Multi-Perspective Characteristics Studies on Various Polymer Fibers based Advanced Nanocomposites for Complicated Real-Time Applications through Coupled and Validated Engineering Approaches

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**Abstract.** Robust flexural strength, load-bearing capacity, and design resilience are critical for complex real-time structural applications, particularly in aerospace components such as propellers, fuselage, and wings. This study presents a dual experimental–computational investigation into the performance of advanced polymer matrix composites reinforced with and without Multi-Wall Carbon Nanotubes (MWCNTs). Utilizing ASTM D7264 standards, test specimens are virtually modeled using ANSYS Build Modeller, with meshing and composite lamination handled through ANSYS Mesh Tool and ANSYS ACP, respectively. Structural simulations are performed on various composite configurations, followed by analytical validation, yielding an impressively low error margin of just 0.3% compared to the simulated results. Among the tested materials, HMS carbon epoxy demonstrated superior flexural performance in the absence of MWCNTs. When MWCNTs are incorporated, both HMS carbon epoxy and AS carbon epoxy composites exhibited enhanced structural characteristics. The findings affirm that MWCNT-reinforced composites offer promising potential for high-strength, lightweight solutions in structural problem-based aerospace and engineering applications.

# INTRODUCTION

Carbon Nanotubes (CNTs) are nanoscale cylindrical structures composed of carbon atoms, known for their exceptional ability to enhance the properties of composite materials. This study focuses on evaluating the flexural behavior of nanocomposites through numerical simulations using Finite Element Analysis (FEA). The composite system in this structural analysis is reinforced with carbon fibers and epoxy resin, while Multi-Walled Carbon Nanotubes (MWCNTs) are incorporated for comparative performance assessment.

The ever-evolving mechanical characteristics of composite materials are largely influenced by the matrix, which not only holds the reinforcing fibers in place but also enhances the overall material strength by ensuring effective bonding. In this investigation, five types of nanocomposites are fabricated by blending varying concentrations of MWCNTs. Among these, four advanced nanocomposites are subjected to flexural testing under typical loading scenarios to evaluate their potential as structural materials.

To identify the optimal configuration, the study concludes by estimating and comparing the strain energy of each nanocomposite variant. Ten distinct MWCNT reinforcement levels are explored to understand their impact on mechanical performance, offering a comprehensive insight into the role of nanotube concentration in material optimization.

## Literature Survey

Raj Kumar G et al. (2019) emphasized that the stiffness of a laminate primarily stems from the reinforcing fibers, which contribute to the composite's notably high stiffness-to-weight ratio [1]. As noted by Zhou et al. (2016), accurate evaluation of fiber orientation is critical, as the load-bearing capacity is significantly influenced by how loads are transmitted through the fibers [2]. According to Prakash et al. (2016), fibers can be arranged in unidirectional, bidirectional, or multidirectional patterns, each impacting structural behavior differently [3]. Zhao et al. (2011) further highlighted that the durability and efficiency of a composite laminate largely depend on the quality of its fiber foundation [4].

Raj Kumar G et al. (2018) supported their numerical results with experimental validation, reinforcing the reliability of their computational approach [5]. Yengejeh et al. (2017) pointed out the importance of incorporating secondary reinforcements that aid both direct and indirect strengthening mechanisms in order to enhance laminate efficiency [6]. M. S. Kumar et al. (2017) underscored that the internal chemical bonding between matrix and fibers is vital for achieving long-lasting composite laminates [7]. Gojny et al. (2005) identified epoxy resin as an optimal matrix material due to its compatibility, strength, and bonding capabilities with various fiber types [8].

In a comprehensive finite element analysis (FEA) study, A.K. Gupta et al. (2014) provided strong evidence supporting the mechanical modeling of CNT-reinforced polymer composites, detailing mesh configuration, material properties, and element data [9]. Kulmani Mehar et al. (2017) expanded on this by using ANSYS Workbench 17.2 to model the tensile performance of nanocomposites, offering deep insights into the structural behavior under load [10]. J-H Du et al. (2007) outlined the multi-functional benefits of CNT-based nanocomposites, such as enhanced electrical conductivity, tensile strength, thermal conductivity, and superior strength-to-weight characteristics [11].

Robiul Islam Rubel et al. (2019) addressed the challenge of CNT agglomeration, showing how it adversely impacts the matrix-reinforcement interface and diminishes mechanical efficiency [12]. Several studies [13–17] have examined flexural performance from different disciplinary perspectives, highlighting that the quantity and proportion of constituents can either enhance or compromise laminate behavior [18]. Kulkarni et al. (2010) noted that although composite thickness may vary with testing conditions, a 10 mm thickness is generally optimal for maximizing the mechanical advantages of nanocomposites [19]. Lastly, M. Rajagurunathan et al. (2018) stressed that a rigorous modeling process encompassing geometry definition, mesh generation, boundary condition assignment, and validation is essential for producing accurate and reliable flexural analysis results [20].

