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Experimental Investigation of Thermal Effects on the Natural Frequencies of GFRP Single-Lap composite Joints Bonded with Al_2O_3 Nano-Reinforced Adhesive

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Abstract. This study is focused on the thermal and vibration characteristics of glass-fibre reinforced polymer (GFRP) structural laminated joints (SLJs) that use epoxies modified through the addition of alumina nanoparticles. Use of adhesive bonded SLJs for lightweight structures is more beneficial than using mechanical fasteners such as bolts or rivets due to advantages related to better distribution of load and lower stress concentration, as well as a lighter overall structural weight. Unfortunately, due to their nature, adhesive bonded joints can fail under simultaneous application of thermal and vibration forces. Therefore, to limit this problem, alumina nanoparticles were added to an epoxy adhesive in various fractions ranging from 0 to 1 wt%. This modified epoxy was then cured along with the bidirectionally woven E-glass/epoxy adherend materials. The modal analysis was conducted using an impact hammer and a frequency response function based vibrational testing apparatus at three different temperatures of 40°C, 50°C, and 60°C. The results demonstrate that the use of nanoparticles significantly increases the stiffness and modal properties of the laminated joint (SLJ). Of the modified epoxies tested, the composition with the addition of 0.50 wt% had the highest thermal stability (i.e., 98.9%) and exhibited the best retention of natural frequency across all temperature ranges. At higher loadings (≥0.75 wt%), thermal stability and frequency retention decreased due to particle agglomeration and micro-void formation. This work gives insight into optimizing nanoparticle concentration for enhancing stability and durability in composite joints loaded thermally. The results provide the basis for the development of high-performance nanocomposite adhesive systems for aerospace, automotive, and marine applications.

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1 Introduction

Composite materials have become a part of advanced structural design due to their higher specific stiffness, high strength-to-weight ratio, and good corrosion resistance. Glass fibre-reinforced polymers (GFRPs) have found wide application in the aerospace, automotive, and marine sectors due to their low weight, mechanical strength, and affordability [5, 13]. Adhesively bonded joints are generally favoured in such structures for their load distribution properties and fatigue resistance, better than mechanical fastening techniques. Specifically, single-lap joints (SLJs) are widely utilized because they are easy to use and effective in structural adhesive bonding but show important stress concentrations at overlap ends resulting from geometric asymmetry and stiffness mismatch of adhesive and adherends [2, 29]. The adhesive layer, often epoxy-based, generally has significantly lower stiffness than the composite adherends and therefore causes stress localisation and interfacial debonding during dynamic loading. This occurs at the detriment of natural frequencies and damping performance of the structure, particularly under operational vibrations. In recent years, scientists have resorted to nano-reinforcing adhesives to overcome such limitations. The addition of nanoparticles to the epoxy matrix raises stiffness, fracture toughness, and interfacial bonding through forming effective stress-transfer bridges between the adherend and adhesive films [18, 20].

Among the available nanofillers, aluminium oxide (Al_2O_3) nanoparticles have attracted growing attention because they exhibit high modulus, hardness, thermal conductivity, and chemical inertness. They offer improved stiffness and thermal resistance without undue density increase, which makes them a potential candidate to reinforce lightweight structural joints [6, 7, 9] reported that Al_2O_3 addition in glass fibre–epoxy composites highly enhanced the tensile and flexural strength, whereas [8] reaffirmed better thermal stability in alumina-strengthened GFRPs. These have been documented for hybrid composites when Al_2O_3 is blended with other fillers like $CaCO_3$ or silica to improve mechanical as well as damping properties [10, 11]. Adhesion joint applications of Al_2O_3 nanoparticles also play an important role in dynamic performance. Through enhanced interfacial stiffness and inhibited crack extension, Al_2O_3-filled adhesives can significantly alter the modal behaviour of SLJs [17, 23] showed that hybrid and nanoparticle-reinforced composite laminates provided enhanced elastic moduli and shifted natural frequencies, indicating enhanced vibration resistance. [24, 27] also indicated that integrating ceramic-based fillers within wind turbine composite structures enhanced modal frequency and damping efficiency. These results highlight the capability of Al_2O_3 nano-reinforcement to enhance the dynamic reliability of composite joints exposed to intricate vibration environments.

Temperature is another essential parameter affecting the mechanical and vibrational behaviour of adhesively bonded composites. The viscoelastic property of epoxy adhesives renders them temperature sensitive; with an increase in temperature, the stiffness of the adhesive and glass-transition modulus become smaller, resulting in lower natural frequencies and increased damping.[30] came to the conclusion that internal energy principles govern thermal expansion and stiffness degradation in polymer composites, but [21] demonstrated experimentally that stiffness degradation in GFRP composites at extremely high temperatures occurs. In automotive engine mounts, aerospace fairings, and power electronics enclosures, where operational temperatures can exceed 50–60 °C, such degradation can have critical implications on structural integrity. Hence, thermally stable fillers such as Al_2O_3 provide a practical route to ensuring performance reliability against thermal–vibrational coupling.

