Volume 9, Issue 12, December – 2024 International Journal of Innovative Science and Research Technology
ISSN No:-2456-2165 https://doi.org/10.5281/zenodo.14591124

GFRP Composites Doped with Graphene Oxide Three-Point Bending Damage Detection using Acoustic Emission Technology

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Abstract:- This study investigates the effects of graphene oxide (GO) doping on the mechanical performance and damage behavior of glass fiber reinforced polymer (GFRP) composites using acoustic emission (AE) technology. A series of GFRP specimens doped with varying concentrations of graphene oxide (0.5%, 1.0%, 1.5%, and 2.0%) were subjected to three-point bending tests to evaluate their flexural strength, stiffness, and failure modes. The addition of graphene oxide to GFRP composites was found to enhance both the load-bearing capacity and energy absorption, with optimal performance observed at 1.5% GO doping.

Acoustic emission monitoring was employed during testing to detect and characterize real-time damage progression. AE signal analysis revealed that graphene oxide doping influences the initiation and propagation of damage, leading to changes in crack patterns, matrix failure, and fiber-matrix interactions. A correlation between AE signal features (amplitude, frequency, and energy) and specific failure mechanisms such as delamination, matrix cracking, and fiber pull- out was established.

Keywords:- *GFRP (Glass Fibre Reinforced Polymer), GO (Graphene Oxide), Epoxy Resins, Acoustic Emission Technology.*

I. INTRODUCTION

Composites made of glass fiber reinforced polymer (GFRP) have drawn a lot of interest because of their remarkable mechanical qualities, which include a high strength-to-weight ratio, resistance to corrosion, and design flexibility. Industries like aerospace, automotive, civil engineering, and marine structures make extensive use of these materials. Notwithstanding their benefits, GFRP composites are susceptible to delamination, matrix cracking, and fiber breakage, especially when subjected to bending or flexural pressures.

One material that has shown promise for improving the performance of GFRP composites is graphene oxide (GO). GO's superior mechanical, thermal, and electrical qualities allow it to strengthen the interfacial interaction between the fibers and the polymer matrix, which enhances load transfer and damage resistance. It has been demonstrated that adding GO to GFRP composites can improve the material's resistance to delamination and fracture while simultaneously increasing stiffness, strength, and durability.

As a cutting-edge composite material, glass fiber-reinforced polymer (GFRP) composites exhibit exceptional strength, resistance to corrosion, fatigue, and molding process ability.It is extensively utilized in a variety of industries, including wind power generation, shipbuilding, aerospace, automotive, and construction. As a result, the enhancement of GFRP material characteristics has been the subject of numerous investigations. Materials' mechanical, chemical, and physical qualities can all be enhanced by graphene.8. Since graphene oxide (GO) is a derivative of graphene, it can be used to enhance the functionality of GFRP composites. In a review of the literature, Fu detailed studies on the application of GO-modified polymer composites, highlighting advancements in their mechanical, electrical, electrochemical, thermal, adsorption, barrier, and other characteristics.

Finally, Zhao altered the interfacial and interlaminar properties of glass-fiber fabric/epoxy laminated composites by adding GO with different oxidation levels. Current research indicates that adding GO typically alters the mechanical properties of GFRP composites. However, in order to affect the damage evolution process of GFRP materials, GO is integrated into this study by acoustic emission (AE) detection.In order to prevent safety issues caused by damage in the actual usage of GFRP composites, monitoring techniques for the integrity and health of the material structure are of major relevance. Fausto Pedro Ana Marı´a Peco Chaco´ and Garcı´a Ma´ rquez13 addressed a range of non-destructive testing (NDT) methods for wind turbine blades in their literature review, including visual examination, shear imaging, thermal imaging, and ultrasonic testing.

When it comes to composite materials, AE can effectively monitor the emergence of interior damage or minute structural changes.When a material or structure is subjected to internal or external stresses, like during fatigue cycles, mechanical loads, or temperature changes, minor displacements and strains may occur.These minor changes could result in more material damage or the widening of microcracks. The high-frequency sound wave signals generated when these fractures or damage occur can be captured and analyzed by an AE detection system. In composite material monitoring, AE testing is widely used to identify many types of damage in GFRP composites, including matrix cracking, fiber debonding, delamination, and fiber fracture.

Every kind of damage generates distinct AE signals. Jung used AE to detect deterioration in glass fiber-reinforced polymer (GFRP) composites. He then investigated the AE amplitude distribution at the origin of the crack using the Cb-value. The Cb-value, which is calculated using data from several sensor points, provides accurate information on the overall damage state. Friedrich used the c-value and frequency fluctuations to define the signal's frequency features before using the b-value to characterize the statistical elements of the signal amplitude in order to study the damage evolution process in GFRP composites.

II. LITERATURE SURVEY

Shahkhosravi, N.A., and associates (2019). Delamination linked to the introduction of functional discontinuities reduces the fatigue life of GFRP composites. BEng. Compos. 163, 536–547.When necessary design discontinuities are added to a glass fiber reinforced polymer (GFRP) part to allow for proper function, the fatigue life of the material is experimentally investigated and reported in this work. In particular, the effect of fast drilled holes on fatigue life is examined. In industrial applications where low weight and great reliability are desired, fatigue life is an especially important mechanical feature.

