Investigations of Structural Integrity Enhancement Through Multi-Walled Carbon Nanotubes in Carbon Fiber Reinforced Polymers Under Tensile Loading Conditions

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**Abstract.** Due to their intricate designs and limited aerodynamic resilience, drone components are particularly vulnerable to structural damage. Minimizing the risk of fractures is crucial to improving the reliability and performance of these components in real-time applications. This study adopts an integrated experimental and computational approach to develop advanced nanocomposites for the fabrication of high-strength, complex drone structures. Emphasis is placed on the structural behavior of composite materials enhanced with multi-walled carbon nanotubes (MWCNTs) and reinforced with six distinct carbon fiber types: carbon fiber reinforced polymer (CFRP)-UD 230-P, CFRP-UD 230-W, CFRP-UD O, CFRP-Wn Fabric O, CFRP-Wn 230-P, and CFRP-Wn 230-W. Test specimens are designed in compliance with ASTM D3039 standards and modeled using ANSYS Workbench. ANSYS Mesh Tool and ANSYS ACP are employed for discretization and composite lamination. Structural performance is validated through a combination of experimental tests, theoretical modeling, and computational simulations. Results clearly indicate that the incorporation of MWCNTs significantly improves the mechanical strength and durability of the carbon fiber composites, making them highly suitable for critical drone applications.

# Introduction

Carbon nanotubes (CNTs) are nanometer-scale cylindrical structures that exhibit remarkable mechanical and physical properties. In this study, Multi-Walled Carbon Nanotubes (MWCNTs) are incorporated into carbon fiber-reinforced polymer (CFRP) composites to enhance their experimental performance. A mixture of epoxy resin and 5% MWCNTs is prepared according to standard specimen preparation procedures. The specimens conform to ASTM D3039 dimensions, measuring 230 × 25 × 5 mm. In the composite formulation, carbon nanotubes are integrated into the matrix, while the reinforcement consists of 60% carbon fiber (263 g) and 40% epoxy resin with a hardener.

Tensile testing—one of the most fundamental and widely used mechanical evaluations—is employed to determine key material properties such as Young’s modulus, ultimate tensile strength, yield strength, percent elongation, and reduction in area. Enhancements to composite materials are achieved through optimization of their constituents. Improvements to the matrix focus on reducing delamination, integrating fillers, and refining material characteristics. Accurate estimation of composite properties heavily depends on the composition and quality of the core components.

This research employs finite element analysis (FEA) to numerically assess the tensile behavior of nanocomposites. The structural model is developed using epoxy as the matrix and carbon fiber as the primary reinforcement, with MWCNTs added to facilitate a comparative analysis based on variations in mixing ratios. CFRP composites, owing to their superior strength-to-weight ratio, are widely used in aerospace applications such as flight control systems, empennage, and structural surfaces.

To validate the numerical simulations, experimental tests are performed. Strain energy values are then calculated and analyzed to optimize the performance of the nanocomposite structures. In this study, the mechanical response of MWCNTs is evaluated at eight different reinforcement levels.

The load-bearing ability of composite materials is primarily influenced by the fiber content. The high stiffness-to-weight ratio in composite laminates is attributed to the stiffness imparted by the fibers [1,2]. Therefore, accurate determination of fiber orientation—whether unidirectional, bidirectional, or multidirectional—is critical. Fibers used in composites may be made from materials like carbon, glass, or boron, and the performance and durability of laminates are closely tied to the quality of the fiber base. Chemical interactions between fibers and matrix materials enhance thermal, electrical, and mechanical performance [3,4].

Adding secondary strengthening elements can further boost composite efficiency. One of the key roles of the matrix is to prevent delamination, and the structural integrity of laminates is achieved through effective chemical bonding between matrix and fiber. Among various matrix materials, epoxy resin is widely preferred due to its excellent bonding capability and compatibility with a range of fibers, making it the ideal primary matrix in advanced composites [5,6].

# Methodology

The nanocomposite is developed and analyzed using ANSYS ACP, a specialized tool for advanced composite modeling. Prior research has established key material properties of carbon nanotubes, including density, Poisson's ratio, and Young’s modulus [7]. This comprehensive structural analysis encompasses conceptual design, finite element modeling, application of boundary conditions, control strategies, governing equations of Finite Element Analysis (FEA), and grid convergence studies [30-38].

