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(Research Article)

Comparative analysis of carbon fibre and glass fibre in blade design

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Abstract

This study investigates the performance, environmental impact, and economic viability of single-blade carbon fibre wind turbines compared to traditional three-blade glass fibre designs. Finite Element Analysis (FEA) demonstrates carbon fibre's superior stiffness and vibration properties, while Computational Fluid Dynamics (CFD) simulations identify optimal aerodynamic performance at specific angles of attack. A Life Cycle Assessment (LCA) reveals that, despite significantly higher carbon emissions and energy consumption during manufacturing, carbon fibre blades produce fewer SO_2-equivalent emissions. Economically, single-blade carbon fibre turbines present potential cost-efficiency due to reduced maintenance and extended lifespan. However, challenges such as manufacturing energy demands, environmental effects, and cost remain barriers to widespread adoption. These findings underscore carbon fibre's suitability for applications requiring high mechanical performance and dimensional stability, establishing it as a viable material for advanced wind turbine designs.

Keywords: Carbon fibre; Glass fibre; Wind turbine blades; Finite Element Analysis (FEA); Computational Fluid Dynamics (CFD); Life Cycle Assessment (LCA); Sustainable energy; Single-blade wind turbine

1. Introduction

To improve and optimise the energy generation of wind turbines, many researchers have explored various designs and materials for turbine blades, with glass fibre being a prominent traditional choice. One particularly unique design is the use of single-blade wind turbines, which differ significantly from the conventional three-blade configuration. These single-blade designs have garnered increasing attention due to their distinct advantages, including reduced manufacturing complexity, lower weight, decreased maintenance requirements, and potential enhancements in aerodynamic performance (Lee et al., 2016).

Previous studies have investigated the application of carbon fibre in traditional three-blade wind turbines, highlighting benefits such as reduced weight, superior fatigue resistance, and improved overall performance (Zheng et al., 2023). However, the potential effectiveness of single-blade carbon fibre designs remains underexplored. This study addresses this gap by comparing the performance of single-blade wind turbines made of carbon fibre with those constructed from glass fibre. Carbon fibre composites, known for their high strength-to-weight ratios, are particularly well-suited for developing strong and lightweight turbine blades (Pender & Yang, 2020).

The comparative analysis involves several methodologies:

- Aerodynamic Modelling: Computational Fluid Dynamics (CFD) simulations are used to analyse the blade's aerodynamic performance.
- Structural Evaluation: Finite Element Analysis (FEA) assesses the structural integrity of the carbon fibre composite blade.

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- Environmental Impact Assessment: Life Cycle Assessment (LCA), conducted in accordance with ISO standards, evaluates the environmental effects of the blades from production to end-of-life.

2. FEA Analysis

Carbon fibre composites consist of continuous fibres embedded in an epoxy resin matrix, offering high stiffness and strength along the fibre orientation. The epoxy resin transfers load and protects the fibres, which achieve an elastic modulus of 120 GPa in the fibre direction and 10 GPa transversely. The composite's orthotropic nature is characterised by a Poisson's ratio of 0.3, reflecting its resistance to deformation across different axes.

In contrast, fibreglass composites use randomly oriented glass fibres embedded in polyester resin, resulting in isotropic material properties. With an elastic modulus of 10 GPa and a Poisson's ratio of 0.2, fibreglass shows significantly reduced stiffness and strength. These distinctions between the two composites are critical for structural applications and are accurately captured in the Finite Element Analysis (FEA) models.

2.1. FEA Modelling and Methodology

The FEA simulations modelled a rectangular composite plate (300 x 200 x 3 mm) to evaluate transverse bending behaviour. The plate geometry, consistent for both materials, ensured that observed differences arose solely from material properties rather than design factors. Three-dimensional solid quadrilateral elements were used for the simulation, with a 5 mm element size providing a balance between computational efficiency and accuracy. This mesh size allowed for at least eight elements across the 3 mm thickness, ensuring adequate resolution of stress and deformation gradients. The use of mapped meshing ensured alignment with the plate's geometry and avoided skewed elements, which can affect result accuracy.

