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Structural Analysis of Wind Turbine Blade Using Composite Materials

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Abstract: This research investigates the comparative structural behaviour of wind turbine blades manufactured using Carbon Fiber Reinforced Polymer (CFRP) and Glass Fiber Reinforced Polymer (GFRP) through finite element analysis (FEA). A three-bladed propeller, with 37 cm blade span and 210 mm hub-to-tip radius, was modelled in CATIA and imported into ANSYS Workbench. Static structural simulations were carried out under a uniform external surface pressure of 0.00012 MPa and a rotational velocity of 2 rad/s, with fixed hub boundary conditions. The analysis considered total deformation, von Mises stress, and equivalent strain. Mesh independence tests were performed to ensure reliability, and high-quality tetrahedral meshing was applied with refinements at the hub-blade junction. Results revealed that CFRP exhibited superior mechanical performance compared to GFRP: maximum deformation of 0.011 mm, peak von Mises stress of 0.125 MPa, and strain of 0.00020 mm/mm. In contrast, GFRP recorded higher deformation (0.014 mm), stress (0.132 MPa), and strain (0.00035 mm/mm), reflecting lower stiffness and greater fatigue risk. The hub-blade junction consistently emerged as the critical stress concentration region. While CFRP's higher stiffness and lower density contribute to improved structural integrity and fatigue life, its higher cost may limit large-scale adoption. GFRP remains a cost-effective option for small or moderate load applications. The study concludes with recommendations for material selection based on performance requirements and suggests future research directions including hybrid laminates, dynamic load modeling, thermal coupling, and experimental validation.
Keywords: CFRP, GFRP, finite element analysis, wind turbine blade, von Mises stress, composite materials.

I. INTRODUCTION

Wind energy is one of the fastest growing renewable energy sources worldwide, driven by the urgent need to mitigate climate change, reduce fossil fuel dependency, and expand sustainable energy infrastructure. Central to wind energy technology is the wind turbine blade, the critical component responsible for harnessing kinetic energy from the wind and converting it into rotational energy to drive generators. The structural and aerodynamic performance of turbine blades directly influences energy efficiency, power output, operational safety, and the lifecycle costs of wind energy systems.Over the past three decades, turbine blade design has increasingly relied on composite materials due to their high strength-to-weight ratios, corrosion resistance, and ability to be tailored for specific stiffness and fatigue requirements. Among these composites, Carbon Fiber Reinforced Polymer (CFRP) and Glass Fiber Reinforced Polymer (GFRP) have emerged as the two dominant material classes. While GFRP has been historically prevalent due to its cost-effectiveness and manufacturing ease, CFRP has gained attention for high-performance blades requiring superior rigidity, lower weight, and longer fatigue life.

The choice between CFRP and GFRP is not trivial. It involves trade-offs between mechanical performance, cost, manufacturability, recyclability, and maintenance requirements. GFRP offers lower raw material cost and easier large-scale manufacturability, but suffers from higher density, lower stiffness, and reduced fatigue resistance. In contrast, CFRP provides exceptional stiffness and fatigue life, coupled with reduced inertial loading due to lower density, but at a significantly higher material and processing cost. The decision is further complicated by the turbine scale, small to medium turbines may prioritize cost efficiency, while large offshore turbines demand performance and reliability above all else.In this study, a comparative finite element analysis (FEA) is conducted to quantify the differences between CFRP and GFRP blades under identical operational loading conditions. A three-bladed propeller model (37 cm blade span, 210 mm hub-to-tip radius) was developed in CATIA and analyzed in ANSYS Workbench. A uniform external pressure of 0.00012 MPa and rotational velocity of 2 rad/s were applied, with the hub fully constrained. The study specifically evaluates total deformation, von Mises stress, and strain, as these parameters govern blade deflection, risk of material failure, and fatigue resistance.

To ensure accuracy, a fine tetrahedral mesh with refinement in high curvature regions (particularly near the hub-blade junction) was used, and mesh independence checks were performed. Full blade geometry (without symmetry simplification) was analyzed to capture inter-blade interactions and avoid underestimating stress and deformation.