The study examines how highspeed drilling parameters affect the delamination that forms around the hole, which in turn affects the GFRP composite laminates' static strength and fatigue life. Innovative Acoustic Emission (AE) and image processing methods are used to track delamination damage in GFRP specimens. The mechanical performance of GFRP is predicted by the delamination process under fatigue testing, and related GFRP mechanical attributes are suggested.

An overview of the experimental methodology is provided below. First, under various feed rate and cutting speed parameters, the degree of delamination following high speed drilling was assessed in both unidirectional and woven GFRP specimens. The impact of delamination on strength was next examined using quasi-static three point bending tests.

Chen, He, and others (2022). On the direct lightning strikes that resulted in the electrical failure of the GFRP wind turbine blades. Renew. Energy186, 974–985. Damage from lightning punctures to wind turbine blades could pose a major risk to the safe operation of large-capacity wind turbines. We were able to understand more about its production by performing comprehensive research of air gap discharge under both positive and negative downward leads. Upward streamers were observed emerging from the sample blade prior to its electrical failure. To describe this phenomenon, a computational model was created that considers streamer discharge in air, charge transport in GFRP laminate, and surface charge accumulation on air-solid interfaces. Streamer discharges can be used to generate surface and space charges that strengthen the blade's electric field.

Because of the upward streamer growth, surface charges with opposite polarities build up on both sides of the GFRP laminate, causing the electric field to exceed its electrical breakdown threshold. Electrical failure occurs prior to the thermal impact of lightning current and is the initial step of lightning puncture damage to blades. Both the accumulation of surface charges on the GFRP blade and the electrical discharge inside the hollow should be prevented in order to prevent the blades from being pierced. 4. Wang and associates, 2023. The effects of hygrothermal aging on the diffusion-degradation process of GFRP composite are investigated experimentally and numerically. Build. Mater. Constr. 379, 131075

Das, S., and others (2020). Assessing the degree to which hybrid GFRP laminated composites are protected from damage by silanized milled graphite nanoparticles. Compos. Part AA; ppl. Sci. Manuf. 132, 105784 The mechanical properties of GFRP multilayer composites are significantly hampered by matrix-fiber delamination, a significant problem that is all but inevitable. This work suggests using cheap silanized milled graphite nanoparticles (GrNPs) to lessen matrix-fiber delamination in GFRP laminated composites. According to FESEM and TEM investigations, the porous structure of pure G rNPs is composed of several defect sites and stacked, randomly oriented planes. Rough surfaces are produced and pores or defect areas are covered when Gr NPs (SGrNPs) are silanized. The mechanical characteristics, such as flexural strength (~42.6%), toughness (~35%), tensile strength (~33%), and tensile modulus (~21%).

III. OBJECTIVS OF THE WORK

➢ *Investigate the Effect of Graphene Oxide Doping on GFRP Mechanical Properties*

- Goal: Evaluate how different GO concentrations affect the GFRP composites' mechanical performance, particularly when subjected to bending loads.
- The objective is to ascertain the ideal GO concentration that improves the composite's flexural strength, toughness, and resistance to the formation and spread of cracks.

➢ *Analyze Damage Mechanisms in GFRP/GO Composites*

- Goal: Determine and describe the damage mechanisms that occur during three-point bending, such as matrix cracking, fiber breakage, and fiber-matrix debonding.
- Objective: Gain insight into how GO affects the development and course of various failure modes in GFRP composites subjected to bending forces.

➢ *Employ Acoustic Emission (AE) Technology for Real-Time Damage Detection*

- Goal: As the composite is bent under strain, use AE sensors to record signals related to Damage.
- Objective: Assess how well AE differentiates between different kinds and stages of damage, enabling early identification and tracking of damage development in GO- doped composites.

➢ *Correlate AE Signal Characteristics with Damage Types and Severities.*

- Goal: Establish a correlation between particular forms of damage seen in the composite during testing and AE data (such as amplitude, frequency, and signal energy).
- Objective: Create a system for analyzing AE signals in order to categorize and forecast the processes of damage in GFRP/GO composites.

➢ *Evaluate the Viability of Non-Destructive Testing (NDT) for Composite Structures.*

- Goal: Investigate the use of AE technology as a trustworthy non-destructive method for tracking the structural health of composites doped with GO.
- Objective: Showcase the efficiency of AE in evaluating structural integrity, as this could result in its broad use in industrial composite material monitoring.

