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Original Article

Comparison of Aerodynamic Performance and Structural Analysis of Wind Turbine Profiles for Power Generators

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Abstract - *This study focuses on the in-depth aerodynamic performance and structural analysis of three different materials used in a model airfoil blade airfoil used in wind turbines. The three materials examined are carbon fiber, fiberglass and Thermoplastic Polyurethane (TPU). In addition, computational modeling tools, such as Computational Fluid Dynamics (CFD), were used to simulate the airflow around each blade profile and evaluate its effectiveness in capturing wind energy. The resilience and durability of each blade design material were also evaluated structurally under different loading situations using finite element methods (FEM). The results show notable differences in the structural characteristics and aerodynamic performance of the wind turbine blade profile when using the three different types of materials. These findings provide useful hints on how to optimize the use of materials in wind turbine blade designs for renewable energy applications in terms of lifetime and energy efficiency*.

Keywords - *Aerodynamic performance, Computational Fluid Dynamics (CFD), Finite Element Method (FEM), Wind turbine blades, Thermoplastic Polyurethane (TPU).*

1. Introduction

There is no doubt that wind energy is one of the most promising renewable energy sources for fighting climate change and combating the excessive use of fossil fuels that seriously damage the environment [1]. However, one of the key parts to obtain this type of energy is the turbine blades because they are vital components to absorb and transform wind energy into electrical energy; for that reason, it is necessary to optimize their design to increase the efficiency and viability of the huge wind generators [2]. Several studies reveal that the amount of energy produced is directly affected by the aerodynamic performance of wind turbine blades. An efficient aerodynamic design can greatly increase electrical power generation even in variable wind conditions. However, the structural characteristics of the materials used to manufacture turbine blades are crucial to ensure their strength and durability under diverse and often adverse operating conditions [3].

The current literature has a wealth of studies on the structural strength and aerodynamic performance of different materials and designs of air turbine blades. For example, carbon fiber has advantages in terms of higher strength and lower weight, but it is also more expensive. In contrast, glass fiber is commonly used because it offers a compromise between strength and weight [4]. While this research is good, comparative research is still needed to evaluate these airfoils' structural robustness and aerodynamic performance in practical operating environments [5]. The study by Mishnaevsky et al. [6] included a detailed analysis of materials used to construct wind turbine blades. Their analysis focused on the many qualities and uses of carbon fiber and fiberglass, two of the most commonly used composite materials in the wind energy sector; however, there is a need to investigate another material that can surpass the qualities of the two mentioned fibers. An additional study [7] examined the relationship between energy efficiency and the aerodynamic design of wind turbines. In that study, researchers examined how different types of blade airfoils affected the ability to harness wind energy using complex numerical models, and the results provided important information for improving the design of future wind turbines, information that was used in the present investigation. In a third paper on the structural analysis of wind turbines, Rajamohan et al. [8] used finite element methods (FEM) to evaluate the structural integrity of wind turbine blade designs subjected to various levels of load and stress so that the most important areas where the durability of wind turbines could be increased could be found.

This study aims to perform a comprehensive aerodynamic performance comparison and detailed structural analysis of a wind turbine blade airfoil model when subjected to a full analysis with three different manufacturing materials: fiberglass, carbon fiber and thermoplastic polyurethane. The optimal wind turbine manufacturing material will be found by evaluating a 3D design using sophisticated computer modeling tools such as Computational Fluid Dynamics (CFD) and Finite Element Methods (FEM). The results obtained in this research will provide valuable information for researchers who want to optimize the use of wind turbine materials, thus contributing to improving the efficiency and sustainability of wind energy as a renewable energy source. The distribution of the information in this work is divided as follows: Section 2 presents some of the work related to this research. Subsequently, Section 3 develops and explains the complete methodology of this proposed system. Section 4 details the methods used to evaluate the wind turbine blade materials. The analysis of the results and discussions obtained are presented in Section 5. Finally, the conclusions of this research are found in Section 6.

