Multi-Perspective Characterization of Carbon Fiber-Based Advanced Nanocomposites for Complex Real-Time UAV Applications: A Coupled and Validated Engineering Framework

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**Abstract.** Carbon Fiber Reinforced Polymers (CFRPs) are high-performance composite materials formed by combining carbon fibers with a polymer matrix, typically epoxy. Their exceptional strength-to-weight ratio, durability, and stiffness make them indispensable across aerospace, automotive, and structural industries. This study explores the enhancement of CFRP composites through the integration of carbon nanotubes (CNTs), including both single-walled (SWCNTs) and multi-walled (MWCNTs) variants. The incorporation of CNTs is shown to significantly improve the flexural strength, tensile performance, and overall mechanical behavior of the composite—even at low concentrations. Test specimens are conceptually modeled in ANSYS Build Modeller according to ASTM D3039 standards, with ANSYS Mesh Tool and ANSYS ACP used for discretization and composite fabrication. Structural simulations and comparative evaluations are conducted using ANSYS Structural to determine the influence of various filler additions. Among the configurations studied, the CFRP Woven-Fabric composite exhibited the least deformation, emerging as the most structurally stable. Furthermore, the inclusion of CNTs led to an approximate 50% reduction in overall deformation, underscoring the effectiveness of CNT reinforcement in enhancing the mechanical performance of CFRP composites.

# INTRODUCTION

Wings, bumpers, fuselages, and propellers are critical components that often struggle with subpar structural performance. When selecting these parts, engineers must balance cost-effectiveness with the need for high strength and lightweight design. However, lightweight materials tend to be less durable and pose challenges in maintaining structural integrity. Complex engineering features, like coaxial rotor setups and sophisticated designs, can generate significant stress, particularly on the lower rotor, and increase the likelihood of failure caused by fluid dynamics and flow interactions. Bumpers are particularly vulnerable to catastrophic failure under sudden impacts, while aquatic vehicle components face ongoing challenges from constant activity and hydrodynamic forces that weaken structural resistance.

Enhancing the durability and robustness of these complex parts is vital for extending their service life while keeping weight low. Advanced materials like metal matrix composites, sandwich composites, hybrid composites, and polymer matrix composites reinforced with Single-Walled Carbon Nanotubes (SWCNTs) and Multi-Walled Carbon Nanotubes (MWCNTs) offer promising solutions. Carbon nanotubes (CNTs) significantly boost toughness by serving as energy-absorbing bridges during fracture, thereby hindering crack growth and enhancing overall durability. Innovative hybrid composites that combine CNTs with materials such as polyaniline further optimize mechanical strength and thermal conductivity through sophisticated manufacturing techniques. These cutting-edge materials are paving the way for more resilient, lightweight, and efficient engineering components.

The development of carbon nanotube (CNT)-enhanced polymer composites has been significantly advanced through key research efforts. A. K. Gupta (2014) pioneered Finite Element Analysis (FEA) for CNT-reinforced composites, establishing essential methodologies for mechanical property evaluation, meshing techniques, and composite modeling—providing a critical framework for this study [1]. Expanding on this, Kulmani Mehar (2017) investigated the bending behavior of nanocomposites, delivering fundamental theoretical insights and mechanical data, despite early-stage computational challenges. Recognizing the robustness of ANSYS for such analyses, this study employs ANSYS Workbench 17.2 to explore nanocomposite tensile behavior [2]. Further contributions came from Mohammed Jawad Aubad (2020), who conducted FEA and experimental tests on hybrid laminates reinforced with multi-walled CNTs (MWCNTs), epoxy resin, carbon fiber, and Kevlar. His findings on MWCNT behavior, simulation approaches, and fabrication techniques proved instrumental in shaping this research [3]. The multifunctional superiority of CNT-based composites was underscored by J.-H. Du (2007), who highlighted their exceptional thermal and electrical conductivity, tensile strength, and strength-to-weight ratio. His review critically examined reinforcement efficiency, manufacturing hurdles, and the effects of CNT concentration, matrix selection, and processing conditions—offering vital guidance for optimizing CNT integration [4]. A comparative study by Florian H. Gojny (2005) on fractured behavior in nanocomposites reinforced with single-walled (SWCNTs) and multi-walled CNTs (MWCNTs) provided direct support for this study’s comparative analysis [5]. Additionally, Robiul Islam Rubel (2019) investigated CNT agglomeration effects, revealing how clustering compromises matrix integrity and reinforcement efficacy—a key consideration for addressing dispersion challenges in this work [6].

# PROPOSED METHODOLOGIES – COMPUTATIONAL APPROACHES

A computational method known as FEA is utilized to predict how an object will behave under various physical conditions, such as heat, stress, and fluid movement [7-9]. This research was significantly supported by the structural analysis and composite preparation tools accessible in ANSYS Workbench [10-12]. Figure 1 illustrates how the process of material analysis is executed with the Carbon fibre reinforced composites (CFRP) composites in this work [34-43].

