Research Article

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Experimental Analysis of Tensile and Flexural Characteristics of GFRP Laminates Infused with Multi-Walled Carbon Nanotube (MWCNT) Nano-fillers

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ABSTRACT

This research investigates the influence of varying concentrations (0%, 1%, and 2%) of multi-walled carbon nanotube (MWCNT) nano-fillers on stretching and bending characteristics of a composite material (glass fiber-reinforced polymer (GFRP) laminates). The results show a significant enhancement in strength with increased nanomaterial content, specifically, the strength under tension increased from 114.51 MPa to 155.53 MPa, while the stress under bending increased from 152.269 MPa to 187.26 MPa. These improvements in mechanical properties are attributed to several strengthening mechanisms, including grain refinement, dislocation pinning, and interface strengthening between the nanomaterial and the matrix. The addition of nanomaterial enhances the material stiffness, as reflected by the increased flexural modulus. A slight reduction in ductility was observed, indicated by a decrease in strain at failure. The uniform dispersion of the nanomaterial within the matrix was crucial in achieving these enhanced properties. The observations indicate potential applications in aviation and automotive sectors, where superior strength and rigidity are essential. Further investigations should examine different nanomaterials and evaluate the material under diverse loading scenarios to enhance its performance.

Keywords: GFRP laminates; Multi-walled Carbon Nanotubes; Glass fiber; Tensile properties; Flexural properties.

1. INTRODUCTION

Composite materials have become indispensable in modern engineering and industrial applications because of their exceptional mechanical qualities, portability, and adaptability in design. Among these, polymer composites reinforced with glass fibers are commonly used worldwide in a range of materials, in aerospace, automotive, marine, and civil infrastructure (Choudhari *et al.* 2024; Cengiz *et al.* 2024). Their elevated strength-to-weight proportion, corrosion resistance, and ease of fabrication make them a preferred choice over conventional materials like metals (Batmaz *et al.* 2024). However, like all materials, GFRP composites have limitations, including brittleness, low impact resistance, and susceptibility to matrix cracking under mechanical loading. Addressing these challenges requires innovative solutions, one of which is the incorporation of nano-fillers to enhance their mechanical properties. Nano-fillers, particularly with remarkable electromagnetic, mechanical and thermal properties of multi-walled carbon nanotubes (MWCNTs) have attracted considerable attention. These nanotubes exhibit high tensile strength, excellent stiffness, and notable aspect ratios, making them ideal candidates for reinforcing polymer matrices (Zhang *et al.* 2024). Their ability to transfer load effectively, restrict crack propagation, and enhance interfacial bonding provides a pathway to improve the performance of GFRP composites. Incorporating MWCNTs into the epoxy resin matrix of GFRP laminates is a promising strategy to overcome the inherent weaknesses of conventional composites (Suja and Mathiya, 2024). The concept of nanotechnology-based reinforcement in composite materials revolves around the principle of altering the matrix at the nanoscale. Multi-walled CNTs with their tubular structure and unique bonding characteristics, can significantly alter the stress distribution within the composite (Chandran *et al.* 2024). When properly dispersed and integrated into the polymer matrix, these nano-fillers enhance tensile and flexural qualities by limiting the development of microcracks and transferring load from the matrix to the fibres (Sabet, 2024). Despite these advantages, the practical implementation of MWCNT reinforcement faces challenges, including achieving uniform dispersion, controlling agglomeration, and determining the optimal filler concentration (Hamdy, 2024).

