Computational Study on Wind Turbine Rotor Blades Using FEA and CFD Approaches

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***Abstract*—The present study focuses on the modelling and static structural analysis of a horizontal axis wind turbine (HAWT) rotor blade. The blade geometry is designed using the NACA 63415 airfoil profile and modelled in SolidWorks. Finite Element Analysis (FEA) is conducted in ANSYS 19.2 to evaluate the blade's structural performance under static loading conditions. The rotor blade is analyzed using hybrid polymer composite materials, including Glass Fiber Reinforced Polymer (GFRP), Carbon Fiber Reinforced Polymer (CFRP), Graphene fillers, Multi walled carbon nanotubes (MWCNTs). The structural analysis focuses on key parameters such as Total deformation, Equivalent stress, and Equivalent elastic strain. Results indicate that all composite configurations demonstrate acceptable levels of stress and strain, with deformations remaining within the material safety limits. This study provides valuable insights into the structural behavior of wind turbine blades fabricated with advanced composite materials and supports the development of more efficient and durable renewable energy systems.**

***Index Terms*—Wind Turbine Blade, NACA 63415, Static Structural Analysis, CFD, FEA, SolidWorks, ANSYS 19.2,**

I. INTRODUCTION

Composite materials are engineered materials composed of two or more constituent materials with significantly different physical or chemical properties. They are widely used in various industries, including aerospace, automotive, and renewable energy, due to their superior strength-to-weight ratio, durability, and resistance to environmental degradation. Composite materials are engineered materials made by combining two or more distinct components to achieve superior properties [1]. Unlike traditional materials such as metals or plastics, composites offer high strength, low weight, corrosion resistance, and design flexibility, making them ideal for structural applications in aerospace, wind energy, automotive, and marine industries [4,6,2].

Composite materials have been used for thousands of years, evolving from natural materials to advanced engineered composites used in modern industries. The development of composites has been driven by the need for stronger, lighter, and more durable materials for construction, transportation, aerospace, and energy applications.

Composite materials can be categorized based on their matrix phase into several types. Polymer matrix composites (PMCs) are the most commonly used and include fiber-reinforced polymers (FRPs) such as glass fiber-reinforced polymer (GFRP) and carbon fiber-reinforced polymer (CFRP). These materials offer a good balance of strength, weight, and cost-effectiveness. Metal matrix composites (MMCs) consist of metal matrices reinforced with ceramic or metal fibers, providing improved strength and high-temperature performance. Ceramic matrix composites (CMCs), on the other hand, feature ceramic matrices combined with ceramic fiber reinforcements, which significantly enhance their thermal resistance and structural integrity under extreme conditions. A specialized class of PMCs, hybrid composites incorporate multiple types of fibers, such as a combination of carbon and glass fibers, to optimize and balance various mechanical properties for specific engineering applications. Figure 1.1 shows the classification of the composite materials.

Wind turbine blades require materials that provide high strength-to-weight ratios, resistance to environmental degradation, and improved fatigue life. Traditional materials such as pure glass fiber-reinforced composites are commonly used, but hybrid composites can offer superior mechanical properties. Studies have shown that combining carbon and glass fibers in a polymer matrix can enhance the overall mechanical performance of wind turbine blades, reducing weight while maintaining or improving structural integrity [4,2,3,5,6].