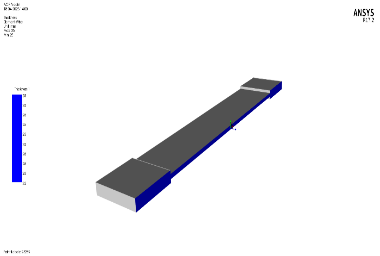
Achieving accurate and reliable results requires adherence to validated simulation methodologies, even when using advanced computational tools. Throughout the analysis, the nanocomposites are systematically evaluated under tensile loading conditions. By exploring various reinforcement combinations and configurations, the mechanical performance can be further optimized [39-44].

**Computational model**

In this numerical simulation study, the composition of material mixtures plays a crucial role in determining the overall performance of the system. The analysis focuses on comparing composite laminates with and without the inclusion of MWCNTs using ANSYS software [8]. Exploring various material combinations enables the optimization of composite properties, particularly when considering specimen thickness, which significantly influences simulation outcomes [45-50].

While thickness may vary depending on the test type and material used, nanocomposites generally exhibit superior mechanical properties within specific dimensional ranges. Key characteristics such as Poisson’s ratio, Young’s modulus, and thermal expansion coefficient are used to define CNTs in numerical modeling [9,10]. Leveraging prior research, MWCNT properties are integrated into the simulation environment through ANSYS’s customizable material property input features [11].

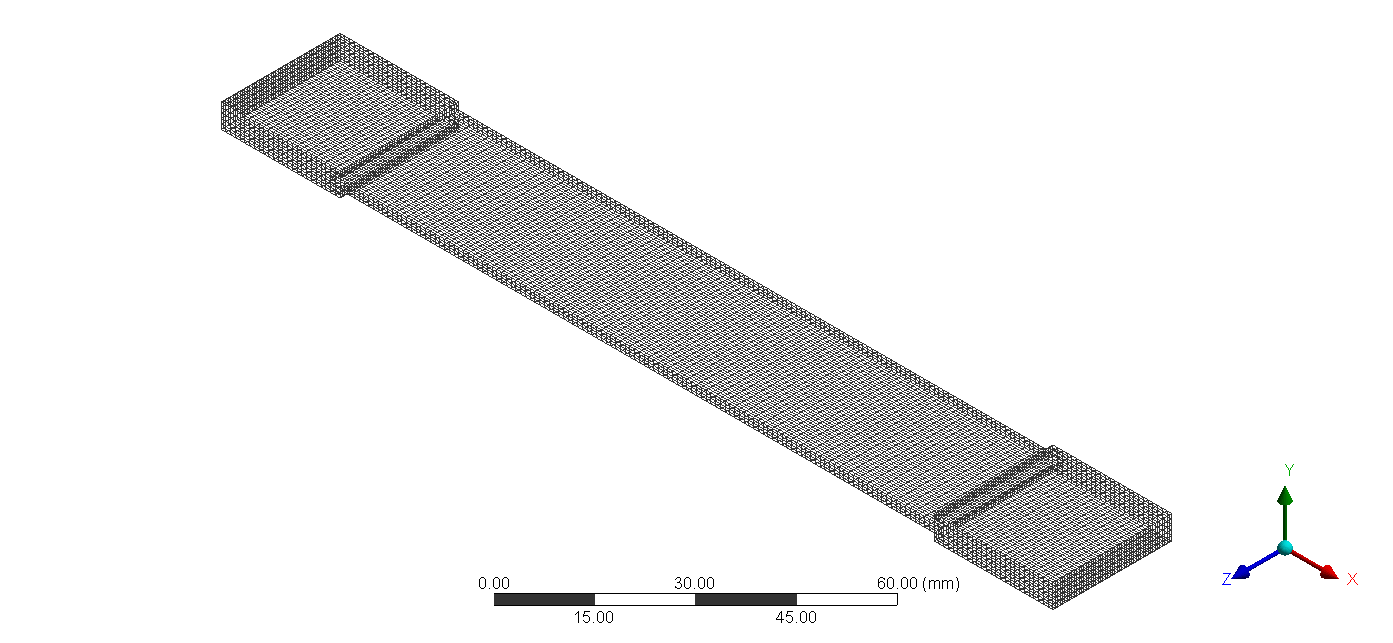
The conceptual design is translated into a three-dimensional test specimen through a systematic data definition and model-building process. For simulation accuracy, the physical test specimen must closely match the computational model. Structural modeling in ANSYS involves both the creation of a computational framework and thorough preprocessing steps to ensure simulation reliability [12,13]. In this study, the specimen is modeled in accordance with the ASTM D3039 standard, utilizing a dog-bone geometry for tensile testing. The finalized 3D model used for the simulation is shown in Figure 1.



