanrao Jagtap**[2,*]

[1] Symbiosis Institute of Technology, Symbiosis International (Deemed University), Pune 412115, India

[2] Operations Management, Symbiosis Institute of Operations Management, Nashik Campus, Constituent of Symbiosis International (DU), Pune 412115, India

*** Corresponding author:** Madan Mohan Jagtap, madan.jagtap@siom.in

CITATION

Londhe VH, Jagtap MM. Vibrational behaviour of MWCNT-reinforced single and cross overlap adhesive joints: Experimental and FEA analysis. Sound & Vibration. 2025; 59(6): 3799. https://doi.org/10.59400/sv3799

ARTICLE INFO

Received: 12 September 2025
Revised: 29 October 2025
Accepted: 3 November 2025
Available online: 15 December 2025

Abstract: Adhesively bonded joints are widely used in lightweight aerospace and automotive structures, but their dynamic performance under vibrational conditions remains a critical design concern. Recent studies have shown that nanofiller-modified adhesives can enhance static strength, but limited experimental evidence is available on their influence on the vibration behaviour of different joint configurations. In this work, the vibrational characteristics of single lap joints (SLJs) and cross lap joints (CLJs) bonded with epoxy adhesive reinforced with 1 wt% multiwall carbon nanotubes (MWCNTs) are investigated through combined experimental and numerical approaches. Modal testing was conducted using an impact hammer technique and fast fourier transform (FFT) based frequency response analysis to determine natural frequencies and damping characteristics. Finite element modal harmonic analyses were performed using a three-dimensional viscoelastic model to simulate the dynamic response of the joints. The results indicate that the incorporation of MWCNTs leads to a consistent increase of the joints. The results indicate that the incorporation of MWCNTs leads to a consistent increase in natural frequencies for both joint types, reflecting enhanced joint stiffness due to nanoscale reinforcement of the adhesive layer. The effect is more pronounced in cross-lap joints, highlighting the strong sensitivity of adhesive-dominated joint geometries to stiffness modification. Numerical predictions show reasonable agreement with experimental measurements, validating the proposed modelling approach despite unavoidable experimental uncertainties. The findings demonstrate the potential of MWCNT-reinforced epoxy adhesives to improve vibration resistance and dynamic stability in bonded joints, providing useful insight for the design and optimization of lightweight structures subjected to dynamic loading.

Keywords: single lap joint; cross lap joint; MWCNT-reinforced epoxy; vibrational analysis; experimental modal analysis; finite element analysis

1. Introduction

Adhesive bonding has become an essential joining technique in modern lightweight engineering structures, particularly in the aerospace, automotive, and marine industries. Compared to traditional mechanical fastening methods such as bolting and riveting, adhesive joints offer several advantages, including reduced stress concentrations, improved load distribution, lower structure weight, enhanced fatigue performance, and improved corrosion resistance. As a result, adhesively bonded joints such as single-lap joint (SLJs), double-lap joints, strap joints, and cross-lap joints are increasingly used in structural assemblies subjected to complex loading.

While the static strength and failure behaviour of adhesively bonded joints have been widely investigated, their dynamic and vibration behaviour remains a critical design concern. In practical applications, bonded joints are frequently exposed to dynamic excitation arising from engine operation, aerodynamic loads, road-induced vibration, and acoustic excitations. Resonance conditions may lead to excessive vibration amplitudes, noise, premature fatigue damage, or even frequencies, mode shapes, and damping of adhesive joints is essential for ensuring structure integrity and long term durability.

Several researchers have examined the vibration behaviour of adhesively bonded joints using experimental, analytical and numerical approaches. Ingole and Chatterjee [1] performed experimental and analytical vibration analysis of single-lap adhesive joints and showed that the presence of an adhesive layer slightly reduce the natural frequencies compared to monolithic beam due to reduced stiffness. Yaman and Şansveren [2] conducted both numerical and experimental studies on different type of adhesively bonded joints, including single-lap and double-lap joints, and reported that joint geometry, adhesive thickness, and overlap length significantly influence resonance frequencies and damping characteristics. Their study also highlighted that double-strap joints generally exhibit superior energy dissipation capabilities compared to single-lap joints.

Further investigations have explored the influence of geometric and material parameters on joint vibration, Güneş et al. [3] analyzed the free vibration behaviour of adhesively bonded single-lap joints made of functionally graded materials and demonstrated that plate width, thickness and material gradation strongly affect natural frequencies, whereas overlap length has comparatively minor effect. Haka et al. [4] studied the vibration response laminated single-lap joints and identified optimal overlap length and strap thickness combinations for enhanced vibration resistance. Marchione [5] investigated vibration mode of double-lap joints and showed that structural modifications such as slotting can significantly alter modal characteristics.

In addition joint geometry, adhesive material properties play a crucial role in governing the dynamic response of bonded joints. Sarila et al. [6] demonstrated that increasing adhesive stiffness leads to higher torsional natural frequencies, while Poisson's ratio has relatively minor influences. Wang et al. [7] developed a layerwise finite element model incorporating adhesive viscoelasticity and showed that adhesive damping, overlap length and bond thickness strongly affect both natural frequencies and modal loss factors. These studies confirm that vibration behaviour of adhesive joints is highly sensitive to adhesive stiffness and damping characteristics.

In recent years, the incorporation of nanoscale fillers into epoxy adhesives has emerged as an effective strategy to enhance mechanical and functional properties. Among various nanofillers, multiwall carbon nanotubes (MWCNTs) have attracted particular interest due to their exceptionally high Young's modules strength and aspect ratio. Ejaz et al. [8] reported that the addition of MWCNTs to epoxy adhesive significantly improves joint strength and fracture resistance, although excessive filler content may lead to agglomeration and performance degradation.

Monteiro and Ávila [9] showed that carbon nanotubes CNT-reinforced adhesives enhance load transfer and increase delaminated areas during joint failure, indicating improved interfacial bonding. Srivastava [10] experimentally demonstrated that MWCNT-modified epoxy adhesives significantly improve bonding strength in carbon-carbon composite joints by impeding crack initiation and propagation.

Despite these advances, most existing studies on CNT-modified adhesives have primarily focused on static strength, fracture behaviour, and failure mechanisms. Only limited attention has been given to their influence on the dynamic and vibration behaviour of adhesively bonded joints. Moreover, the majority of vibration studies reported in the literature are restricted to single-lap or double-lap joint configuration. Experimental and numerical investigations addressing the vibration response of cross-lap adhesive joints, particularly those incorporating nano modified adhesives, remain scarce.

Cross-lap joints differ fundamentally from single-lap joints in terms of load transfer paths, stress distribution, and deformation mechanisms. Due to their orthogonal geometry, cross-lap joints are often more compliant and exhibit deformation modes dominated by adhesive shear behaviour consequently, their dynamic response is expected to be highly sensitive to changes in adhesives stiffness and damping. However, to the authors' Knowledge, on comprehensive experimental-numerical study has systematically examined the effect of MWCNT-reinforced epoxy adhesives on the vibration characteristics of cross-lap joints, nor has a direct comparison between single-lap and cross-lap joints under identical material, geometric, and boundary conditions been reported.

To address these research gaps, the present work investigates the vibrational behaviour of single-lap and cross-lap adhesive joints bonded with epoxy adhesive containing 1 wt% multiwall carbon nanotubes. Experimental modal analysis is conducted using an impact hammer and FFT-based frequency response measurements to determine natural frequencies and damping characteristics. In parallel, three-dimensional finite element models incorporating adhesive material properties are developed to perform modal and harmonic analyses. A comparative assessment between experimental and numerical results is presented to evaluate the influence of nanoscale adhesive reinforcement on joint stiffness and dynamic response. The findings aim to provide valuable insights into the design and optimization of adhesive joints for vibration-critical lightweight structures.

2. Adhesive and substrate material

2.1. Selection of substrate material for single lap joint and cross lap joint

Single lap joint as shown in **Figure 1**, aluminum alloy 5251 is used to prepare SLJ. As shown both substrates have a length of 101.6 mm each. Adhesive layer applied with 1 mm thickness (t_a), substrate thickness (t) is 3 mm, width (w) is 25.4 mm and overlap area is 12.5 mm^2.

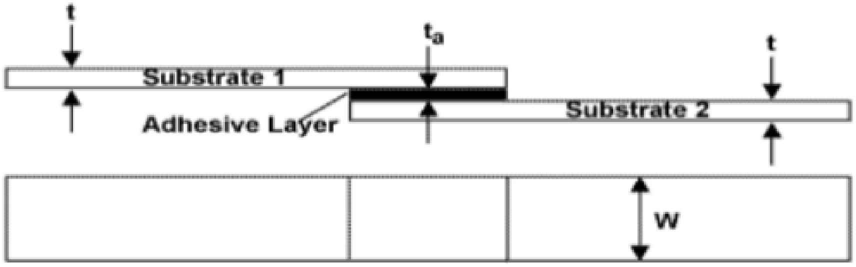


Figure 1. Adhesive lap joint geometry [11].

An aluminum-copper alloy was chosen as the substrate material for preparing lap joints. Araldite AW 106 and Hardener HV 953 were used as the epoxy resin. Aluminum alloy 5251 was used for this study due to its notable properties, including good strength, excellent ductility, and superior formability. It is also known for its ability to harden quickly through work and its ease of welding. To evaluate the impact of multiwall carbon nanotubes (MWCNTs), the adhesive was modified by incorporating MWCNTs in adhesive, and single-lap joints were prepared both with and without the nanotube-enhanced adhesive [12].

An adhesively bonded cross lap joint is as shown in **Figure 2**. Aluminum alloy 5251 is used to prepare above joint. Length of the substrate is 102 mm, width is 10 mm, and thickness of substrate is 3 mm. The overlap area is 10 mm^2. An adhesive layer of 1 mm thickness is applied at the center of strap so that joint can be prepared uniformly.