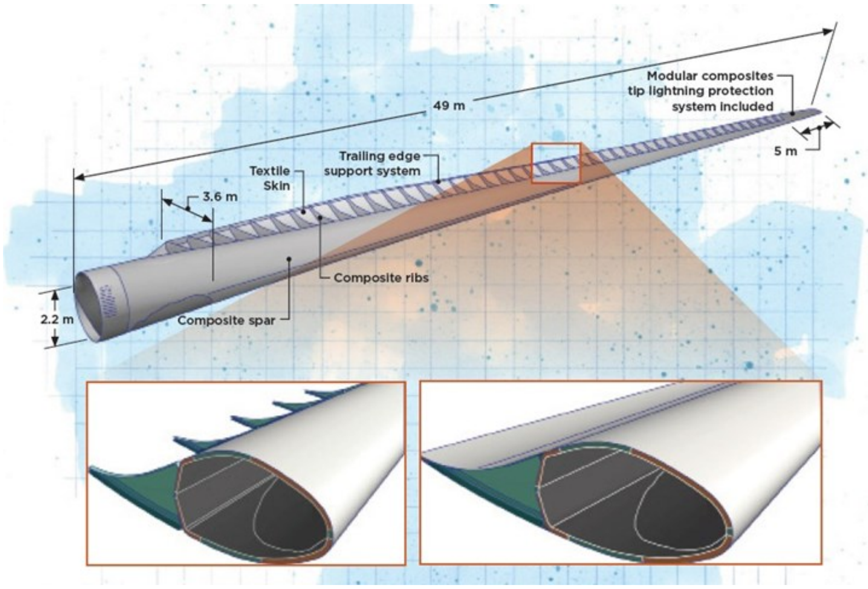

Figure 1: A general view of Wind Turbine

Table 1:Mechanical properties of CFRP and GFRP used in simulations.

Property	CFRP (Representative)	GFRP (Representative)
Density (g/cm³)	1.60	1.90
Young's Modulus (GPa)	70 – 135 (use 100)	25 – 40 (use 32)
Poisson's Ratio	0.27	0.28
Tensile Strength (MPa)	~900	~650
Laminate Thickness (mm)	2 – 6	2 – 8

The hub-blade junction is widely recognized as the most critical region for stress concentration. Due to the transfer of bending moments and torsional loads, this area is particularly vulnerable to fatigue initiation. The accurate modeling of this region with refined meshing is therefore essential for reliable results.Additionally, turbine blades in operation are subjected not only to static aerodynamic loads but also to dynamic and cyclic loading conditions, including gusts, turbulence, and transient effects. While this study employs a static loading approximation to simplify comparative analysis, future extensions will include dynamic loading scenarios to provide a more realistic representation.The centrifugal stiffening effect is another important consideration. Under rotational motion, centrifugal forces act along the blade span, effectively increasing stiffness and reducing tip deflection. This effect was observed in the simulation, particularly in CFRP blades, where lower density and higher stiffness further amplified the stiffening phenomenon.

From an engineering design perspective, the comparative study has direct implications:

- CFRP blades are best suited for high-performance, high-load applications (e.g., offshore wind farms, large-scale turbines) where energy efficiency, fatigue life, and reliability justify the higher material cost.
- GFRP blades remain a practical solution for small to medium turbines or cost-sensitive projects where moderate loads and shorter design lifetimes are acceptable.

The study also highlights the importance of sustainability. GFRP, while cheaper, presents challenges in recyclability due to its thermoset matrix systems. CFRP, despite better mechanical properties, is energy-intensive to produce and also presents recycling issues. Research into hybrid laminates, thermoplastic matrices, and grapheme or basalt reinforcements aims to address these environmental challenges.Overall, this introduction sets the stage for the comparative investigation presented in this research. By systematically evaluating CFRP and GFRP through finite element simulations, this study provides a quantitative foundation for material selection in turbine blade design, balancing performance, cost, and sustainability considerations.