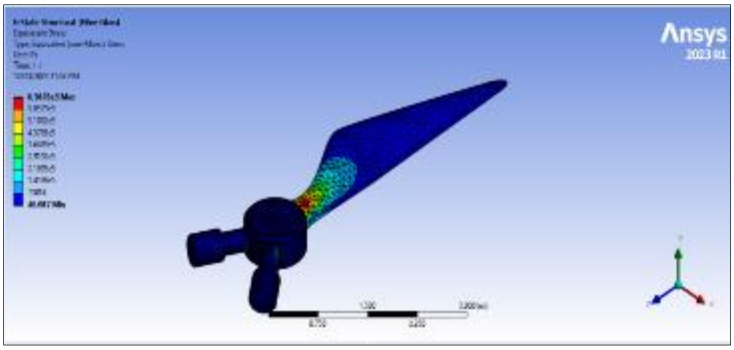

Figure 1 Equivalent stress; fibreglass

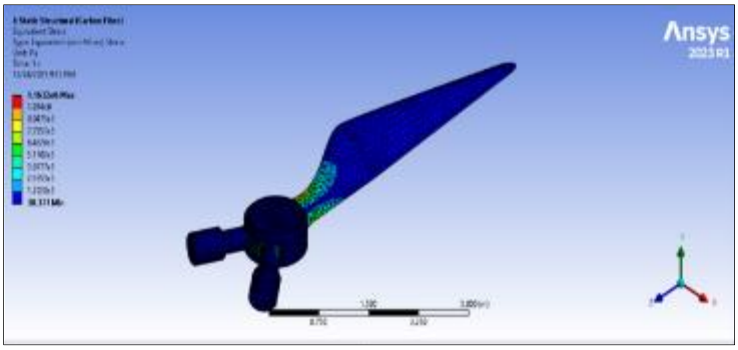

Figure 2 Equivalent stress; Carbon fibre

Boundary conditions included fixing one short edge to simulate a cantilever beam while applying a 1 MPa uniformly distributed load across the free edge. This load represented realistic transverse pressure, akin to wind forces on a structural panel, and ensured smooth stress gradients throughout the model.

2.2. Simulation Results

- Carbon Fibre Composite: Maximum displacement at the free edge was 1.8 mm, with a peak von Mises stress of 24 MPa concentrated near the fixed edge. The smooth deformation gradient reflected the material's high stiffness and resistance to bending.
- Fibreglass Composite: Maximum displacement was significantly higher at 18 mm, with a peak von Mises stress of 240 MPa. This level of stress and deformation highlighted fibreglass's reduced rigidity and strength under bending loads.

