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Article

## Strength Analysis of Micro Wind Turbine Blade Structure Made of Composite Material Using Finite Element Analysis

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### ABSTRACT

This study analyzes the Structural Strength of micro wind turbine blades made of CFRP and GFRP composites using the Finite Element Analysis (FEA) method. Aerodynamic loads are obtained from QBlade simulations at a wind speed of 12 m/s and applied as non-uniform pressure on the blades. Composite modeling is performed with ANSYS Composite PrepPost (ACP) using a 4-ply laminated composite configuration with fiber orientations of 0°, 45°, -45°, and 90° and varying ply thicknesses along the blade. Static analysis shows that the CFRP blade produces a Von Mises stress of 15,648 MPa with a maximum displacement of 3.1616 mm, while the GFRP blade produces a stress of 12,786 MPa with a maximum displacement of 6,947 mm. These results indicate that CFRP has better Structural stiffness than GFRP, making it more suitable for micro wind turbine blade applications that require high Structural stability.

## 1. Introduction

The use of renewable energy continues to grow along with increasing global energy needs and demands to reduce dependence on fossil fuels which have an impact on the environment.(Trisnawati & Sudiarto, 2024)Wind energy is a renewable energy source with significant potential for development due to its abundant availability and environmental friendliness. On a small scale, micro-wind turbines offer an effective solution for providing electricity in remote areas, distributed energy systems, and household electricity needs, due to their ease of installation and relatively low operating costs.(Harianto & Karjadi, 2024).

Wind turbine blades are the main components that play a direct role in capturing the kinetic energy of the wind and converting it into mechanical energy to drive the generator.(Mita & Rudiyanto, 2021). In addition to being required to have good aerodynamic performance, wind turbine blades must also have adequate structural strength and stiffness to withstand aerodynamic loads during operation. These aerodynamic loads vary along the blade span to represent real-world operating conditions and can cause significant stresses and deformations, particularly at the blade base, which is a critical point due to the transfer of bending and torsional moments. Failure in this area can reduce the service life and compromise the safety of the wind turbine system.(Ikaningsih & Saefudin, 2018).

The use of composite materials in the manufacture of wind turbine blades is widely applied because it has a high strength-to-weight ratio, resistance to corrosion, and flexibility in structural design through the arrangement of the orientation and arrangement of fiber layers. Carbon Fiber Reinforced Polymer (CFRP) and Glass Fiber Reinforced Polymer (GFRP) are two types of composite materials most commonly used in wind turbine blades. GFRP is known to have advantages in terms of material cost and ease of manufacture, while CFRP offers higher stiffness and strength with a lighter weight. These differences in mechanical characteristics make material selection a critical aspect in the design of efficient and reliable micro wind turbine blades.(Matasina et al., 2014; Widodo, 2022).

To ensure that wind turbine blade designs meet structural strength and stiffness requirements, accurate and systematic analysis is required. The Finite Element Analysis (FEA) method is widely used in wind turbine blade structure studies because it is able to model complex geometries, anisotropic material properties, and non-uniform aerodynamic load distributions. Through FEA, the response of the blade structure can be analyzed numerically, particularly in the form of stress and deformation distributions, which are the main indicators of the strength and stability of the wind turbine blade structure.(Hardiputra et al., 2018; Singh & Patel, 2025).

This research is limited to the structural strength analysis of micro wind turbine blades made of composite materials using the Finite Element Analysis method. Aerodynamic loads are obtained from the QBlade simulation results at a wind speed of 12 m/s and applied as non-uniform pressure on the blade surface. Composite material modeling is carried out using a laminated composite ply approach with four layers (4 ply) and fiber orientations of 0°, 45°, -45°, and 90°, as well as thickness variations along the blade. The analysis is carried out statically using ANSYS Static Structural, with evaluation parameters including Von Mises stress and total deformation. Aspects of dynamic analysis, material fatigue, and the influence of the manufacturing process are not discussed in this study.