A diagram of a process

Description automatically generated

1. Division of analysis of CFRP composites

## Computational Model

In modern research, computational models are crucial, particularly when analyzing three-dimensional data to understand the fundamental properties of materials [13-15]. In this scenario, ASTM standards provide common design parameters that simplify the creation of customized numerical models for specific tests and material properties. The testing procedures for evaluating the flexural characteristics of polymer matrix composites are outlined in the ASTM D7264 standard [16-18]. Adherence to this standard is vital for accurately measuring the flexural properties of composite materials under predetermined conditions [19-21]. The ASTM D7264 design specifications of 100 m span, 20 mm width, and 7 mm thickness are used in this study. Ten layers are permitted for multidimensional composite fibre research. In FEA, boundary conditions (BCs) are crucial for defining how a model interacts with its surroundings [44-60] and influencing the accuracy and reliability of the simulation results [22-24]. Choosing the wrong boundary conditions, such as over- or under-constraining the model, can lead to significant inaccuracies in the results [25-28]. For example, if a model is improperly constrained, it may show incorrect deformations or stress distributions. In this study, the concentrated load is applied at the center of the simply supported composite beams, and the lower edges of the rectangular composite structure are supported by rollers [29-33].

# Results And Discussions

## Computational analysis of CFRP composites under compression test

In this section, the CFRP composites are made to undergo compression test without any CNTs and the resulting contours for the best performing materials are shown in Figures 2 to 5. Meanwhile, Figures 6 to 9 show the compiled results of various structural factors that determine the performance of material. It is seen from the graphical representations that the CFRP -Woven Fabric composite works the best as it possesses the lowest total deformation, equivalent elastic strain, equivalent stress, and strain energy [61-68].

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| --- | --- |
| A blue and green colored object  AI-generated content may be incorrect. |  |
| 1. Total deformation of CFRP-Woven Fabric composite | 1. Equivalent stress of CFRP-Woven Fabric Composite |
|  |  |
| 1. Equivalent elastic strain of CFRP-Woven Fabric Composite | 1. Strain energy of CFRP-Woven Fabric composite |

**A graph of different colored rectangles

AI-generated content may be incorrect.**

1. Total Deformation of CFRP composites without CNTs

**A graph of different colored rectangular shapes

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1. Equivalent stress of CFRP composites without CNTs

A graph of different colored bars

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1. Equivalent elastic strain of CFRP composites without CNTs

A graph of different colored squares

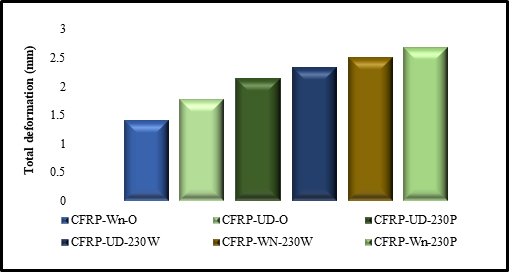
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1. Strain energy of CFRP composites without CNTs

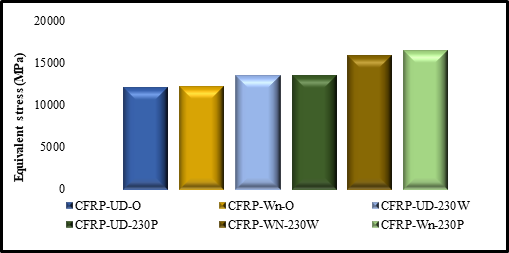
## Computational analysis of CFRP composites associated with SWCNTs under compression test

The CFRP composites are subjected to a compression test in this section in the presence of SWCNTs, and the resulting contours for the top-performing materials are displayed in Figures 10 through 13. In the meantime, the combined results of numerous structural parameters that affect a given material's performance are displayed in Figures 14 to 17. The graphs demonstrate that the CFRP – Woven composite and CFRP- unidirectional - orthogonal composite give best structural outcomes [69-73].

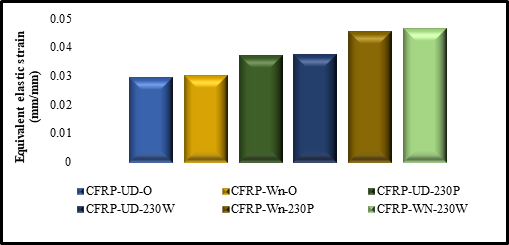
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| --- | --- |
|  | A blue object with black lines  Description automatically generated |
| 1. Total Deformation of CFRP-Woven Fabric composite | 1. Equivalent stress of CFRP – unidirectional – orthogonal composite |
| A blue and green striped object  Description automatically generated | A blue and green object with text  Description automatically generated |
| 1. Equivalent elastic strain of CFRP – unidirectional – orthogonal composite | 1. Strain energy of CFRP-Woven Fabric composite |