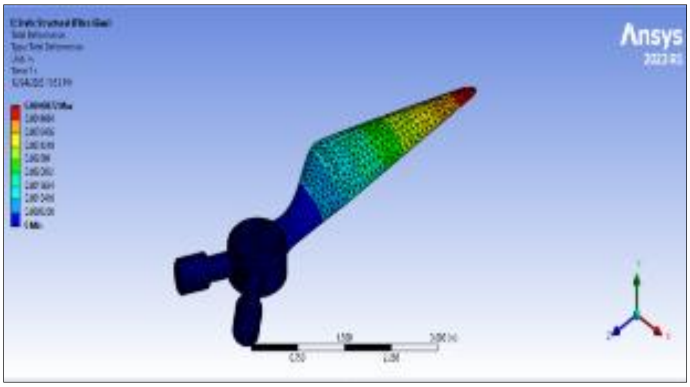

Figure 3 Total Deformation; Fibreglass

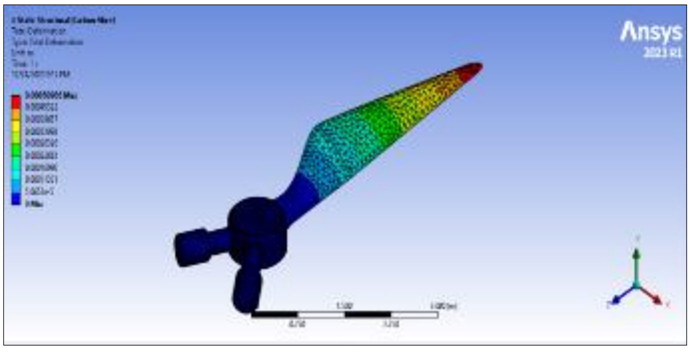

Figure 4 Total Deformation; Carbon fibre

The stark differences in displacement and stress levels between the two composites underscore carbon fibre's superior bending performance. Its ability to maintain structural integrity under loading conditions makes it highly suitable for demanding applications.

2.3. Material Properties and Their Impact

The mechanical superiority of carbon fibre composites stems from their high longitudinal elastic modulus (120 GPa), which is five to ten times greater than that of fibreglass. This stiffness minimises deformation, ensuring dimensional stability under significant loads. Furthermore, the higher Poisson's ratio of carbon fibre (0.3 vs 0.2) indicates reduced contraction perpendicular to the load, contributing to shape retention during deformation.

Fibreglass, with its isotropic properties and lower modulus, exhibits greater deformation under identical loading. The randomly oriented fibres in fibreglass reduce its load-bearing efficiency, particularly under bending stresses. Carbon fibre's anisotropic nature, on the other hand, offers enhanced shear and transverse modulus, further boosting its performance in structural applications.

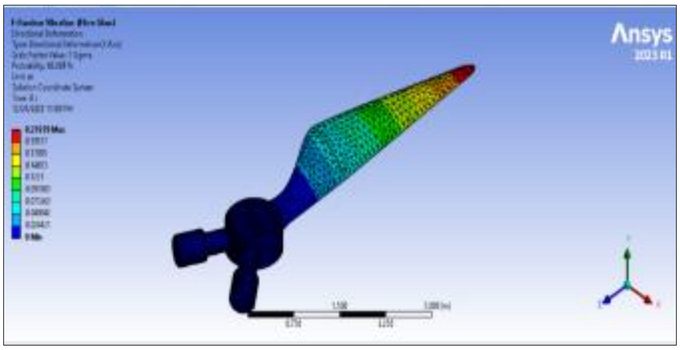

Figure 5 Directional Deformation; Fibre glass

2.4. Mesh Design and Boundary Conditions

Accurate meshing and boundary configurations were crucial for reliable simulations. The 5 mm global element size struck a balance between computational efficiency and detail, allowing stress gradients to be captured effectively. With mapped meshing, quadrilateral elements aligned with the plate geometry, avoiding distortions commonly seen with free meshing techniques.

The cantilever boundary condition, with one fixed edge, restricted all translations and rotations (UX, UY, UZ, ROTX, ROTY, ROTZ). This ensured realistic simulation of bending forces, allowing the plate to deflect from a stable, immobile base. A distributed load of 1 MPa provided consistent bending stress across the free edge, generating smooth stress gradients that enhanced simulation accuracy.