# Computational Methodology

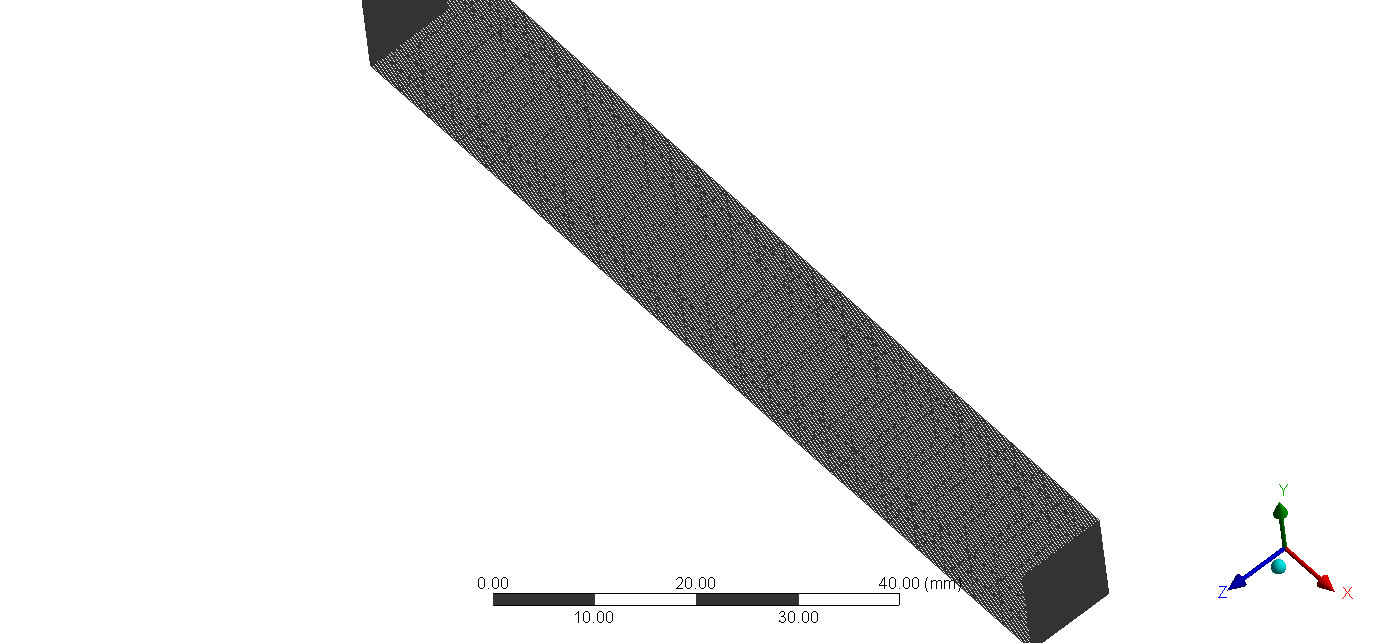
Computational structural analyses are carried out using FEA [21-23], a method that utilizes preloaded numerical codes. The structural analysis and composite preparation tools in ANSYS Workbench made significant contributions to this work [21-23].

## Computational Model

When studying fundamental properties, ASTM standards provide universal design parameters to make it easier to build a numerical model depending on the nature of the test and the properties of the material. 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 multi-dimensional composite fiber research [24-26, 71-74].

## Discretization

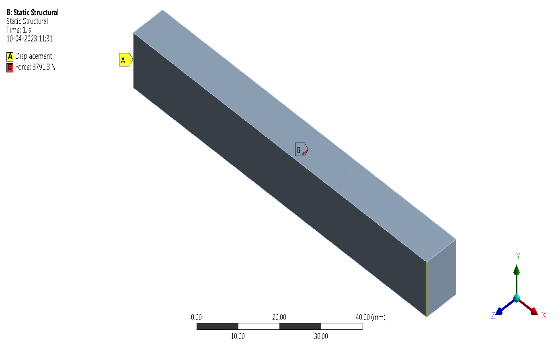
The 3-D brick pieces used in this piece are discretized. The structural formation is the reason why this mesh's quality is greater than 90% [27-29]. Test specimen discretization is shown in Figure 1.