More recent developments in nano-engineered adhesives have also highlighted hybrid filler systems.[20] obtained enhanced shear and flexural strengths in SLJs co-cured with graphene nanoparticle (GNP)-enhanced adhesives and obtained significant modal stiffness gain under dynamic testing. [29] stated that the modification of multi-walled carbon nanotube (MWCNT) enhanced the modal frequency by about 30% and damping by nanoscale bridging. [19] examined graphene and Al_2O_3 reinforcements on shear strength in GFRP joints, confirming the synergistic effect of nano-ceramic and carbon fillers. Together, these articles confirm that proper dispersal of the nanoparticles and co-curing methods play a critical role in providing uniform load transfer along with high vibrational stability. Though there have been tremendous advances in mechanical optimization of nano-reinforced composite joints, very limited work has been presented on modelling nanoparticle concentration, thermal stability, and modal response in Al_2O_3-filled GFRP single-lap joints. No systematic work is available on co-cured GFRP SLJs reinforced with 0–1 wt% % Al_2O_3 subjected to controlled thermal and vibrational loading. To fill the void, the current work produces Al_2O_3-reinforced GFRP SLJs by vacuum-bag co-curing and analyse their modal frequencies and stiffness characteristics at different filler contents. The work seeks to establish the optimal Al_2O_3 content to achieve maximum stiffness and thermal resistance using FFT-based modal analysis. The results are anticipated to offer a useful understanding of the design of bonded structures with high vibration resistance and low weight for high-temperature engineering uses like car brackets, aerospace joints, and electronic enclosures.

Taking into account the collective findings of existing studies, one can conclude that both the concentration of nanoparticles and uniformity of dispersion determine Nanoparticle-Modified GFRP single-lap joint stiffness and vibration behaviour. Nevertheless, the effect of Al_2O_3 nanoparticles on the modal properties of co-cured GFRP joints under realistic boundary conditions remains insufficiently quantified. To cater to this, the current study aims at creating a thorough experimental setup that supports accurate fabrication, homogeneous nanoparticle distribution, and precise vibration analysis. The next section describes the material choice, fabrication process, and experimental setup employed to assess the vibrational behaviour of Al_2O_3-reinforced GFRP single-lap joints using FFT-based modal testing.

2 Material Selection

Materials used in this work were chosen to provide the optimum combination of mechanical stiffness, processability, and cost-effectiveness. The choice of each component was made after considering its established performance in composite jointing applications and compatibility with thermal–vibration test conditions. Bidirectionally woven E-glass fibre of nominal areal density of 220 g/m² (220 GSM) is used as the primary reinforcement material. This type of woven configuration is expected to exhibit nearly isotropic in-plane mechanical properties, ensuring uniform load transfer along the longitudinal and transverse directions. E-glass fibres possess a high tensile strength of approximately 3.4 GPa and a Young's modulus value of 72 GPa, along with superior corrosion and moisture resistance [9]. These properties make them extremely reliable for adhesive-bonded joints, which exhibit good adhesion at the interface and efficient load transfer under dynamic excitation.

The polymer matrix consists of LY556 epoxy resin and hardener HY951, mixed in a weight ratio of 10:1. The proportion of this material was selected due to its high adhesion, low curing shrinkage, and satisfactory dimensional stability under abnormal cyclic thermal ageing. LY556–HY951 combination efficiently wets fibre surfaces throughout vacuum bagging, developing a dense and void-free laminate structure. Its chemical resistance and even curing properties reduce the matrix degradation of the material during long-time vibration tests, providing sustainable dynamic results [6].

Aluminium oxide (Al_2O_3) nanoparticles with a nominal particle size of around 50 nanometres and an areal density of 3.95 g/cm³ are utilized as nano-reinforcements in the epoxy matrix. Al_2O_3 was chosen because it has very good mechanical and thermal characteristics—its high elastic modulus (~400 GPa), hardness (15–20 GPa), and melting point over 2000 °C [7]. These ceramic nanoparticles serve as stress-transfer bridges within the polymer, significantly enhancing load transmission and the stiffness and damping characteristics of the composite.

Fig. 1. Al_2O_3 nanoparticles powder

Weight percentages studied were 0.00 %, 0.25 %, 0.50 %, 0.75 %, and 1.00 % by weight of the epoxy. These percentages of weight proportions are selected from previous work that discovered this range to be optimal for delivering the most amount of stiffness without inducing particle agglomeration [19, 28]. Excessive nanoparticle loading greater than 1 wt % will lead to clustering and poor wetting and reduce mechanical efficiency and negatively affect dynamic performance. Therefore, the chosen range facilitates extensive investigation of Al_2O_3 dispersion effect on modal frequencies responses of GFRP single-lap joints.

A wax-based mold-release agent was applied to all mold surfaces to prevent fibre adhesion and to facilitate easy demolding of cured laminates. Peel plies and breather cloths were employed to maintain surface smoothness and allow for proper air evacuation during the vacuum process. Airtight sealing during curing was ensured by vacuum bags and high-tack sealant tapes. Vacuum pressure was held at around –0.8 bar, allowing for even resin flow and minimizing void content throughout the laminate structure. This controlled fabrication process is necessary to provide homogeneous nanoparticle dispersion and uniform laminate thickness—both are highly significant parameters for vibration characterization accuracy.