2.5. Comparative Analysis

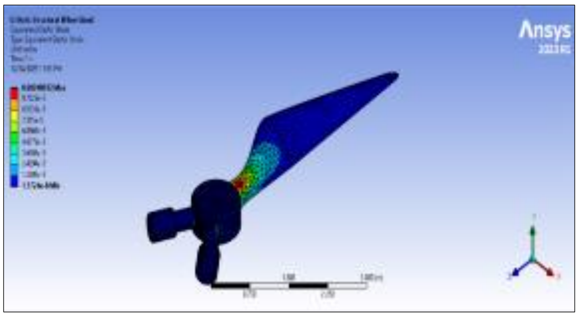

Figure 6 Equivalent Elastic Strain; Fibre glass

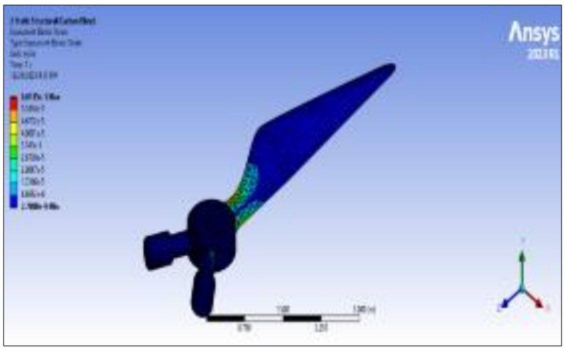

Figure 7 Equivalent Elastic Strain; Carbon Fibre

The FEA results quantitatively demonstrate carbon fibre composites' significant advantages over fibreglass. With 1.8 mm displacement under transverse loading compared to fibreglass's 18 mm, carbon fibre exhibits ten times less deformation. Additionally, the von Mises stress of carbon fibre remains an order of magnitude lower (24 MPa vs 240 MPa), reflecting its superior load resistance.

These results align with the theoretical mechanical properties of the materials. Carbon fibre's continuous, aligned fibres provide exceptional axial stiffness, while its higher transverse and shear moduli enhance resistance to bending forces. Fibreglass's randomly oriented fibres dilute its load-bearing capacity, resulting in increased deformation and stress under similar conditions.

3. FEA Result

The first 100 natural vibration modes and frequencies of carbon fibre and fibreglass composite structures were compared. Carbon fibre consistently demonstrated significantly higher natural frequencies, indicating greater stiffness and rigidity. The fundamental frequency of carbon fibre in the first natural mode is 3.412 Hz, over 50% higher than fibreglass at 2.2395 Hz. Across 100 modes, the frequency difference persists, with carbon fibre frequencies approximately 30–60% higher. For example, in mode 50, carbon fibre reaches 1364.9 Hz compared to 853.65 Hz for fibreglass, showcasing a nearly 60% improvement.

The superior natural frequencies of carbon fibre stem from its high elastic modulus and aligned continuous fibres, enhancing axial stiffness and structural rigidity. In contrast, fibreglass, with randomly oriented fibres, exhibits lower stiffness. Carbon fibre's higher damping capabilities further improve vibration and noise reduction. This modal study confirms that carbon fibre composites provide superior stiffness, dimensional stability, and vibration response compared to fibreglass. These qualities make carbon fibre suitable for high-performance structural applications.

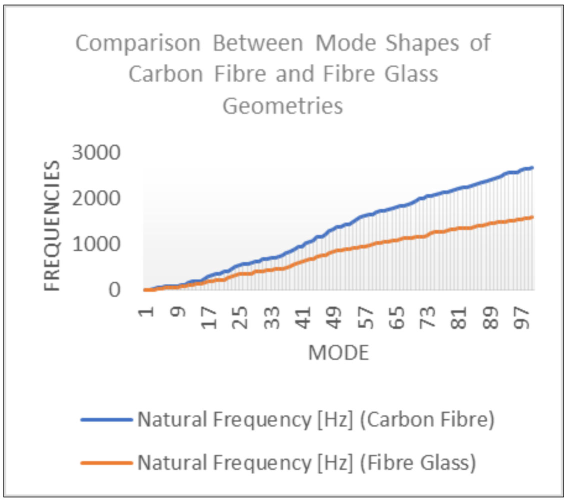

Figure 8 Fundamental Frequency of Carbon fibre vs. Fibre Glass

4. CFD Analysis

The geometry of the aerofoil follows the NACA 4-digit series aerofoil form, which employs a mean camber line that is mathematically determined by the first digit, a second digit that defines the position of the maximum camber, and two last digits that define the maximum thickness. This makes methodical shaping of the aerofoil possible. NREL S818, S827, and S828 aerofoils were used to model the blades by infusing all three aerofoils in one blade design to maximize the high performance of each aerofoil model at the tip, mid and root respectively. This aerofoil was designed to provide a low drag coefficient and high lift coefficient.