1. Computational model of Tensile test specimen

**Discretization**

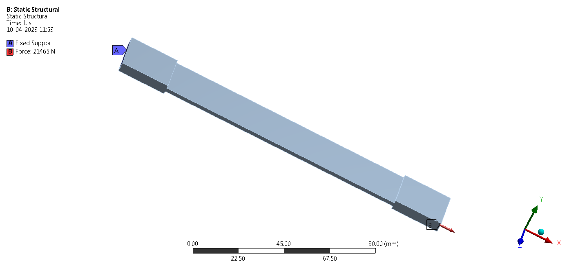
Discretizing a test model creates a finite element model. This strategy is best with organized grid formations because it shows results faster. Intermediate-level specs generate nodes and elements. This study generates structured meshes from a dog bone-shaped test model using ANSYS mesh. Figure 2 depicts a discrete model. FEA methods using ANSYS may provide high-quality structured meshes for test models [51-60]. This analysis shows 0.9 mesh quality potential for future discoveries. Due to the availability of external stress conditions, this work used stiffness-based grid convergence to reduce mesh flaws [14-16].



1. The typical meshed structure of test specimen

**Boundary conditions**

Adding boundary conditions to numerical simulations causes deformations and stress. Mechanical properties including density, Poisson's ratio, Young's modulus, thermal conductivity, and three-dimensional geometric attributes are initial inputs. For boundary values, the test model needs forces, support, cross-sectional areas, and connections. As shown in this work, external tensile stress, orientation, support type, and nanocomposites' mechanical characteristics affect results [61-69]. A tensile force of 21465 N is applied to the test specimen for analysis for all the cases. A fixed support replicates testing loading circumstances opposite the test model's cross-section [17-19]. Figure 3 shows the investigation's boundary conditions: steady support and a tensile load at one extremity.



1. Boundary condition of impact test

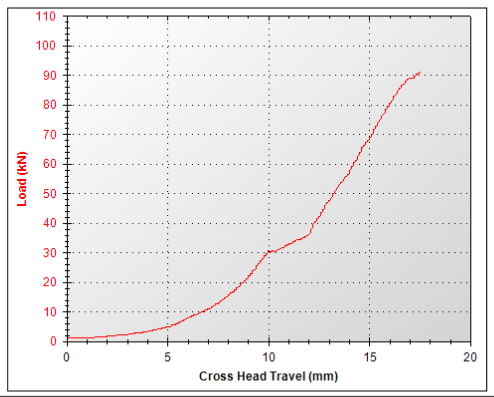
# Validation study – Tensile load

Carbon fiber is widely employed as a load-bearing reinforcement material due to its excellent mechanical properties. Graphene serves as a foundational element in the production of carbon fibers, which are typically available in two forms: dry fabric and prepreg. Naturally dark grey or black in appearance, carbon fibers are highly compatible with epoxy resins, which are thermosetting polymers known for their transition from liquid to solid during curing [20-22].

To further enhance the structural performance of carbon fiber reinforced polymers (CFRPs), multi-walled carbon nanotubes (MWCNTs) are incorporated into the matrix. These nanotubes, with diameters in the nanometer range, significantly boost the mechanical strength and durability of the composite. In this study, epoxy resin is blended with 5% MWCNTs prior to fabrication [23-24]. Tensile test specimens are designed according to ASTM D3039 standards, with dimensions of 230 mm × 25 mm × 5 mm, ensuring consistency and reliability of the test results. The final nanocomposite comprises 60% carbon fiber (263 g), 40% epoxy resin (including hardener), and 5% MWCNTs by weight. Upon finalizing the material composition, fabrication is carried out using the compression molding technique. Compression molding is chosen for its simplicity and ability to produce consistent, high-quality composites. The process is executed under a pressure of 3 psi, following standardized procedures to ensure reliable performance of the resulting nanocomposite material [25-29].

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| 1. A typical view of tensile test specimen | 1. Test Specimens – prototype |

Figure 4 illustrates the dimensional layout of the tensile test specimen, while Figure 5 displays the fabricated sample prepared for experimental analysis within the testing setup. Mechanical testing is employed to evaluate the structural behavior of materials and to develop problem-solving competencies in material characterization. Among the various structural evaluation methods, tensile, bending, and impact tests are the most commonly utilized, with tensile testing being the most prevalent due to its ability to reveal critical material properties. Key mechanical parameters assessed during the tensile test include elastic modulus, yield strength, ultimate tensile strength, elongation, and percentage reduction in area. In the tensile testing procedure, one end of the specimen is subjected to an axial load, while the opposite end is secured to the grips of the UTM. Using the gauge length and cross-sectional area of the specimen, stress and strain values are computed, enabling accurate analysis of the material’s structural performance under load.