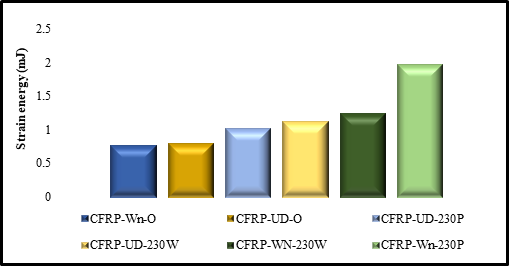
1. Total deformation of CFRP composites with SWCNTs



1. Equivalent stress of CFRP composites with SWCNTs



1. Equivalent elastic strain of CFRP composites with SWCNTs

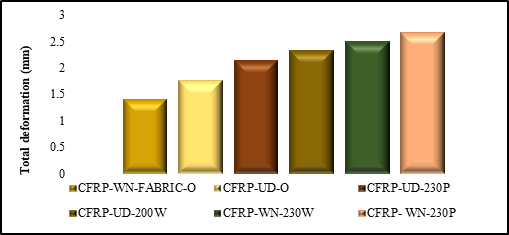


1. Strain energy of CFRP composites with SWCNTs

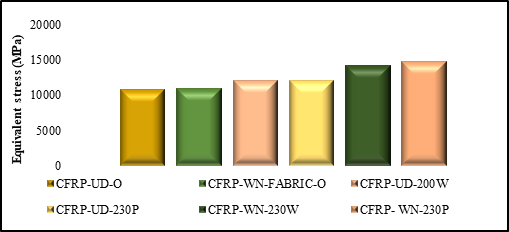
## Computational analysis of CFRP composites with MWCNTs under compression test

The CFRP composites with MWCNTs are subjected to a compression test in this section. The contours for the CFRP – Woven Fabric Composite and CFRP – Unidirectional-orthogonal composite is displayed from Figures 18 to 21. In the meantime, the combined results of numerous structural parameters that affect a given material's performance are displayed in Figures 22 through 25. The graphs demonstrate that CFRP – Woven Fabric Composite have the lowest total deformation, but CFRP – unidirectional – orthogonal composite has lower stress values.

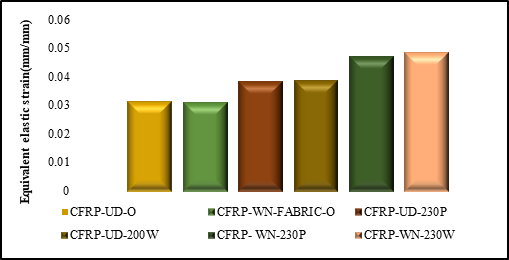
|  |  |
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|  |  |
| 1. Total deformation of CFRP – Woven Fabric Composite | 1. Equivalent stress of CFRP – unidirectional – orthogonal composite |
| A blue and green striped object  Description automatically generated | A blue and green striped object  Description automatically generated |
| 1. Equivalent elastic strain of CFRP – unidirectional – orthogonal composite | 1. Strain energy of CFRP – unidirectional – orthogonal composite |



1. Total deformation of CFRP composites with MWCNTs



1. Equivalent stress of CFRP composites with MWCNTs



1. Equivalent elastic strain of CFRP composites with MWCNTs

A graph of different colored squares

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1. Strain energy of CFRP composites with MWCNTs

# Conclusion

All the fundamental data such as 3-Dimensional information, mechanical properties of used materials, boundary conditions, selections of main and sub elements of nanocomposite of this work are obtained from the standard literature survey. The pre-processing of this simulation methodology is completed with the help of ANSYS Design Modeler, ANSYS Mesh Tool, and ANSYS ACP. The solving process of this work is executed based on stiffness approach in ANSYS Static Structural tool. The fundamental needs of this work for evaluation purposes are total deformation, equivalent stress, equivalent elastic strain and strain energy that provided the path for stiffness-based selection and solution. Finally, the comparative analyses are executed which show that CFRP – Woven Fabric Composite and CFRP – unidirectional – orthogonal composite perform the best, having the lowest total deformation, stress and strain values among others. However, it is seen that the total deformation is far lesser in case of CFRP – Woven Fabric Composite, hence making it a reliable material. It is observed that this composite performs even better when the CNTs are associated in its composition. Around half of the total deformation is further reduced when the CNTs are added, thus proving the fact that the addition of CNTs always enhances the mechanical properties of the CFRP composites. The observed differences in performance between SWCNTs and MWCNTs reveal key considerations for composite material design, particularly in applications like UAV landing gear where structural integrity is paramount. SWCNTs, exhibiting lower total deformation and elastic strain, demonstrate superior stiffness and dimensional stability under load, making them ideal for resisting bending and maintaining precise geometry. Conversely, MWCNTs showcase reduced equivalent stress and strain energy, indicating enhanced stress distribution and energy absorption capabilities, which are crucial for mitigating impact forces and damping vibrations. The selection between SWCNTs and MWCNTs as reinforcing agents depends on the specific design priorities: prioritizing stiffness favors SWCNTs, while emphasizing impact resistance suggests MWCNTs.

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