Based on the identified background and research limitations, this study aims to evaluate the structural performance of micro wind turbine blades made of CFRP and GFRP composites through static Finite Element Analysis (FEA). Aerodynamic loads obtained from QBlade simulations at a wind speed of 12 m/s are applied as non-uniform pressure distributions along the blade span. The structural response is assessed in terms of Von Mises stress and total displacement to compare the stiffness and strength characteristics of both materials. The results are expected to provide a quantitative basis for material selection and structural optimization of composite micro wind turbine blades, contributing to the development of efficient and structurally reliable small-scale renewable energy systems.

## 2. Literature Review

### 2.1 Micro Wind Turbines and the Role of Blades

Micro wind turbines are small-scale wind energy conversion systems commonly used for household and remote applications. One of the main components that determines the performance of a micro wind turbine is the blades, as they capture the wind's kinetic energy and convert it into mechanical energy through aerodynamic forces. (Tyas Amalia et al., 2022) Blade performance is greatly influenced by the geometry design, airfoil profile, and materials used. Poorly designed blades can lead to low efficiency, excessive deformation, and even structural failure. In addition to aerodynamic aspects, micro wind turbine blades must also have adequate structural strength to withstand aerodynamic loads, centrifugal forces, and gravitational loads during operation. Therefore, blade structural strength analysis is a crucial aspect in micro wind turbine design. (Kumar et al., 2024)

### 2.2 Composite Materials in Wind Turbine Blades

Composite materials have been widely used as wind turbine blade materials because they have a high strength to weight ratio, resistance to corrosion, and flexibility in structural design. (Fadhillah et al., 2017). Some commonly used composite materials are Glass Fiber Reinforced Polymer (GFRP) and Carbon Fiber Reinforced Polymer (CFRP). GFRP has the advantage of relatively low production costs and ease of manufacture, but has a lower modulus of elasticity and therefore tends to produce greater deformation. CFRP has higher stiffness and strength than GFRP, thus minimizing displacement in the blade, but has a higher cost.

### 2.3 Von Mises Stress

In engineering mechanics, stress is denoted by the symbol  $\sigma$  and has units of Newtons per square meter ( $\text{N/m}^2$  or Pa). Stress is defined as the intensity of the force acting on a cross-sectional area of material due to loading. In structural elements subjected to axial forces, stress can be divided into normal stress and shear stress. Normal stress is the stress acting perpendicular to the cross-sectional plane and is formulated as

follows: (Peeters et al., 2018):

$$\sigma = \frac{F}{A}$$

(1)

Caption:  $\sigma$  : normal stress (Pa)  $F$  : axial force (N)  $A$  : cross-sectional area ( $\text{m}^2$ )

Meanwhile, shear stress is stress that works parallel to the cross-sectional plane, which is formulated as:

$$\tau = \frac{V}{A}$$

(2)

Description:  $\tau$  : shear stress (Pa)  $V$  : shear force (N)  $A$  : cross-sectional area ( $\text{m}^2$ )

In structural analysis using the finite element method, complex loading conditions cause a combination of normal and shear stresses. Therefore, the Von Mises stress criterion is used to evaluate the potential for material failure due to multiaxial loading. The Von Mises stress value is compared with the allowable stress of the material to determine the safety of the wind turbine blade structure.

### 2.4. Total Displacement

Loading a structure can cause changes in shape or size, known as deformation or displacement. Displacement indicates the magnitude of a point's displacement within the structure due to the applied force. Generally, deformation is divided into elastic and plastic deformation. Elastic deformation is temporary, and the material can return to its original shape after the load is removed, while plastic deformation is permanent. The maximum deflection of a structural element can be calculated using the following equation: (Mohammad Zakarianto et al., 2023):

$$V_{max} = \frac{PL^3}{3EI}$$

(3)

Description:  $V_{max}$  : maximum deflection (m)  $P$  : working load (N)  $L$  : element length (m)  $E$  : modulus of elasticity of material (Pa)  $I$  : moment of inertia of cross-section ( $\text{m}^4$ )