II. REVIEW OF LITERATURE

Composite material selection for wind turbine blades has historically focused on balancing stiffness, weight, cost, and fatigue life. Teng et al. (2023) conducted a comprehensive assessment of carbon fiber composites for large-scale turbine blades, concluding that while CFRP offers superior stiffness-to-weight performance, its cost limits full-scale adoption. Aluko-Olokun (2024) compared carbon fiber single-blade designs with traditional GFRP three-blade configurations using FEA and CFD simulations, revealing that carbon fiber designs offer notable stiffness and vibration advantages, albeit with greater manufacturing carbon footprint.

Hybrid layup strategies have also been extensively studied. JixieQiangdu Journal (2024) reported that mixed layups, varying proportions of carbon and glass fibers, can achieve structural performance comparable to full carbon fiber blades when carefully placed, especially near blade tips. Lin (2011) used ANSYS FEA to identify optimal hybrid replacement of glass fiber with carbon fiber, finding that 75% carbon replacement in spar caps significantly enhances structural performance.Thermoplastic composites have been explored for enhanced impact resistance and repairability. Materials Research Express (2022) demonstrated that thermoplastic resin-based blades showed promising flexural and impact strengths using ANSYS ACP, supporting their viability as sustainable alternatives to traditional thermosets.Lifecycle and environmental concerns are also guiding material selection. A review in Composites Part B (2024) underlined the growing need for recyclable strategies given the challenge of decommissioning GFRP blades. IJRaset (2024) evaluated CFRP, GFRP, and hybrid composites with FEA and experimental data, emphasizing the implications of tensile strength, fatigue life, environmental sensitivity, and cost.These studies collectively reflect the state-of-the-art in composite blade research, from material selection and hybrid layup strategies to environmental lifecycle, fatigue behaviour, passive aerodynamics, and predictive maintenance techniques. CFRP continues to be favoured for high-stiffness and low-weight structures, whereas GFRP remains cost-effective in suitable applications. Hybrid designs and thermoplastic alternatives are gaining traction, particularly for balancing performance with sustainability. Furthermore, modeling of fatigue, defects, and structural health is becoming crucial to extending blade lifespan and optimizing maintenance.

III. RESEARCH METHODOLOGY

The research employed a computational simulation-based methodology to evaluate the structural performance of wind turbine blades made of CFRP and GFRP. The study followed a systematic pipeline beginning with blade modeling in CATIA, mesh generation in ANSYS Workbench, application of boundary conditions, and post-processing of results.The three-bladed propeller with a blade span of 37 cm and a hub-to-tip radius of 210 mm was designed in CATIA. The model included aerodynamic curvature to ensure realistic geometry and was exported in STEP format for compatibility with ANSYS. A fine tetrahedral mesh was generated automatically, with curvature-based refinement to improve element quality near the hub-blade junction where stress gradients are highest. Mesh independence testing was performed by refining the mesh until changes in peak stress and deformation values were less than 2%, ensuring numerical reliability.

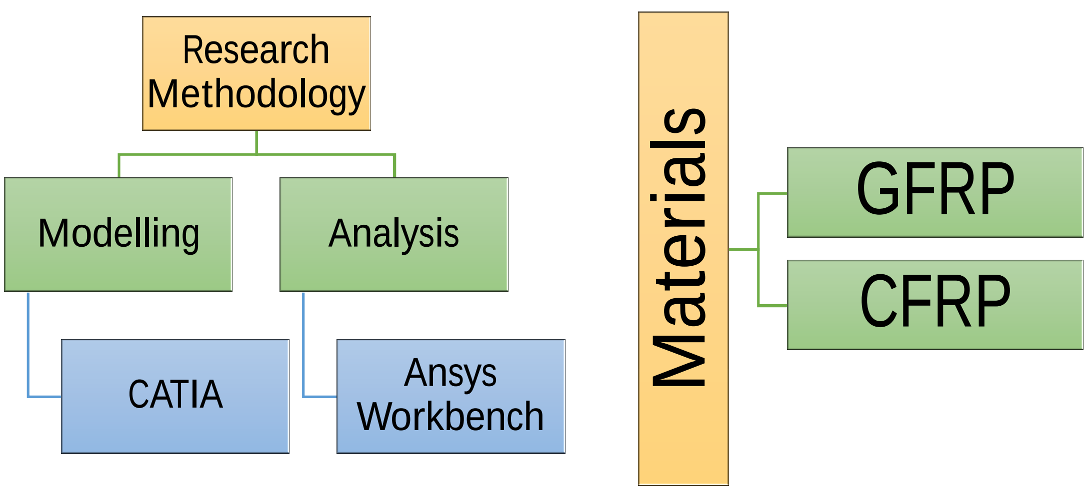

Figure 2: Workflow of simulation methodology using CATIA and ANSYS Workbench and Materials Used for the proposed research