Studies have explored the incorporation of MWCNTs into polymer matrices to enhance mechanical properties, including impact resistance, flexural modulus and tensile strength (Shahabaz *et al.* 2023). However, the degree of enhancement largely depends on factors such as the dispersion method, filler loading percentage, and the bonding between the matrix and the nano-fillers on the surface (Maurya *et al.* 2023). Techniques like ultrasonication, mechanical stirring, and surface functionalization have been employed in the past to address dispersion challenges, ensuring that the nano-fillers are uniformly distributed throughout the matrix. Epoxy resin, a widely used thermosetting polymer, is commonly employed as the matrix material in GFRP composites due to its excellent adhesive properties, thermal stability and resistance to chemicals (Parasuram *et al.* 2023). The addition of MWCNTs to epoxy resin has been shown to enhance its mechanical performance by improving stiffness, strength, and fracture toughness. A stronger composite is produced as a result of the enhanced load transfer brought about by the strong interfacial interaction between MWCNTs and epoxy chains (Rathinasabapathi *et al.* 2023). However, optimizing the epoxy-to-MWCNT ratio and understanding the influence of nano-filler concentration on composite properties remain critical areas of research (Zhao *et al.* 2023). Ejaz *et al.* (2022) in their experimental investigation fabricated GFRP laminates using a combination of woven glass fibers and an epoxy resin matrix reinforced with MWCNTs. The matrix was reinforced with MWCNTs at varying weight fractions to enhance the mechanical performance of the laminates. Fard *et al.* (2014) focused on assessing the influence of MWCNT addition on the Elastic and flexibility characteristics of the combination, aiming to identify the suitable filler concentration for achieving superior properties. This research explores the synergistic effects of glass fiber reinforcement and MWCNTs in hybrid composites, focusing on their tensile and flexural performance. By analyzing GFRP laminates with varying MWCNT concentrations, it provides valuable insights into the potential of nano-reinforced composites for high-performance applications. The study addresses challenges such as dispersion and filler optimization, aiming to establish a framework for developing next-generation composites with superior mechanical properties for demanding engineering environments.