3 Adhesive and composite preparation

Preparation of Al_2O_3-reinforced GFRP single-lap joints can be detailed in three significant steps: (i) nanoparticle blended adhesive preparation, (ii) vacuum bagging laminate plate fabrication, and (iii) co-curing of the single-lap joint after the joining. Every process step was planned to provide uniform nanoparticle dispersion, high interfacial bonding, and uniform laminate quality for dynamic vibration testing.

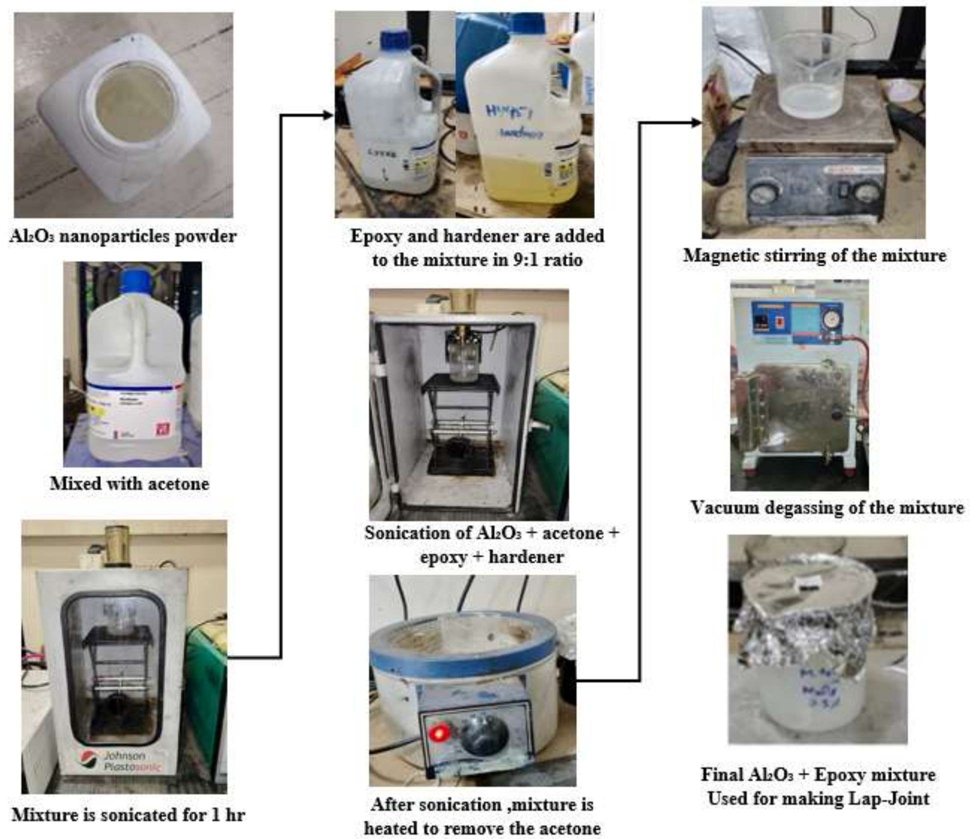

Fig. 2. Preparation of Al_2O_3 nanoparticles reinforced Adhesive

3.1 Preparation of Nanoparticle-Modified Adhesive

For homogeneous dispersion of the Al_2O_3 nanoparticles in the epoxy matrix, a multi-stage ultrasonic mixing and degassing process was used. In order to achieve uniform dispersal of Al_2O_3 nanoparticles and to de-agglomerate initial clusters, ultrasonic sonication was applied to the adhesive mixture for 60 min by ultrasonic bath. Acetone was added temporarily to the epoxy in order to reduce its viscosity and hence provide higher mobility of particles during sonication. The mixture was stirred continuously in order to avoid sedimentation, while sonication took place under controlled temperature conditions to avoid premature curing of the resin. For large-volume preparation, the same mechanism of dispersion can be achieved using industrial-scale high-shear mixers or inline ultrasonic processors, which scale up the required energy input for nanoparticle de-agglomeration in higher quantities of resin.

Following the mixing process, the solution was slowly warmed to 50–60 °C to allow the acetone to evaporate so that there was no residual solvent present that would contaminate curing or cross-linking. The mixture was kept in a vacuum chamber and locked inside for about 10 minutes to remove air bubbles that were trapped inside, giving a void-free Al_2O_3–epoxy adhesive without any trapped air. This process was conducted for every weight fraction of Al_2O_3 from 0 to 1%, with the same viscosity and resin flow behaviour in each composition.

The uniform dispersion of Al_2O_3 nanoparticles in epoxy not only enhances the stiffness of the adhesive but also promotes interfacial bonding by nanoscale mechanical interlocking and reduces the possibility of crack development with loading. Proper homogeneous dispersion is crucial in this case, as improper particle distribution can lead to stress concentrations in localized areas of the composite, and this reduces dynamic performance under vibration testing.