The relationship between stress and strain is expressed through the modulus of elasticity or Young's Modulus, which is formulated as:

$$E = \frac{\sigma}{\epsilon}$$

(4)

Caption:  $E$  : modulus of elasticity (Pa)  $\sigma$  : stress (Pa)  $\epsilon$  : strain (without units)

In the analysis of micro-wind turbine

blades, the total displacement value is used as an indicator of structural stiffness. Excessive displacement can reduce aerodynamic efficiency and increase the risk of structural failure, so it must be within safe limits.(Muyan & Coker, 2020)

### 3. Research Methodology

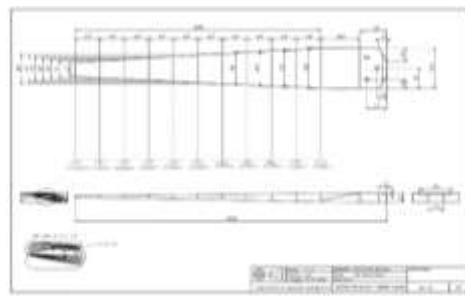
This study uses a numerical analysis approach based on Finite Element Analysis (FEA) to analyze the structural response of micro wind turbine blades with variations in composite materials. The stages of the research method include creating a three-dimensional model of the wind turbine blade, determining variations in composite materials, establishing boundary conditions, providing aerodynamic loading, and analyzing simulation results using ANSYS Workbench software. Blade geometry modeling was carried out using Autodesk Inventor Professional 2025 with a NACA 4412 airfoil profile and a taper-type blade configuration. All stages of the analysis aim to evaluate the effect of material variations on the Von Mises equivalent stress and displacement of the micro wind turbine blade as a basis for determining the material with the best structural performance.

#### 3.1 Blade Geometry Design and Model

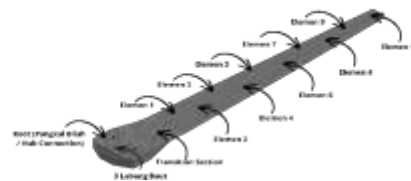
In this study, a micro wind turbine blade geometry model was designed based on aerodynamic design parameters commonly used in small-scale wind turbines. The blade design refers to the NACA 4412 airfoil profile, which was selected because it has good aerodynamic characteristics at low wind speeds. The purpose of this geometry design is to obtain a blade model that is representative of actual operating conditions so that structural strength analysis can be carried out accurately.

Initial modeling was carried out in the form of a two-dimensional (2D) design to define the airfoil profile and chord distribution along the blade span. Next, the design was developed into a three-dimensional (3D) geometric model with a taper-type blade configuration using Autodesk Inventor Professional 2025 software. This 3D model was then used as the basis for numerical analysis using the finite element method. Figure 1 shows the 2D design of the NACA 4412 airfoil profile used as the basis for blade formation, while Figure 2 shows the 3D geometric model of the micro wind turbine

blade resulting from the modeling.



Picture1. 2D Profile Design NACA 4412 airfoil



Picture 2. 3D Geometry Model of Micro Wind Turbine Blades

The blade geometry is designed with a total length of 800 mm and varying chord length from the root to the tip to achieve an optimal taper configuration. The blade root has larger dimensions to increase structural strength in the support area, while the tip is made slimmer to reduce mass and bending loads. This dimensional difference along the blade span aims to minimize stress concentrations while increasing the blade's structural efficiency under aerodynamic loads.

As a basis for evaluating the structural strength, the same geometric model was used for all composite material variations analyzed. Thus, the resulting differences in structural response are entirely due to the influence of the material variations, not to differences in the blade's geometric shape or dimensions. A summary of the main dimensional parameters of the microwind turbine blades is presented in Table 1 in meters.