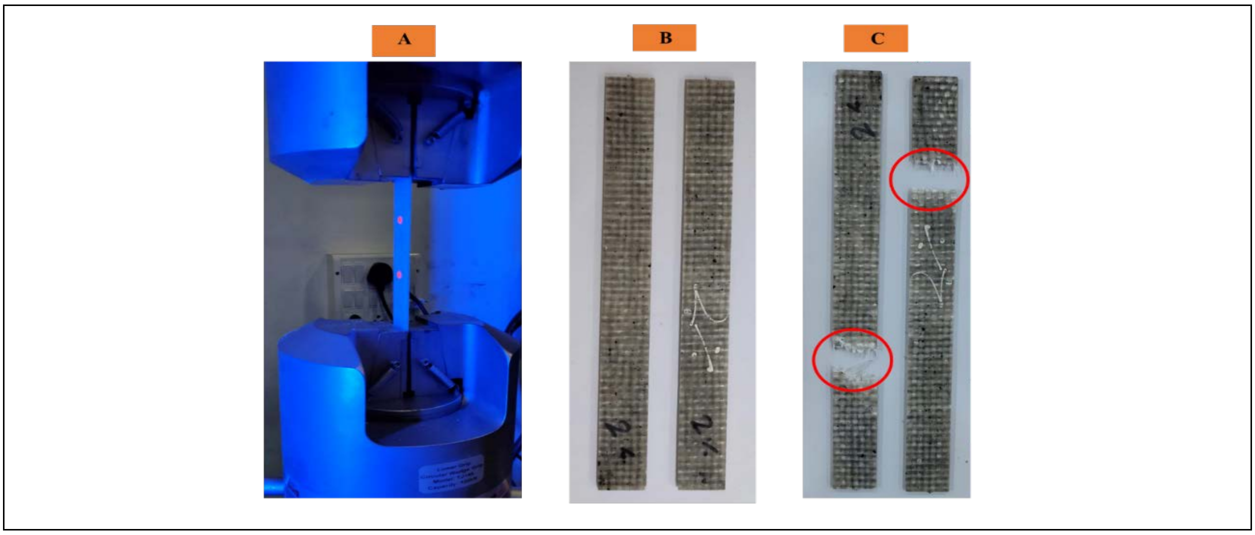

Fig. 1: Tensile test setup with specimen with and without failure

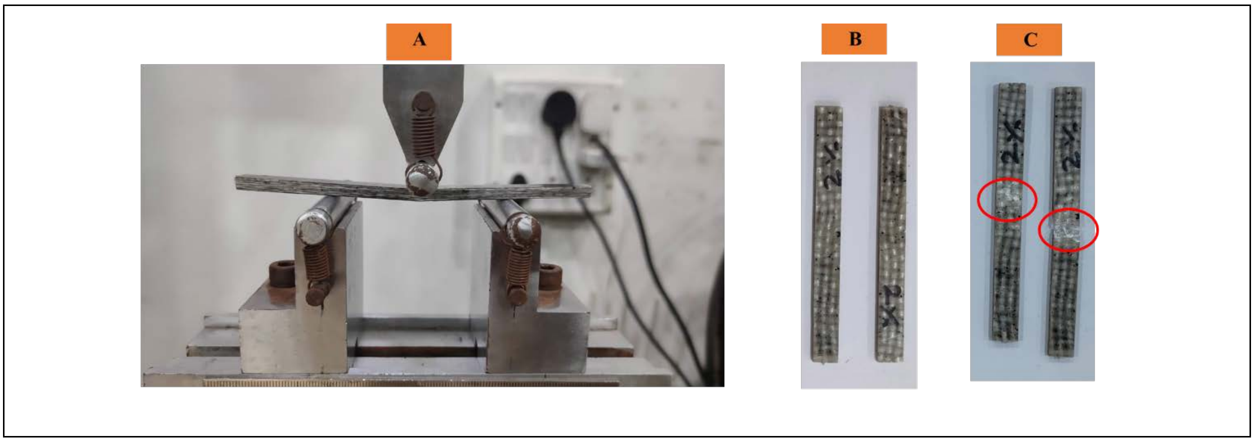

Fig. 2: Three-Point bending test setup with specimen with and without failure

2. EXPERIMENTAL PROCEDURE AND METHODOLOGY

2.1. Materials

Fibres of glass were sourced from Marktech Composites Pvt. Ltd., Bangalore, India, while epoxy resin (LY556) with the hardener (Aradur HY951) was procured from Huntsman, Pune, India. Multiwall carbon nanotubes, strong 99%, with a diameter ranging from 10 to 20 nm and a length of around 10 µm, were used as the filler material. The MWCNTs, with a surface area of ~230 m²/g and a bulk density of 0.3 g/cm³, were incorporated into the epoxy resin matrix at 0%, 1%, and 2% weight percentages to enhance the composite's mechanical properties. To ensure uniform dispersion, the MWCNTs were first sonicated for one hour. Epoxy resin and hardener were combined in a 10:1 ratio. The glass fiber fabric was then impregnated with the prepared epoxy-MWCNT mixture using the hand layup method, subsequently processed through compression molding. The composite laminates were cured for 24 hours at room temperature under constant pressure. For testing, 8-layer laminates were prepared for tensile testing and 6-layer laminates for flexural testing, both with a final thickness of 4.5 mm. Standard ASTM dimensions were used to cut the specimens: 127 mm × 12.7 mm × 4.5 mm for flexural testing (ASTM D790) and 300 mm × 25 mm × 4.5 mm for tensile testing (ASTM D3039). This method guarantees constant testing of the created composite materials and dependable manufacture.

2.2 Methods

2.2.1 Tensile Experimental Setup

In a tensile experimental set up, Fig. 1 A depicts a tensile testing machine used to measure mechanical characteristics such as elongation, young's modulus, and tensile strength, where the specimen is held between the machine's grips and subjected to tensile force, with the resulting deformation being measured. Fig. 1B shows two composite specimens that have undergone tensile testing, revealing signs of deformation such as necking and cracking, indicating that the material has reached its failure point. Fig. 1C focuses on the failure modes of these specimens, with red circles highlighting the areas of fracture, which appear brittle, suggesting low ductility in the material. Collectively, the images illustrate the process of tensile testing and the resulting failure modes of a composite material.