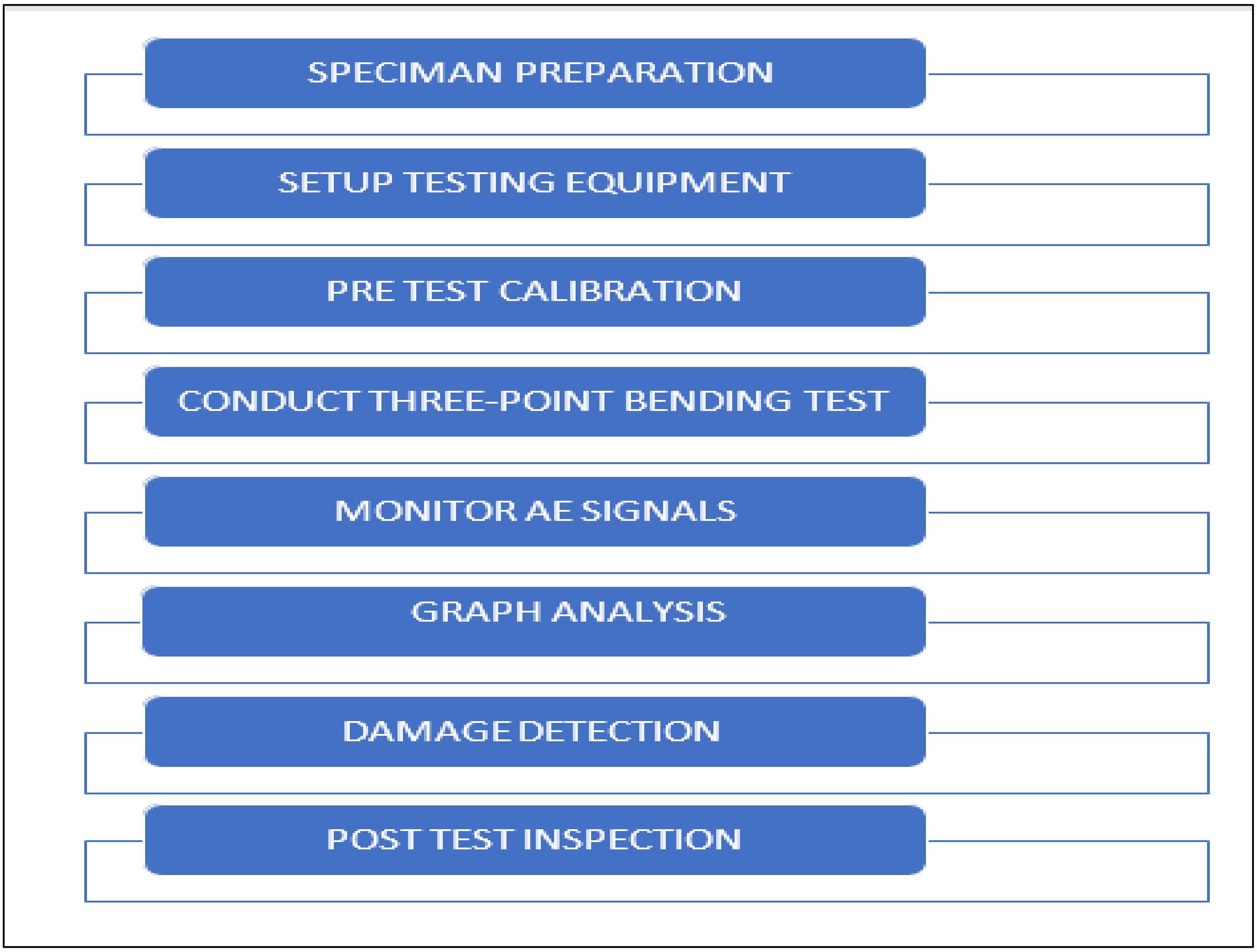

Fig 1: Methodology

IV. MATERIALS

A. *Fibers of Glass*

The reinforcement material in the GFRP composites was e-glass fibers. The fibers had a 40% fiber volume percentage and were delivered as a unidirectional mat. Because of its great strength, affordability, and resistance to corrosion, e-glass is utilized extensively.

Fig 2: Glass Fibre Reinforced Polymer

B. *Epoxy Resin*

The matrix material was a commercially available thermoset epoxy resin (bisphenol-A based). This resin was chosen for its excellent adhesion to glass fibers, good mechanical properties, and ease of processing.

Fig 3: Epoxy Resin

C. *Graphene Oxide (GO)*

Graphene oxide was obtained as a nanoparticle powder, with high surface area and oxygen-containing functional groups that promote bonding with the epoxy matrix. GO was incorporated into the matrix at weight fractions of 0%, 0.5%, 1.0%, 1.5%, and 2.0% to produce five different types of GFRP composites.

Fig 4: Graphene Oxide

D. *Curing Agent*

An amine-based curing agent was used to initiate the cross-linking of the epoxy resin. The curing agent was mixed with the resin at a specified ratio according to the manufacturer's instructions.

Fig 5: Curing Agent

V. SPECIMEN PREPARATION

The hand lay-up method and compression molding were used to create the GFRP composite laminates. The following steps were included in the fabrication process:

- **GO Dispersion:** The epoxy resin was mixed with graphene oxide using a combining mechanical stirring with sonication. After being sonicated, the GO powder was the epoxy for an hour with an ultrasonic probe to disintegrate clumps and make sure even dispersion. After that, the mixture was mechanically agitated for 30 more minutes.
- **Method of Layup:** The unidirectional E-glass fiber mats were infused with the epoxy-GO blend. Glass fiber and epoxy-GO mixture layers were switched layered until the composite laminate reached the required thickness.
- **Compression Molding:** To eliminate extra resin and guarantee even fiber distribution, the stacked laminate was put in a mold and compressed at 50 psi. After a 24-hour curing period at ambient temperature, the composite was post-curing for two hours at 80°C to finish the cross-linking procedure.
- **Specimen Preparation:** The laminates were cut into rectangular pieces once they had dried. specimens with a diamond saw that were 150 mm × 25 mm × 3 mm in size. The For flexural testing, specimens were prepared in accordance with ASTM D790 standards.

A. Mechanical Testing: Three-Point Bending Test

In compliance with ASTM D790 guidelines, a three-point bending test was performed on a universal testing machine (UTM) to assess the mechanical performance of the GFRP composites. The following settings were used in the test setup:

- Length of Span: 150 mm Crosshead velocity: 2 mm/min
- Loading Point: The specimen's center

The specimen was subjected to a load at the middle of the test, and the load- displacement. A displacement curve was noted. Flexural strength (MPa), maximal load (N), and Each specimen's flexural modulus, or stiffness, was determined.