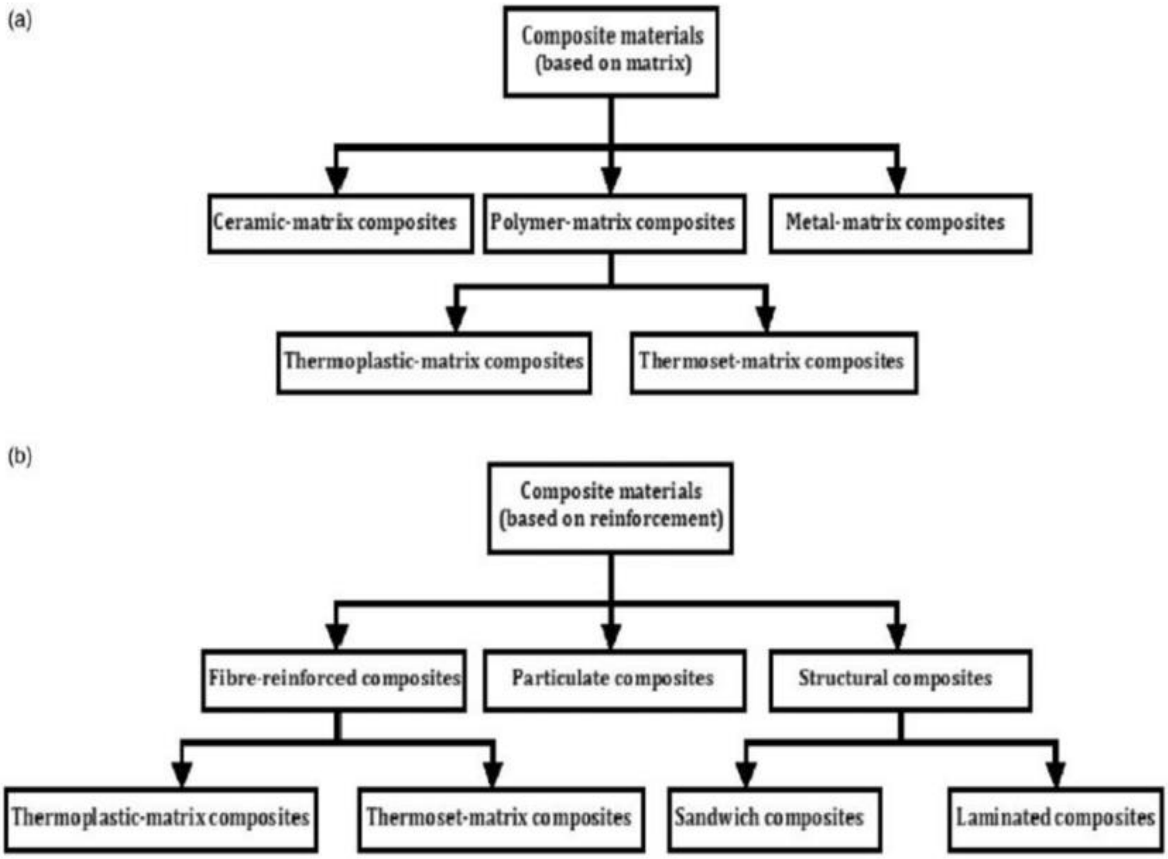


Fig.1.1: Classification of Composite materials

II. LITERATURE REVIEW

Lagouge Tartibu, Mark Kilfoil, A. J. van der Merwe, [1] The paper focuses on the vibration analysis of a variable length blade wind turbine, where the blade consists of a fixed portion and a movable portion that can slide in and out. The study uses MATLAB and Unigraphics NX5 to calculate the natural frequencies of the blade in different configurations. The analysis considers flap-wise, edge-wise, and torsional vibrations and identifies the natural frequencies for ten different blade configurations. The results show that as the blade length increases, the natural frequencies decrease, making the blade more flexible. The study concludes that the first flap-wise natural frequency is the most critical, as it falls within the range of excitation frequencies (0.5 Hz to 30 Hz) that could lead to resonance. The paper suggests that variable length blades can reduce the risk of resonance by adjusting the blade length to avoid critical frequencies. Ganesh B. Taware, Sham H. Mankar, V. B. Ghagare, G. P. Bharambe, Sandip A. Kale 2016, [2] The paper investigates the natural frequencies and mode shapes of small wind turbine blades made from Glass Fiber Reinforced Plastic (GFRP) and GFRP with steel wire mesh reinforcement. The blades are manufactured using a hand layup process, and their dynamic behaviour is analysed using Finite Element Analysis (FEA) in ANSYS 16.0. Deepak J N, Chandan R, Doddanna K (2017), (3) The paper focuses on the design and optimization of a small wind turbine blade for low wind speed conditions. The blade is designed using CATIA V5 and analysed using ABAQUS for static structural analysis. The study considers factors such as tip loss, hub loss, drag coefficient, and wake effects. The blade is made of balsa wood for the core and glass fiber composite for the skin, with aluminium used for certain parts. T. Krishnamurthy, Y. Sesharao (2017) [4] .