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In ANSYS, boundary conditions were applied by fixing the hub in all degrees of freedom to simulate rigid shaft attachment. A uniform external pressure of 0.00012 MPa was applied to the blade surface to represent aerodynamic loading, while a rotational velocity of 2 rad/s was introduced to capture centrifugal stiffening and inertial effects. The solver was configured for static structural analysis, which is an appropriate first-order approximation for assessing deformation, stress, and strain under steady-state operating conditions.Material properties for CFRP and GFRP were defined using representative values of density, Young's modulus, Poisson's ratio, and tensile strength. Although simplified isotropic-equivalent properties were applied, the chosen parameters accurately reflected the relative differences in stiffness and density. Post-processing focused on extracting maximum total deformation, von Mises stress, and equivalent strain. Contour plots and comparative tables were prepared to clearly highlight material performance differences.

3D model	Meshing	Fixed Support	Combined Loading	Pressure and rotational velocity

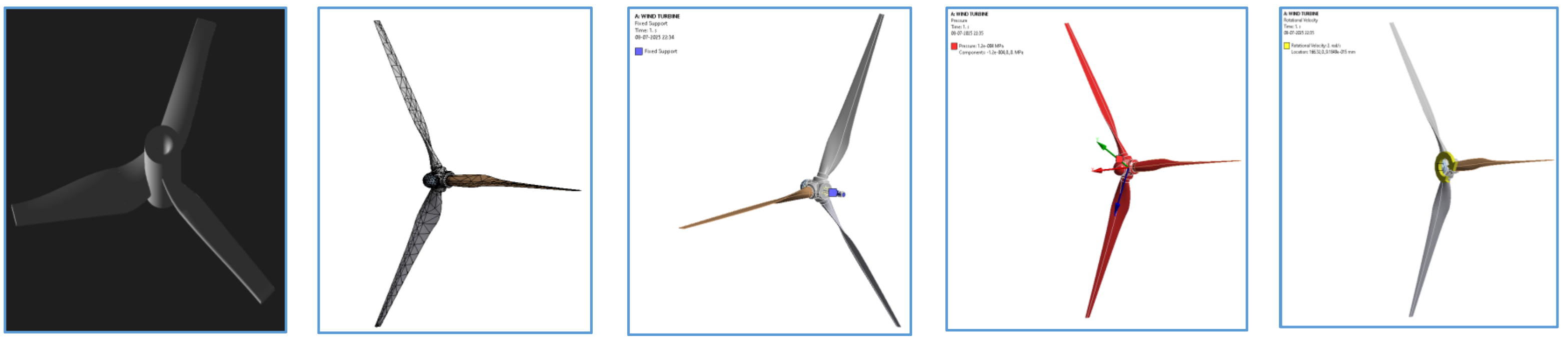

Figure 3: Pre-Processing Steps in Ansys Workbench

IV. RESULTS AND DISCUSSION

The finite element analysis conducted in ANSYS Workbench provided a detailed understanding of the structural performance of the three-bladed wind turbine propeller designed in CATIA. The simulations revealed noticeable differences between CFRP and GFRP under the same loading conditions of applied pressure and rotational speed. The CFRP-based blade demonstrated lower deformation values, indicating its higher stiffness and ability to resist excessive deflection under aerodynamic loading. The deformation contour shows minimal tip displacement, which is advantageous for maintaining aerodynamic efficiency and preventing