1. Load Vs Elongation graph

Figure 6 presents the graphical illustration of the material's behavior under tensile loading, based on experimental analysis conducted at room temperature. Table 1 outlines the input parameters including specimen geometry, material type, and dimensions along with the corresponding output data obtained from testing.

1. Tensile Test report

|  |  |
| --- | --- |
| **Input Data** | **Output Data** |
| Specimen Shape: Dog-Bone Shape | Load At Yield: 91.10 kN |
| Specimen Type: Nanocomposite | Elongation At Yield: 1.5300 mm |
| Specimen Description: Carbon fiber+ MWCNTs | Yield Stress: 581.600 N/mm2 |
| Specimen Width, Thickens, Length: | 25mm, 10 mm, 175 mm |

The experimental results clearly indicate that the test specimens reinforced with MWCNTs exhibit excellent load-bearing capacity, withstanding the applied forces without experiencing significant deformation. This confirms the enhanced structural integrity of the developed nanocomposite.

# RESULTS AND DISCUSSIONS

The designed test specimen is computationally analyzed with different types of CFRP materials, and their respective results are obtained. Figures 7-9 represents the total deformation, Equivalent stress, Equivalent elastic strain of CFRP UD – O base material.

A colorful rectangular object with a scale

Description automatically generated with medium confidence

1. Total deformation of CFRP UD-O base material

A blue and green rectangular object

Description automatically generated

1. Equivalent Elastic Strain of CFRP UD-O base material

A long rectangular object with blue and yellow squares

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1. Equivalent Stress of CFRP UD-O base material

Figures 10-12 represents the total deformation, Equivalent stress, Equivalent elastic strain of CFRP UD – O material with MWCNTs,

A rainbow colored rectangular object

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1. Total Deformation of CFRP UD-O material with MWCNTs

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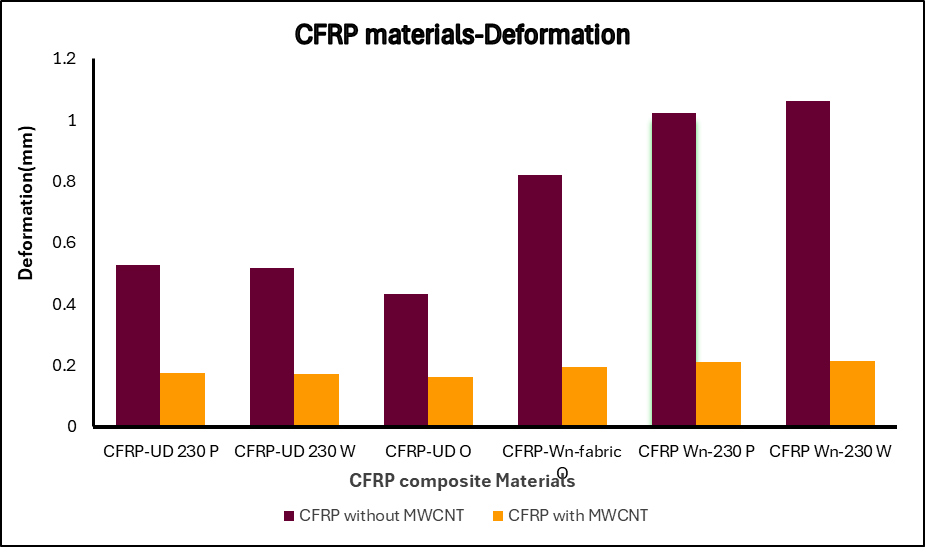
1. Equivalent Elastic Strain of CFRP UD-O material with MWCNTs