2. Related Work

Numerous studies on aerodynamic performance and structural analysis of wind turbines have been published in scientific journals. Some relevant research on this topic is presented below. Firoozi et al. [9] conducted a comprehensive review of the materials used to manufacture wind turbine blades in their article. This study comprehensively analysed the most commonly used composite materials, such as carbon fiber and fiberglass. This study highlighted these materials' mechanical and strength characteristics and their advantages and disadvantages in wind energy applications. The scientists in that paper concluded that although the strength-to-weight ratio of carbon fiber is superior to that of glass fiber, its high cost prevents its widespread use, which is why glass fiber is still used today [1]. Researchers Li et al. [10] examined the direct connection between wind turbines' energy efficiency and the turbines' aerodynamic design using advanced numerical simulations based on Computational Fluid Dynamics (CFD). The researchers discovered how different blade aerodynamic profiles affected the ability to capture wind energy, which is vital information for optimization, and these results provided useful information for improving wind turbine design [2]. Researchers in another paper evaluated the structural integrity of various blade designs subjected to aerodynamic and gravity stresses using the finite element method (FEM). The results of that research suggest that the service life of turbine blades can be significantly increased by combining good design with the use of materials with better physical characteristics [11]. An integrated approach for optimizing the design of wind turbine blades was given by Nguyen et al. [12]. The work combines CFD simulations with a genetic algorithm to explore a large design space and find combinations that minimize structural stresses and increase aerodynamic performance. The authors of that study demonstrated the potential of computational optimization techniques in wind engineering by showing that this method can produce blade designs that are more robust and efficient than current designs that are produced using more conventional methods [4]. Another study was commissioned to investigate the performance of various wind turbine blade profiles through practical experiments in wind tunnels [13]. This study confirmed theoretical predictions by including real data in numerical simulations and provided a solid basis for evaluating blade designs. Based on the experimental study by Pradeep et al. [5], airfoils that have been improved have the ability to significantly increase the energy efficiency of the wind turbine compared to using classical turbine airfoils, especially in conditions where the wind flow is not constant. That study is a good basis for the present research because it highlights how crucial it is to select the best building material for renewable energy production. The combination of state-of-the-art numerical models with experimental evaluations provides a sound methodology to increase the durability and efficiency of wind turbines, thus promoting optimization and reducing the economic losses that can occur during fabrication and installation.

3. Methodology

This study compares the aerodynamic performance and structural analysis of three different materials widely used to manufacture wind turbine airfoils through a methodology that employs numerical calculations with advanced simulations. The selection of materials for blade airfoils is a crucial step of this study since the variety of designs and materials used in wind turbines can significantly influence their aerodynamic performance and structural strength. The literature review identified the most commonly used blade airfoil materials and those reflecting the most recent advances in wind turbine technology. A comprehensive analysis of academic journals, patents, technical articles and industry publications was conducted to understand better the different blade profiles used in wind turbines and the following three materials were selected for comparison and subsequently subjected to FEM and CFD testing:

- Fiberglass blades: Widely used material due to its good strength-to-weight ratio and low cost.
- Carbon fiber blades: Advanced material known for its high strength and lightweight, although more expensive than fiberglass.
- TPU blades: Thermoplastic polyurethane is a material used for its flexibility and durability, which makes it suitable for various applications.

Selection criteria included industry representativeness, data availability, and potential for improving wind turbine efficiency and durability.

4. Experimental Development

This section explains the process to perform the structural and aerodynamic analysis of three wind turbine blade airfoils. Three types of airfoils were chosen: carbon fiber, fiberglass and a typical airfoil design. The industrial importance of these airfoils led to their selection; fiberglass is a popular material because it strikes a balance between strength and cost, while carbon fiber provides high strength at a lower weight but at a higher cost. The wind turbine and 3D designs of one of its blades are shown in Figure 1.