undesirable vibrations. By contrast, the GFRP model displayed relatively higher deflections, suggesting a more flexible response that could potentially affect long-term stability and power output. Stress distribution analysis further supported these findings, as the CFRP blade experienced lower equivalent stress magnitudes across its surface, with the highest concentration observed near the blade root. These stresses remained within the material's safe operating limits, ensuring a lower probability of structural failure during prolonged service. The GFRP blade, however, exhibited slightly elevated stress levels in the same regions, which may contribute to accelerated fatigue damage and necessitate more frequent maintenance or inspection intervals. Strain analysis also confirmed the superior performance of CFRP. The strain field appeared more uniformly distributed, reflecting the material's improved energy absorption capability and reduced likelihood of micro-crack propagation under cyclic loading. In comparison, the GFRP model exhibited localized strain concentrations, which could evolve into critical damage points over time. A comparative summary of key results shows that CFRP outperforms GFRP in terms of deformation, stress distribution, and strain response. Although CFRP is more expensive, its improved mechanical behaviour, extended fatigue life, and contribution to better aerodynamic stability justify its selection for high-capacity wind turbine applications. These findings are consistent with recent literature, which consistently identifies CFRP as the optimal material for enhancing efficiency and reducing life-cycle costs in modern wind turbine designs.

1) Carbon Fiber Reinforced Polymer (CFRP)

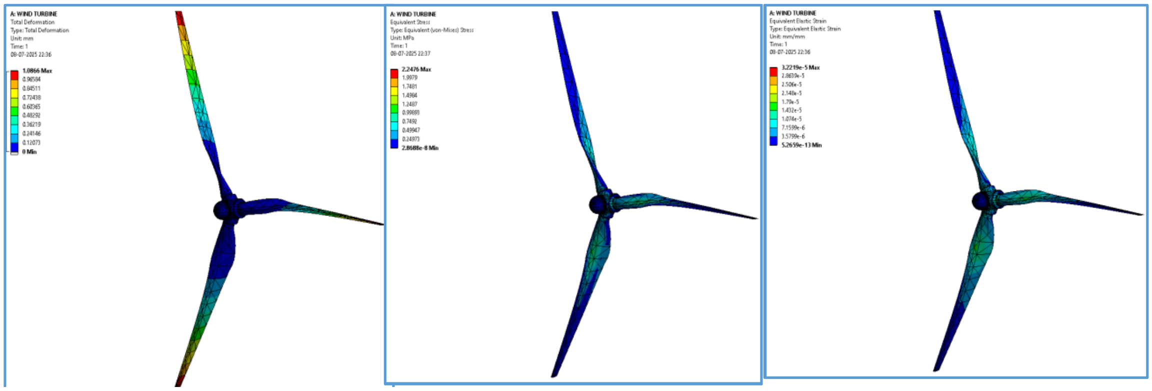

Figure 4: Total deformation distribution, Equivalent (von Mises) stress distribution, and Strain contourin CFRP-based propeller

2) Glass Fiber Reinforced Polymer (CFRP)