3.2 Fabrication of GFRP Laminates by Vacuum Bagging

High-grade GFRP laminates were fabricated with the vacuum bag technique to minimize voids and achieve desirable fibre–matrix impregnation. The bidirectional E-glass fabrics in four layers, each with dimensions 240 mm × 180 mm, were cut and stacked with the same orientation of the fibres in order to maintain the same longitudinal and transverse stiffness. The layers were individually impregnated with the Al_2O_3-modified epoxy resin after each other with the aim of obtaining full matrix penetration and wetting among the layers.

The assembly of the fibres was stacked onto a release-coated mould surface with the aid of a wax-based release agent to prevent bonding of the fibres. The peel plies, the breather cloths, and the release films were arranged in the correct order, and the entire setup was covered in an inner vacuum bag prepared previously. The vacuum pump generated a steady pressure in the range of approximately –0.8 bar while curing. The vacuum pipe is inserted into the bag to eliminate the trapped air and remove excess resin in between the plies. The process ensured the consistent thickness of the laminate, low porosity, and good fibre-matrix interface bonding—factors of the highest priority in achieving consistent vibration characteristics [10] Then the laminates were left in the vacuum bag for ambient curing for 24 hours in order to obtain a stabilised composite lap joint plate. After curing, the laminates were demoulded with due caution and cut into precise dimensions Suitable for single-lap joint preparation.

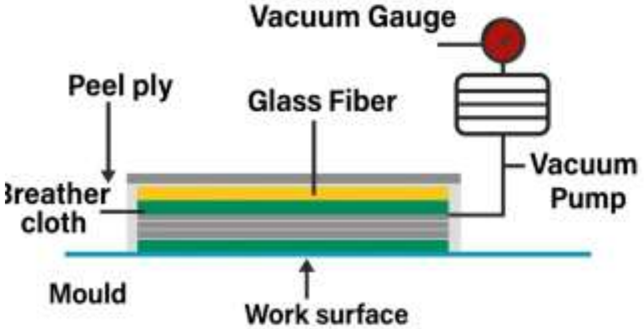

Fig. 3. Schematic diagram of the Vacuum Bagging method

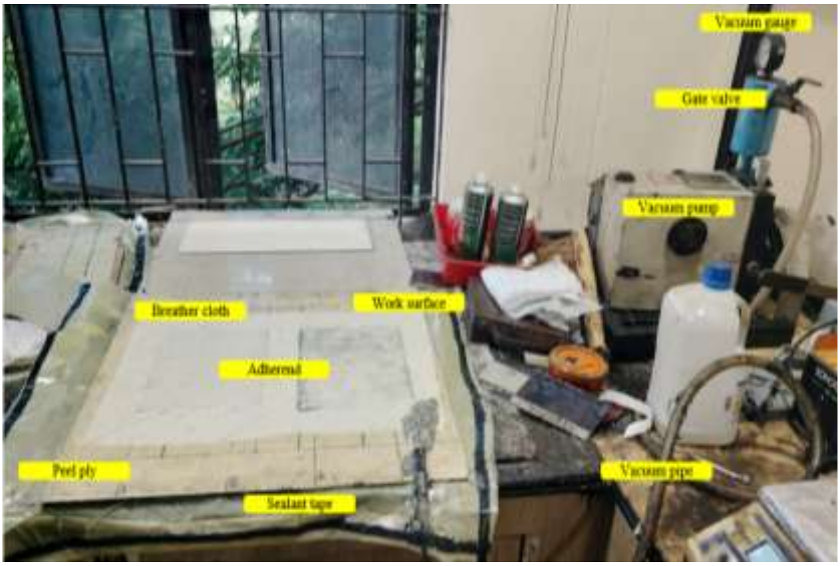

Fig. 4. Vacuum bagging setup for composite plate fabrication

3.3 Co-Curing of Single-Lap Joints

The GFRP laminates were co-cured with the modified epoxy adhesive in an attempt to exhibit superior adhesion and structural strength. The two composite plates were overlaid with an overlap length of 25.4 mm, in alignment with ASTM D5868 guidelines for single-lap joint testing. The overlap section was coated with an equal thickness layer of the modified epoxy adhesive, and the adherends were properly aligned.

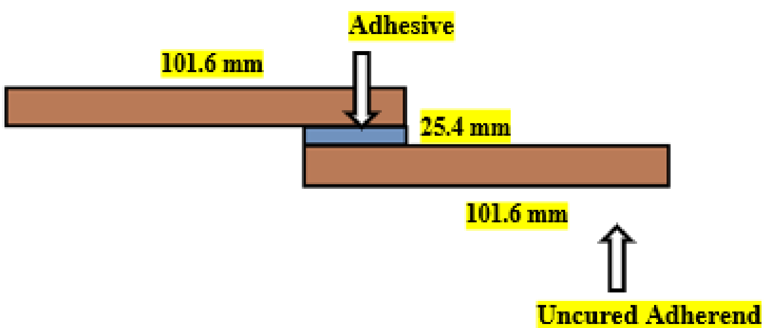

Fig. 5. Schematic diagram of Single-Lap Joint

At the cure, a dead weight was used in order to provide a controlled compressive load and keep the pressure at the joint interface always the same, ensuring intimate contact and preventing the possibility of voids. The joints were also cured at ambient temperature and in static load conditions for 24 hours in order to cure the adhesive and laminate layers simultaneously and produce a coherent co-cured interface.