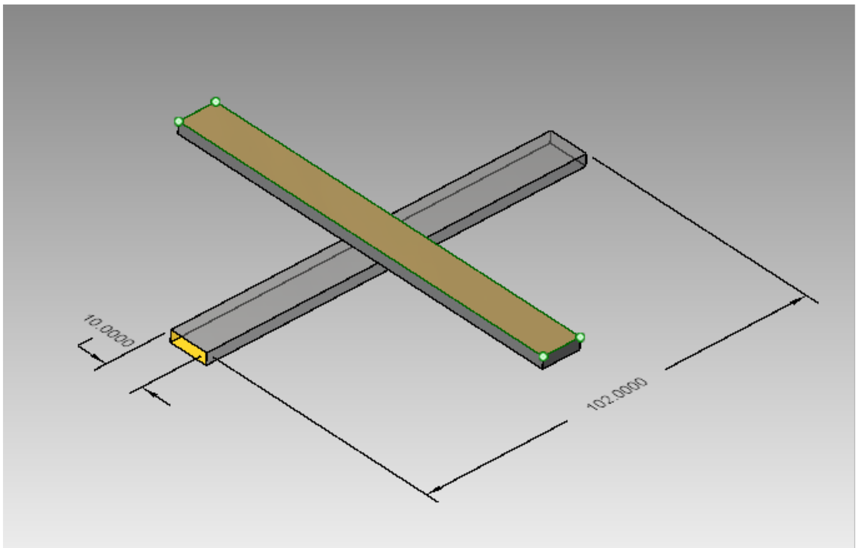


Figure 2. Adhesive cross lap joint geometry.

2.2. Selection of adhesive material and MWCNTs for bonding

In this study Araldite AW 106, combined with Hardener HV 953, as an epoxy resin. This adhesive is a reliable and versatile material known for its effectiveness in bonding also multiwall carbon nanotubes (MWCNTs) are mixed in epoxy resin using the ultrasonication process. Curing temperatures are between 68 °F (20 °C) and 356 °F (180 °C) without releasing any volatile substances during the process.

2.3. Bonding process of substrate and adhesive

A single-lap joint was prepared following ASTM standards. Dimensions of aluminum substrates were 101.6 × 25.4 × 3 mm. Before preparing the joint, the aluminum substrates need to cleaned to remove dust and oil if any therefore acetone is used to clean the substrate material and allowed to dry [13, 14]. An adhesive mixture was prepared using Araldite AW 106 and Hardener HV 953 in equal proportions by weight (50% each). This adhesive was applied to join two aluminum substrates with a 10 mm overlap area, which is the shared region where the adhesive is applied. Additionally, 1% by weight of carbon nanotubes with multiple wall (MWCNTs) was incorporated into the Araldite using ultrasonication process. Previous studies have shown that MWCNT contents above 1 wt% often lead to agglomeration and deterioration of mechanical properties, while lower contents result in marginal improvements. Based on these findings and processing limitations, 1 wt% was selected as an optimal compromise [8, 15, 16].

For preparation of a cross-lap joint same process is followed. Dimensions of aluminum substrates were 102 × 10 × 3 mm. Both substrates were held at 90° and adhesive was applied between overlap areas. Adhesive thickness is 1 mm.

3. Experimental setup for vibration analysis

3.1. Experimental setup and instrumentation

Experimental modal analysis was performed to determine the natural frequencies and dynamic response of the single-lap and cross-lap adhesive joints. The tests were conducted under controlled laboratory conditions using an impact hammer excitation method. An instrumented impact hammer (PCB Piezotronics, Model 086C03) equipped with a built-in force transducer was used to apply impulse excitation to the specimens. The dynamic response of the joints was measured using a lightweight piezoelectric accelerometer (PCB Piezotronics, Model 352C33) to minimize mass-loading effects.

The excitation force and acceleration response signals were acquired using a two-channel FFT analyser (NI CDAQ-9174 with NI 9234 dynamic signal acquisition module). Data acquisition and signal processing were performed using NI LabVIEW-based modal analysis software. The frequency range for all measurements was set between 0 and 2000 Hz, which adequately covered the first five vibration modes of both joint configurations.

3.2. Specimen mounting and boundary conditions

To replicate fully restrained boundary conditions, specially designed steel fixtures were used to clamp the ends of the specimens during testing. For single-lap joints, both adherend ends were rigidly clamped, leaving the overlap region free to vibrate. For cross-lap joints, all outer ends of the orthogonal adherends were clamped to ensure fixed-fixed boundary conditions. The clamping length was maintained constant for all tests to ensure repeatability and consistency across specimens [17, 18].

The boundary conditions adopted during experimental testing were carefully reproduced in the finite element simulations to allow meaningful comparison between experimental and numerical results.

3.3. Excitation and sensor locations

The impact excitation was applied at the geometric center of the overlap region for both joint types to effectively excite bending and torsional vibration modes. The accelerometer was mounted near the mid-span of one adherend, away from the clamped region, where maximum vibration amplitude was expected. A thin layer of adhesive wax was used to attach the accelerometer to reduce mass-loading and ensure reliable signal transmission.

The orientation of the accelerometer was aligned along the out-of-plane (Z-axis) direction, as this direction corresponds to dominant bending deformation in both joint configurations [18].

3.4. Calibration and data acquisition procedure

Prior to testing, the impact hammer and accelerometer were calibrated using the manufacturer-provided calibration constants to ensure accurate force and acceleration measurements. Signal conditioning parameters, including input sensitivity and trigger thresholds, were adjusted to avoid signal saturation and noise contamination.

For each specimen, a minimum of five impact tests were performed at the same excitation and sensor locations to ensure measurement consistency. The recorded force and acceleration signals were averaged in the frequency domain to improve the signal-to-noise ratio. Hanning windowing was applied to both input and output signals, and frequency response functions (FRFs) were calculated in the form of acceleration-to-force reacceptance [18].

3.5. Modal parameter identification

Natural frequencies were identified from the peaks of the averaged frequency response functions. Modal parameters were extracted using a single-degree-of-freedom curve-fitting technique applied to each resonance peak. The repeatability of the identified natural frequencies was verified by comparing results from multiple impacts, and variations were found to be within +3%, indicating good experimental consistency.

This experimental procedure was applied uniformly to all specimens, including joints bonded with pure epoxy adhesive and those reinforced with 1 wt% MWCNTs, ensuring a reliable comparative assessment of their vibrational behaviour.

4. Experimental test result of single lap joint

Figure 3 shows a graphical representation of natural frequency vs displacement for single lap joint. The first natural frequency obtained at 250 Hz is shown by cursor. Similarly, natural frequencies are calculated for a single lap joint with 1% MWCNTs filled in araldite.

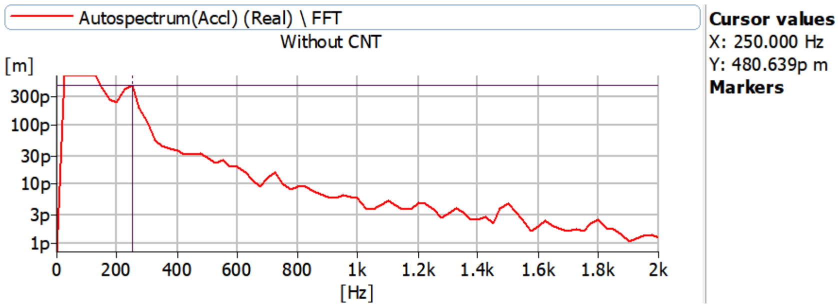


Figure 3. Natural frequency vs displacement graph for single lap joint.

Table 1 shows values of natural frequencies in Hz are calculated for all types of single overlap specimens. First five frequencies are obtained for all types of single overlap specimens.

Table 1. Experimental natural frequencies of all single lap joints.

Mode	Natural frequency in Hz	
	Single lap joint without MWCNT	Single lap joint with1% MWCNT
1	250	275
2	475	518
3	550	650
4	725	775
5	825	850

Figure 4 shows a line chart for single lap joints with and without MWCNT in epoxy resin, which shows a slightly increase in the natural frequency of the system with the mixing of multiwall carbon nanotubes in epoxy resin.

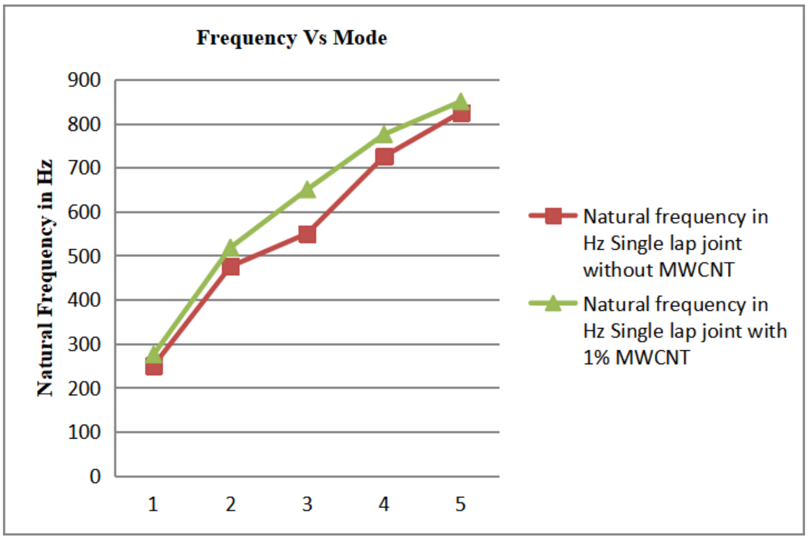


Figure 4. Natural frequency vs modes graph for single lap joint.

5. Vibrational analysis of single lap joint using finite element method

5.1. Finite element analysis of lap joints

In this study vibrational analysis of adhesive-bonded overlap joints is divided into two parts.

(1) Vibrational analysis of a single overlap adhesive joint prepared with MWNCT's-reinforced epoxy and base epoxy resin.
(2) Vibrational analysis of a single overlap adhesive joint prepared with base epoxy resin.

Natural frequencies are calculated for all above types, and the difference in natural frequency is due to the addition of MWCNTs in epoxy resin.

5.2. Modal analysis of single lap joint without MWCNT's added in epoxyresin

To carry out finite element analysis of a single lap joint with unfilled MWCNTs in epoxy resin, a 3D Model of a single lap joint is made in ANSYS Design Modeler, which has the same dimensions as the test specimenas shown in **Figure 5** [19,20].