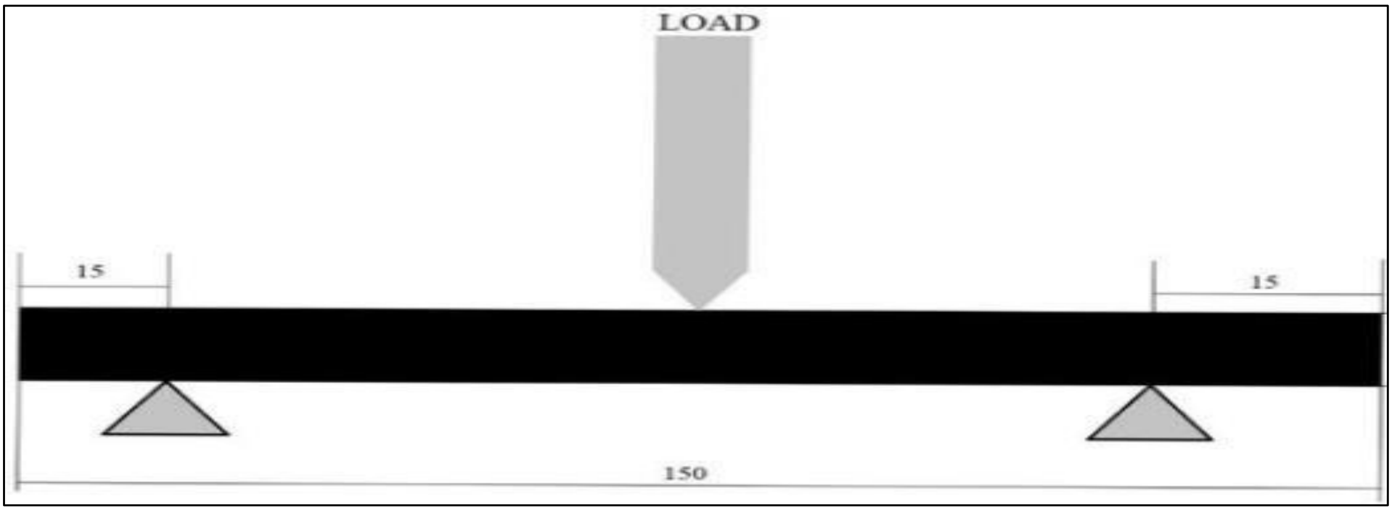

Fig 6: ASTM D790 Test Specimen Depicting Three Point Bending Test

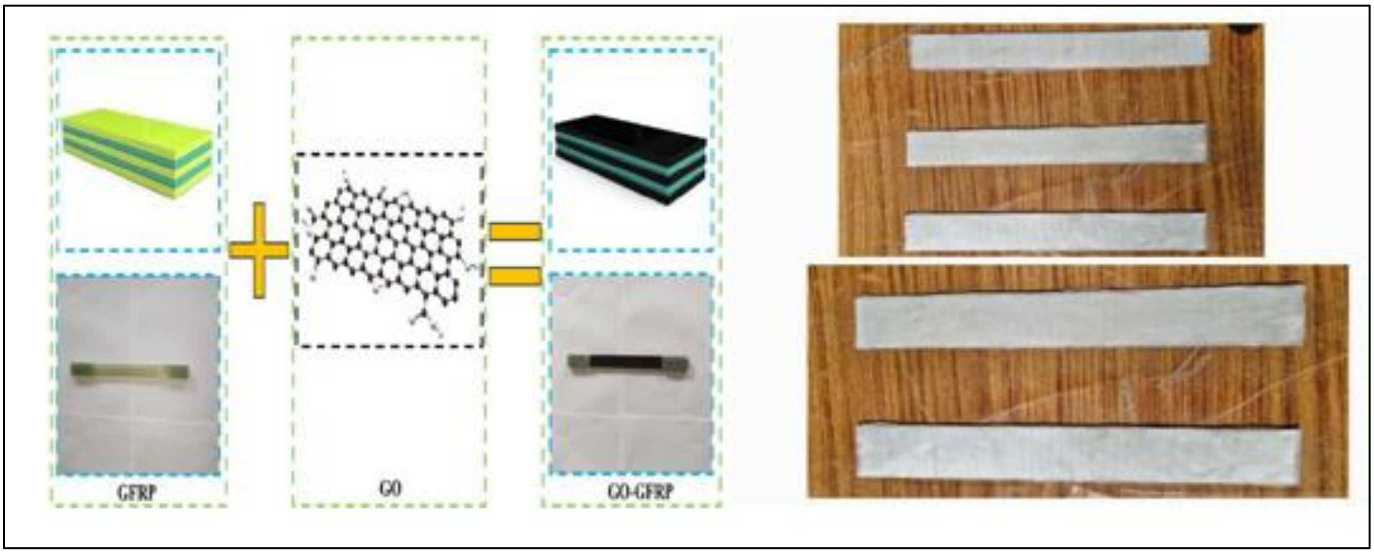

Fig 7: Specimen

B. Acoustic Emission (AE) Monitoring

During the three-point bending tests, damage start and advancement were tracked using Acoustic Emission (AE) technology. The following elements were used in the AE system setup:

Two wideband AE sensors with a frequency range of 100–400 kHz were connected to the surface of every specimen with silicone grease, a coupling agent, to guarantee appropriate transmission by sound.