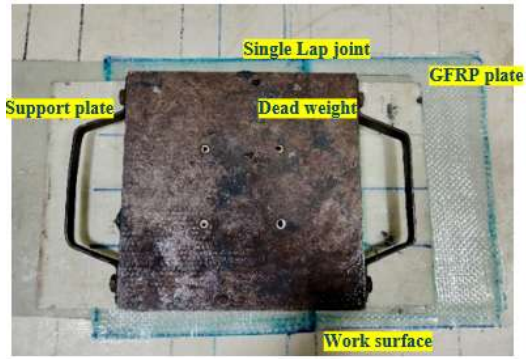

Fig. 6. Co-curing process under Heavy weights

Five specimens each for the corresponding concentrations of the constituents (Al_2O_3) (0 %, 0.25 %, 0.50 %, 0.75 %, and 1.00 %) were thus prepared. After curing, the specimens were visually checked manually and also instrumentally in order to verify geometric consistency and thickness consistency of the adhesive before the modal test.

4 Experimental procedure

The experimental tests were carried out with the intention of identifying the temperature and vibrational characteristics of the manufactured Al_2O_3-enhanced GFRP single-lap joints (SLJs). Modal experimental analysis (EMA) was utilized in order to identify the mode shapes and the natural frequencies of the ambient and high temperature conditions. Specialized experimental arrangement, exciting process and acquisition process were developed with the intention to aid in repeatability and the elimination of the effect of the measurement errors.

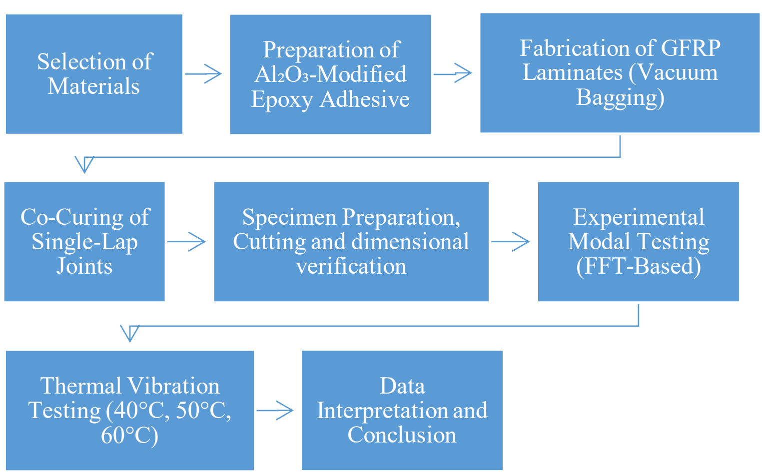

Fig. 7. Flow chart of the overall process

4.1 Experimental Setup

Experimental modal testing was conducted with the aid of an instrumented impact hammer, piezoelectric accelerometer, and Dewesoft FFT analyzer in association with a high-resolution data acquisition (DAQ) system. The accelerometer was attached to the specimen's surface of the material type SLJ with the assistance of heat-resistant wax for the ambient test, while temperature-Stable adhesive was used in high-temperature tests in an attempt to avoid detachment with softening.

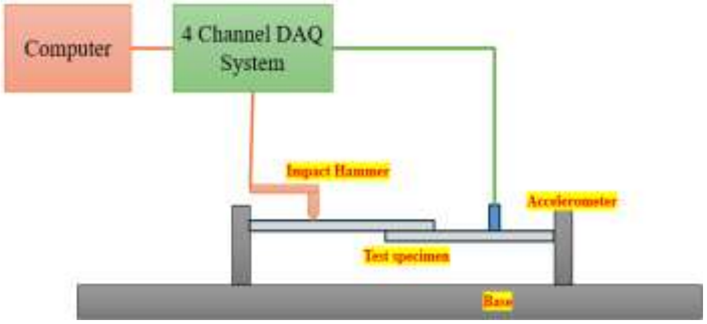

Fig. 8. Schematic diagram of the Modal analysis setup

The specimens were restrained in a clamped–free–clamped–free (CFCF) boundary condition, which modelled realistic restraints encountered in structural assemblies such as the automotive bracket and the aerospace composite joint. The choice relied on a reasonable balance between bending and shear effects such that the dynamic parameters can be properly extracted.