The rotor blade model was designed using solidworks software, the length of blade is 5.15m, maximum chord length is 0.88m and tip position at end is 0.24m. Blade is sectioned into 3parts each section with respective airfoil model. The design specification for wind turbine power capacity of 20kw was considered in which a specification was derived and comparing the output power and efficiency with traditional three-blade wind turbine. Wind turbines use variable swept areas to increase their efficiency, which is about 59% according to Betz law.

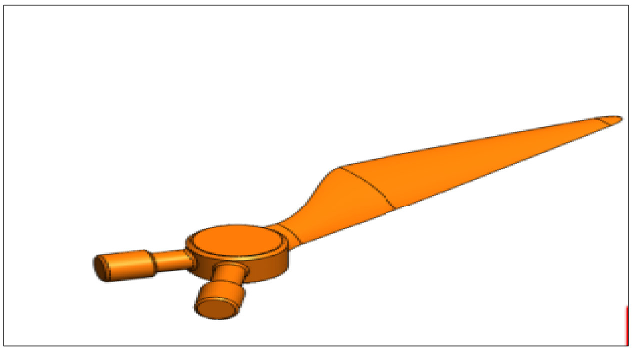

Figure 9 Geometry of Blade Generated in Solidworks

Different parameters of the blade aerofoil are analysed by ANSYS software. The important parameters include the lift coefficient and drag coefficient and their results are plotted on a graph. For simulation Reynolds number and wind speed were kept constant at 822000 and 10m/s respectively. The air density of 1.225 kg/m3 at ambient temperature is considered. The kinematic viscosity 1.789 10-5 kg/m-s is taken varying the angle of attack between 8° to 12°.

In 0.5-degree increments, 2D models were built at angles of attack ranging from 8 to 12 degrees. The sole difference between the models was the angle of attack; all other details remained the same. This makes it possible to compare performance directly to AOA.