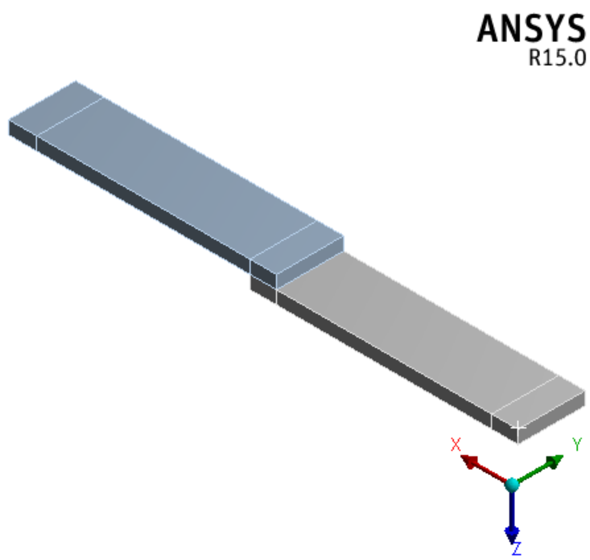


Figure 5. 3D Model of single lap joint.

Specifications of a single overlap adhesive joint without MWCNTs added in the epoxy resin are mention in the **Table 2**.

Table 2. Specification of single lap joint with and without MWCNT added in araldite.

Specimen. No.	Material	Adhesive used	Type of lap joint	Overlap length (mm)	Single straplength (mm)	Single strap width (mm)	Single strap thickness (mm)
1st	Aluminium alloy 5152	Araldite AW106 and Hardener HV 953	Single lap joint	10	102	25.4	3.0
2nd	Aluminium alloy 5152	Araldite AW106 with MWCNTs and Hardener HV 953	Single lap joint	10	102	25.4	3.0

For modal analysis of a single lap joint specimen, 1 was held between the fixtures as shown in the **Figure 6**. Both ends of the specimen were clamped. The length of the specimen other than clamped was free to deform. Therefore, the nodes in the clamped region were constrained in X,Y,Z direction for translational as well as rotational motion. Impact is applied at the centre of the lap joint and deformation response is as shown in **Figure 7**. In modal analysis of a single lap joint, The first 6 natural frequencies are consider. Mode shapes of adhesive joints can be classified as transverse (bending) and torsional. NFs for bending mode shape are 250, 1584.2, 2374.4, 4418.1 Hz and that of torsional mode shapes are 1439.3, 2370.4 Hz as shown in **Figures 7–12** [21,22].

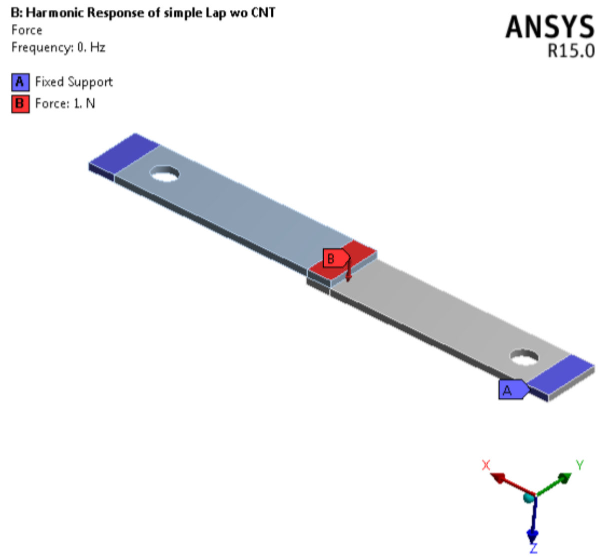


Figure 6. Boundary condition for modal analysis of single lap joint.

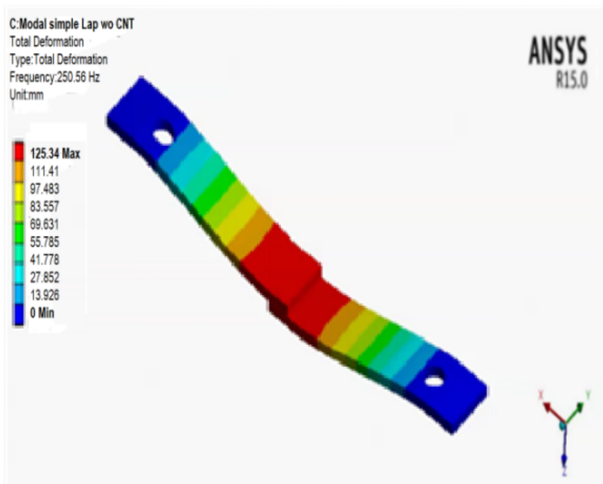


Figure 7. Mode 1, ω_1 = 250.56 Hz.

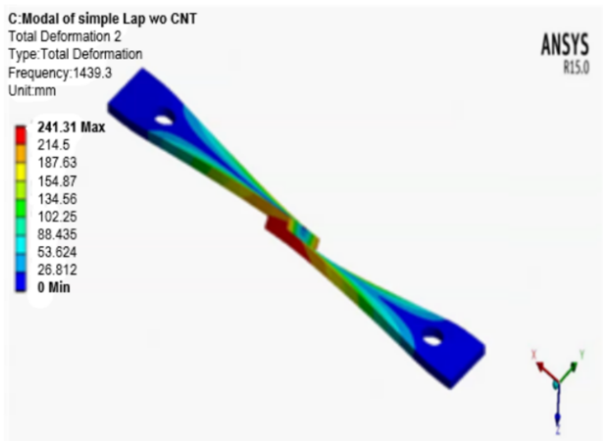


Figure 8. Mode 2, ω_2 = 1439.3 Hz.

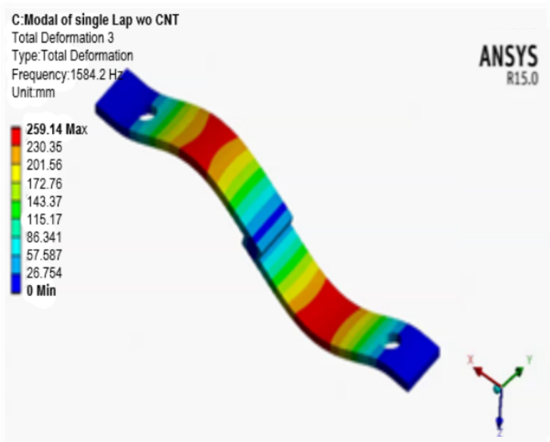


Figure 9. Mode 3, ω_3 = 1584.2 Hz.

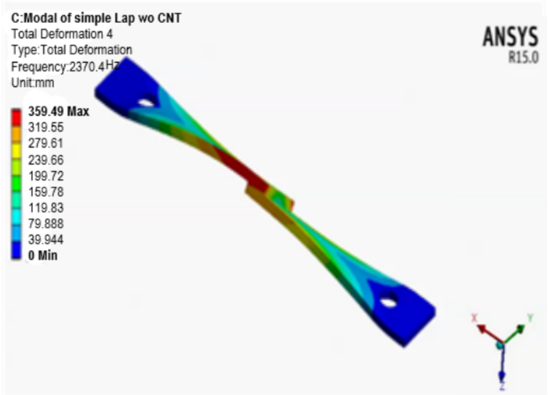


Figure 10. Mode 4, ω_4 = 2370.4 Hz.

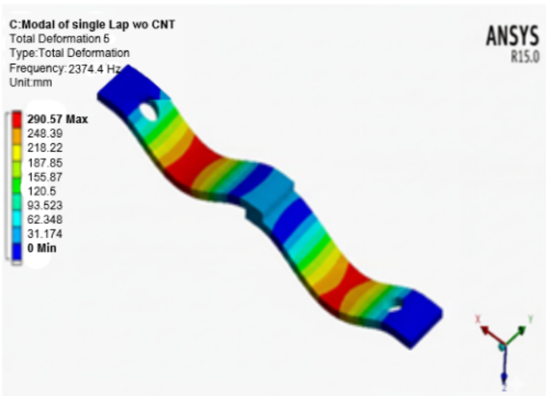


Figure 11. Mode 5, ω_5 = 2374.4 Hz.

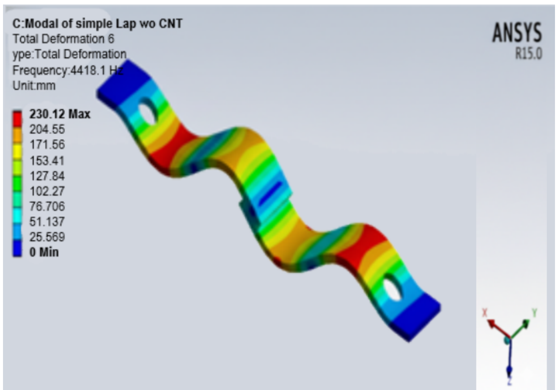


Figure 12. Mode 6, ω_6 = 4418.1 Hz.

Harmonic analysis of a single overlap adhesive joint is carried out in which 1 N force is applied at the centre of joint. **Figure 13** shows the deformation response of a single lap joint without MWCNTs at a natural frequency of 250 Hz and displacement 0.062 mm deformation direction is along Z axis.

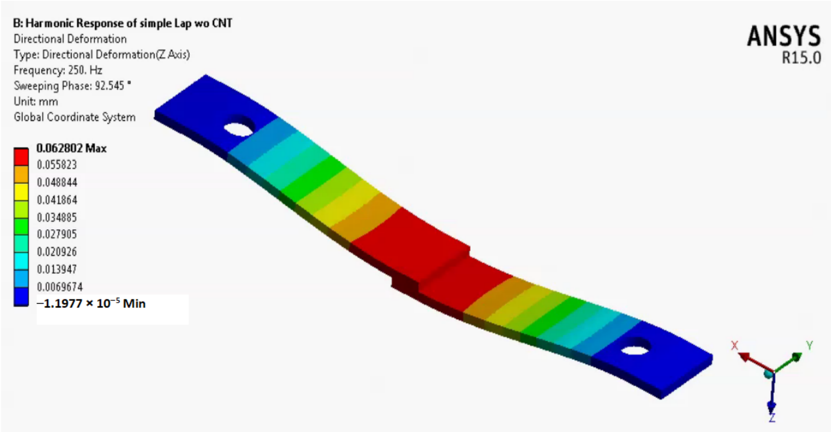


Figure 13. Deformation response of single lap joint without MWCNTs during harmonic analysis.