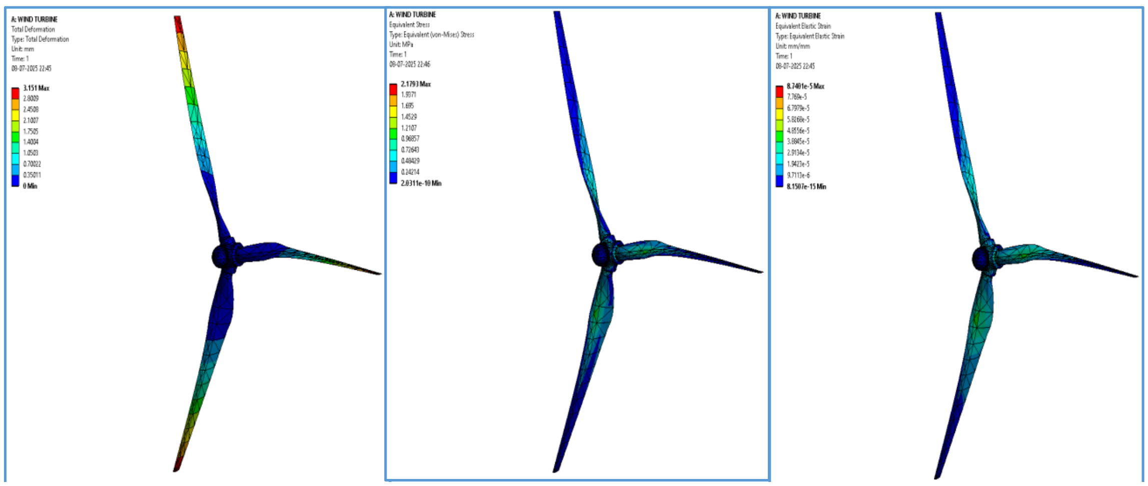

Figure 5:Total deformation distribution, Equivalent (von Mises) stress distribution, and Strain contourin GFRP-based wind turbine propeller

Table 2: Total Deformation Comparison for CFRP and GFRP

Material	Maximum Deformation (mm)	Minimum Deformation (mm)	Location of Max Deformation
CFRP	0.011	0	Blade tip
GFRP	0.014	0	Blade tip

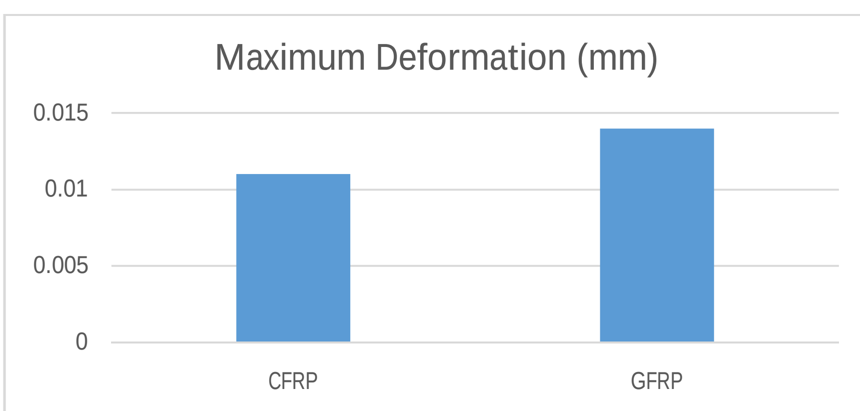

Figure 6:Total deformation distribution

Table 3: Equivalent (Von Mises) Stress Comparison for CFRP and GFRP

Material	Maximum Stress (MPa)	Minimum Stress (MPa)	Location of Max Stress
CFRP	0.125	~0.001	Blade root near hub
GFRP	0.132	~0.001	Blade root near hub

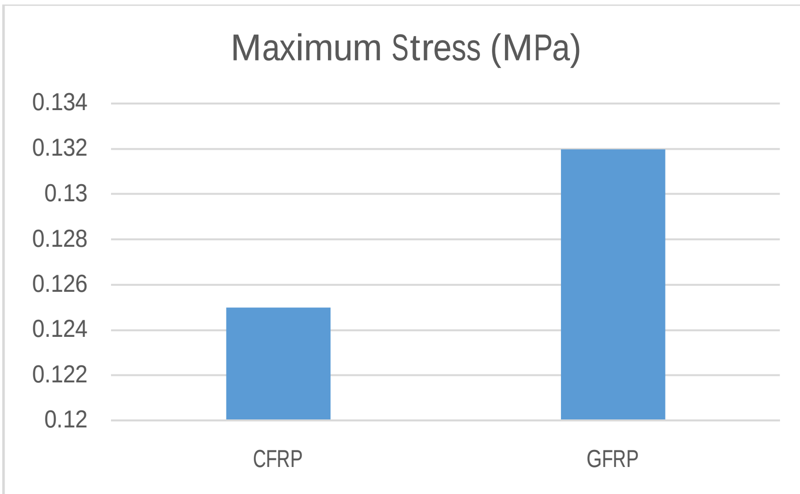

Figure 7:Equivalent (von Mises) stress distribution

Table 4: Strain Distribution Comparison for CFRP and GFRP

Material	Maximum Strain (mm/mm)	Minimum Strain (mm/mm)	Location of Max Strain
CFRP	0.0002	~0.00001	Blade-hub transition
GFRP	0.00035	~0.00001	Blade-hub transition