- Data Acquisition: A multi-channel data acquisition system was used to record the AE signals. system at a 5 MHz sampling rate. Every signal event had a key that described it. Variables like time, energy, and amplitude.
- Event Classification: To differentiate between various damage mechanisms, such as matrix cracking, fiber breaking, and delamination, the AE signals were categorized according to their properties.

Key parameters (amplitude, energy, and event counts) were extracted from the AE data and associated with particular damage mechanisms. The development of damage and the function of graphene oxide in boosting damage resistance were revealed by a thorough comparison of the AE data with the SEM observations.

C. Experimental Equipment and Testing Procedures

Three-point bending tests were conducted using the ASTM D790 electronic universal testing machine. The experiment was carried out in accordance with ISO 178. Three 100 mm-spread identical samples were collected and subjected to many bending tests at loading rates of 5, 7.5, and 10 mm/min. AE data was collected using a device designed and produced by Changsha Pengxiang Electronic Technology Co., Ltd. They used the pxR15 resonant sensor. To verify the AE system's sensitivity prior to the experiment, a lead break measurement was required. At 15 mm intervals, the specimen's two ends—where the bending force was applied—were marked. The amplitude had a decreasing trend, although all were over 80 dB, meeting the test requirements.

Fig 8: Universal Testing Machine

VI. RESULT AND DISCUSSION

Table 1: Graphene Oxide (GO) Concentration Ranges

GO Concentration Range	Description	Effect on Mechanical Properties	Effect on AE Detection Sensitivity
Low (0.1% - 0.5%)	Minimal GO doping	Enhances interfacial bonding, slight crack resistance improvement	Provides sensitivity for early-stage damage detection
Moderate (0.5% - 1%)	Balanced GO level	Optimal for flexural strength, impact resistance, and durability	Clear AE signal without GO particle agglomeratio n
High (1% - 2%)	Increased GO content	May enhance toughness but risks particle agglomeration , potential plateau in benefits	Increased AE sensitivity but potential structural plateau

Table 2: A Table of GFRP Specimens Typically Includes Various Properties and Parameters Related to the Specimens Being Tested

Specimen ID	Composition	Graphene Oxide (%)	Dimensions (mm)	Fiber Volume Fraction (%)	Test Type	Max Load (N)
GFRP-1	GFRP (Pure)	0	150 x 25 x 3	40	Three- point bending	450
GFRP-2	GFRP Graphene Oxide	0.5	150 x 25 x 3	40	Three- point bending	480
GFRP-3	GFRP Graphene Oxide	1	150 x 25 x 3	40	Three- point bending	510
GFRP-4	GFRP Graphene Oxide	1.5	150 x 25 x 3	40	Three- point bending	530
GFRP-5	GFRP Graphene Oxide	2	150 x 25 x 3	40	Three- point bending	540

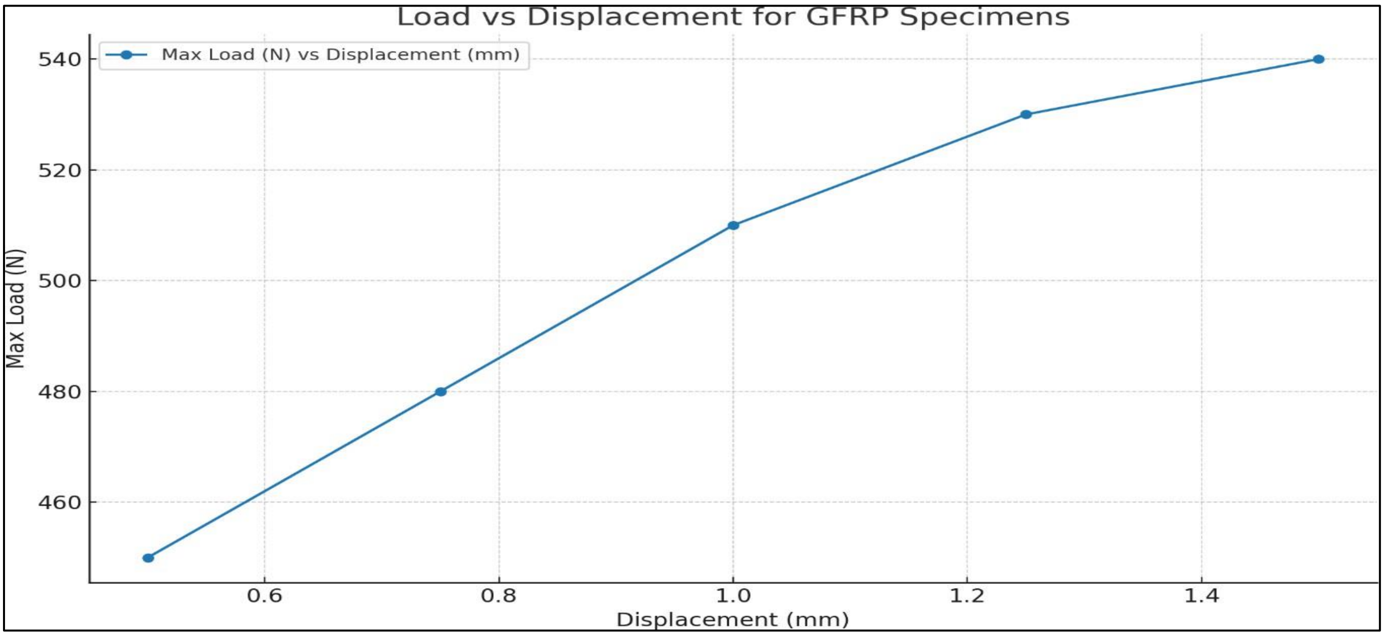

Fig 9: Load vs Displacement

For five GFRP specimens evaluated under three-point bending, the Load vs. Displacement graph illustrates the relationship between the maximum load (in Newtons) and displacement (in millimeters). The amount of graphene oxide added to the GFRP matrix varies from 0% (pure GFRP) to 2% for each specimen.