Figure 10 AOA 8.5

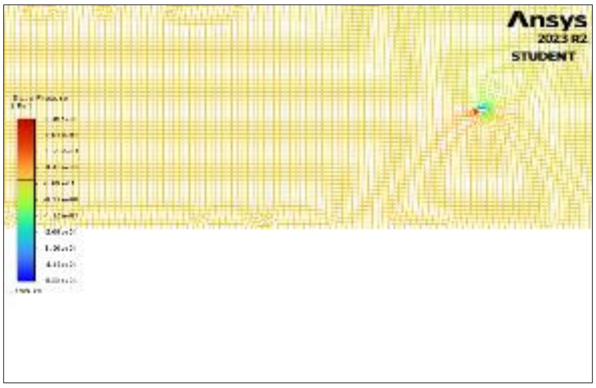

Figure 11 AOA 8.5

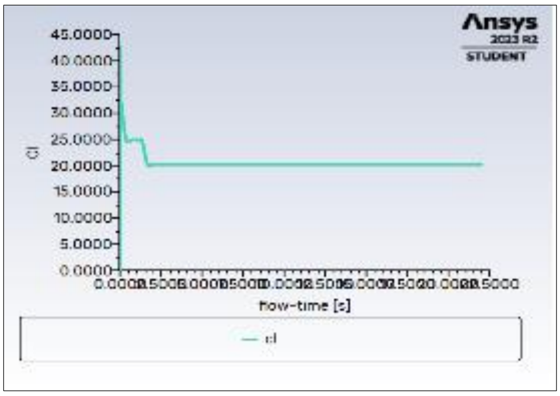

Figure 12 AOA 8.5

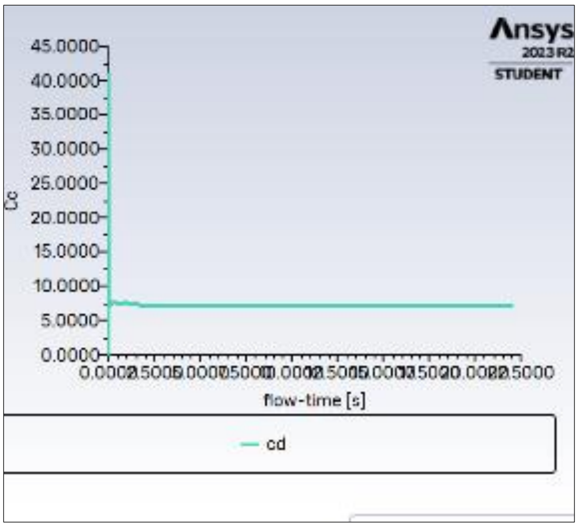

Figure 13 AOA 8.5

A wind tunnel test part was modelled by a rectangular computational domain. With a velocity intake upstream, a pressure outlet downstream, and no-slip walls on the sides and top/bottom, the aerofoil was centred in the tunnel.

Prescriptive flow velocity specification that replicates wind tunnel speed is made possible by the velocity inlet boundary. The walls serve as a model for the test section's confinement and uniform flow across the aerofoil.