1. Discretization image of flexural test specimen

## Boundary Conditions

Computational simulation can be perfectly demonstrated with the right boundary conditions. Support for test specimens, external loads and vibrational loads served as the main boundary conditions in FEA[30-34]. In this work, the focused load is projected at the midspan of the simply supported composite beams, and the bottom margins of the rectangular composite structure are supported by rollers. Details of the boundary condition implementation are shown in Figure 2.

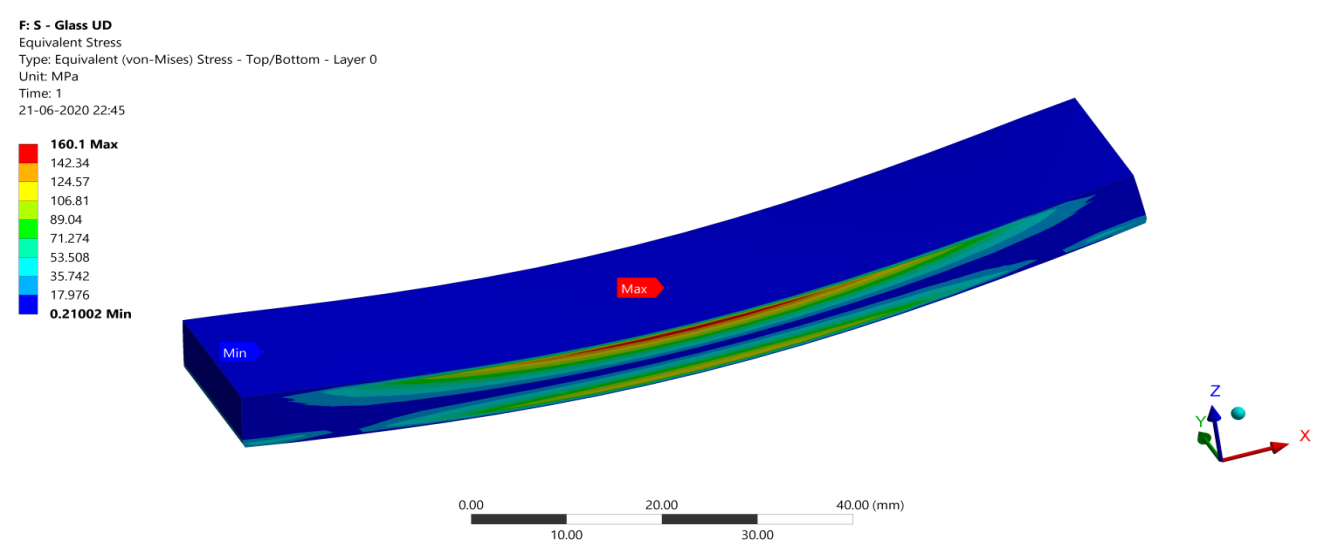


1. Boundary condition of flexural test specimen

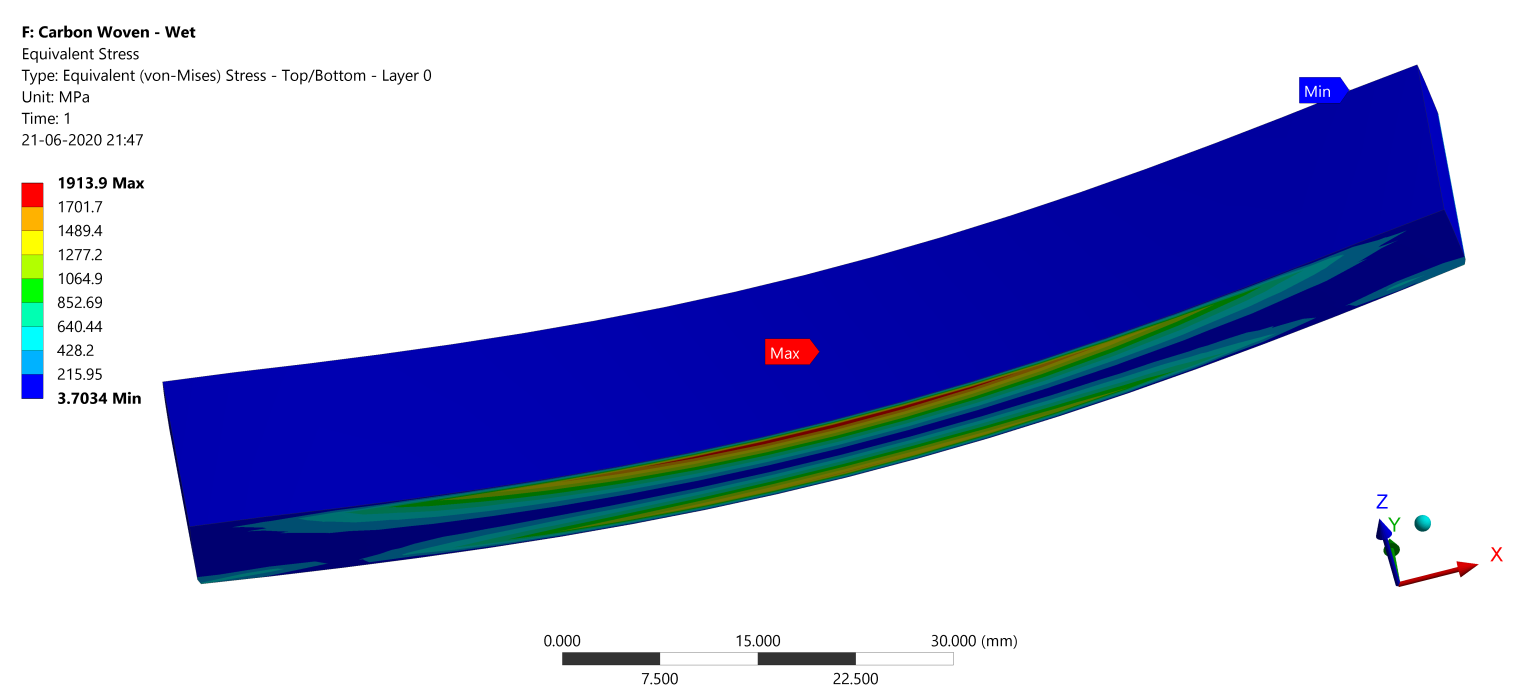
## Validation Study

To increase its robustness, the sensitivity test must be run on advanced results. In this instance, Equations. (1) and (2) are used to perform the validation based on the conventional theoretical procedure [35-40]. First, the maximum flexural stress fluctuations based on epoxy S-glass UD with MWCNTs are estimated theoretically and numerically using FEA [66-70]. The relevant stress variations on test specimens made of GFRP-based nanocomposite are shown in Figure 3.

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| --- | --- |
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|  |  |



1. The equivalent stress variations on Epoxy S-Glass UD



1. The equivalent stress variations on Epoxy Carbon-Woven-Wet

After comparing the computed maximum stress to one another, the error percentage is found to be 0.24%. The same standard formula is expanded for the greater flexural load instance, which is a CFRP-based nanocomposite, due to the little error [41-50]. In the second validation, epoxy carbon-woven-wet are in the lead. The method described below is used to determine theoretical stress value. The CFRP-nanocomposite's equivalent stress FEA simulation result is also displayed in Figure 4. Table 1 provided comprehensive information on error percentages, FEA simulation results, and theoretical estimations [51-55].

1. Comparative analysis of advanced composite materials