Figure 14 illustrates the frequency response of the single overlap adhesive joint without MWCNTs under harmonic excitation. The graph shows that the vibration amplitude rises steadily with increasing frequency and reaches its maximum value at around 250 Hz, representing the first natural frequency of the unmodified joint. At this point, the structure enters a resonant state, resulting in a pronounced peak in response. Beyond this resonance, the amplitude drops quickly and then maintains a relatively constant, low level over the higher frequency range. This behaviour reflects the inherent damping present in the adhesive layer, which dissipates energy and prevents large vibrations after resonance. Compared with the MWCNT-reinforced joint, the amplitude at resonance is noticeably higher, indicating lower stiffness and less energy dissipation in the pure adhesive. Consequently, the natural frequency appears at a slightly lower value, confirming that the addition of MWCNTs enhances the joint's rigidity and reduces its vibration amplitude under similar loading conditions.

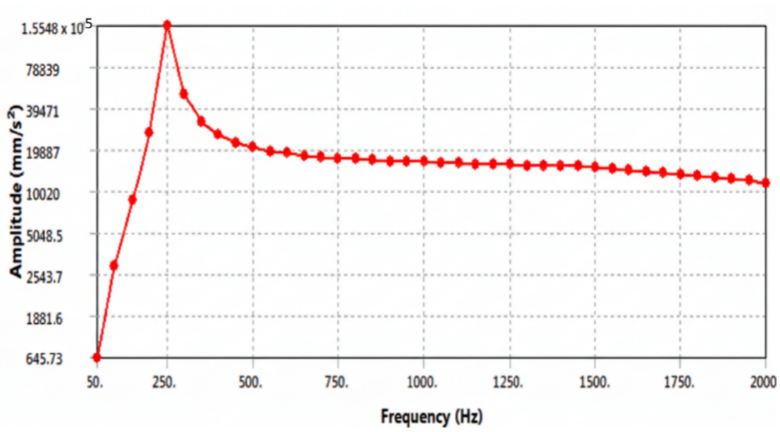


Figure 14. Frequency response of single lap joint without MWCNTs during harmonic analysis.

5.3. Modal analysis of single overlap adhesive joint contained MWCNT's in epoxy resin

To carry out finite element analysis (FEA) of the single overlap adhesive joint with MWCNT filled adhesive, a detailed 3D model of the joint was developed in ANSYS Design Modeler as shown in **Figure 5**. The geometrical and material specifications of the specimen are given in **Table 2**. The analysis was performed using the modal analysis to calculate the fundamental frequencies and corresponding mode shape of the joint

In this study the first six resonant frequencies were studied to evaluate vibrational behaviour of the joint. Among these modes ω_1, ω_2, ω_4, and ω_6 corresponding to bending mode shapes with frequencies of 312.5 Hz, 1596.4 Hz, 2436 Hz, and 4653.5 Hz respectively. The remaining modes, ω_3 and ω_5, are identified as torsional modes, occurring at 1683.2 Hz and 2469 Hz as illustrated in **Figures 15–20**.

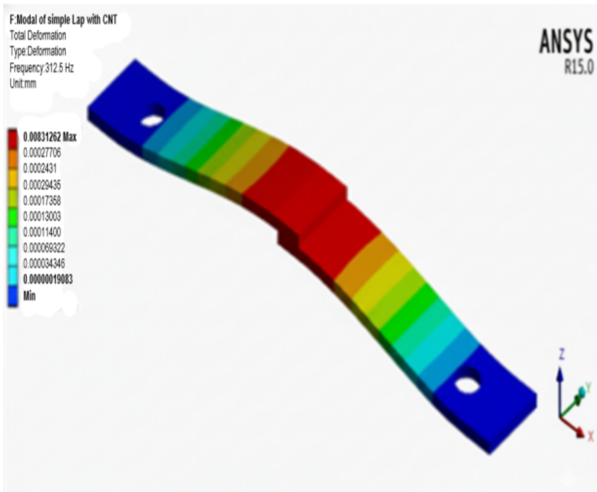


Figure 15. Mode 1, ω_1 = 312.5 Hz.

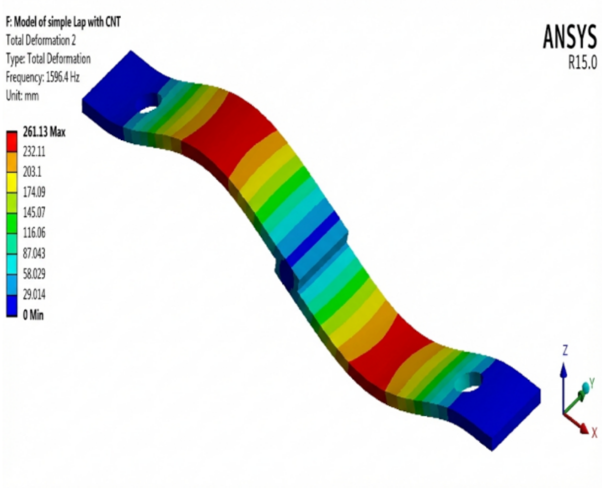


Figure 16. Mode 2, ω_2 = 1596.4 Hz.

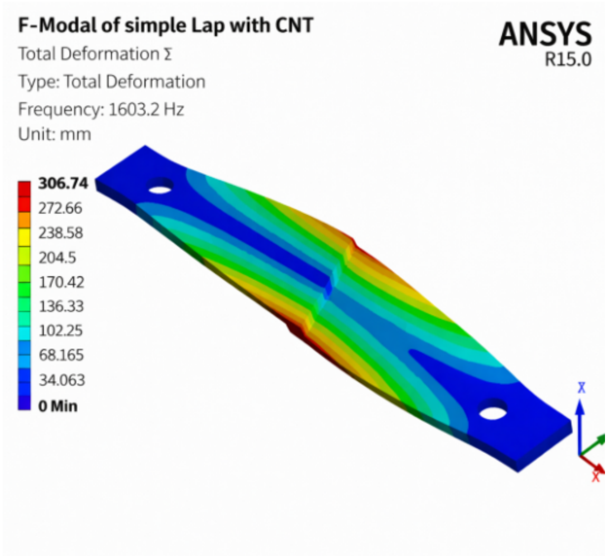


Figure 17. Mode 3, ω_3 = 1603.2 Hz.

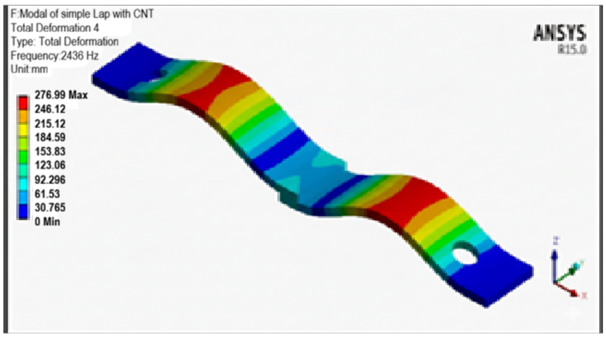


Figure 18. Mode 4, ω_4 = 2436 Hz.

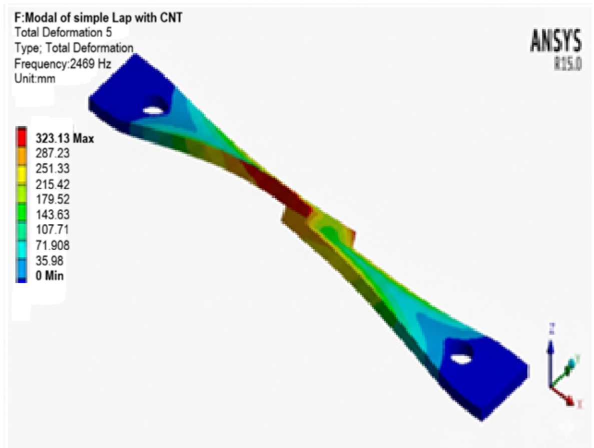


Figure 19. Mode 5, ω_5 = 2469 Hz.

Figure 21 shows the deformation response of a single lap joint without MWCNTs at a natural frequency 250 Hz and displacement 0.062 mm. Deformation direction is along the Z axis.

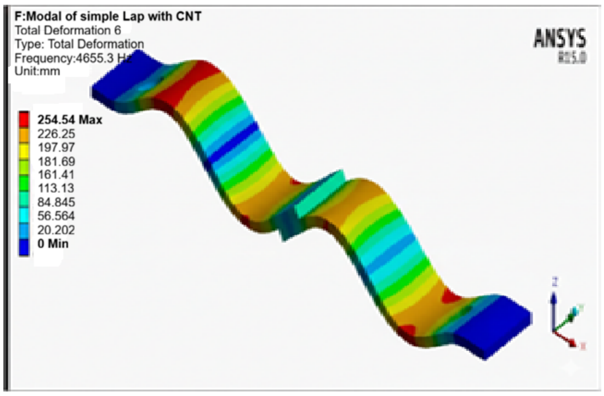


Figure 20. Mode 6, ω_6 = 4655.3 Hz.