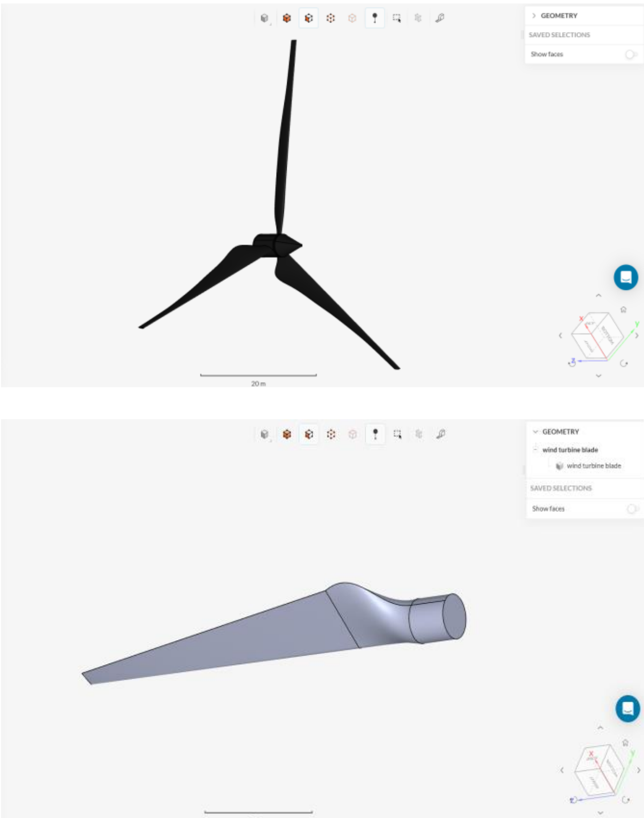


Fig. 1 Experimental development

4.1. Material Parameters

Table 1 shows a summary of the parameters used for each material when performing the simulation in the specialized software; among the main parameters are (E) Young's Modulus, (ν) Poisson's Coefficient, (ρ) Density, etc.

Table 1. Material parameters of materials

Parameters	Fiberglass	Carbon Fiber	TPU
Young's modulus (E)	7.5e+9 Pa	5e+9 Pa	3e+7 Pa
Poisson's ratio (ν)	0.25	0.3	0.4
Density (ρ)	2500 kg/m³	2000 kg/m³	1200 kg/m³

4.2. Geometric Modeling and CFD Simulation Preparation

Computational Fluid Dynamics (CFD), a technique for evaluating and predicting airflow interaction with wind turbine blades, was used to evaluate the aerodynamic performance of the chosen blade profiles. At the beginning of the procedure, accurate three-dimensional geometric models of each blade profile were created using CAD software to ensure that all relevant geometric parameters, such as angles of attack and profile curvature, were represented. These models were validated to make sure they were accurate.

Further, an appropriate simulation domain was constructed to mimic the airflow environment surrounding the blades. This domain included the airflow outlet, the air inlet area, and the analysis area around the blades. The actual wind turbine operating data served as the basis for establishing the boundary conditions, such as wind speed. The blade profiles were then surrounded by an upper three-dimensional mesh, fine-tuned in the near-surface areas to accurately represent the pressure and velocity gradients. Additionally, a mesh independence study was performed to validate the resulting mesh's size and ensure that the results were not affected, especially since the software can process the resulting mesh and the computational cost is moderate.

CFD simulations were performed using the specialized software called SimScale with a free license to investigate the airflow surrounding the blades. Finite volume techniques were used to solve the Navier-Stokes equations. Important factors such as lift coefficient (CL), drag coefficient (CD) and power coefficient (CP) were calculated. Finally, simulation results were examined to evaluate the aerodynamic performance of each airfoil under different wind scenarios.

To facilitate the understanding of the data, graphs and visualizations representing pressure distribution, streamlines and velocity vectors were created. This methodology allowed for accurate and well-informed adjustments by providing a comprehensive and quantitative understanding of how different blade designs and materials influence overall wind turbine performance.