2.2.2 Flexural Experimental sStup

Fig. 2(A) shows three-point test set up, where the composite undergoes a three-point bending test. Image shows a specimen supported at both ends and loaded at the center in a universal testing machine. Fig. 2B presents the composite specimens before testing, highlighting their rectangular shape and uniform appearance. Fig. 2C shows the failure mode after the test (marked with red circles) in the areas of fracture initiation and propagation, which generally occurs at the bottom surface of the specimen due to maximum tensile stress concentration.

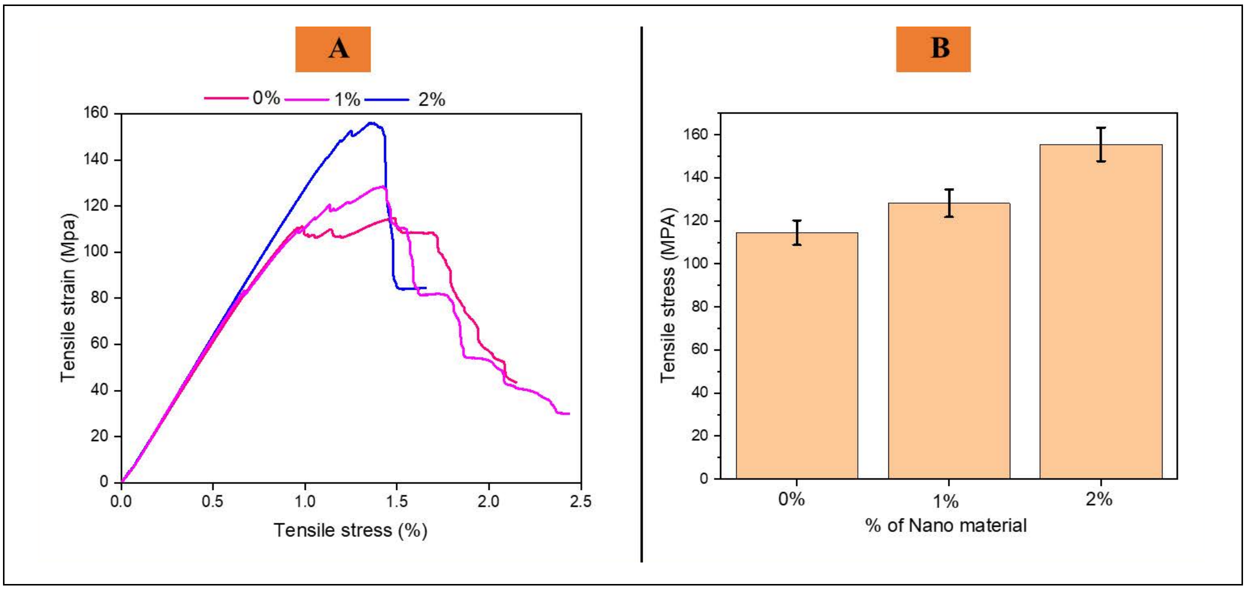

Fig. 3A: Tensile stress-strain curve for samples at 0%, 1%, and 2% nanomaterial concentrations B. Data shown as bar graph