The paper focuses on the design and dynamic analysis of a wind turbine blade using the NACA

63415 aerofoil profile. The blade geometry is designed using the Blade Element Momentum (BEM) method and modelled as a ruled 3D surface in CATIA V5. The study employs ANSYS for modal analysis, evaluating natural frequencies and mode shapes under aerodynamic, centrifugal, and gravity loads. Chaudhary M.K. and Anindita Roy, 2015 [5]. The paper focuses on the design and optimization of small wind turbine blades for low wind speed conditions. The study employs Blade Element Momentum (BEM) theory for blade design and uses ANSYS simulations to analyse aerodynamic performance. The SG 6043 air foil is selected for its favourable lift-to-drag characteristics. Finite Element Analysis (FEA) is conducted to assess structural integrity, including deformation and stress distribution. Selvan Nambi and Joselin Herbert (2018) [6] investigated the design and analysis of wind turbine blades (WTBs) considering aerodynamic performance and structural integrity. The study employed Blade Element Momentum Theory (BEMT) for aerodynamic modelling and Finite Element Analysis (FEA) in ANSYS for structural evaluation. Aditya Arvind Yadav et al., L. Mishnaevsky et al., Wei T. (2020) [7] The studies emphasize material selection, FEA, and monitoring systems for better *+durability and efficiency of wind turbine blades analysed a wind turbine blade prototype using Finite Element Analysis (FEA) in ANSYS. Benhadda Yamina et al., (2023) [8] This study presents a modelling and stress analysis of a 61.5-meter wind turbine blade using COMSOL Multiphysics 6.0. The blade is designed for high wind speed locations, incorporating materials like carbon-epoxy, glass-vinylester, and PVC foam. The analysis considers gravitational and centrifugal loads, with maximum Von Mises stress reaching 3.07×10^8 N/m² in the skin and 2.47×10^8 N/m² in the spar. The research highlights the importance of material selection and structural integrity in ensuring blade durability. -Mishnaevsky et al., (2017) [9] This study examines compo*site materials for wind turbine blades, focusing on fatigue failure, delamination, and impact resistance. The results suggest that carbon fiber composites provide higher stiffness and strength than glass fiber, though at a higher cost. Christ & Abeykoon, (2015) [10] The paper discusses wind turbine modelling and numerical simulations to optimize blade performance. The study emphasizes the need for advanced material testing and structural analysis for improved efficiency. Wang et al., 2019 [11] This research focuses on structural optimization of wind turbine towers using finite element analysis (FEA). The study highlights the role of genetic algorithms in improving load distribution and material selection for better performance.

Fakada et al., (2021) [12] The study evaluates fatigue and stress distribution in horizontal axis wind turbine blades, considering aeroelastic behaviour and cyclic loading conditions. The results emphasize the need for high-strength composite materials to withstand long-term operational stresses. Shiv N. Prajapati & Manish Kumar, (2023) [13] This study investigates finite element structural analysis of horizontal axis wind turbine (HAWT) blades using ANSYS 14.5. The authors analyses the aerodynamic performance of the *NACA 4420 air foil, known for its high lift-to-drag ratio at small angles of attack. Stress analysis shows that blade thickness variation reduces bending stress and improves durability. The study concludes that optimizing the blade's structural properties enhances its lifespan while reducing failure risks.Kim et al. (2011) [14] Conducted static, dynamic, and modal tests on 750 kW composite wind turbine blades using fiber Bragg grating sensors. These sensors provided accurate stress and deflection measurements, demonstrating their effectiveness in monitoring structural performance. Curtu et al. (2014) [15] Evaluated NACA 44XX wind turbine blades under gravitational, aerodynamic, operational, and gyroscopic forces. This study identified stress concentration zones, which are critical for preventing blade failure during static and dynamic loading. Wang et al. (2014) [16] Performed finite element analysis (FEA) on NACA 0012 aerofoil blades, showing that the central portion experiences maximum stress, while blade tips undergo maximum displacement under load. Mathew et al. (2015) [17] Analysed blades made from aluminium alloys, structural steel, and carbon Fibers, finding that epoxy-carbon composites offer superior strength for wind turbine applications. Kumar et al. (2017) [18] Compared natural fiber composites (banana, sisal, and jute) *for small wind turbine blades. Banana and sisal composites provided higher tensile strength than jute. Benham et al. (2013) [19] Analysed blades made from E-glass, carbon fiber, S-glass, and Kevlar. Among these, Kevlar had the lowest deformation and highest stress resistance under aerodynamic loading. RS Amano, R.J Malloy (2009) [20] investigated the possibility of increasing the efficiency of the turbine blades at higher wind speeds while maintaining the efficiency at lower wind speeds by selecting the appropriate orientation and size of the air foil cross sections based on low oncoming wind speed and given constant rotation rate. Swept blade profile was implemented to achieve the efficiency at higher wind speeds. Performance was investigated using CFD.