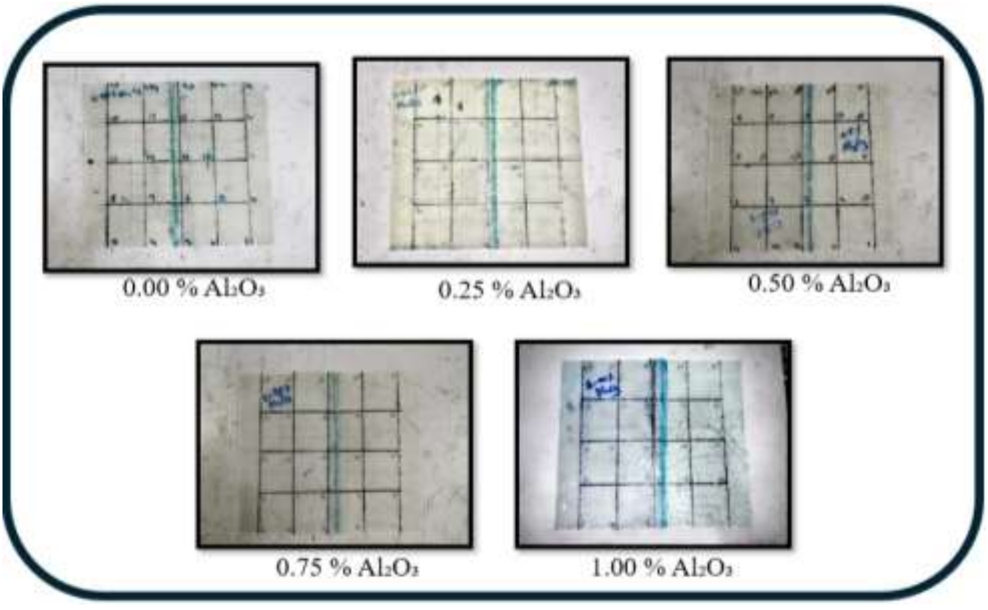

Fig. 9. GFRP single-lap joint specimens with varying Al_2O_3 nanoparticle concentrations

Each sample surface was defined with a regular grid size of 5 × 5, which comprised 25 points of excitation, for modal mapping. Controlled impulse inputs were generated at each point in the grid with the impact hammer, and the respective vibration response was measured with the accelerometer. FFT analysis was performed on the acceleration signals captured using Dewesoft software. The FFT processing transformed the time-domain data to their frequency-domain representation. The vibration response was recorded by the Dewesoft data acquisition system at a sampling frequency of 25.6 kHz, which offers adequate resolution to identify the dynamic characteristics of the joint. The FRFs that resulted from this were analysed to identify the resonant peaks corresponding to the first five modes. These frequencies were then compared for the different Al_2O_3 concentrations to determine how the nanoparticle content impacted the stiffness of the joint.

4.2 Thermal Vibration Testing

To study the influence of temperature on the dynamic behaviour of the Al_2O_3-matric GFRP SLJs, in-situ temperature vibration testing was carried out with the aid of a temperature-controlled laboratory oven and the modal test setup. The oven chamber had an accurate digital thermostat with the facility for maintaining the temperatures with an accuracy of ±1 °C. The specimens were all preheated up to the respective level of the target temperatures 40°C, 50°C, and 60°C and maintained for 30 minutes, such that full uniform thermal equilibrium exists in the joint area before testing.

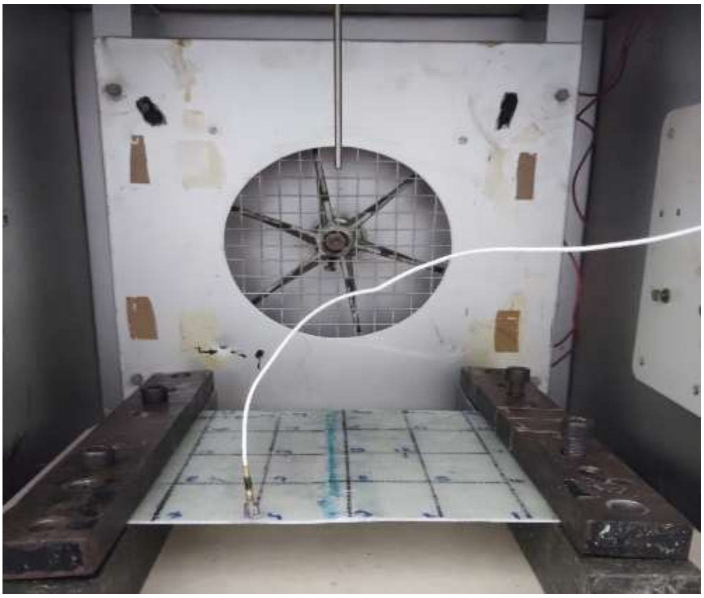

Fig. 10. Experimental Thermal Modal Vibration analysis setup

The accelerometer, sensor cables, and DAQ components were thermally insulated to minimize drift and signal distortion during high-temperature operation. At each temperature condition, impact excitation and FFT data collection were carried out under the same boundary conditions. The shift in resonant frequencies across temperature intervals was used to quantify the thermal stability coefficient, defined as the ratio of the natural frequency at 60 °C to that measured at 40 °C.