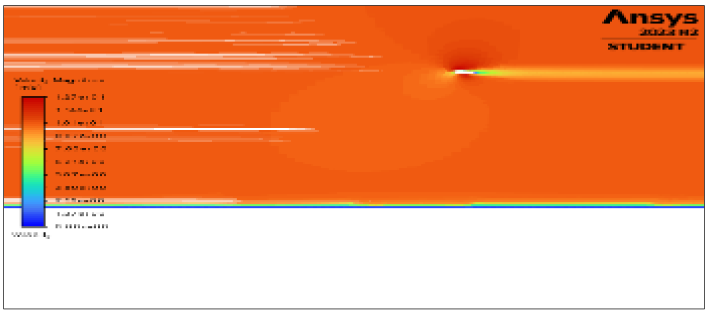

Figure 14 AOA 9

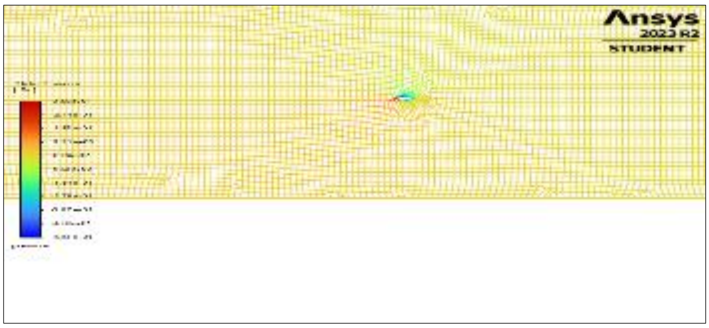

Figure 15 AOA 9

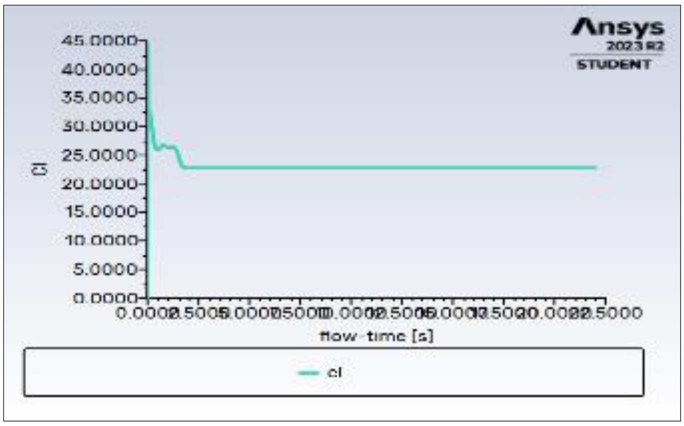

Figure 16 AOA 9

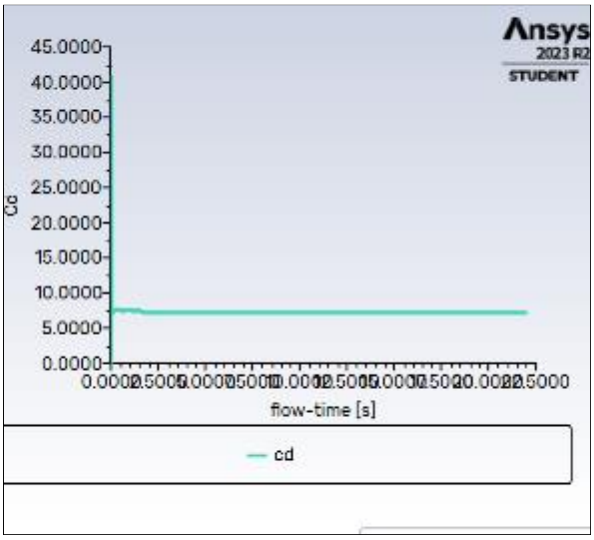

Figure 17 AOA 9

5. CFD Result

A wind turbine blade's aerodynamic performance metrics are displayed in the data at different angles of attack (AOA), ranging from 8 to 12 degrees. Pressure distributions, computed power output, and lift and drag coefficients (Cl, Cd) are important outputs that are examined.

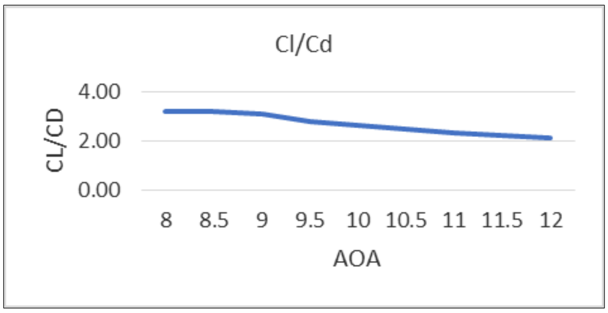

Figure 18 CFD Simulation Result of CI/Cd Against AOA

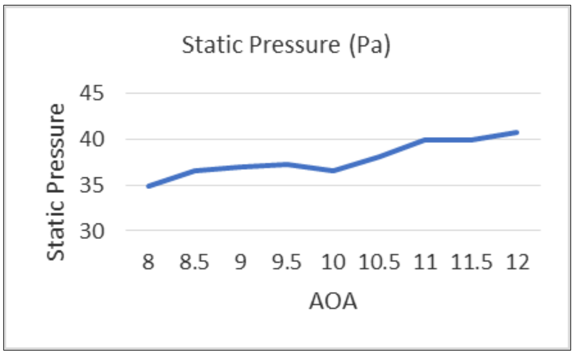

Figure 19 CFD Simulation Result (Static Pressure)

- The lift coefficient (Cl), at 8.5 degrees AOA, first climbs to a high of 22.74 as AOA increases from 8 to 12 degrees. After the 8.5-degree maximum, Cl gradually decreases as the blade experiences stalling at increasing angles of attack.
- The drag coefficient (Cd) rises from 6.4 at 8 deg to 9.03 at 12 deg, almost linearly with AOA, as predicted. Greater Cd denotes increased drag forces with increasing separation.
- The Cl/Cd ratio, which has a ratio of 3.20, indicates that optimal aerodynamic efficiency happens at 8.5 degrees. Because Cd rises more quickly than Cl, performance falls on both sides.
- At lower AOAs, pressure distributions reveal a somewhat homogeneous suction peak on the top surface. The peak suction pressure moves downstream with increasing AOA, signifying flow separation.
- Massive flow separation and stall are reflected by a dramatic suction pressure spike that happens further downstream at 12 degrees AOA. This corresponds to the decline in Cl relative to AOA.
- The computed power output, which peaks at 8.5 degrees AOA and decreases at higher angles when the stall is met, has a strong correlation with the Cl. It reaches its maximum power somewhat below the stall angle.