4.3. Structural Analysis by the Finite Element Method (FEM)

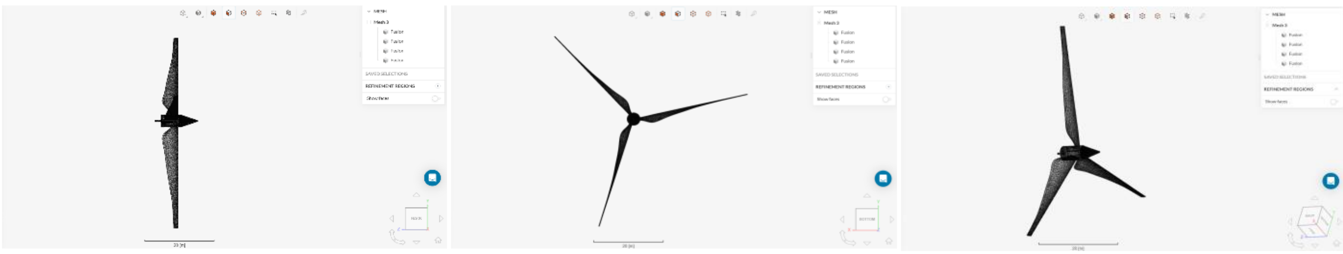
The model designed and generated in FreeCAD 3D software was used to apply the Finite Element Method (FEM) to perform the structural analysis, ensuring uniformity in geometric properties and dimensions. The strength and elastic modulus of the materials of each profile (carbon fiber, glass fiber and thermoplastic polyurethane) were considered and assigned the corresponding attributes. The aerodynamic loads obtained from the CFD simulations were applied together with gravitational and inertial forces typical of wind turbine operation. Calculations of stresses, strains and safety factors were performed under different loading scenarios. In addition, structural fatigue was evaluated by analyzing the effects of cyclic loading on the projected lifetime of the blades.

5. Results and Discussion

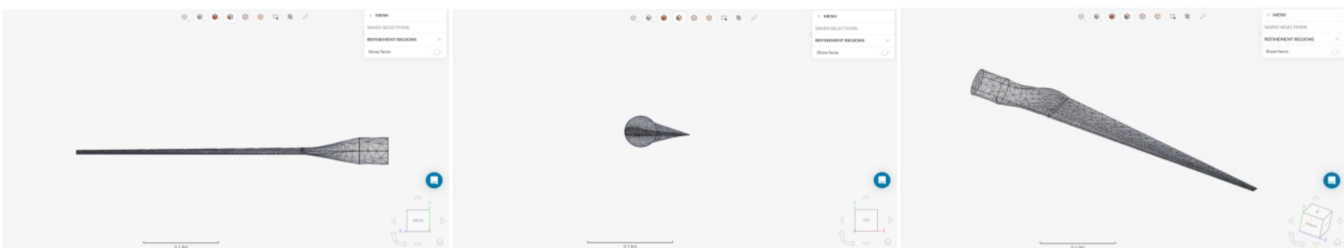
This section presents the results obtained from both the aerodynamic analysis and the structural analysis of the three selected blade profiles.

5.1. Mesh Generation

In order to perform the tests, first, a finite volume mesh created with SimScale online software was used to discretize the computational domain. A hybrid mesh structure, with tetrahedral cells for the bulk regions and prismatic boundary layers near the wind turbine blade surfaces, was used to capture aerodynamic effects accurately. In addition, to increase numerical accuracy in areas with significant velocity gradients, local modifications were made around curved surfaces and sharp edges. Mesh quality was evaluated using measures such as aspect ratio and asymmetry, with values kept below 27 to ensure stability and convergence of the simulation. A total of 6.1k cells were chosen to balance computational cost and solution quality. Figure 2 shows the mesh generated for the wind turbine and one blade.



(a)



(b)

Fig. 2 Mesh generation (a) Complete wind turbine generation (b) Turbine blade generation

5.2. Aerodynamic Simulation Results

Figure 3 shows how the different force components acting on the analyzed wind turbine blade model have changed over time. Significant forces such as pressure, viscous and porous forces are shown along the X, Y and Z axes. The pressure force, which reaches a maximum of approximately 5×10^4 N and represents the main aerodynamic load, is the dominant force in the Y-axis direction. After the initial fluctuations of the transient phase (up to approximately 200 seconds), the forces stabilize, indicating convergence to steady-state behavior. Because the viscous forces are relatively smaller, there are fewer drag effects than the total aerodynamic loading.