Fig. 11. Experimental setup for Modal vibration analysis using an FFT analyser

This systematic method permitted accurate measurement of temperature-dependent stiffness effect and temperature-dependent variations in the stiffness of the nanoparticle-enhanced adhesive layer and shed light on the behaviour of composite joints with thermal stress.

4.3 Standards Followed

The material characterisation and experimental preparation then followed agreed-upon ASTM procedures in the spirit of method consistency and reliable data. Modal behaviour was calculated in accordance with procedures in ASTM E756, which outlines standardised procedures in the vibration-based characterisation. With such standardised procedures, the experimental results from the current investigation remain in direct correlation with existing literature for vibration analysis of composite joints reinforced with fibres. The process also ensures reproducibility and provides a stable platform for correlation between the nanoparticle concentration, temperature, and the nature of the vibrating response.

5 Results and discussion

The experimental analysis provided valuable insights into how the addition of Al_2O_3 nanoparticles and temperature variations affect the dynamic performance of glass fibre-reinforced polymer (GFRP) single-lap joints (SLJs). Noticeable changes were observed in the modal frequencies and overall stiffness response as the nanoparticle concentration and testing temperature were varied. Across all configurations, five distinct vibration modes were consistently identified, and their corresponding natural frequencies were recorded within the 40 °C to 60 °C range. These observations clearly indicate that both nanoparticle reinforcement and temperature conditions have a pronounced influence on the vibrational characteristics and thermal stability of the composite joints.

Table 1. Natural frequencies of 0.00 % Al_2O_3 concentrations at varying temperatures

Mode	40 °C (Hz)	50 °C (Hz)	60 °C (Hz)	Stability (%)
f1	113.75	113.43	112.81	99.00

f2	255.62	253.46	248.12	96.80
f3	300.62	300.31	292.81	95.70
f4	356.56	354.37	346.56	99.60
f5	511.25	506.25	495.62	97.80

Table 2. Natural frequencies of 0.25 % Al_2O_3 concentrations at varying temperatures

Mode	40 °C (Hz)	50 °C (Hz)	60 °C (Hz)	Stability (%)
f1	124.06	124.06	124.06	100.00
f2	234.68	232.56	227.17	98.40
f3	324.06	316.87	310.31	98.60
f4	422.18	420.65	420.62	98.30
f5	499.56	492.81	488.43	96.80

Table 3. Natural frequencies of 0.50 % Al_2O_3 concentrations at varying temperatures

Mode	40 °C (Hz)	50 °C (Hz)	60 °C (Hz)	Stability (%)
f1	124.06	124.37	124.06	100.00
f2	255.31	253.75	251.12	98.30
f3	388.43	384.88	382.82	98.60
f4	444.37	437.56	436.87	97.90
f5	542.56	539.62	538.31	99.20

Table 4. Natural frequencies of 0.75 % Al_2O_3 concentrations at varying temperatures

Mode	40 °C (Hz)	50 °C (Hz)	60 °C (Hz)	Stability (%)
f1	124.06	124.37	120.03	98.00
f2	256.62	253.12	248.48	86.40
f3	361.81	360.93	359.37	89.90
f4	439.68	436.25	430.31	97.70
f5	540.25	534.37	521.87	95.70

Table 5. Natural frequencies of 1.00 % Al_2O_3 concentrations at varying temperatures

Mode	40 °C (Hz)	50 °C (Hz)	60 °C (Hz)	Stability (%)
f1	114.06	113.75	111.87	97.00
f2	298.48	267.57	257.87	86.40
f3	425.93	405.62	383.87	86.87
f4	493.75	492.81	482.18	97.80
f5	568.12	560.92	543.43	95.65

From the observed values, the temperature dependency of the natural frequencies for all the concentrations of Al_2O_3 is seen. The modal frequencies for all the specimens decreased gradually with temperature due to the viscoelastic softening of the epoxy matrix.

5.1 Thermal Stability Evaluation

Thermal stability measures how much the composite joint keeps its stiffness even when heated. Since the rise in temperature decreases the hardness of the matrix, the monitoring of frequency retention aids in determining the structure's resistance to thermal softening. A higher thermal stability value signifies greater stiffness retention and hints at the interfacial bonding and the heat conduction of Al_2O_3 nanoparticles being the superior ones. This parameter is very important for the vibration-sensitive parts that are subjected to changing temperatures, as it proves that the addition of nanoparticles has helped in maintaining dynamic performance throughout the realistic service conditions. The Thermal stability of each specimen was evaluated by using the frequency-retention ratio method adapted from vibration–temperature studies [31]. The formula is,

$$TS\,(\%) = (f_{40°C}/f_{60°C})\times 100 \qquad (1)$$

where $f_{60°C}$ and $f_{40°C}$ are the fundamental natural frequencies recorded at 60 °C and 40 °C, respectively.