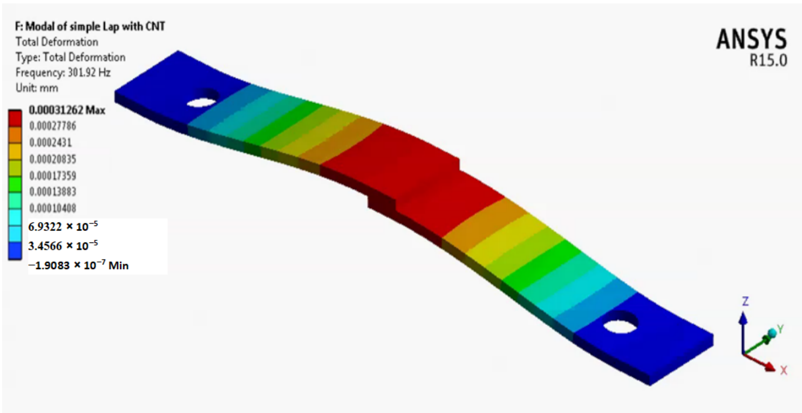


Figure 21. Deformation response of single lap joint with MWCNTs during harmonic analysis.

Figure 22 shows the frequency response curve of the single lap joint with MWCNTs-reinforced epoxy adhesive obtained from the harmonic analysis in ANSYS. It can be observed that the response amplitude increases gradually with frequency and reaches a maximum peak at 312.5 Hz, which corresponds to the first natural frequency of the joint. At this point structure experiences resonance where the excitation frequency matches the natural frequency, resulting in a sharp rise in vibration amplitude [22,23].

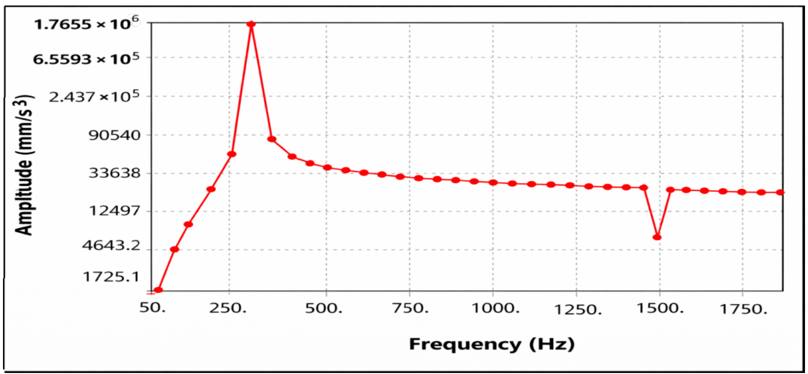


Figure 22. Recorded frequency of single lap joint with MWCNTs during harmonic analysis.

After reaching this peak the amplitude decreases gradually as the frequency increases, indicating that the system moves away from the resonant condition. The drop in amplitude beyond resonance suggests that the damping effect of the epoxy resin and structural stiffness of the adherends effectively limit further vibration response. A smaller peak or dip near 1725 Hz can also be noticed, which corresponds to the second mode of vibration, likely a torsional mode [24].

Table 3 shows natural frequencies increase with addition of MWCNTs in adhesive.

Table 3. Natural frequencies of single lap joints calculated by FEM.

Mode	Natural frequency in Hz	
	Single lap joint without MWCNT	Single lap joint with1% MWCNT
1	250	312.5
3	1584.2	1596.4
5	2374.4	2436
6	4418.1	4653.5

From **Table 4**, it is observed that epoxy resin prepared with MWCNTs shows rise in natural frequency of single overlap adhesive joint.

Table 4. Natural frequency obtained for various types of lap joints using FEA.

Various types of lap joints	FEA reading (natural frequency (Hz))
SLJ without MWCNTs	250
SLJ with MWCNT	312.5

In the plotted **Figure 23**, it is clear that due to the use of MWCNTs in epoxy resin natural frequency of lap joint is increased.

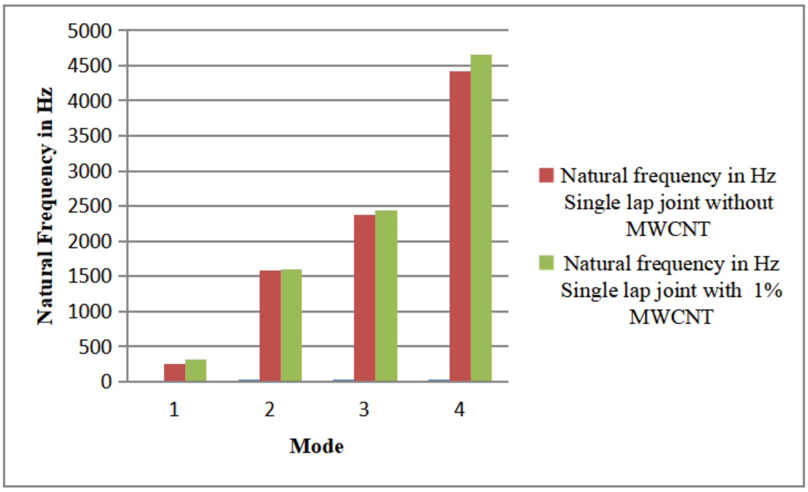


Figure 23. Influence of MWCNTs on natural frequency of various lap joint.

6. Vibration analysis of cross lap joint without MWCNTs added in epoxy resin

To carry out finite element analysis of cross lap joint with filled MWCNTs in epoxy resin 3D Model of cross lap joint is made in ANSYS Design Modeler which has same dimensions as per test specimen. Specifications of cross lap joint without MWCNTs added in araldite are mention in the **Table 5**, and as shown in **Figure 24**. **Figure 25** shows 3D model of cross lap joint with mesh convergence. Total 2454 no of elements and 3515 no of nodes are used for this model as mentioned in **Figure 26**.

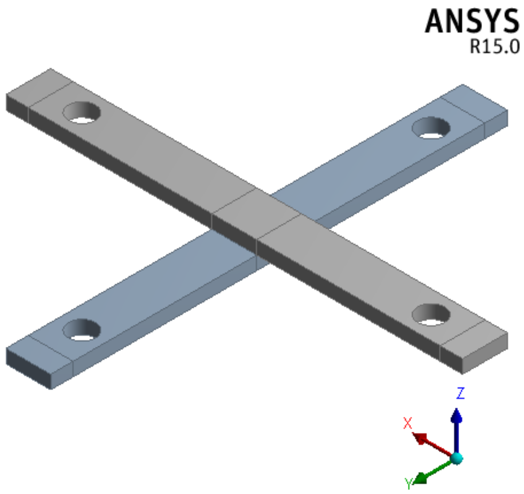


Figure 24. 3D Model of cross lap joint.

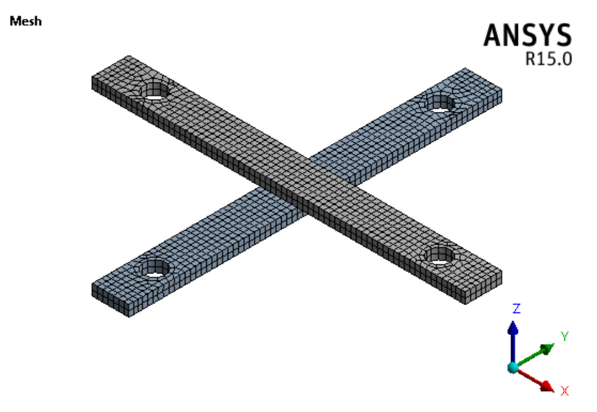
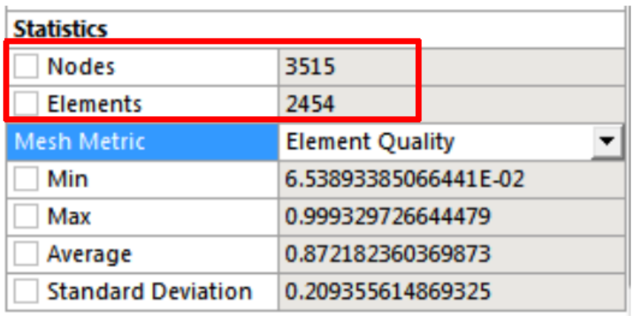


Figure 25. 3D Model of cross lap joint.



Statistics	
Nodes	3515
Elements	2454
Mesh Metric	Element Quality
Min	6.53893385066441E-02
Max	0.999329726644479
Average	0.872182360369873
Standard Deviation	0.209355614869325

Figure 26. Nodes and elements used in cross lap joint.

Table 5. Specification of cross lap joint with and without MWCNT added in epoxy resin araldite AW 106.

Specimen. No.	Material	Adhesive used	Type of lap joint	Overlaplength (mm)	Single straplength (mm)	Single strap width (mm)	Single strap thickness (mm)
1st	Aluminium alloy 5152	Araldite AW106 and Hardener HV 953	Cross lap joint	10	102	10	3.0
2nd	Aluminium alloy 5152	Araldite AW106 with MWCNTs and Hardener HV 953	Cross lap joint	10	102	10	3.0

6.1. Experimental test results of cross lap joint

Figure 27 shows graphical representation of natural frequency vs displacement for cross lap joint. First natural frequency obtained at 175 Hz shown by curser. Graph also shows 2nd, 3rd, 4th and 5th natural frequency obtained are 300,350,and 850.Similarly natural frequencies are calculated for single lap joint with 1% MWCNTs filled in araldite [22,25].

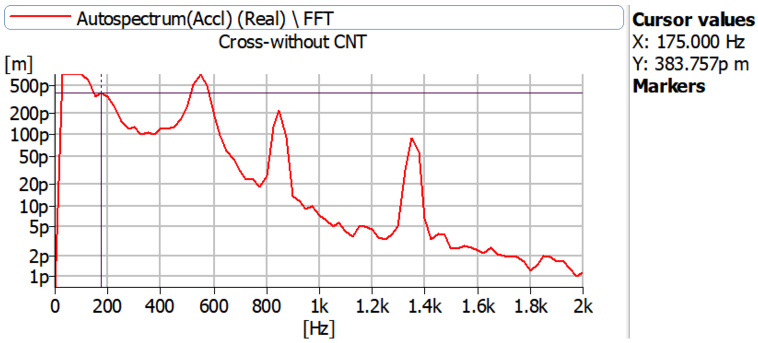


Figure 27. Natural frequency vs displacement graph for cross lap joint.

Table 6 shows values of natural frequencies in Hz are calculated for all types of cross lap joints. First five frequencies are obtained for all types of cross lap joints.