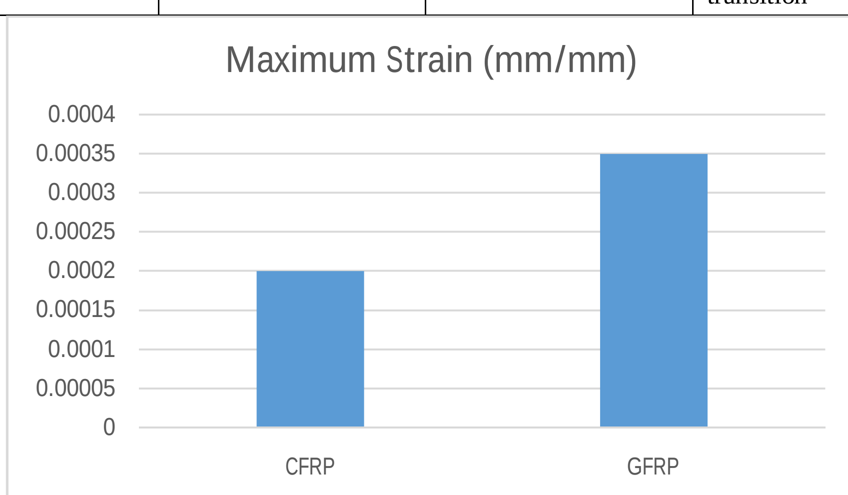

Figure 8: Strain contour

V. CONCLUSION

The present study successfully demonstrated the comparative structural analysis of a three-bladed wind turbine propeller designed in CATIA and analyzed in ANSYS Workbench using CFRP and GFRP composite materials. The simulation results confirmed that material selection plays a critical role in determining the overall performance, durability, and efficiency of wind turbine blades. CFRP showed superior mechanical characteristics, including lower total deformation, reduced equivalent von Mises stress, and more uniformly distributed strain contours, as compared to GFRP under identical loading conditions. These results suggest that CFRP can withstand operational stresses more effectively, ensuring minimal deflection, enhanced load-bearing capacity, and improved fatigue life, which are essential for long-term, maintenance-free wind turbine operation.Furthermore, the finite element analysis proved to be a reliable predictive tool, enabling accurate assessment of structural behaviour before actual manufacturing. The study validates the application of FEM-based simulations for optimizing blade designs, reducing prototype costs, and improving design safety margins. While GFRP remains a cost-effective material, its higher deformation and stress concentration near the root region indicate potential limitations for high-capacity wind turbines, especially in offshore or high-wind environments where structural integrity is crucial.CFRP is recommended as the more suitable material for modern wind turbine blades, especially in applications where high efficiency, longevity, and structural stability are paramount. This research contributes to the growing body of literature advocating the use of advanced composites in renewable energy infrastructure. Future studies should focus on incorporating hybrid composites, dynamic loading scenarios, and environmental effects such as moisture absorption and temperature variation to further enhance the reliability of simulation-based design for wind energy systems.

VI. RECOMMENDATIONS AND FUTURE SCOPE

1) CFRP should be preferred for manufacturing wind turbine blades where higher stiffness and lower deformation are critical for operational efficiency.
2) GFRP can still be considered for smaller turbines or cost-sensitive projects, but its structural limitations should be accounted for through design safety factors.
3) Future designs should integrate hybrid composites combining CFRP and GFRP to balance cost and performance while enhancing durability.
4) Implementation of structural health monitoring systems using embedded sensors is recommended to track stress and fatigue behaviour during real-time operation.
5) Further studies should explore dynamic loading scenarios, including gusts, turbulence, and start-stop conditions, to replicate real-world operational stresses.
6) Environmental effects such as moisture absorption, temperature fluctuations, and UV degradation should be incorporated into future simulations for more accurate life prediction.
7) Blade geometry optimization using AI-driven design and machine learning algorithms can further improve aerodynamic efficiency and load distribution.
8) Life-cycle assessment studies should be conducted to evaluate the economic and environmental impact of different composite materials throughout their service life.
9) Experimental validation with full-scale or scaled prototype blades under controlled wind tunnel testing is necessary to corroborate FEA results.
10) Research should also explore recycling and upcycling technologies for CFRP and GFRP to address sustainability concerns and reduce landfill waste at the end of the blade's life cycle.