Table1. Wind Turbine Geometry Design Parameters

No	r (m)	Chord (m)	Twist (Degree)
0	0.17	0.12	10.77
1	0.23	0.112	9.78
2	0.3	0.104	8.8
3	0.36	0.097	7.81
4	0.42	0.089	6.83
5	0.49	0.081	5.84
6	0.55	0.073	4.85

7	0.61	0.065	3.87
8	0.67	0.058	2.88
9	0.74	0.05	1.9
10	0.8	0.042	0.91

### 3.2 Material Selection

Materials play a crucial role in the structural analysis of microwind turbine blades because their mechanical characteristics directly influence the structure's response to aerodynamic and operational loading. Therefore, selecting accurate material data is a key factor in producing numerical simulations that are representative of actual conditions.

In this study, Carbon Fiber Reinforced Polymer (CFRP) and Glass Fiber Reinforced Polymer (GFRP) composite materials were used, as well as a hybrid material configuration which is a combination of CFRP as a skin layer and GFRP as a backing layer. The mechanical property data of each material was taken directly from the Engineering Data library in ANSYS Workbench software, which is a standard material database that has been widely used and validated in various Element Analysis (FEA)-based simulation studies.

The main mechanical parameters used in the simulation include Young's modulus, Poisson's ratio, tensile strength, and material density. All of these parameters are used to ensure that the numerical analysis results can realistically represent the behavior of the composite material under working loads. These mechanical properties form the basis for calculating the Von Mises stress distribution and displacement, thus allowing a more accurate evaluation of the structural performance of micro wind turbine blades for each material variation.

**Table 2.** Mechanical Properties of CFRP and GFRP

Source:(Singh & Patel, 2025)

Property	CFRP	GFRP
Density(g/cm <sup>3</sup> )	1.60	1.90
Young's Modulus(GPa)	70 – 135 (used value: 100)	25 – 40 (used value: 32)
Poisson's Ratio	0.27	0.28
TensileStrength (MPa)	~900	~650

### 3.3 Laminate Configuration of the Blade

The laminate configuration is constructed using a ply-by-ply approach with fiber orientations of [0° / +45° / -45° / 90°]. The 0° orientation serves to withstand the main bending load along the blade, the ±45° layer withstands shear and torsional loads, while the 90° layer increases transverse stability and reduces the risk of delamination.(Nugroho et al., 2011). The blade structure is divided into three cross-sections, namely the base, middle, and tip, each of which consists of the blade skin and shear web sections with varying ply thicknesses.

**Table 3.** Composite Laminate Configuration

Cross Section of Blade	Material	Fiber Orientation (°)	Thickness per Ply (mm)
Skin & Shear web (Base)	CFRP / GFRP	[0 / +45 / -45 / 90]	1.0
Skin & Shear web (Center)	CFRP / GFRP	[0 / +45 / -45 / 90]	0.75
Skin & Shear web (Edge)	CFRP / GFRP	[0 / +45 / -45 / 90]	0.5

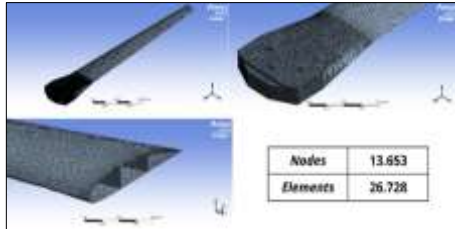
This lamination configuration is then used as the main input in the Element Analysis (FEA) analysis using ANSYS Workbench, so that the results of the Von Mises stress and displacement simulation can represent the structural behavior of the micro wind turbine blades realistically (Yeh & Wang, 2017).

