Investigations of the Structural Performances of Various Carbon Fiber Reinforced Polymers Added With and Without Single-Walled Carbon Nanotubes

Gopinath Vinayagam1, Ramesh Mageswaran2, Rajkumar Gunasekar3, Balaji Ganesan4, Subhav Singh5,6,7, Deekshant Varshney8,9, and Vijayanandh Raja1, a)

1Department of Aeronautical Engineering, Kumaraguru College of Technology, Coimbatore-641049, Tamil Nadu, India

2Department of Aerospace Engineering, SNS College of Technology, Coimbatore-641035, Tamil Nadu, India

3Department of Automobile Engineering, Kumaraguru College of Technology, Coimbatore-641049, Tamil Nadu, India

4Department of Aerospace Engineering, Hindustan Institute of Technology and Science, Chennai-603103, Tamil Nadu, India

5Centre for Promotion of Research, Graphic Era (Deemed to be University), Uttarakhand, Dehradun, India

6Division of research and development, Lovely Professional University, Phagwara, Punjab, India

7Chitkara Centre for Research and Development, Chitkara University, Himachal Pradesh-174103, India

8Division of Research & innovation, Uttaranchal University, Dehradun, Uttarakhand, India

9Centre of Research Impact and Outcome, Chitkara University, Rajpura-140417, Punjab, India

Corresponding author: a) [vijayanandh.raja@gmail.com](mailto:vijayanandh.raja@gmail.com)

**Abstract.** Durability plays a crucial role in the structural integrity and performance of components used in demanding real-time applications, such as unmanned aerial vehicles (UAVs), including their propellers, fuselage, and wings. To address these challenges, this study explores the development of high-reliability polymer matrix composites, both with and without single-wall carbon nanotubes (SWCNTs), through a combined experimental and computational approach. Test specimens are designed in accordance with ASTM D3039 standards using ANSYS Build Modeller. The composite modeling process involved discretization through ANSYS Mesh Tool and material layer configuration via ANSYS ACP. Advanced simulation and optimization are performed using ANSYS Structural to evaluate the mechanical behavior under varying filler compositions. Comparative simulations demonstrated that the integration of SWCNTs led to a 51% reduction in deformation, underscoring their effectiveness in enhancing structural performance. These findings highlight the potential of SWCNT-reinforced composites as lightweight, durable solutions for complex structural applications in aerospace and other high-performance engineering fields.

# INTRODUCTION

Carbon Nanotubes (CNTs) are cylindrical nanostructures engineered to enhance the physical and mechanical performance of materials at the microscopic level. In this study, tensile characteristics of CNT-based nanocomposites are investigated through Finite Element Analysis (FEA). The test specimens, adhering to ASTM D3039 standards, measure 230 mm × 25 mm × 5 mm and are composed of a hybrid mixture: 60% carbon fiber (263g), 40% epoxy resin, hardener, and embedded CNTs. Fabrication was performed using compression molding, where the resin was cured under a pressure of 3 psi.

This research utilizes Single-Walled Carbon Nanotubes (SWCNTs) to reinforce the composite structure, significantly boosting its load-bearing capacity. The addition of carbon fibers imparts superior stiffness and a high strength-to-weight ratio to the laminate. Fiber orientation, whether unidirectional, bidirectional, or multidirectional are plays the crucial role in load distribution and overall structural integrity, necessitating precise alignment for optimal performance.

The efficiency and longevity of these laminates are closely tied to the quality of fiber-matrix bonding. The internal chemical interaction between epoxy resin and carbon fibers is fundamental to creating robust and durable composites. Epoxy, known for its strength, versatility, and durability, remains a preferred matrix material in high-performance applications [1–7].