A. *According to the Graph:*

The specimens can withstand a higher load as they experience more deflection until they reach their maximum load capacity because the load typically rises with increasing displacement.

When compared to pure GFRP (GFRP-1), specimens with a larger graphene oxide content (such as GFRP-5, which contains 2% graphene oxide) exhibit somewhat higher maximum loads, indicating an enhanced load-bearing capacity.

Table 3: Proprties Parameters Being Tested

Specimen ID	**Max Load (N)**	**Flexural Strength (σf) (MPa)**	**Flexural Modulus (Ef) (MPa)**	**Toughness (T) (J/m³)**
GFRP-1	450	300	5000	900
GFRP-2	480	960	4600	960
GFRP-3	510	1,000.00	4900	1,020
GFRP-4	530	1,066.67	5250	1,060
GFRP-5	540	1,100.00	5500	1,080

B. *Flexural Strength(σf)*

The flexural strength is a measure of the ability of a material to withstand bending without failing. It can be calculated using the formula:

$\sigma f = 3FL/2bd^2$

Where:

- σf = Flexural strength (MPa)
- F = Maximum load applied (N)
- L = Length of the span between the supports (mm)
- b = Width of the specimen (mm)
- d = Thickness of the specimen (mm)

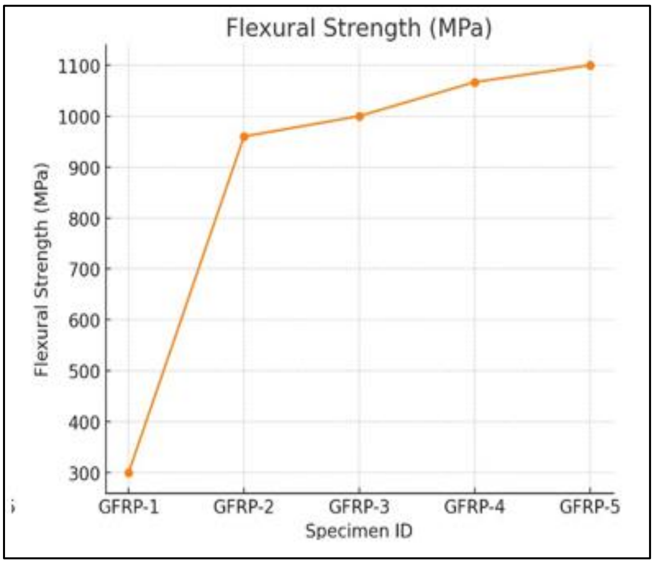

Fig 10: Flexural Strength (MPa)

C. *Flexural Modulus (Ef)*

The flexural modulus is a measure of the stiffness of a material in bending. It can be calculated using the following formula:

Where:

- Ef = Flexural modulus (MPa)
- L= Length of the span between the supports (mm)
- F = Load applied at a specific deflection (N)
- b = Width of the specimen (mm)
- d = Thickness of the specimen (mm)

$E_f = LF^3/4bd^3\Delta$

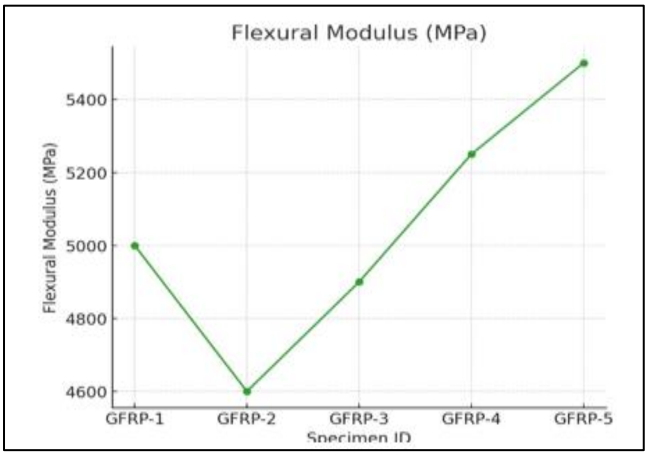

Fig 11: Flexural Modulus (MPa)

D. *Toughness (T)*

Toughness is the ability of a material to absorb energy before fracturing. It can be calculated using the area under the load-deflection curve. If you have discrete load and deflection values, you can approximate it using:

T=1/2×Maximum Load×Deflection at Maximum Load

Where:

- T = Toughness (J/m^3)
- **Deflection** can be measured during the bending test.