### 3.4 Meshing and Mesh Convergence Test

The meshing process in this study was carried out using triangular elements suitable for representing the complex geometry of micro wind turbine blades, especially in curved areas and connection areas. To improve the accuracy of the simulation results, a face sizing technique was applied with an element size of 2 mm in critical areas that have the potential to experience high stress concentrations, such as the blade base (root) and hub, while the element size in other parts of the blade was varied according to the needs of the mesh convergence test. This approach aims to obtain an accurate stress distribution without

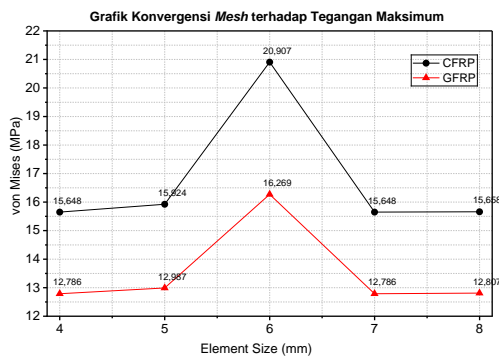
excessively increasing the computational load.

The final meshing results yielded 13,653 nodes and 26,728 elements, indicating sufficient mesh density to capture the structural response of a micro-wind turbine blade in detail. A visualization of the meshing results is shown in Figure 4.10.



**Picture 3.** Results Meshing

A mesh convergence test was conducted to ensure that the simulation results were not significantly affected by the mesh element size. This test was conducted by varying the global element size by 4, 5, 6, 7, and 8 mm, with the evaluation parameter being the maximum Von Mises stress on the wind turbine blade for CFRP and GFRP materials. The graph of the convergence test results is shown in Figure 4



**Picture 4.** Convergence Graph Mesh to Maximum Stress

The simulation results show that the change in the maximum Von Mises stress value at mesh sizes of 7 mm and 8 mm is relatively small for both materials, indicating that the simulation results have reached a convergent condition. Based on these results, a mesh size of 7 mm was chosen as the final mesh size because it provides an optimal balance between simulation accuracy and computational efficiency. This mesh size was subsequently used in all analyses of the micro wind turbine blade structures in this study.

### 3.5 Boundary conditions and loading

The loading on the micro wind turbine blade structure simulation was obtained from the results of an aerodynamic analysis using

QBlade software based on the Blade Element Momentum (BEM) method at a wind speed of 12 m/s. QBlade was used to calculate the distribution of aerodynamic normal forces per unit blade length ( $F_n$ ) along the blade span. The force distribution is uneven, with values tending to increase from the root to the tip, in accordance with the actual working conditions of the wind turbine.

The aerodynamic normal force data calculated from QBlade is exported in CSV format and then used as the basis for structural loading. The aerodynamic pressure at each radial position of the blade is calculated based on the relationship between the aerodynamic normal force and the blade chord length, which is expressed by the equation:

$$p(r) = \frac{F_n(r)}{c(r)}$$

(5)

Information:

$p(r)$  : aerodynamic pressure at radial position (Pa or  $N/m^2$ ) $r$

$F_n(r)$  : aerodynamic normal force per unit length of the blade at position (N/m) $r$

$c(r)$  : blade chord length in radial position (m) $r$

**Table 4.** Aerodynamic Pressure Distribution Along the Blade

Radial Position, $r$ (m)	Pressure, $p$ (Pa)
0.17	270
0.23	370
0.29	510
0.36	650
0.43	840
0.50	1,060
0.55	1,290
0.61	1,620
0.68	2,050
0.74	2,580
0.80	3,100

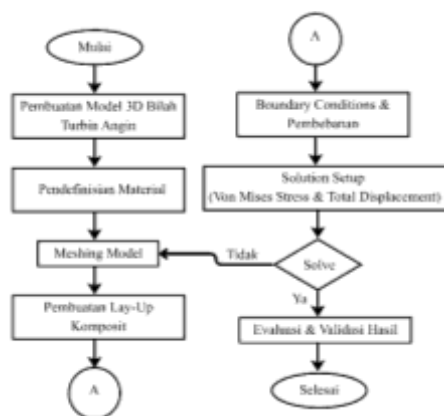
The resulting aerodynamic pressure distribution is then imported into ANSYS Workbench 2025 R2 and applied to the blade surface as mapped pressure, so that the simulation is able to represent the effect of non-uniform wind loads along the blade span.