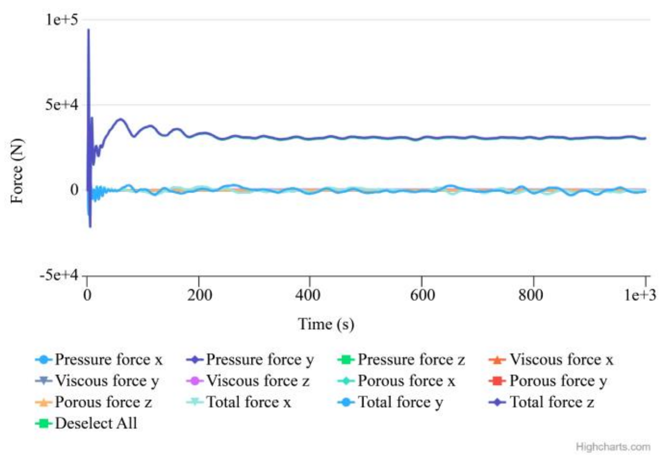


Fig. 3 Force analysis over time

Figure 4 shows the evolution of moments (in N-m) on three axes (X, Y and Z) as a function of time (in seconds). The moments are broken down into three main components: pressure, viscosity and porosity, in addition to the total moment for each axis. The momentum values first see a dramatic shift, particularly along the X-axis, where the total momentum drops significantly before leveling off.

Following this brief interval, the curves converge to a steady state, and exhibit damped oscillatory behavior. This implies the system achieves a dynamic equilibrium where the forces resulting from porosity, viscosity, and pressure are balanced. These first oscillations seem to have the greatest impact on the X-axis.

In addition, the pressure distribution and streamlines surrounding the blades were visualized. The pressure distribution within the carbon fiber airfoil at high wind speeds is depicted in Figure 5. The concentration of the highest-pressure zones at the front of the airfoil, the zones ranging in color from yellow to red, maximizes the efficiency of wind energy capture, as can be demonstrated in the pressure distribution test performed. Finally, the lower pressure zones, represented in the blue to the green color range, are located at the rear of the turbine blades, confirming the creation of an adequate pressure gradient to generate lift.

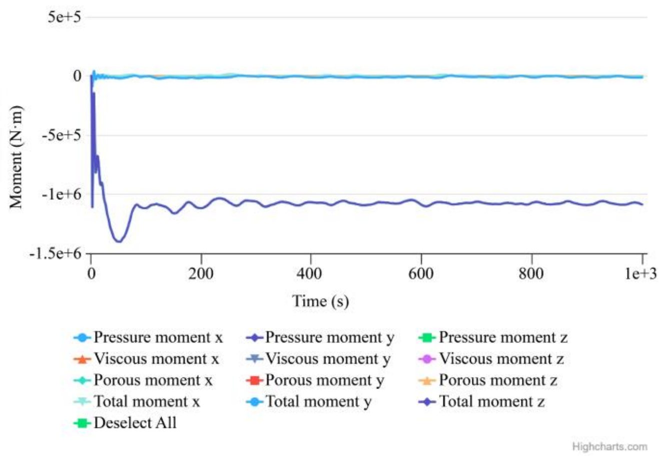


Fig. 4 Moment Analysis Over Time

Fig. 5 Pressure distribution around the wind turbine

Figure 6 represents the results of a computational fluid dynamics (CFD) simulation for a wind turbine, specifically illustrating the velocity distribution (Z-component) across the turbine blades. The color scale at the bottom indicates the regions where the velocity magnitude varies, from -18.07 m/s (dark blue) to 44.73 m/s (red). In these tests, it was observed that the design only has light blue colored areas, and this reflects that the aerodynamic design of the turbine means that no areas suffer more wind impact.