Supporting this work, A.K. Gupta (2014) demonstrated the effectiveness of FEA in evaluating CNT-infused polymer composites, providing insights into mesh design, mechanical properties, and material modeling [8]. Similarly, Kulmani Mehar (2017) offered a comprehensive exploration of structural modeling using ANSYS Workbench to simulate nanocomposite behavior under tensile loads [9]. The multifaceted benefits of CNT-based materials such as enhanced strength-to-weight ratio, improved electrical and thermal conductivity, and superior tensile strength were highlighted in J.-H. Du’s study (2007) [10]. Addressing challenges in nanocomposite design, Robiul Islam Rubel (2019) investigated CNT agglomeration and its detrimental impact on composite reinforcement and matrix interaction [11, 70-73].

# Computational Methodology

The nanocomposite is constructed using the sophisticated numerical tool ANSYS ACP. Composite elements pose challenges for numerical representation [12-15]. Earlier work and studies helped determine properties of CNT such as Young's modulus, poison's ratio, and density. Consequently, comparable numerical evaluations of the nanocomposite under tensile strain are conducted utilizing the steps. Testing is conducted to identify novel combinations that may enhance a property [16-19]. Numerical simulations are employed to examine the impact of mixtures on material performance. This study compares composites with and without Multi-Walled Carbon Nanotubes utilizing ANSYS ACP [20-23]. The performance of a composite laminate can be increased or inhibited by the number of mixtures used. The thickness may fluctuate according to the test and the substance; however, nanocomposites exhibit superior mechanical properties. Thus, 10 mm is the standard for Nanotubes [24-27]. In numerical simulation, a computational model represents a real-time entity. Determining and producing three-dimensional test specimen data are important in conceptual design. A test specimen must accurately replicate a numerical simulation. This study utilized an ANSYS Workbench based ASTM D-3039 computational model of a dog bone-shaped test specimen. A test model is discretized into finite element models [28 - 30]. For discretization, organized grid formations are recommended since they offer solid results quickly. Construction of an unstructured grid needs more time, which increases computation time and output consistency [31, 32]. Using the ANSYS mesh tool, structured meshes are created in this work from the test model. Figure 1 illustrates the discrete model. The initial input conditions encompass mechanical parameters such as the Poisson ratio, density, Young's modulus, thermal conductivity, and three-dimensional geometrical characteristics [33]. The test model imposes support, cross-sectional areas, linkages, etc., which play key roles in setting boundary values. Two distinct tensile strains are exerted during the external loading phase. In the first environment, an ultimate tensile stress of 72700 N is applied at one end. Following validation, nanocomposites are compared using a tensile force of 1000 Pa at a single cross-section. Figure 2 illustrates the whole boundary condition of this study [66-69].