Table 6. Average thermal stability values for different Al_2O_3 wt%

Al_2O_3 (wt%)	Thermal Stability (%)
0.00	94.20
0.25	96.70
0.50	98.90
0.75	93.10
1.00	91.80

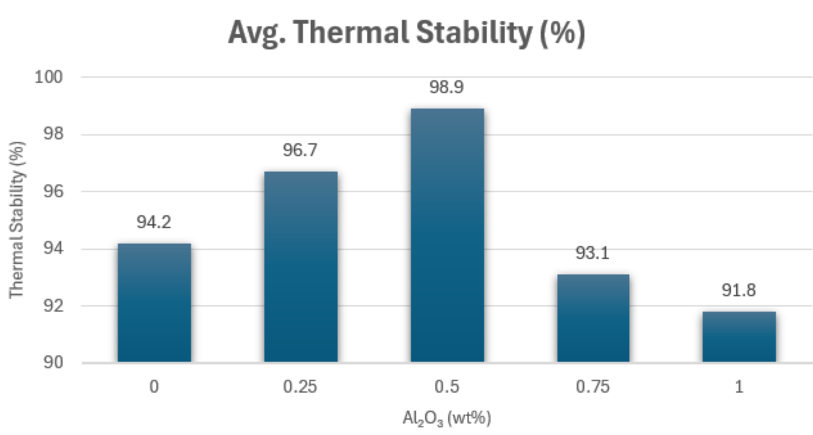

Fig. 12. Average thermal stability of GFRP SLJs at various Al_2O_3 concentrations

The findings verified that the moderate incorporation of nanoparticles enhances the retention of stiffness and structural stability at high temperatures. The 0.5 wt% specimen displayed the highest thermal stability, confirming the beneficial role of uniform particle dispersion and the superior heat conduction properties of Al_2O_3. The ceramic nanoparticles improve heat dissipation along the adhesive layer, reducing localized thermal gradients and preventing early matrix relaxation. Conversely, higher filler concentrations (≥0.75 wt%) led to a loss in stability due to particle agglomeration and resin-rich regions that weaken fibre–matrix bonding.

Although only short-duration heating was examined, prolonged exposure (6–8 hours) at elevated temperatures would further reduce natural frequency due to continued viscoelastic relaxation of the epoxy. Extended heating gradually lowers stiffness and weakens stress transfer at the joint interface. Future work will quantify these time-dependent effects through long-duration thermal aging and thermal cycling.

5.2 Discussion on Stiffness Behaviour

The inclusion of Al_2O_3 nanoparticles introduced a dual effect on the composite joint: increased stiffness. At moderate loading (0.5 wt%), nanoparticles act as nanoscale stress-transfer bridges that reinforce the fibre–matrix interface, effectively redistributing stress concentrations and reducing localized deformation. This enhancement elevates resonance frequencies while maintaining adequate damping, an essential combination for vibration-sensitive structures [7]. At higher nanoparticle loadings, however, the formation of clusters and voids introduced microstructural discontinuities, which increased interfacial frictional losses but reduced effective stiffness.

6 Conclusion

In this investigation, the experimental modal analysis accompanied by controlled thermal environments brought a key insight into the manner of alterations that nano-ceramic fillers effect in stiffness and natural frequency behaviour in bonded composite joints. The most noticeable change caused by the addition of Al_2O_3 nanoparticles was the increase in stiffness and natural frequencies of the SLJ composites, which peaked at 0.5 wt % concentration, with nanoparticles' agglomeration and resin gaps being the causes of weakening after that. Closure of the temperature operating range from 40 °C to 60 °C gave rise to a modal frequency fall that was common to all specimens; however, the 0.5 wt% reinforced composite held almost 98.9% of the baseline frequency and thereby proved to be thermally Stable and structurally sound. The performance increase is primarily attributed to the improved interfacial stress transfer, uniform particle dispersion and Al_2O_3 nanoparticles' high thermal conductivity, which are all responsible for the delay in the matrix softening under higher temperatures. Overall, the results highlight that the 0.5 wt% Al_2O_3 composition achieves a balanced combination of rigidity and damping, making it the most effective configuration for vibration suppression in thermally loaded composite joints.

7 Limitations and Future Work

Limitations of the present study provide guidelines for future research. The work does not involve microstructural characterization like SEM or EDS analysis, which could have validated the dispersion of Al_2O_3 nanoparticles in the epoxy matrix. The thermal investigation was conducted under short-duration steady-state temperatures, while extended thermal exposure or cyclic thermal loading was not considered. Also, only one specimen per nanoparticle concentration has been tested, which reduces the statistical strength of the results. This study also focused on only natural frequency and damping behaviour, without any evaluation of fatigue, fracture characteristics, or long-term degradation performance under combined loads.

Future work will, therefore, be directed towards the incorporation of SEM/EDS analysis to establish correlations between nanoparticle dispersion and thermo-mechanical performance. Tests of long-duration thermal aging (6–8 hours) and thermal cycling will be carried out to understand viscoelastic relaxation and long-term stability. For each composition, multiple specimens will be fabricated in order to enable statistical validation. The studies will be extended to hybrid nanoparticles such as Al_2O_3–GNP and surface-functionalized fillers in order to further enhance stiffness and damping. Additional tests will be conducted to study the fatigue life and fracture behaviour, along with vibration–thermal coupling under realistic service conditions.

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