Fig. 6 Velocity distribution around the wind turbine

A simulation of the pressure distribution and velocity streamlines surrounding the wind turbine blade is shown in Figure 7. Strong aerodynamic activity is indicated by high-velocity zones, concentrated at the blade edges and displayed in yellow and red (around 45.41 m/s). In contrast, areas with lower velocities (green to blue) are more common below and near the central axis of the analyzed model, suggesting the formation of wakes and a drop in flow energy. The windward side, the part from where the wind is coming from with respect to a given point or location, of the pressure distribution exhibits regions of high pressure (red, up to 556 Pa), which are visible on the blade surface and add to the lift force. The low-pressure regions on the leeward side, the part where the wind is directed, create suction (blue, up to -1187 Pa), which increases the overall aerodynamic efficiency of the turbine blade pattern.

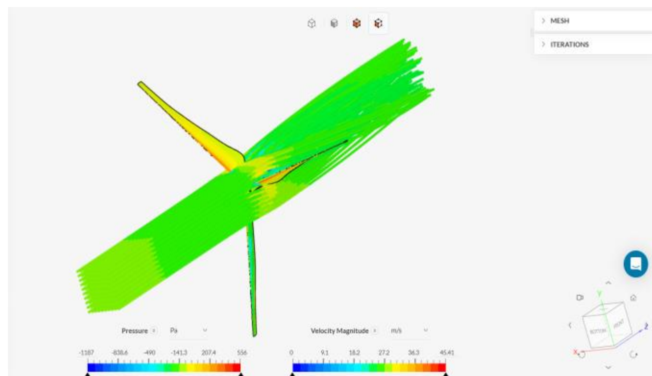
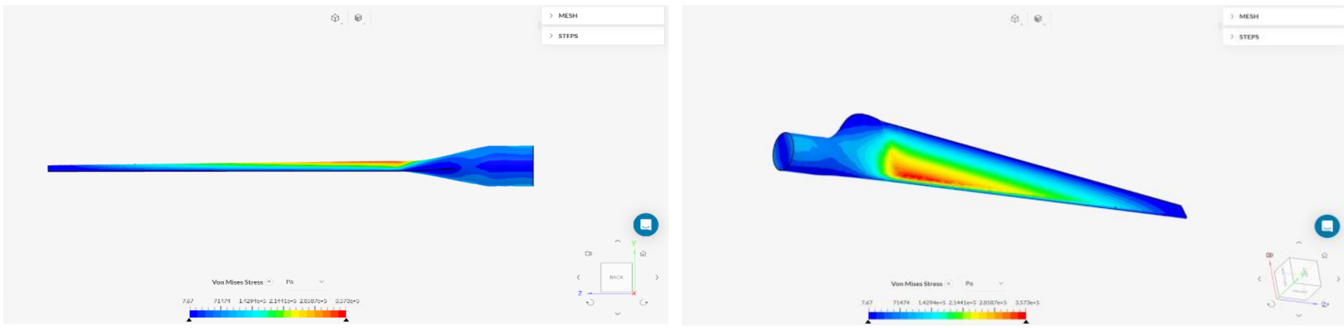