III. COMPUTATIONAL DETAILS

The global focus on clean and renewable energy has intensified the need for efficient wind turbine systems. Rotor blade design is a critical aspect of wind turbine performance. The blade must o*ffer optimal aerodynamic characteristics while maintaining structural integrity under dynamic loading. Computer-aided design (CAD) tools, particularly SolidWorks, have transformed the design process by enabling precise and parametric 3D modelling. This paper details the complete modelling workflow of a rotor blade using the NACA 63415 air foil and SolidWorks software.

3.1 Software Tool: SolidWorks

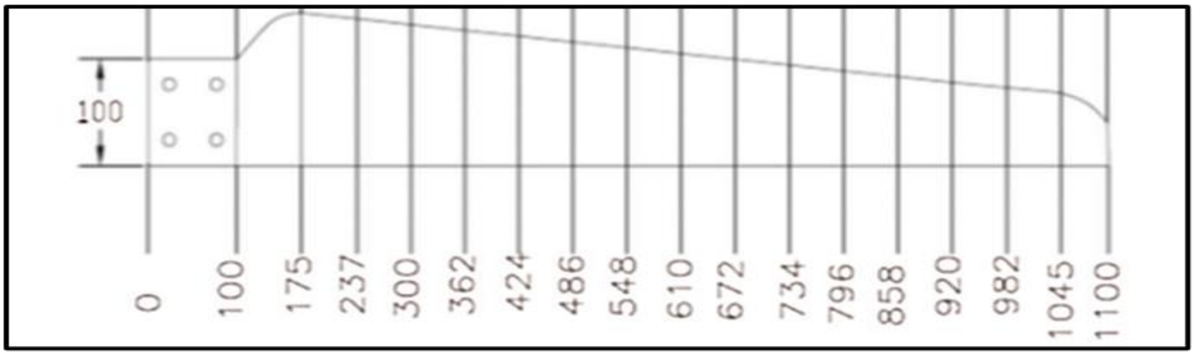
SolidWorks, developed by Dassault Systems, is an advanced CAD and CAE software used across industries for design and simulation. Its capabilities relevant to this study include:

- 3D Modelling: Precision modelling of complex shapes.
- Parametric Design: Easy modification of geometry using constraints.
- Simulation Integration: Compatibility with FEA tools.
- Lofting & Surfacing: Ideal for aerodynamic designs.
- File Interoperability: Supports various formats (.IGES, .STEP, .DXF).