3. RESULT AND DISCUSSION

3.1. Tensile Graph

Fig .3(A) describes the Tensile stress-strain curves, with stress on the X-axis and strain on the Y-axis, by adding nano fillers of multi-wall carbon nanotubes (MWCNTs) of 0%, 1%, and 2%, concentration leading to enhanced mechanical performance. The (0%) specimen, serving as the control, showed a minimum yield strength of 102 MPa, representing the baseline strength of the glass fiber composite without reinforcement. A noticeable increase in yield strength was observed with (1%), highlighting the positive effect of the nano filler. However, the most significant enhancement occurred at (2%) where the composite reached a maximum yield strength of 150 MPa, marking a substantial improvement. high tensile strength, large surface area, and excellent conductivity, acted as reinforcements within the matrix, improving load-bearing capacity and resistance to deformation. The (2%) nano filler composite demonstrated superior performance, with a more pronounced elastic modulus, indicating increased stiffness. This aligns with previous research on polymer composites with carbon nanotubes, reinforcing the idea that nano fillers enhance composite strength and stiffness. Yang *et al.* (2014) There is greater flow stress when the MWCNT proportion rises above 0.5%. Additionally, the strain percentage rises to 0.54.is greater. AdditionallyThese findings underscore the potential of MWCNTs as effective reinforcements for glass fiber composites, enhancing their tensile strength, stiffness, and durability for structural applications. This study sets the stage for developing high-performance composites with tailored properties, using carbon nanotubes as a solution for improving the durability of products made of fibreglass. Regarding the tensile strength measurements. Fig.3(B) indicates variability, with the first sample exhibiting a tensile strength of 114.51 MPa and an error of ±5.7255 MPa, suggesting the true tensile strength lies between 108.78 MPa and 120.24 MPa. The second sample, with a tensile strength of 128.21 MPa and an error of ±6.4105 MPa, indicates the true value could range between 121.80 MPa and 134.62 MPa. The third sample showed a tensile strength of 155.53 MPa with an error of ±7.7765 MPa, meaning the true strength could range between 147.75 MPa and 163.31 MPa. These error bars reflect the variability in the data, with larger error bars indicating greater uncertainty and smaller ones suggesting more precise measurements.

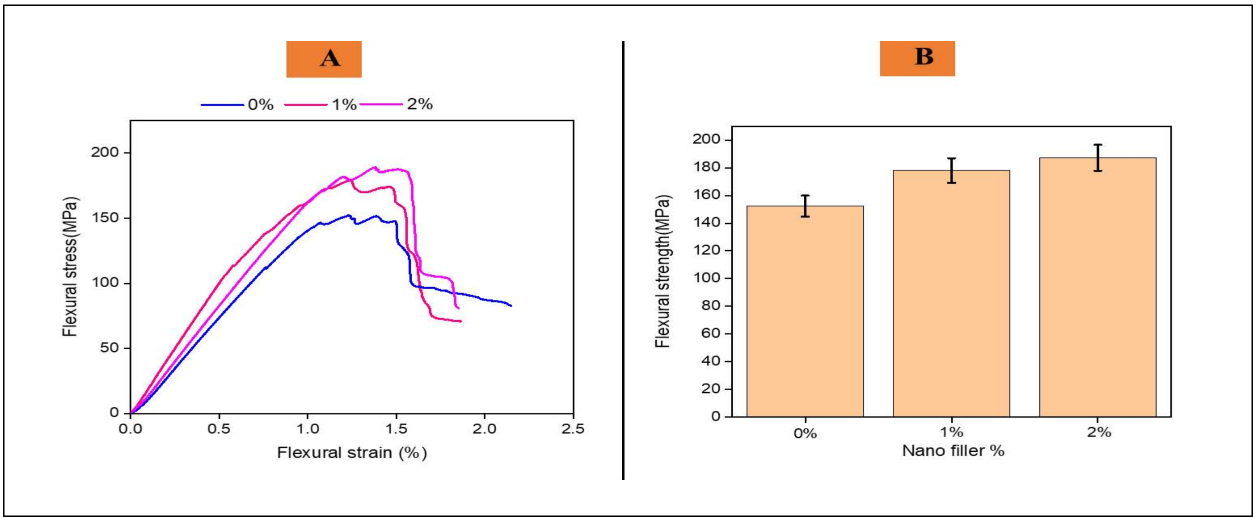

Fig. 4: A: Flexural stress-strain curve for samples with 0%, 1%, and 2% nanomaterial concentrations. B. Data shown as bar graph