A blue and green rectangular object

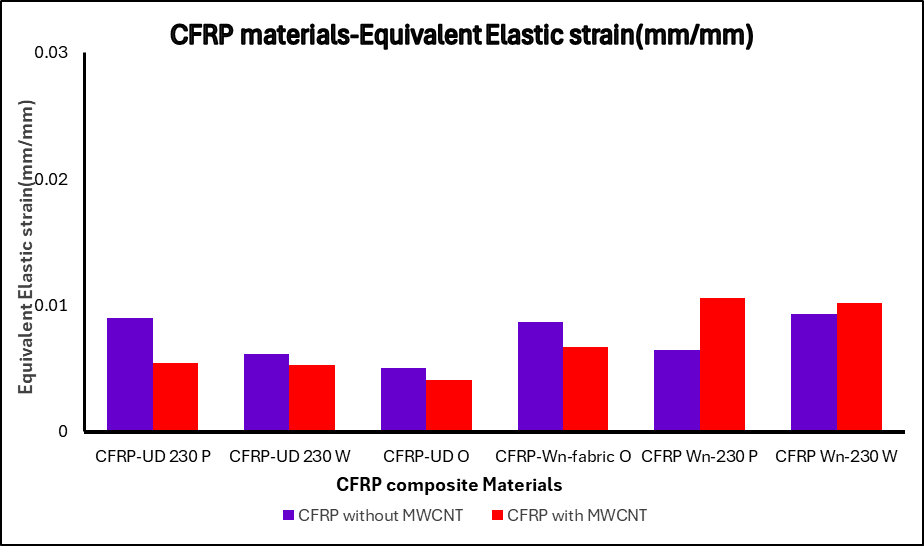
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1. Equivalent Stress of CFRP UD-O material with MWCNTs

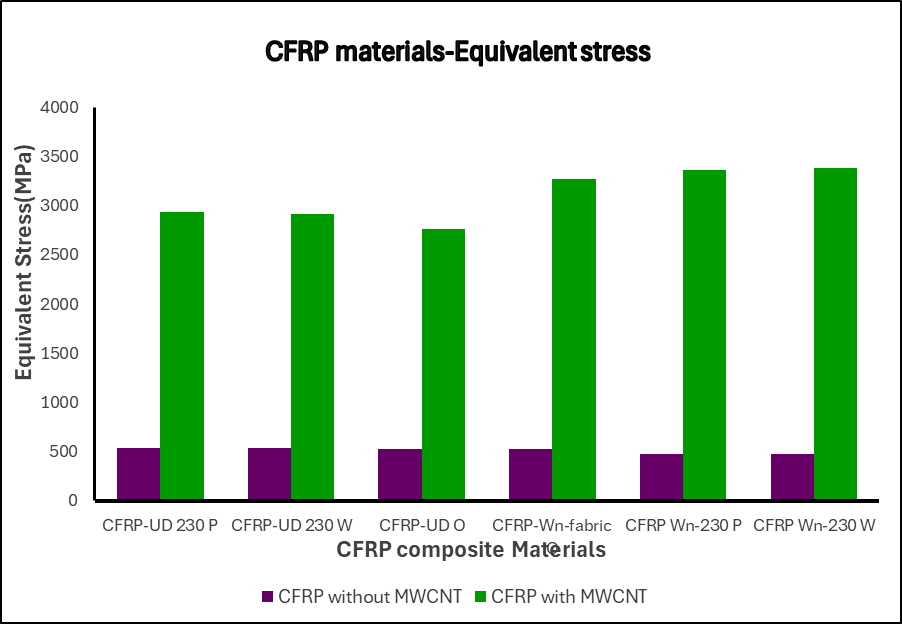
From Figures 13-15 represents the comparative data of the various CFRP base composites with CFRP material with MWCNT materials.



1. Comprehensive report of Total deformation of various CFRP composites



1. Comprehensive report of Equivalent Elastic strain of various CFRP composites



1. Comprehensive report of Equivalent stress of various CFRP composites

# CONCLUSION

This study employed literature to get main and secondary nanocomposite elements, mechanical properties, boundary conditions, and three-dimensional information. Initial simulation processing is done in ANSYS Design Modeler, Mesh Tool, and ACP. Results like total deformation and strain energy guided the stiffness-based selection and solution procedure in the ANSYS Structural tool during the solutions phase. After comparative testing on nanocomposites with different compositions, numerical results for a 5% MWCNT nanocomposite are validated using regular experimental testing. Validation showed that this study's advanced one-way coupled methodology is best for solving composite problems. Research on nanocomposites shows that MWCNTs perform well under tensile tension. MWCNT materials outperform other carbon nanotube materials tested and loaded similarly. Performance-wise, these MWCNT materials show negligible deformation and strain despite high stress. The proposed CFRP 230 W provides 66% less deformation and 14% less elastic strain than the base CFRP 230 W material and it is due to the addition of MWCNTs, similarly other proposed material also had a better performance. The CFRP 230 W composite material outperformed the other six materials, followed by CFRP UD O having the best structural performance. This study found that MWCNT-based CFRP materials outperform basic CFRP.

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