3.2 Methodology: Rotor Blade Design Steps

3.2.1 Reference Plane Creation*

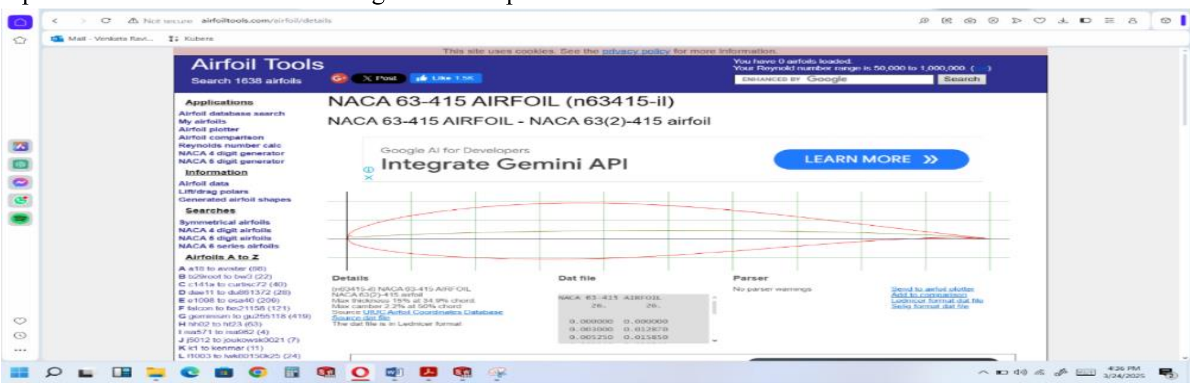
To represent the changing cross-sections of the blade, reference planes were created at designated distances from the root (e.g., 0, 100, 175, 237 mm, etc.) using the *Features → Reference Geometry → Plane* function in SolidWorks.



3.1 Reference blade

3.2.2 Air foil Curve Import

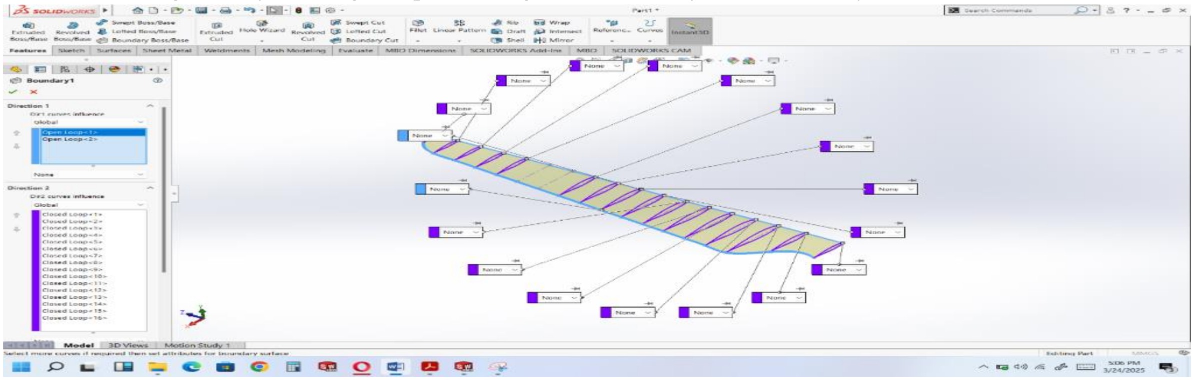
NACA 63415 air foil data was downloaded from online repositories (e.g., Air foil Tools), formatted into XYZ coordinate format, and imported into SolidWorks using *Tools → Curve → Curve Through XYZ Points*. The imported curve was validated through visual inspection.