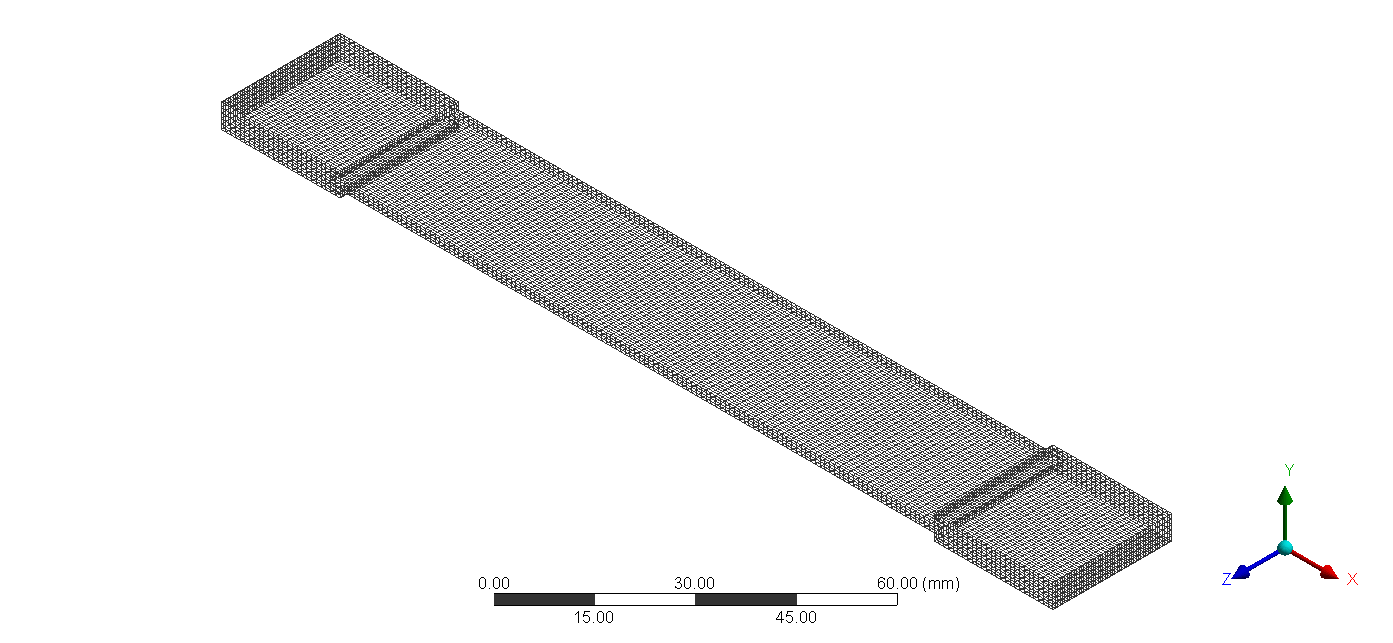


Figure 1: Discretization model

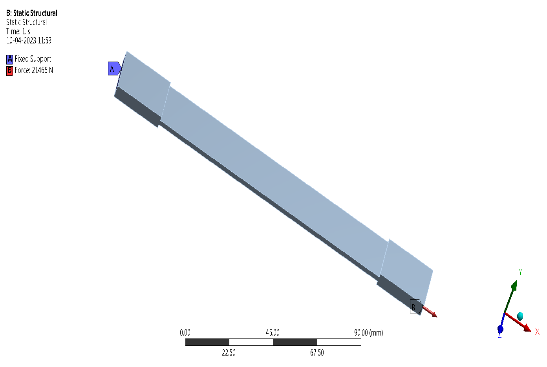


Figure 2: Boundary condition of flexural test specimen

## Validation Study

To enhance the reliability of the advanced simulation results, a sensitivity analysis is essential. In this context, validation is performed using conventional theoretical methods, specifically through Equations (1) and (2). The analysis begins with a comparison between theoretical predictions and FEA-based numerical simulations of maximum flexural stress for epoxy-based S-glass unidirectional (UD) composites reinforced with MWCNTs. Figure 3 illustrates the corresponding stress variations observed in GFRP-based nanocomposite test specimens [34-39].

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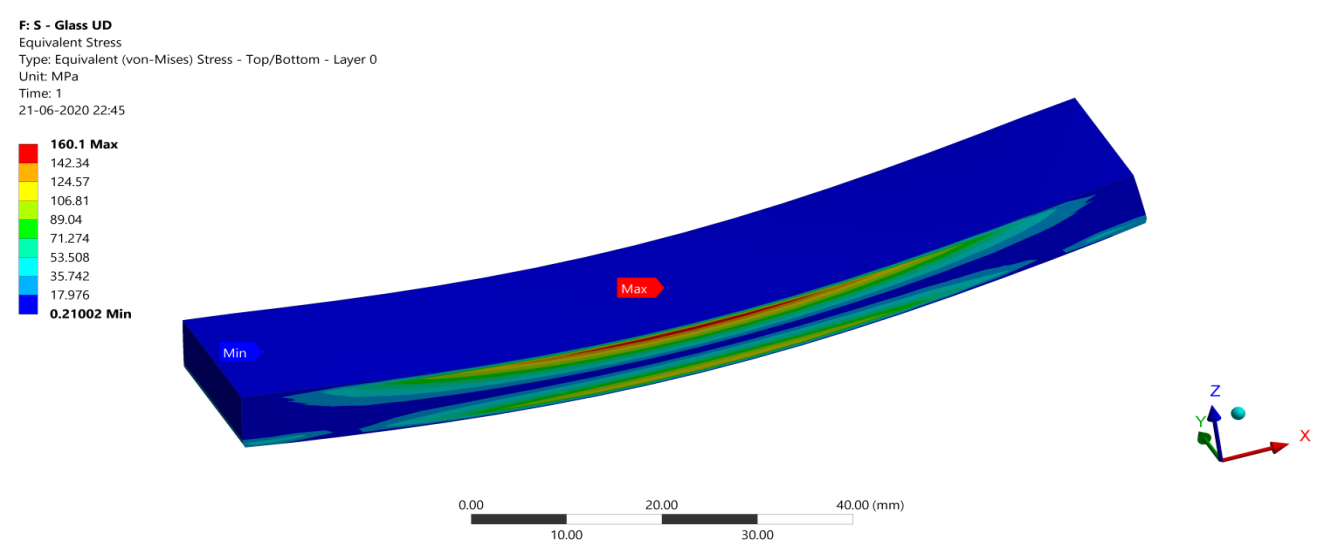