Table 6. Experimental natural frequencies of all cross lap joints.

Mode	Natural frequency in Hz	
	Cross lap joint without MWCNT	Cross lap joint with1% MWCNT
1	175	375
2	300	500
3	350	550
4	550	650
5	850	725

Figure 28 shows line chart for cross lap joints with and without MWCNT in epoxy resin, which shows slightly increase in natural frequency of system with addition of MWCNTs in araldite AW 106.

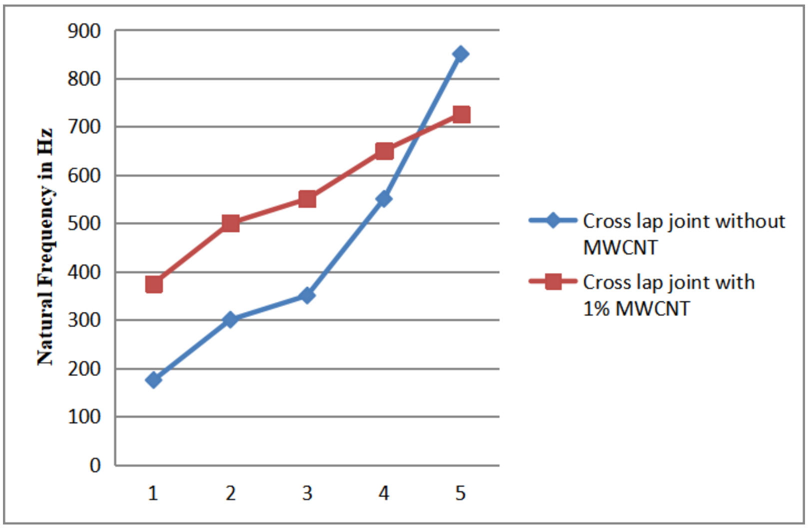


Figure 28. Natural frequency vs mode graph for cross lap joint.

6.2. Modal analysis of cross lap joint

For modal analysis of cross lap joint specimen, 1 was held between the fixtures. All ends of the specimen are clamped by fixed support A as shown in **Figure 29**. The length of the specimen other than clamped was free to deform. Therefore the nodes in the clamped region were constrained in X, Y, Z direction for translational as well as rotational motion. Impact is applied at the centre of lap joint and deformation response is as shown in **Figures 30–35**.

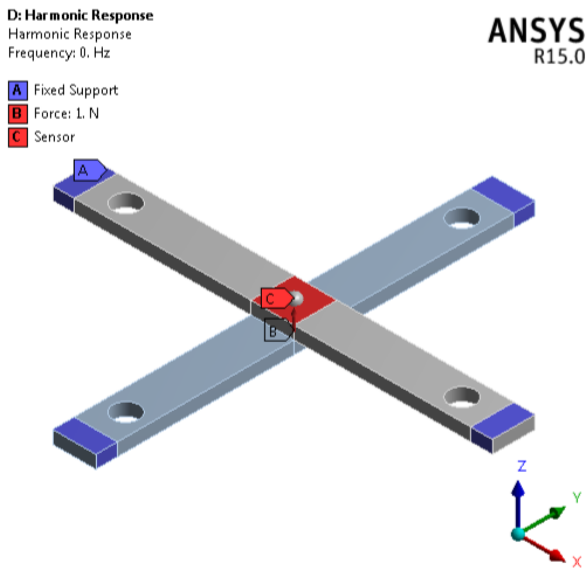


Figure 29. Boundary condition for harmonic analysis of cross lap joint.

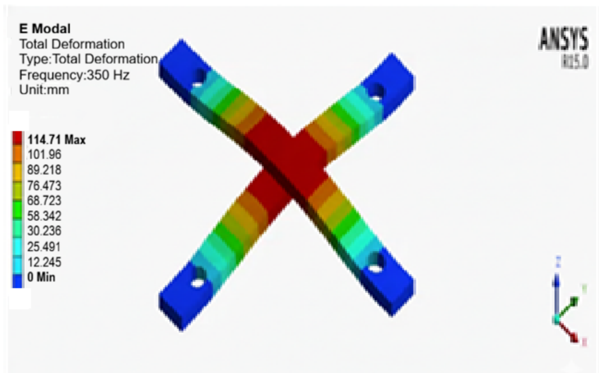


Figure 30. Mode 1, ω_1 = 350 Hz.

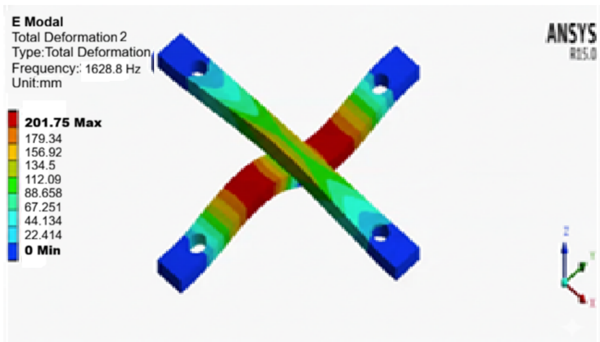


Figure 31. Mode 2, ω_2 = 1628.8 Hz.

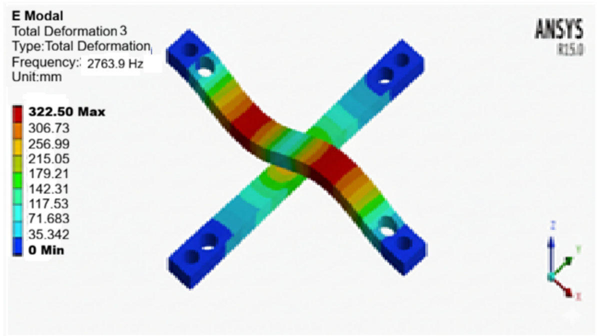


Figure 32. Mode 3, ω_3 = 2763.9 Hz.

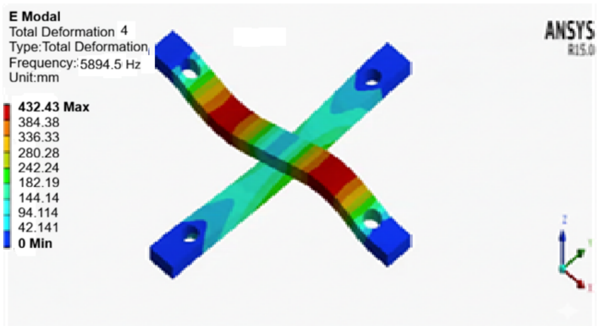


Figure 33. Mode 4, ω_4 = 5894.5 Hz.

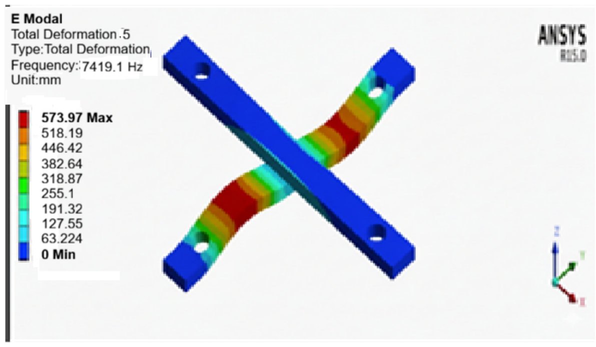


Figure 34. Mode 5, ω_5 = 7491.1 Hz.

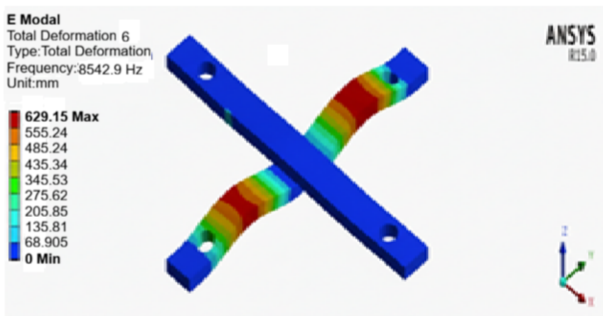


Figure 35. Mode 6, ω_6 = 8542.9 Hz.

Figure 36 shows deformation response of cross lap joint without MWCNTs at natural frequency 550 Hz and displacement 0.0011 mm. deformation direction is along Z axis.

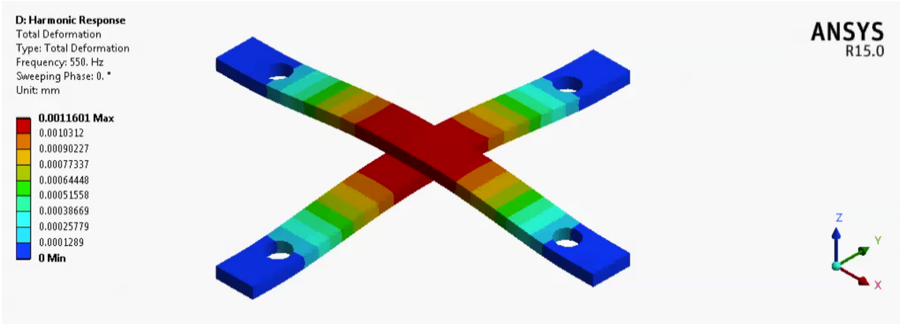


Figure 36. Deformation response of cross lap joint without MWCNTs during harmonic analysis.

In **Figure 37**, the highest amplitude is shown at frequency 350 Hz, and then it decreases slowly.

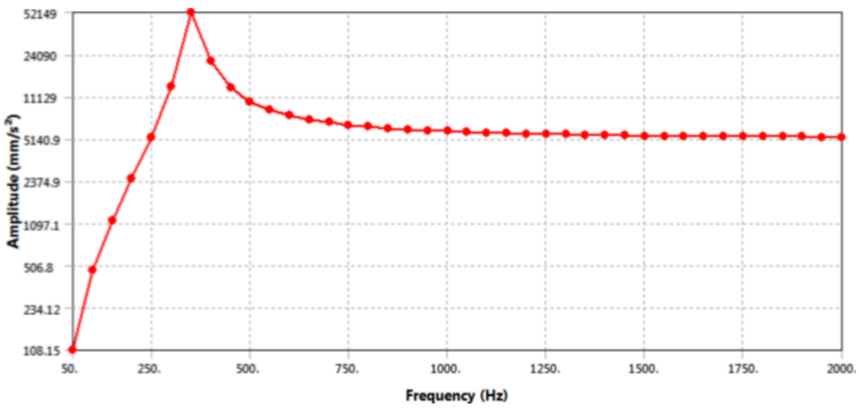


Figure 37. Frequency response of cross lap joint without MWCNTs during harmonic analysis.