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Material Name** | **Structural Output** | **FEA Computational outcomes** | **Analytical outcomes** | **Error Percentage (%)** |
| GFRP-Nanocomposite | Maximum Equivalent Stress (MPa) | 160.1 | 160.564 | 0.29 |
| CFRP-Nanocomposite | 1913.9 | 1931.748 | 0.93 |

# Results and Discussions

## Computational analysis of various composites associated with and without MWCNTs

Structural analysis of various composite material with and without MWCNTs are carried out. The corresponding FEA outcomes of normal stress and equivalent stress are revealed in Figures 5 and 6.

A computer screen shot of a curved object

AI-generated content may be incorrect.

1. Computational analysis of Normal stress of MWCNTs material

A blue and green curved object

AI-generated content may be incorrect.

1. Computational analysis of Equivalent stress of MWCNTs material
2. Comparative outcomes of various composite materials
3. Comparative outcomes of various composite materials with MWCNT

Based on the comprehensive FEA results for composite materials without MWCNT reinforcement, HMS epoxy carbon demonstrated superior performance compared to other evaluated materials [56-60]. The detailed quantitative findings from the FEA simulations are presented in Figures 7 and 8. When MWCNTs were incorporated, both HMS epoxy carbon and AS carbon epoxy composites exhibited reduced values in key structural parameters, including equivalent stress, normal stress, and stress intensity [61-65].

# CONCLUSION

The various aspects of advanced nanocomposites characteristics and the studies of flexural properties are carried out. There is a 0.9 percent error in the validation between computational and analytical results. With the same testing and load, after comparing various nanocomposites associated with and without MWCNTs. Without MWCNT material, HMS carbon epoxy gives better results compared with others. And with MWCNT based materials, HMS epoxy carbon and AS carbon epoxy both provide better performance over other composites. The results are almost the same for both the materials

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