Figure 3: The equivalent stress variations on Epoxy S-Glass UD with SWCNTs

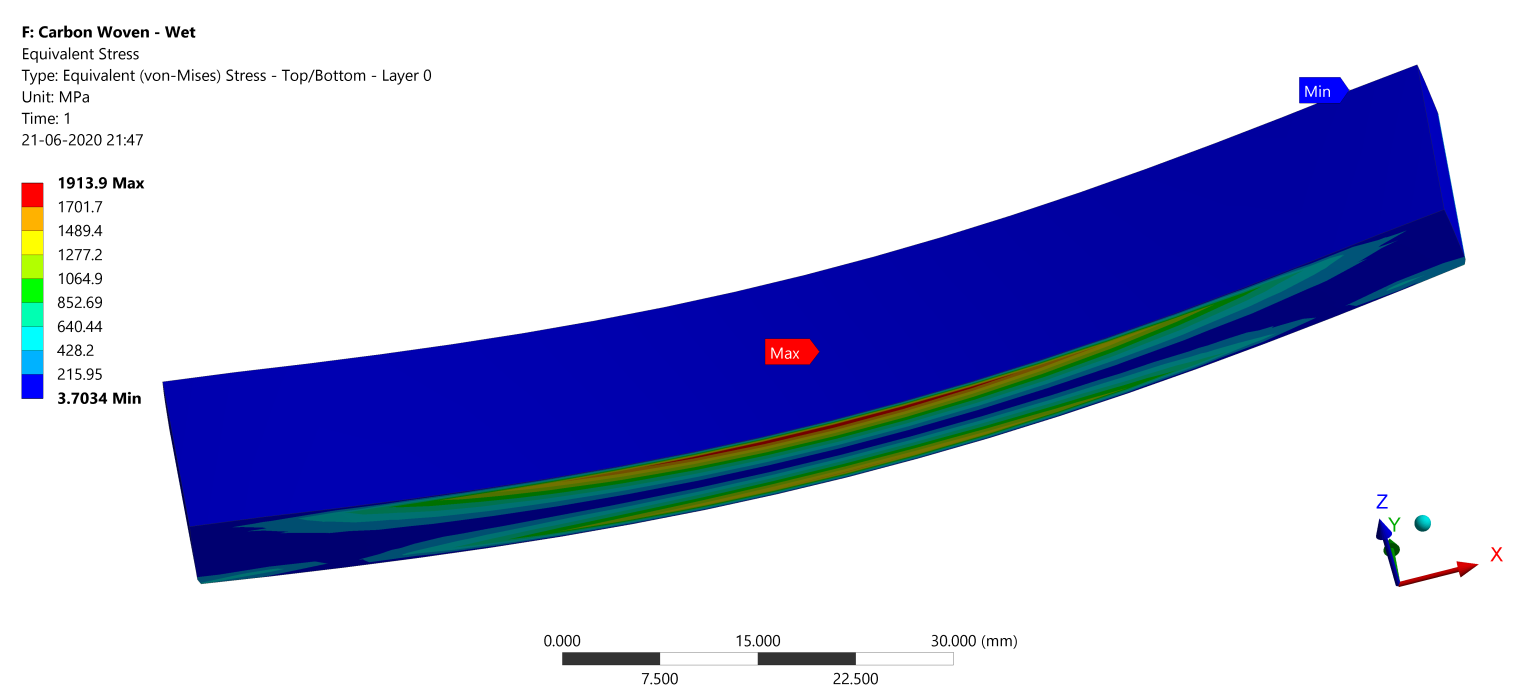


Figure 4: The equivalent stress variations on Epoxy Carbon-Woven-Wet SWCNTs

The calculated maximum stress values from theoretical analysis and FEA simulation are compared, revealing a minimal error percentage of just 0.24%. Due to this negligible discrepancy, the same conventional formula is applied to a more demanding flexural load scenario involving a CFRP-based nanocomposite [40-46]. In this second validation, the epoxy carbon-woven-wet composite reinforced with SWCNTs demonstrated superior performance. Theoretical stress values were computed using the established methodology, and the corresponding FEA simulation results for equivalent stress in the CFRP nanocomposite are illustrated in Figure 4. Comprehensive data, including theoretical predictions, FEA outcomes, and associated error percentages are summarized in Table 1.

Table 1: Comparative analysis of advanced composite materials

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| --- | --- | --- | --- | --- |
| **Material Name** | **Structural Output** | **FEA Simulation results** | **Analytical Results** | **Error Percentage (%)** |
| GFRP-Nanocomposite | Maximum Equivalent Stress (MPa) | 160.1 | 159.71 | 0.24 |
| CFRP-Nanocomposite | 1913.9 | 1919.13 | 0.27 |

# Results and Discussions

## Computational analyses of various composites with and without SWCNTs

The comprehensive structural analysis of various composite material for a tensile load is studied. Figure 5 reveals the computational result of shear stress for CF-GY-70 epoxy. Figure 6 shows the comprehensive outcomes of material associated with SWCNTs for a tensile load [47-51].

A rainbow colored rectangular object

AI-generated content may be incorrect.

Figure 5: Computational result of total deformation for CF-GY-70 Epoxy

A blue and red rectangular object