6.3. Vibration analysis of cross lap joint with MWCNTs added in epoxy resin

Similar to **Figure 24**, resin 3D model of cross lap joint is prepared in ANSYS design modeler as shown in **Figure 24** and specifications of specimen 2 is shown in **Tables 5** and **6**. Boundry conditions and testing conditions are same for this testing is as shown in **Figure 29** and impact is given at center of joint and deformation response is as shown below from **Figure 38** to **43**.

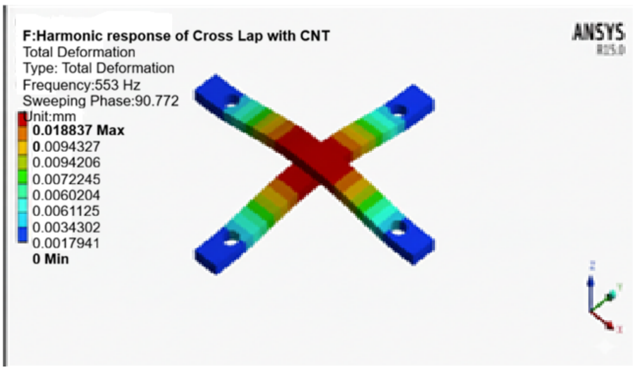


Figure 38. Mode 1, ω_1 = 553 Hz.

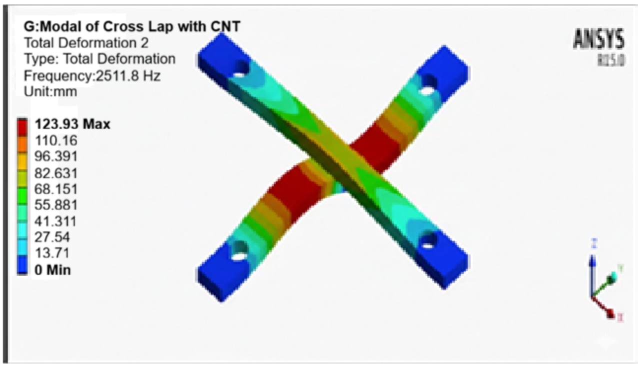


Figure 39. Mode 2, ω_2 = 2511.8 Hz.

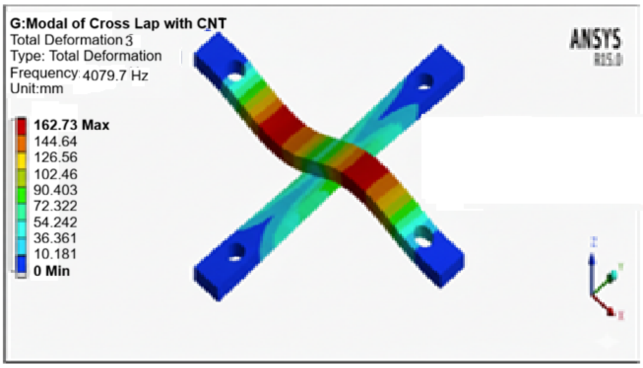


Figure 40. Mode 3, ω_3 = 4079.7 Hz.

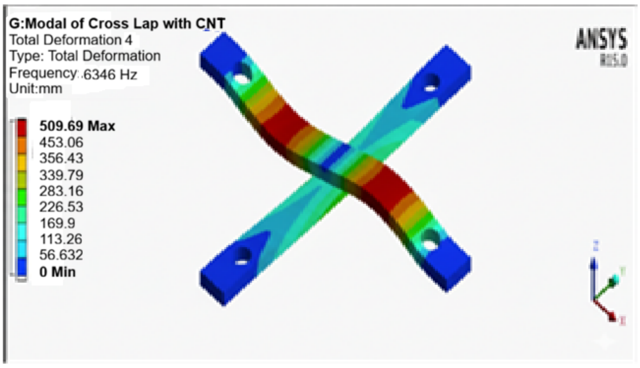


Figure 41. Mode 4, ω_4 = 6346 Hz.

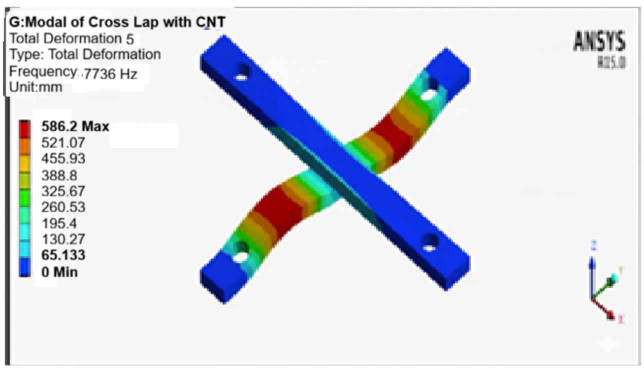


Figure 42. Mode 5, ω_5 = 7736 Hz.

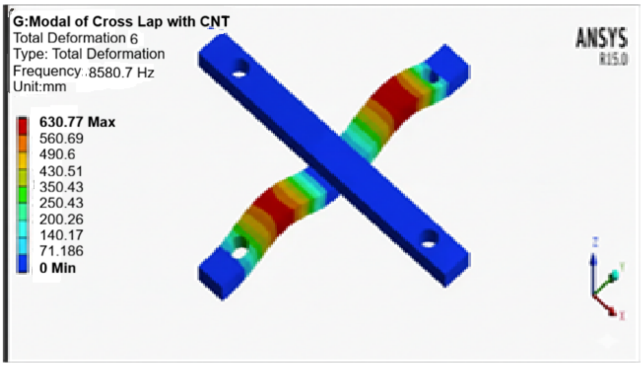


Figure 43. Mode 6, ω_6 = 8580.7 Hz.

Figure 44 shows deformation response of cross lap joint with MWCNTs at natural frequency 350 Hz and displacement 0.010 mm. deformation direction is along Z axis.

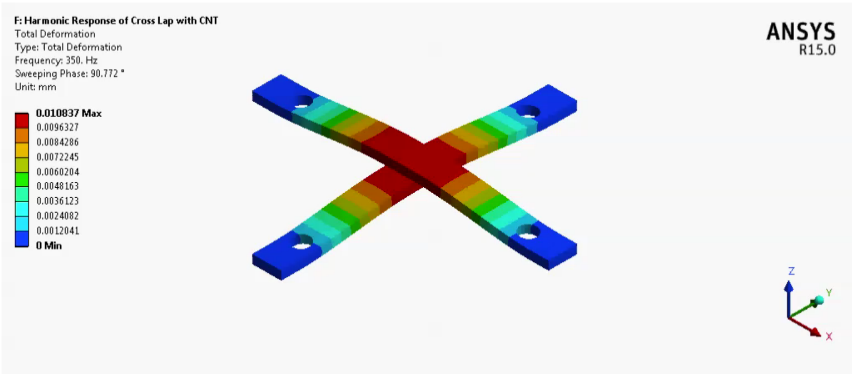


Figure 44. Deformation response of cross lap joint with MWCNTs during harmonic analysis.

The graph in **Figure 45** shows how the vibration amplitude of a cross lap joint reinforced with multi wall carbon nanotubes (MWCNTs) changes when it is excited by harmonic loads over a range of frequencies (50–2000 Hz).The amplitude reaches its maximum value at around 550 Hz. This indicates that 550 Hz is close to the natural frequency (resonant frequency) of the joint structure. At resonance, the dynamic stiffness of the structure is at its minimum, causing vibration amplitude to rise sharply. Adding MWCNTs typically increases the stiffness and damping properties of the composite joint. Because of this, the peak amplitude appears sharp but controlled, suggesting enhanced stiffness raises the natural frequency slightly. After the resonant frequency, the amplitude decreases steadily. This happens because, beyond resonance, the structure becomes dynamically stiffer.The system is no longer absorbing energy as efficiently. Damping gradually dissipates vibrational energy.

Amplitude is flattering at higher from ~900 Hz to 2000 Hz, the curve becomes almost flat. This indicates that the structure is largely dominated by stiffness in this region has reached a state where higher-frequency excitation produces very little additional response is behaving like a well-damped composite system with good vibration resistance. This frequency response curve helps identify the natural frequency of the joint. The damping effectiveness of MWNCT-reinforced joints. The operating frequency ranges where vibration amplitude will be low and safe. Designers can use this information to avoid operating machines near 550 Hz, where the structure is most vulnerable to large vibrations.

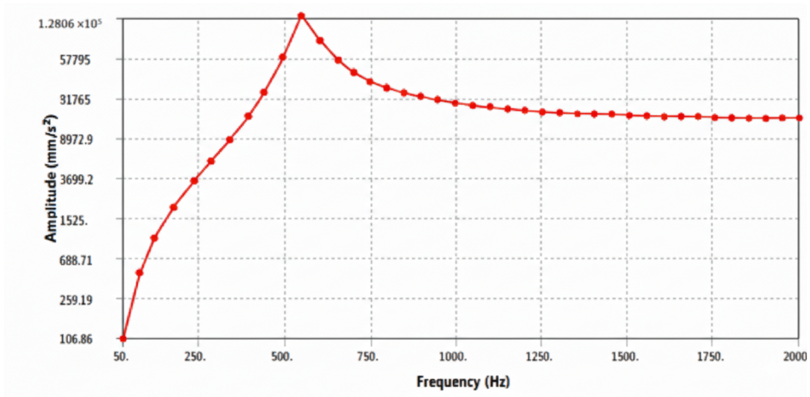


Figure 45. Frequency response of cross lap joint with MWCNTs during harmonic analysis.