Boundary conditions are applied to the blade base using fixed supports, where all translational and rotational degrees of freedom are locked. This approach is used to represent the rigid connection between the blade base and the rotor hub. The blade materials are modeled using CFRP and GFRP with mechanical properties referenced from the ANSYS Workbench built-in material database. The differences in mechanical properties of the two materials result in different structural responses to aerodynamic loading, both in terms of Von Mises stress distribution and total deformation.

### 3.6 Analysis Procedure

The structural strength analysis of micro wind turbine blades was conducted using ANSYS Workbench software with an Element Analysis (FEA) approach. The analysis stage begins with the creation of a three-dimensional model of the wind turbine blade according to its geometric design, then continues with the definition of Carbon Fiber Reinforced Polymer (CFRP) and Glass Fiber Reinforced Polymer (GFRP) composite materials based on the ANSYS built-in material database.

Next, a meshing process is performed to divide the model into finite elements, with mesh compaction in critical areas such as the blade root and the connection area with the hub. After that, a fixed support boundary condition is applied to the blade root, and the aerodynamic pressure loading obtained from the QBlade calculation is applied to the blade surface as mapped pressure.



Picture 5. Analysis Flowchart

The solving process was carried out to obtain the structural response due to the applied loading. Evaluation of the results was carried out in the post-processing stage by reviewing the main parameters, namely the Von Mises

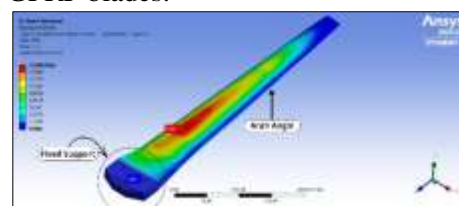
equivalent stress and total displacement. The stress and deformation distribution were analyzed to identify critical areas that have the potential to experience stress concentration. The results of this analysis were used as a basis for evaluating the structural performance of micro wind turbine blades and comparing the structural response between CFRP and GFRP materials.

## 4. Results and Discussion

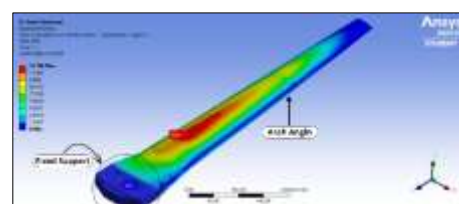
At this stage, an analysis of the simulation results was carried out using ANSYS Workbench to evaluate the structural response of micro wind turbine blades made of CFRP and GFRP. The main parameters analyzed include the Von Mises equivalent stress and total displacement, which are used to describe the mechanical behavior of the blade under aerodynamic pressure loading acting along the blade span. The results of this analysis are used to compare the structural performance of the two materials and to assess the feasibility of the blade structure based on the resulting stress and deformation responses.

### 4.1 Von Mises Stress

Von Mises stress analysis was performed to evaluate the maximum stress response that occurs in a micro wind turbine blade due to the applied static aerodynamic loading. Simulations were performed using the Static Structural method in ANSYS Workbench, with stress units in MPa. The stress distribution was analyzed to identify critical locations and compare the structural performance of CFRP and GFRP blades.



Picture 6. Voltage Distribution Von Mises CFRP

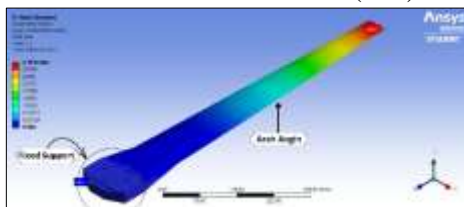


Picture 7. Voltage Distribution Von Mises GFRP

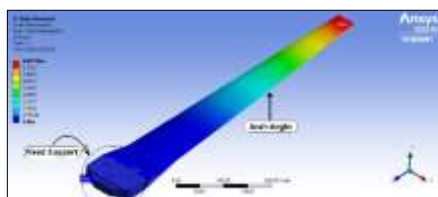
The simulation results show that the CFRP wind turbine blade experiences a maximum Von Mises stress of 15.648 MPa, while the GFRP blade produces a maximum stress of 12.786 MPa. In both materials, the highest stress concentration occurs at the base of the blade (root) due to the accumulation of bending moments and the application of boundary conditions. Although the stress value in CFRP is higher than GFRP, all stress values obtained are still far below the tensile strength limit of each material, thus indicating that the wind turbine blade structure made of CFRP and GFRP is still in a safe condition against the given aerodynamic loading.