3.2 Air Foil NACA 63-415

3.2.3 Lofted Blade Generation

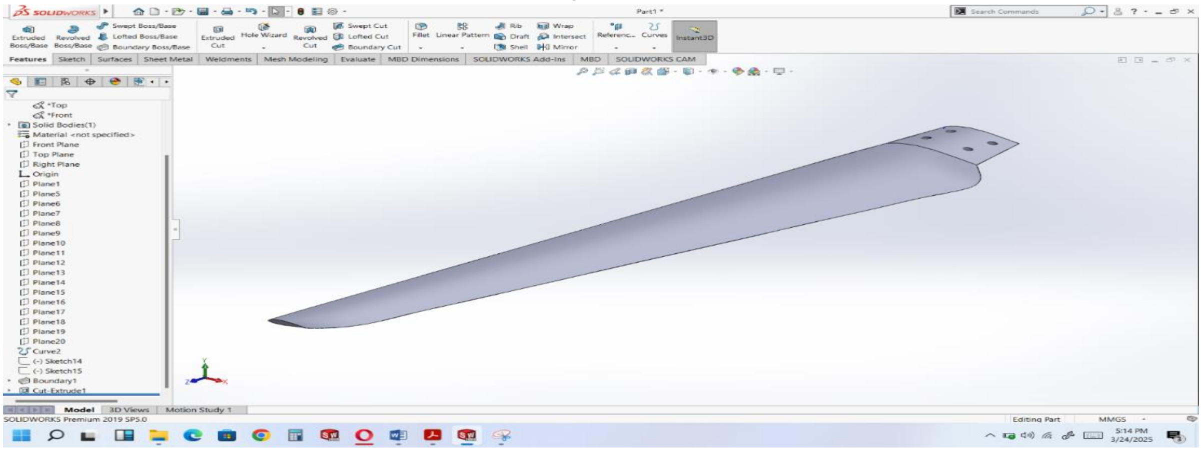
Multiple air foil profiles were aligned across the reference planes and lofted using the *Lofted Boss/Base* feature to create the blade geometry. Scaling and positioning ensured aerodynamic accuracy.



3.3 Section of Air Foil

3.2.4 Structural Detailing

- The blade body was hollowed to reduce weight using *Shell* features.
- UV hard foam bars were embedded between the internal walls for additional reinforcement.
- Cut-Extrude was used to simulate drilling and other machining operations.
- Fillets and Chamfers were added to smoothen edges and reduce stress concentrations.