From **Table 7**, it is observed that with addition of MWCNTs natural frequency of both single lap joint and cross lap joint is increased.

Table 7. Natural frequency obtained for various types of lap joints using FEA.

Various types of lap joints	FEA reading (natural frequency (Hz))
SLJ without MWCNTs	250
SLJ with MWCNT	312.5
Cross lap without MWCNTs	175
Cross lap withMWCNTs	350

From **Figure 46**, it is clear that epoxy adhesive reinforced with 1% multiwall carbon nanotubes (MWCNTs) for both single-lap and cross-lap shows better natural frequency than normal epoxy adhesive.

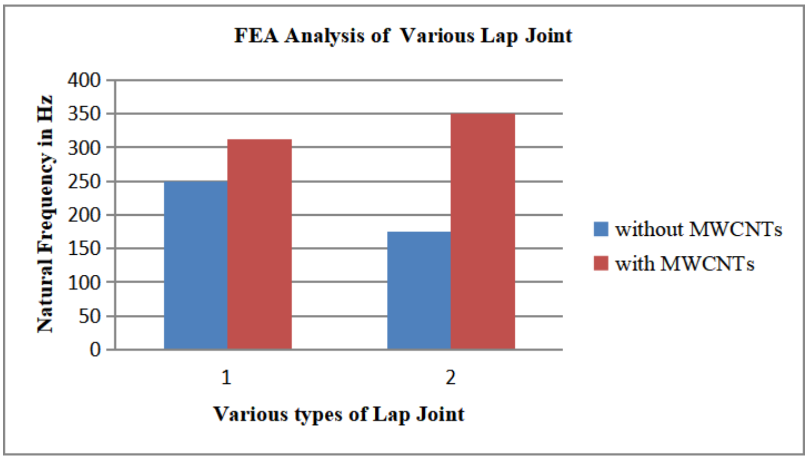


Figure 46. Influence of MWCNTs on natural frequency of various lap joint.

7. Conclusion

This study presented a combined experimental and numerical investigation into the vibrational behaviour of single-lap and cross-lap adhesive joints bonded with epoxy adhesive reinforced with 1 wt% multiwall carbon nanotubes (MWCNTs). The primary objective was to evaluate how nanoscale adhesive reinforcement influences joint stiffness and dynamic response under vibratory loading conditions.

Experimental modal analysis demonstrated a consistent upward shift in natural frequencies for both joint configurations when MWCNTs were incorporated into the adhesive. This behaviour indicates an increase in effective joint stiffness resulting from improved load transfer and enhanced adhesive modulus at the nanoscale. The effect was found to be more pronounced in cross-lap joints, which are inherently more compliant and whose deformation response is dominated by adhesive shear behaviour. The relatively large increase observed in the first natural frequency of the cross-lap joint requires careful interpretation. Unlike the single-lap joint, the cross-lap configuration exhibits load transfer through two orthogonal adherends, resulting in a deformation mechanism that is strongly governed by the shear stiffness of the adhesive layer.

Finite element modal and harmonic analyses successfully captured the qualitative trends observed experimentally, confirming the stiffness-dominated nature of the frequency shifts induced by MWCNT reinforcement. Although quantitative differences were observed between experimental and numerical results, these discrepancies can be attributed to idealized boundary conditions, uncertainties in adhesive viscoelastic properties, fixture compliance, and potential non-uniform dispersion of carbon nanotubes within the adhesive layer. Despite these limitations, the numerical model provided valuable insight into mode shapes and deformation mechanisms, supporting its applicability for comparative and design-oriented studies.

The findings of this work confirm that MWCNT-modified epoxy adhesives can effectively enhance the vibration resistance of adhesively bonded joints, particularly in geometries where adhesive deformation plays a dominant role. However, the conclusions drawn are subject to certain limitations. Only a single nanotube concentration was examined, and the influence of dispersion quality, agglomeration effects, environmental conditions, and long-term cyclic loading was not addressed. Moreover, the experimental investigation focused primarily on natural frequency response, while damping behaviour was evaluated in a limited scope.

Future research should therefore focus on a systematic parametric study involving multiple CNT weight fractions to identify optimal reinforcement levels and to characterize non-linear trends in dynamic properties. Additional investigations incorporating detailed dispersion characterization, temperature and humidity-dependent behaviour, and vibration-fatigue coupling would further enhance the understanding of CNT-modified adhesive joints. Extending the analysis to other joint configurations and adhesive systems would also aid in generalizing the applicability of the proposed approach. Overall, this study provides a foundation for the design and optimization of nano modified adhesive joints intended for vibration-critical lightweight structural applications.

Author contributions: V.H.L.: methodology, writing—original draft; M.M.J.: investigation, methodology. Both authors have read and approved the final manuscript.

Funding: The authors declare that no funds, grants, or other financial support were received during the preparation of this manuscript.

Institutional review board statement: Not applicable.

Informed consent statement: Not applicable.

Data availability statement: The authors declare that the data supporting the findings of this study are available within the paper. Should any raw data files be needed in another format, they are available from the corresponding author upon reasonable request.

Acknowledgment: The authors would like to thank their respective institutions for providing the necessary facilities and support to carry out this research. The authors also acknowledge the valuable feedback from anonymous reviewers, which helped improve the quality of this manuscript.

Conflict of interest: The authors declare that they have no competing interests.

References

1. Ingole SB, Chatterjee A. Vibration analysis of single lap adhesive joint: Experimental and analytical investigation. Journal of Vibration and Control. 2011; 17(10): 1547–1556.
2. Yaman M, Şansveren MF. Numerical and experimental vibration analysis of different types of adhesively bonded joints. Structures. 2021; 34: 368–380.
3. Güneş R, Apalak MK, Yıldırım M. Free vibration analysis of adhesively bonded single lap joints with wide and narrow functionally graded plates. Composite Structures. 2010; 92: 1–17.
4. Haka BY, Hidayat MIP, Widyastuti. Vibration analysis of single lap joint of composite plates based on variations of plate thickness and overlap length. Materials Research Communications. 2021; 2(2): 20–28.
5. Marchione F. Investigation of vibration modes of double-lap adhesive joints: Effect of slot. International Journal of Engineering. 2020; 33(10): 1917–1923.
6. Sarila VK, Koneru HP, Pathapalli VR, et al. Wear and microstructural characteristics of Colmonoy 4 and Stellite-6 additive layer deposits on En19 steel by laser cladding. Transactions of the Indian Institute of Metals. 2022; 76: 457–464.
7. Wang S, Li Y, Xie Z. Free vibration analysis of adhesively bonded lap joints through layerwise finite element method. Composite Structures. 2019; 223: 110943. doi: 10.1016/j.compstruct.2019.110943
8. Ejaz H, Mubashar A, Uddin E, et al. Influence of MWCNTs on strength properties of high viscous epoxy adhesive and fracture behaviour of adhesively bonded joints. Theoretical and Applied Fracture Mechanics. 2022; 120: 103412.
9. Monteiro EC, Ávila AF. The carbon nanotubes effect into single-lap joint failure modes and load capacity: A macromechanical analysis. Materials Research. 2017; 20(4): 1106–1113. doi: 10.1590/1980-5373-MR-2017-0442
10. Srivastava VK. Effect of Carbon Nanotubes on the Strength of Adhesive Lap Joints of C/C and C/C–SiC Ceramic Fiber Composites [PhD Thesis]. Indian Institute of Technology (BHU); 2011.
11. Tavakoli SM, Kellar EJC, Vlattas C. Mechanical testing and characterisation of a steel adherend bonded using an automotive grade epoxy adhesive. In: Proceedings of the Society of Plastics Engineers ANTEC 2001 Conference; 6–10 May 2001; Dallas, TX, USA.
12. Londhe VH, Jagtap MM. Finite element analysis of multiwall carbon nanotubes enabled single lap joint. Journal of Polymer Composites. 2025; 13(2): 195–203.
13. da Silva LFM, Öchsner A, Adams RD. Handbook of Adhesion Technology. Springer; 2018.
14. Adams RD, Wake WC. Structural Adhesive Joints in Engineering. Elsevier Applied Science; 1984.
15. Lai WL, Zhang Y, Liu J, et al. Experimental assessment on the mechanical and physical properties of epoxy adhesives incorporated with multi-walled carbon nanotubes. Polymer Testing. 2023; 116: 107792.
16. Karthikeyan N, Naveen J, Venugopal A, et al. Prediction of mechanical properties of MWCNT-modified epoxy adhesives and co-cured composite joints using machine learning. Journal of Materials Research and Technology. 2025; 29: 10245–10256.
17. Tsai MY, Morton J. An investigation into the stresses in double-lap adhesive joints. International Journal of Solids and Structures. 1994; 31(18): 2537–2563.
18. Chełmecki J, Szeptyński P, Jasińska D, et al. Analyzing the vibration response of adhesively bonded composite cantilevers. Materials. 2025; 18(1): 93.
19. Ewins DJ. Modal Testing: Theory, Practice and Application, 2nd ed. Research Studies Press; 2000.
20. Maia NMM, Silva JMM. Theoretical and Experimental Modal Analysis. Wiley; 1997.

21. Yildirim B, Kucukarslan S, Demir O. Free vibration parametric study of a single lap joint using the radial point interpolation method. Composite Structures. 2023; 308: 116668.
22. Acar V. Numerical modal analysis of adhesively bonded joints of aramid fiber composites with interply and intraply carbon fiber hybridization. Erzincan University Journal of Science and Technology. 2025; 18(2): 618–630.
23. Kaya AI. Effect of different step-lap joints on the natural frequencies of adhesively bonded metallic materials: A numerical study. Black Sea Journal of Engineering and Science. 2024; 7(1): 121–128.
24. Natesan K, Naveen J, Rajesh M, et al. Flexural and vibration behaviours of adhesive joints with multi-walled carbon nanotube modified adhesive. Nanotechnology Reviews. 2024; 1.
25. He X, Zhang Y, Li M. Numerical and experimental modal analysis of adhesively bonded joints under clamped boundary conditions. Journal of Adhesion Science and Technology. 2022; 36(14): 1561–1576.