AI-generated content may be incorrect.

Figure 6: Computational result of strain energy of SWCNTs material

Figure 7: Comparative outcomes of various composite materials

Figure 7 depicts the computational outcomes of different composite materials and the corresponding results of Equivalent Elastic strain, Total deformation and strain energy. Among the outcomes, CF-GY-70 Epoxy provides much better structural property than others [52-58].

Figure 8: Comprehensive outcomes of various composite materials associated with SWCNTs

Figure 8 depicts the computational outcomes of different composite materials with SWNTs and the corresponding results of equivalent elastic strain, total deformation and strain energy. From the outcomes here also, CF-GY-70 Epoxy provides much better structural property than others. But it’s very less compared to various composite materials without SWCNTs [59-65].

# CONCLUSION

The ANSYS Structural tool is used to carry out the computational solving method for this work, which is based on the stiffness approach. Finally, comparative assessments are carried out for a variety of composites that do and do not contain SWCNTs. Among the usual composites, CF-GY-70 Epoxy is selected as the one that offers the lowest total deformation (0.22689 mm), strain energy (0.17076 µJ), and equivalent elastic strain (0.0017025 mm/mm). As a result of the imposition of carbon nanotube material in the subsequent research, the results are less than those obtained with conventional composite materials. In this regard as well, the CF-GY-70 Epoxy with SWCNT material offers less computational outputs of total deformation (0.11127 mm), which is 51 percent less than what is achieved with traditional composite material. The incorporation of CNTs into a composite material that is ideal for structural engineering components that are tensile load-oriented problems.

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