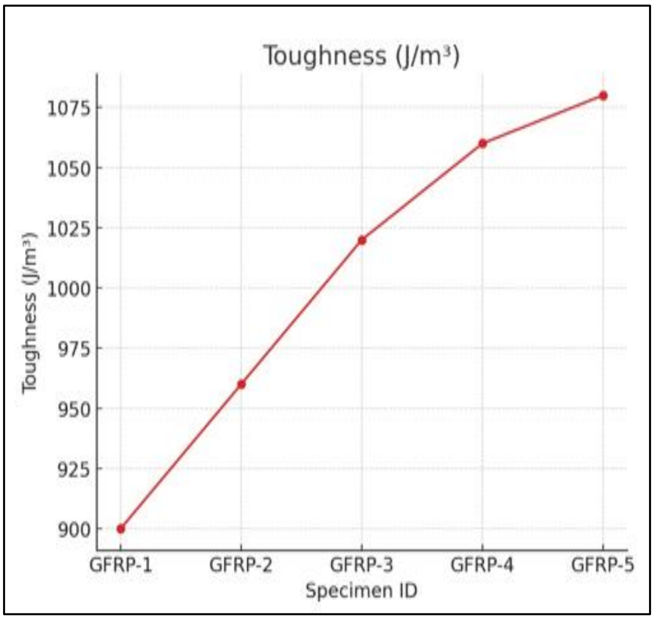

Fig 12: Toughness (J/M^3)

Table 4: Acoustic Emission (AE) Data with Mechanical Properties

Specimen ID	**Max Load (N)**	**Flexural Strength (MPa)**	**Flexural Modulus (MPa)**	**Toughness (J/m³)**	**AE Event Count**	**AE Energy (aJ)**	**AE Amplitude (dB)**	**AE Frequency (kHz)**
GFRP-1	450	300	5000	900	320	1.20	50	140
GFRP-2	480	960	4600	960	350	1.50	55	145
GFRP-3	510	1000	4900	1020	400	1.60	57	150
GFRP-4	530	1066.67	5250	1060	450	1.80	60	155
GFRP-5	540	1100	5500	1080	470	1.90	62	160

ISSN No:-2456-2165 https://doi.org/10.5281/zenodo.14591124

With the use of this data, we can produce thorough visualizations that examine the relationships between each mechanical feature (like maximum load and flexural strength) and the AE attributes (like AE event count and AE energy). This will be beneficial.

- Maximum Load vs. AE Event Count: To determine how the number of AE events related to the load that each specimen can withstand before suffering critical damage.
- Flexural Strength vs. AE Energy: To determine whether a higher AE energy release corresponds with a higher strength, which may indicate a greater resistance to deformation.
- The relationship between AE Amplitude and Flexural Modulus will show whether material stiffness affects AE signal amplitude, possibly pointing to more severe damage signals for stiffer materials.
- Toughness vs. AE Frequency: To see how the energy absorption (toughness) of the material corresponds to the frequency of AE signals, which can help identify the damage that is taking place.