Fig. 7 Analysis of velocity streamlines and pressure contours

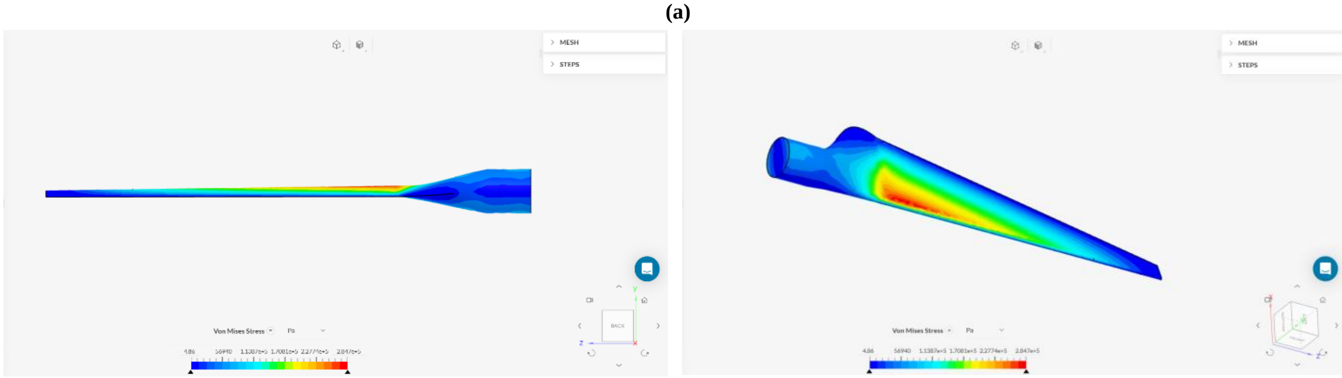
5.3. Results of the Structural Analysis

In order to evaluate the mechanical performance of the blade under applied loading conditions, a Finite Element Method (FEM) structural study was performed using three different materials: fiberglass, carbon fiber and thermoplastic polyurethane (TPU). This study details the overall structural integrity, deformation and stress distribution of each material. In Figure 8 (a), the fiberglass showed a fairly uniform stress distribution throughout the simulation. A noticeable but manageable deformation demonstrated the material's ability to absorb energy under load while maintaining its integrity. However, the results indicated specific regions of increased stress, which could prove problematic under cyclic or prolonged loading. Due to its intermediate strength-to-weight ratio, fiberglass-based air turbine construction is the best choice for applications requiring higher performance and moderate cost-effectiveness.

The simulation of a wind turbine blade made of carbon fiber is shown in Figure 8(b). In terms of structural efficiency, carbon fiber performed better than the other materials due to its higher stiffness and strength-to-weight ratio. The findings obtained from the finite element method showed good stiffness and good flexural strength with little deformation after being subjected to a load. The superior load distribution of carbon fiber meant that stress concentrations were much lower than those observed in glass fiber. In addition, the low weight of carbon fiber makes it ideal for high-performance uses where weight reduction is crucial, such as aircraft or automotive components. However, in applications where funds are limited, the high cost of carbon fiber remains a barrier to its widespread use, so when the overall cost of turbine manufacture is taken into account, glass fiber remains the most recommended option.



(a)



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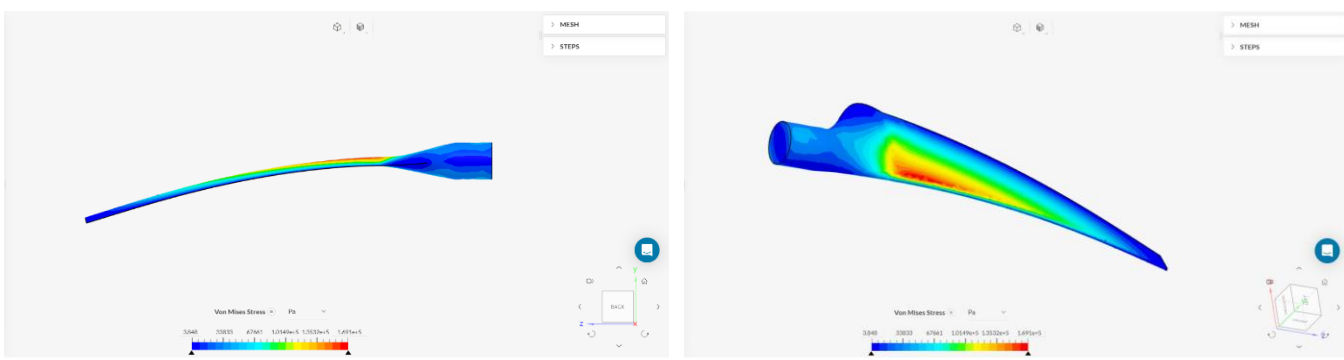

(c)

Fig. 8 Results of the Structural Analysis (a) Fiberglass. (b) Carbon fiber. (c) Thermoplastic polyurethane (TPU)