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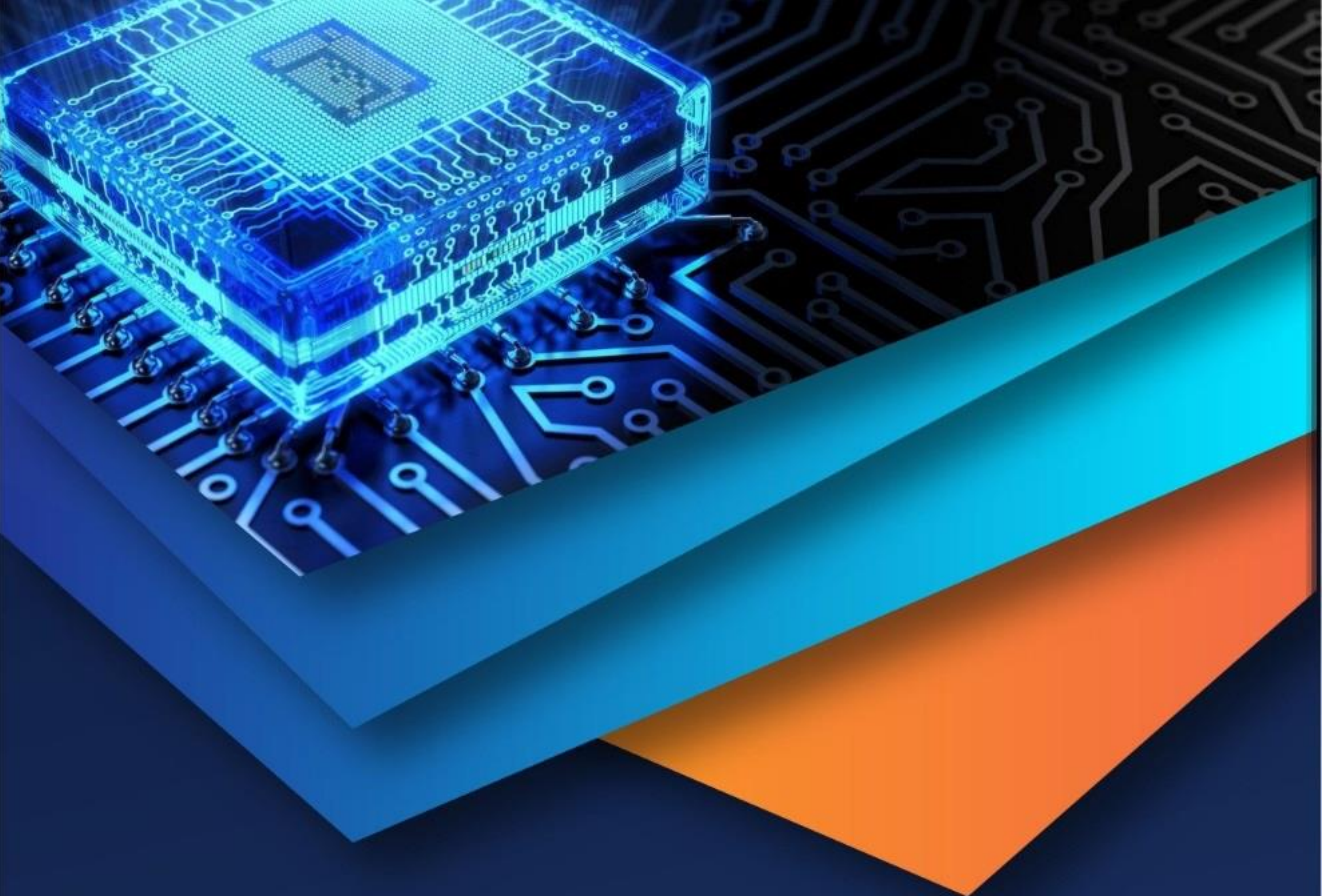

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