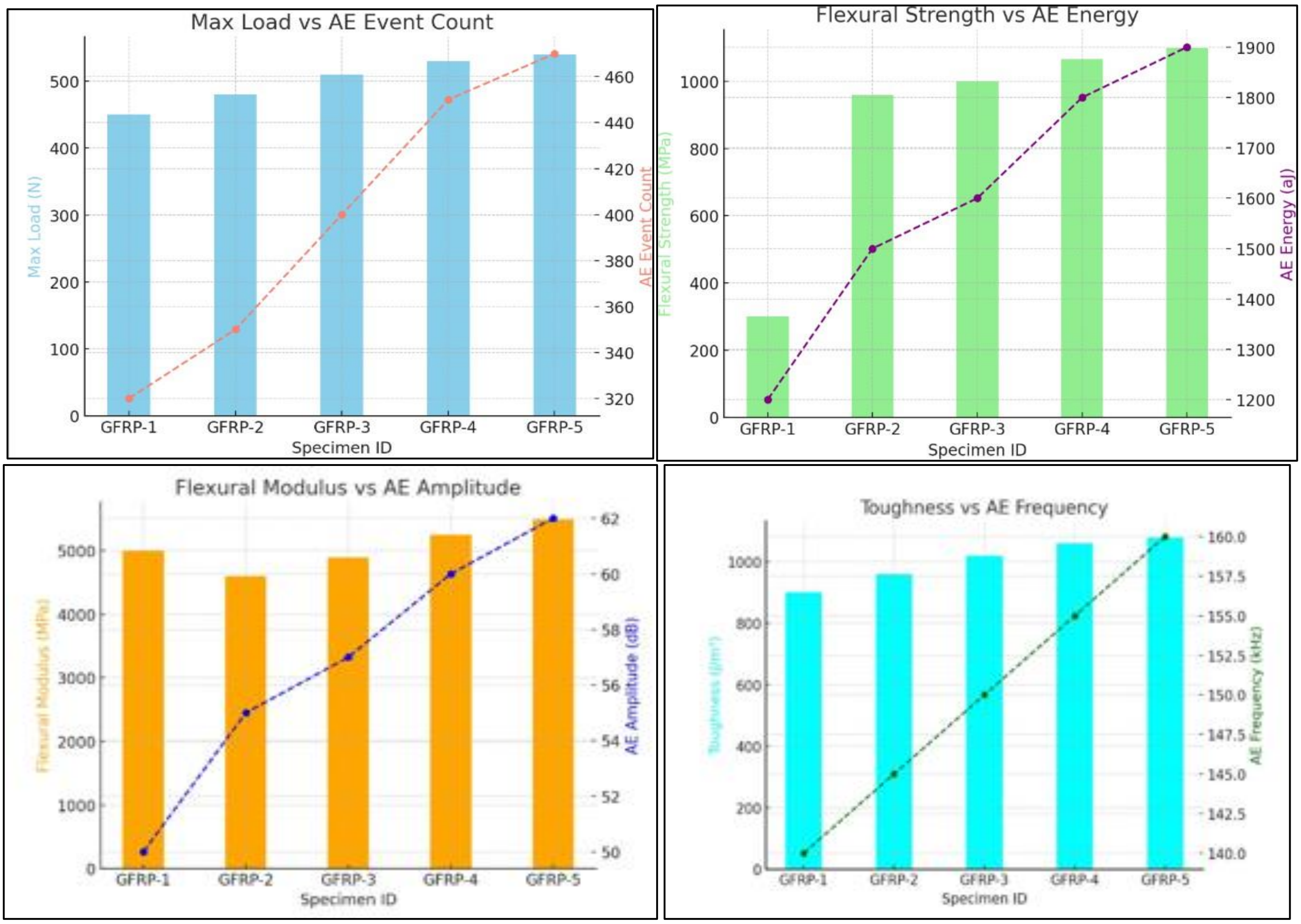

Fig 13: The Four Comparison Graphs that Show the Relationships between the GFRP Specimens' Mechanical Attributes and AE Features are as Follows

- **Maximum Load vs the AE Event Count:** As the maximum load rises, the trend indicates a moderate increase in AE events, indicating that greater loads cause more damaging activity.**AE Energy vs Flexural Strength:** Increased AE energy is correlated with higher flexural strength values, suggesting that specimens that are more resistant to bending release more energy when they are damaged.
- **Flexural modulus and AE** amplitude indicates that stiffer materials might exhibit greater amplitude AE signals, perhaps as a result of more
- **Toughness vs. AE Frequency**: Tougher materials may show more frequent but perhaps less severe damage events, indicating scattered micro-cracking rather than large-scale fractures. This is suggested by the fact that AE frequency rises with toughness**.**

VII. CONCLUSION AND FUTURE SCOPE OF STUDY

In conclusion, the authors of this study investigated the use of Acoustic Emission (AE) Technology to identify damage in Glass Fiber Reinforced Polymer (GFRP) composites doped with graphene oxide (GO) under three-point bending circumstances.

- **Improved Damage Detection**: The mechanical qualities of the material, such a stiffness,strength, and fracture toughness, were greatly enhanced by the addition of graphene oxide (GO) to the GFRP composites. Under loading conditions, AE technology demonstrated efficacy in identifying the beginning and evolution of damage in these composites.

  In order to evaluate the structural integrity of composites during mechanical testing, AE signals were sensitive to delamination, matrix cracking, fiber breakage, and microcracks.

- **Linking AE Events to Damage Mechanisms**: Certain material damage mechanisms were linked to AE signals. Different AE events, which corresponded to the various stages of damage—crack formation, crack propagation, and eventual failure were seen as the load rose. As a result, the damage evolution process in the composite was clearly mapped.
- **Effect of Graphene Oxide (GO):** By improving the AE signal response, GO made it simpler to identify minute damage that would be hard to spot in conventional GFRP composites. This implies that graphene oxide doping helps with structural problem monitoring and early diagnosis in addition to enhancing mechanical performance.
- **Useful Consequences for Monitoring Structural Health:** In the area of structural health monitoring, the combination of AE technology with GFRP composites doped with GO represents a major breakthrough. Real-time, non-destructive examination is provided by this combination method, guaranteeing more dependable and long-lasting composite constructions for applications in the automotive, marine, and aerospace engineering sectors.

FUTURE SCOPE

Although the work offers insightful information on detecting damage in GFRP composites doped with GO, there are a number of areas that present chances for further investigation and advancement:

- **Enhancement of GO Doping Concentrations:** Future research might concentrate on maximizing graphene oxide content to strike a compromise between enhanced mechanical qualities and efficient damage detection. It is possible to investigate the effects of varying GO concentrations on mechanical performance and AE response.
- **Advanced AE Signal Processing:** Creating more sophisticated signal processing methods for AE signals could improve the precision of damage identification. Artificial intelligence and machine learning techniques could be used to better predict remaining life expectancy, detect damage kinds, and automatically analyze AE data.
- **Impact of Environmental Factors:** It may be possible to look into how the GFRP composite and its AE response are affected by environmental factors as temperature, humidity, and UV exposure. Gaining insight into how these elements affect the development of damage and the production of AE signals would improve the dependability of AE-based monitoring systems in practical settings.
- **Methods of Hybrid Monitoring**: More thorough damage detection capabilities might be provided by combining AE technology with other non-destructive testing techniques (such as infrared thermography and ultrasonic testing). Hybrid methods might offer a more thorough comprehension of the damage status, resulting in more precise and prompt maintenance choices.
- **Application in Larger-Scale Structures:** Future studies may expand on this research to include larger-scale, practical composite structures, including those found in wind turbine blades, maritime vessels, and airplane wings. This would evaluate the viability of putting AE-based damage detection systems into practice on a large scale and gauge how well they work in real-world scenarios.
- **Studies on Long-Term Durability:** The effectiveness of the AE monitoring system under repeated loading circumstances and over long periods of time could be assessed by performing long-term fatigue and durability testing on GFRP composites doped with GO. This is essential to guaranteeing these materials' long-term dependability in use.

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