3.2 Flexural Graph

Stress-strain curves of flexural for a material with different nanomaterial concentrations (0%, 1%, and 2%), are shown in Fig.4(A). The stress-strain curve goes upward as there is greater nanomaterial concentration, suggesting improved material stiffness and strength. The concentrations of nanomaterial were 152.269 MPa, 178.046 MPa, and 187.26 MPa, respectively, indicating a definite increase in material strength as the nanomaterial content progressed. This upward shift in the curve also reflects an increase in yield strength, which is consistent with the increase in flexural stress values as the nano material content rises. The observed strengthening effects can be explained by several mechanisms. First, grain refinement, which occurs when nanomaterials are incorporated into the matrix, results in a finer microstructure that restricts dislocation movement. According to the Hall-Petch relationship, smaller grains inhibit dislocation motion, leading to higher strength, as evidenced by the increased flexural stress and strength. However, finer grains also reduce the ductility of the material since they make it more difficult for the material to deform plastically before failure. In addition to grain refinement, dislocation pinning contributes to the observed results. Nano materials can act as obstacles to dislocation movement, effectively pinning dislocations in place. This phenomenon increases both yield strength and ultimate tensile strength by preventing dislocations from moving freely through the matrix. As the nanomaterial concentration increases, dislocation motion becomes more restricted, leading to higher strength but reduced ductility, as observed in the decrease in strain at failure. Interface strengthening also plays a critical role. Better load transmission between the two phases may result from a stronger link between the nanomaterial and the matrix interface than from the matrix material itself.

The Fig .4(B) of bar chart shows the flexural strength of the material with varying amounts of nano filler. The flexural strength is 150 MPa at 0% nano filler, but it increases to 180 MPa and 190 MPa at 1% and 2% nano filler concentrations, respectively. The measurement uncertainty is shown by the error bars, which imply that the actual strength may differ by 10–20 MPa. (Dhilipkumar and Rajesh, 2022) According to the experimental findings, the flexural characteristics of composites increased by 26.16% (379.12 MPa) when 1 weight percent of MWCNTs was added. There are probably a number of reasons for the observed increase in flexural strength as the concentration of nano filler increases. As reinforcing agents, nano fillers build a strong network inside the matrix that effectively distributes stress and stops cracks from spreading. Due to their even distribution across the matrix, these nanoparticles improve the composite's capacity for load bearing and mechanical interlocking. Additionally, they strengthen the interfacial bond between the reinforcement and matrix, which is crucial for maximizing structural integrity. The well-dispersed nano fillers, which minimize defects and lower the likelihood of fracture initiation and propagation, are also associated with the improvement in flexural strength. By strengthening the polymer chains at the nanometric scale, nano fillers can raise the modulus of elasticity, increasing the material's resistance to bending and deformation. This results in increased stiffness and strength potential of nanomaterial-enhanced materials in practical applications.

4. CONCLUSION

This investigation examines the impact of varying nanomaterial concentrations (0%, 1%, and 2%) on the flexural and tensile characteristics of the material. Results show that higher nanomaterial content increased the tensile strength from 114.51 MPa to 155.53 MPa, while flexural stress increased from 152.269 MPa to 187.26 MPa. Nanomaterial addition refines the grain structure, enhances dislocation resistance, and strengthens the matrix-nano material interface, improving overall mechanical performance. The increase in material stiffness further supports these findings, as indicated by higher flexural modulus values. However, a trade-off between strength and ductility is observed, with reduced strain at failure as nanomaterial content increases. Effective dispersion of the nanomaterial is critical for achieving these enhancements. The results suggest promising applications in industries requiring high strength and stiffness.

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CONFLICT OF INTEREST

The authors declared no conflict of interest in this manuscript regarding publication.

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