#### 4.2 Total Displacement

Displacement analysis was performed to evaluate the magnitude of total displacement (total deformation) in wind turbine blades due to static aerodynamic loading. Displacement parameters are used to describe the deformation response and flexural behavior of the blade structure during operating conditions. Simulations were performed using the Static Structural method in ANSYS Workbench, with displacement units in millimeters (mm).



**Picture 8.** Total Distribution Displacement CFRP



**Picture 9.** Total Distribution Displacement GFRP

The simulation results show that the CFRP wind turbine blade experiences a maximum displacement of 3.1616 mm, while the GFRP blade exhibits a larger maximum displacement of 6.947 mm. In both materials, the minimum displacement occurs at the root of the blade due to the application of boundary conditions, while the maximum displacement is concentrated at the tip of the blade. This pattern indicates

typical blade bending behavior, where the root is firmly restrained and the tip experiences the greatest displacement due to the acting aerodynamic loads.

The comparison of the results shows that the CFRP blades have a smaller displacement than the GFRP, which indicates the higher structural stiffness of the CFRP. However, the displacement values for both materials are still within the elastic limit and do not show any indication of excessive deformation, so that the wind turbine blades made of CFRP and GFRP are declared structurally safe against the analyzed aerodynamic loading.

**Table 5.** Comparative Analysis Results of CFRP and GFRP Structural Strength

Material	Von Mises(Mpa)	Displacement(mm)
CFRP	15,648	3,1616
GFRP	12,786	6,947

Based on the summary of simulation results in table 5, wind turbine blades made of CFRP show better structural performance than GFRP in resisting static aerodynamic loading. CFRP material produces a maximum Von Mises stress of 15.648 MPa with a maximum total displacement of 3.1616 mm, while GFRP shows a maximum Von Mises stress of 12.786 MPa and a maximum total displacement of 6.947 mm. The smaller displacement value in CFRP indicates higher structural stiffness, thus providing a better safety margin than GFRP, although both materials are still within the elastic and safe limits for the analyzed loading.

#### 5. Conclusion

This study evaluated the structural performance of micro wind turbine blades made of CFRP and GFRP composites using static Finite Element Analysis under non-uniform aerodynamic loading obtained from QBlade simulations. The results indicate that CFRP blades exhibit significantly lower total displacement (3.1616 mm) compared to GFRP blades (6.947 mm), demonstrating higher structural stiffness due to the greater modulus of elasticity of CFRP. Although the maximum Von Mises stress in CFRP (15.648 MPa) is slightly higher than in GFRP (12.786 MPa), both values remain far below the respective tensile strength limits of the materials, indicating that the blade structures operate

within safe elastic conditions.

From a structural standpoint, CFRP provides better stiffness and deformation control, making it more suitable for micro wind turbine applications that require higher dimensional stability and reduced deflection at the blade tip. Meanwhile, GFRP remains a viable alternative where cost efficiency is a primary consideration.

However, this study is limited to static structural analysis and does not consider dynamic loading, centrifugal effects due to rotation, fatigue behavior, or advanced composite failure criteria such as Tsai-Wu or Hashin. Future research should incorporate dynamic and fatigue analysis, detailed composite failure modeling, and experimental validation to enhance the reliability and applicability of the numerical results.

Overall, this research provides a quantitative basis for material selection in micro wind turbine blade design and contributes to the structural optimization of small-scale renewable energy systems.

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