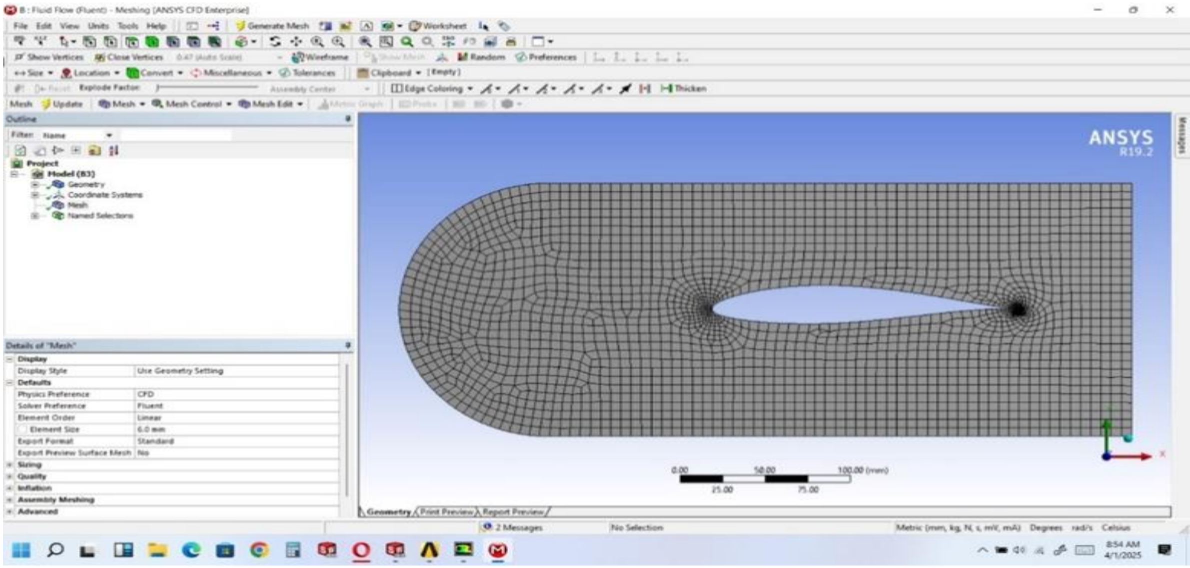
1.4 View of the Blade

3.3 Boundary Conditions

The materials evaluated include combinations of Glass Fiber Reinforced Polymer (GFRP) with different matrices and nano-fillers. The first material, GFRP combined with polyester and graphene fillers, exhibited a modulus of elasticity ranging from 2.0×1072.0 \times 10^72.0×107 to 2.4×1072.4 \times 10^72.4×107 N/mm^2, a Poisson's ratio between 0.25 and 0.27, a density of 1950–2000 kg/m^3, and a yield stress of 135–150 N/mm^2. UV hard foam, used primarily as a lightweight core material, had a significantly lower modulus of elasticity (86328 N/mm^2), a Poisson's ratio of 0.24, and a density of 320 kg/m^3, with no defined yield stress due to its foam structure. GFRP with epoxy and graphene fillers showed improved stiffness, with a modulus ranging from 2.0×1072.0 \times 10^72.0×107 to 2.5×1072.5 \times 10^72.5×107 N/mm^2 and yield stress between 145 and 180 N/mm^2. GFRP combined with polyester and carbon fiber reinforced polymer (CFRP) presented even higher stiffness and strength, with modulus values between 2.5×1072.5 \times 10^72.5×107 and 3.2×1073.2 \times 10^73.2×107 N/mm^2 and yield stress ranging from 160 to 190 N/mm^2. Similarly, GFRP with epoxy and CFRP demonstrated the highest mechanical properties in the group, having a modulus between 2.8×1072.8 \times 10^72.8×107 and 3.2×1073.2 \times 10^73.2×107 N/mm^2 and yield stress from 170 to 200 N/mm^2. Composites containing multi-walled carbon nanotubes (MWCNTs), such as GFRP with polyester or epoxy matrices, also displayed strong mechanical characteristics, with moduli in the range of 2.2×1072.2 \times 10^72.2×107 to 3.0×1073.0 \times 10^73.0×107 N/mm^2 and yield stress ranging from 140 to 170 N/mm². These material variations provided a comprehensive basis for analyzing the blade's structural behavior under static loads.

3.4 Meshing

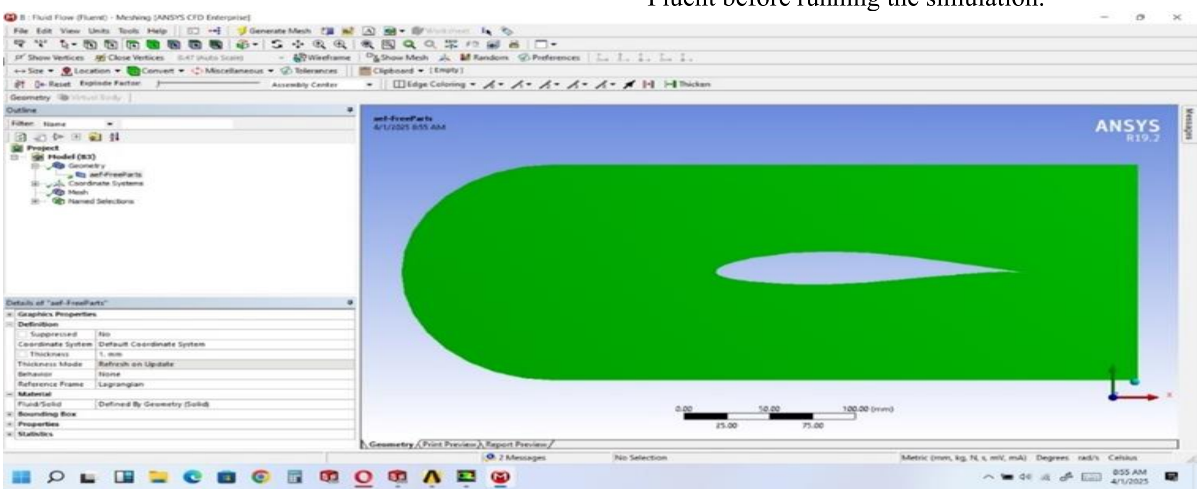
The geometry of the wind turbine blade was developed in SolidWorks and subsequently imported into ANSYS Workbench for finite element analysis as shown in figure 3.5. A detailed mesh was generated using tetrahedral elements to capture the complex surface geometry of the blade, resulting in a total of 6640 nodes and 3118 elements. To simulate real-world loading conditions, a fixed support was applied at the root of the blade, representing its attachment to the hub. Additionally, two concentrated point loads of 343.45 N and 343.35 N were applied along the span of the blade to replicate aerodynamic forces experienced during operation. This setup provided a realistic foundation for evaluating the structural performance of the blade under static loading conditions.