6. Life Cycle Analysis

6.1. Carbon Fibre vs. Glass Fibre (Single-blade)

The carbon fibre blade has a significantly larger carbon footprint and energy consumption compared to glass fibre, with 28,000 kg of CO2 equivalent emissions and 480,000 MJ of energy used. The carbon fibre blade's production requires energy-intensive manufacturing processes, such as high-temperature pyrolysation and oxidation, compared to lower-temperature melts in glass fibre. Carbon fibre outperforms glass fibre in air acidification, but worse in water eutrophication, releasing more nutrients and causing increased air pollutants and wastewater discharges due to increased electricity demand.

6.2. Single-blade carbon fibre vs. three-blade glass fibre

The life cycle assessment (LCA) reveals that single-blade carbon fibre has a significantly higher carbon footprint than three-blade E-glass. The single-blade carbon fibre emits 2.8 million kg CO2 equivalent emissions, twice as much as the three-blade glass fibre's 1.6 million kg CO2e emissions. The carbon fibre composite requires significantly more energy, with 4.8 million MJ needed for it compared to 1.8 million MJ for the three-blade glass fibre. The single-blade carbon fibre also releases more phosphate equivalent, increasing air pollution and nutrient-rich wastewater discharges.

6.3. Capital Costs

NOTE: $1 = £0.79

Table 1 Capital Cost

Component	Cost
Turbine/Drivetrain	£ 3,746.37
Rotor Hub	£1,248.79
Carbon Fibre Blade	£22,093.24
Steel Lattice Tower	£749.27
Transportation	£312.20
Installation (15%)	£480.91
Total	£28,630.78

(6830.29€ 50% OFF|20KW Wind Turbine Generator 20000W Windmill Big Power 96V 220V 380V Free Energy Wind Generator High Efficiency| | - AliExpress, n.d.)

Table 2 Total Fibre Cost

Fibre	Total mass	Unit Cost	Total cost
Carbon Fibre	1,400kg	15.80 £/kg	£22,093.24
Fibre Glass	2 843.12kg	0.474£/kg	£1,347.63

(Carbon Fiber Price per Kg Sold in Bulk - Alibaba.com, n.d.)

7. Conclusion

This study assessed the performance and design of a single-blade carbon fibre wind turbine. Finite element analysis (FEA) demonstrated the superior stiffness and vibration properties of the orthotropic carbon fibre composite, highlighting its structural advantages over fibreglass. Computational fluid dynamics (CFD) simulations identified the optimal pitch angle for maximum aerodynamic efficiency, enhancing blade performance under varying operational conditions.

A life cycle assessment (LCA) highlighted the trade-offs of carbon fibre blades: they exhibit significantly higher emissions and energy consumption compared to glass fibre but produce fewer SO_2-equivalent emissions. Despite their structural and aerodynamic advantages, the high environmental impact and energy demands of carbon fibre manufacturing remain critical challenges.

The findings underscore the suitability of carbon fibre composites for structural applications requiring high stiffness, strength, and dimensional stability under transverse loads. These properties make them ideal for wind turbine blades, aerospace components, and other engineering designs where minimising deformation and maximising durability are critical. Fibreglass, despite its lower performance, remains viable for less demanding applications where cost considerations take precedence over mechanical superiority. However, for high-performance applications, carbon fibre's higher material cost is offset by its extended lifespan and reduced maintenance needs, making it a more economical choice over time.

While a cost-benefit analysis indicates potential economic viability for single-blade turbines, practical challenges persist, including limitations in manufacturing maturity, environmental considerations, and overall economic feasibility. This research provides a foundational framework for virtual prototyping in wind turbine development, combining structural, aerodynamic, and environmental analyses to inform future innovations in turbine technology.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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