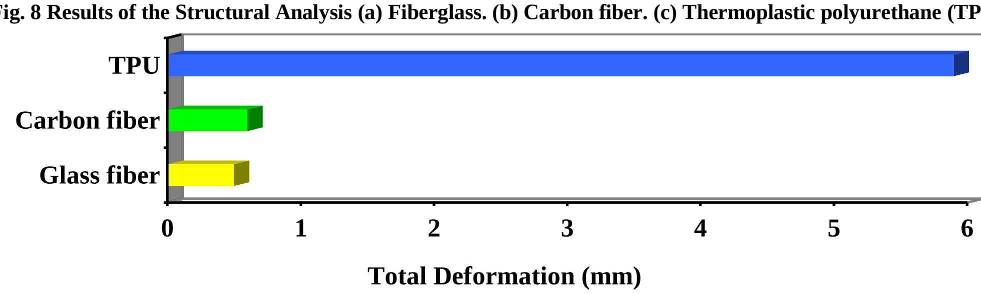

Fig. 9 Variation of the total design deformation with the three different materials

Finally, Figure 8 (c) shows the simulation of the blade using TPU, and due to its lower stiffness and more elastic nature, the TPU structure showed significantly more deformation. Although TPU lacks the structural stiffness of glass or carbon fiber, it is appropriate for applications needing flexibility and impact resistance due to its capacity to withstand significant elastic deformations without suffering irreversible damage. TPU is a great choice for applications such as shock absorbers, seals and shielding components due to its ability to absorb energy and reduce vibrations, as demonstrated by FEM analysis. In summary, the comparative analysis using FEM showed that the choice of material has a major impact on the mechanical performance of the structure. These tests show that carbon fiber is the perfect material for applications requiring high performance with minimal weight due to its remarkable strength and stiffness. It was also observed that fiberglass offers balanced performance at a lower cost, making it an excellent alternative to traditional structural components, as is the case in the construction of air turbines. The highest degree of duplicity was also found in TPU since, although it is less stiff; it is perfect for applications that need flexibility and energy absorption. Figure 9 shows the variation of the total design deflection with the three different materials. A comparison of the three materials' various features is summarized in Table 2.

In general, fiberglass is the best material in terms of cost-benefit and is widely used in medium and large-scale commercial wind turbines due to its strength and durability at a reasonable cost. Technically speaking, carbon fiber is the best material, but due to its high cost, it is more suitable for sophisticated turbines, particularly those used in marine or state-of-the-art applications. TPU's rigidity and strength limits make it unsuitable for large wind turbines. It might be helpful for small turbines or experimental uses. Fiberglass would often be the more sensible option for traditional projects, while carbon fiber would be the better option in situations when performance and efficiency are top concerns and money is more available.

Table 2. General comparison of materials

Property	Fiberglass	Carbon Fiber	TPU
Strength	Medium	High	Low
Stiffness	Medium	Very high	Low
Weight	Moderate	Low	Moderate
Durability	High	Very high	Medium
Cost	Low	Very high	Moderate

6. Conclusion

This study compared the aerodynamic and structural performance of three materials used in a wind turbine blade airfoil: a glass fiber airfoil, a carbon fiber airfoil and a Thermoplastic Polyurethane (TPU) airfoil. Results obtained from Computational Fluid Dynamics (CFD) simulations and structural analysis using the Finite Element Method (FEM) show that the carbon fiber airfoil offers the best overall performance. Taken together, these results provide key information for the selection of optimal materials and designs in the wind industry, providing a balance between cost, energy efficiency and structural durability. Turbines incorporating optimized profiles such as carbon fiber have the potential to significantly improve efficiency in renewable energy generation.

Future work will improve the analysis performed in this study. First, validation studies in wind tunnels would be useful in validating the numerical results obtained from the CFD simulations. In addition, evaluating the effects of severe weather conditions, such as intense turbulence or abrupt changes in wind speed, may provide additional information on how the blade profiles behave under more demanding conditions.

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