1.5 Meshing Of CFD

IV. RESULTS AND DISCUSSIONS

The green region represents the fluid domain, while the blue shape represents an air foil or an obstacle within the fluid. The thickness of the domain is set o 1.0 mm, which suggests that the model may be configured for a 2D analysis with an extrusion thickness. The fluid/solid behaviour is determined by the geometry, meaning the material properties will be assigned in the physics setup. The Larangian reference frame is selected, but for typical CFD simulations, an Eulerian reference frame is usually used. This setup will be followed by mesh generation, where an appropriate grid will be applied to capture flow characteristics accurately. For the next steps, the meshing process should ensure refinement around the air foil and boundary layers to improve accuracy. After meshing, boundary conditions such as velocity inlet, pressure outlet, and wall definitions need to be specified in ANSYS Fluent before running the simulation.



Geometry Of CFD

4.1 STREAM VISUALIZATION

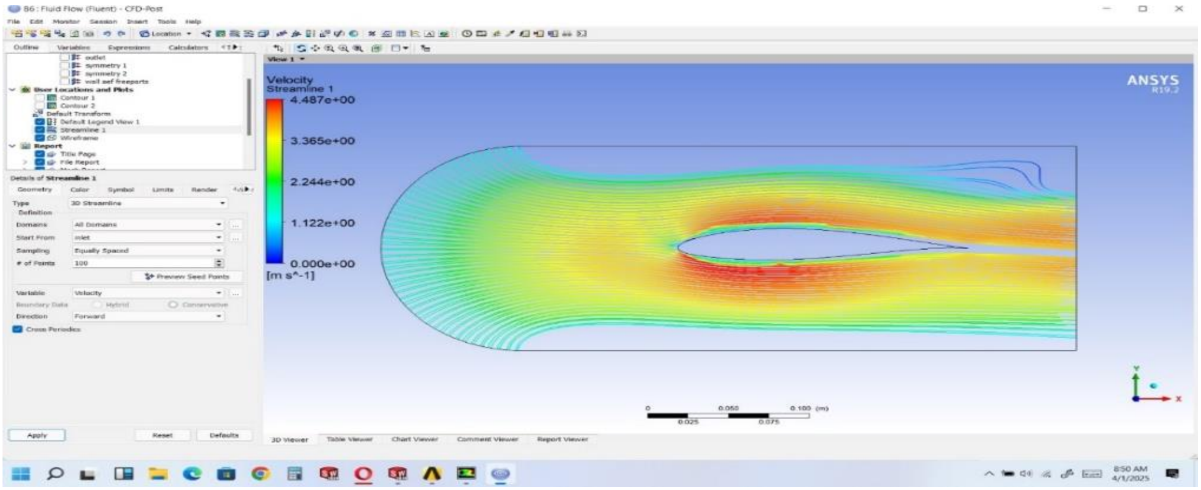


Fig 4.1: Stream visualization

1. Streamlines Representation: The coloured streamlines indicate the velocity of airflow around the air foil. The colour scale ranges from blue (low velocity) to red (high velocity). Airflow smoothly adheres to the air foil's shape, showing how fluid moves from the inlet (left side) to the outlet (right side).
2. Velocity Distribution: The upper surface of the air foil has higher velocity (yellow-red regions), suggesting a low-pressure region due to Bernoulli's principle. The lower surface has relatively lower velocity (green-blue regions), indicating a higher-pressure region. This velocity difference is crucial for lift generation.
3. Wake Formation and Flow Separation: At the trailing edge, the streamlines begin to diverge, forming a wake region. Some recirculating patterns in the blue region near the trailing edge suggest possible flow separation or minor turbulence.
4. Simulation Parameters: The left panel shows that 100 streamlines were generated, starting from the inlet with equally spaced seed points. The velocity variable is used for streamline visualization. The computational domain appears to be 0.1–0.2 meters in length.

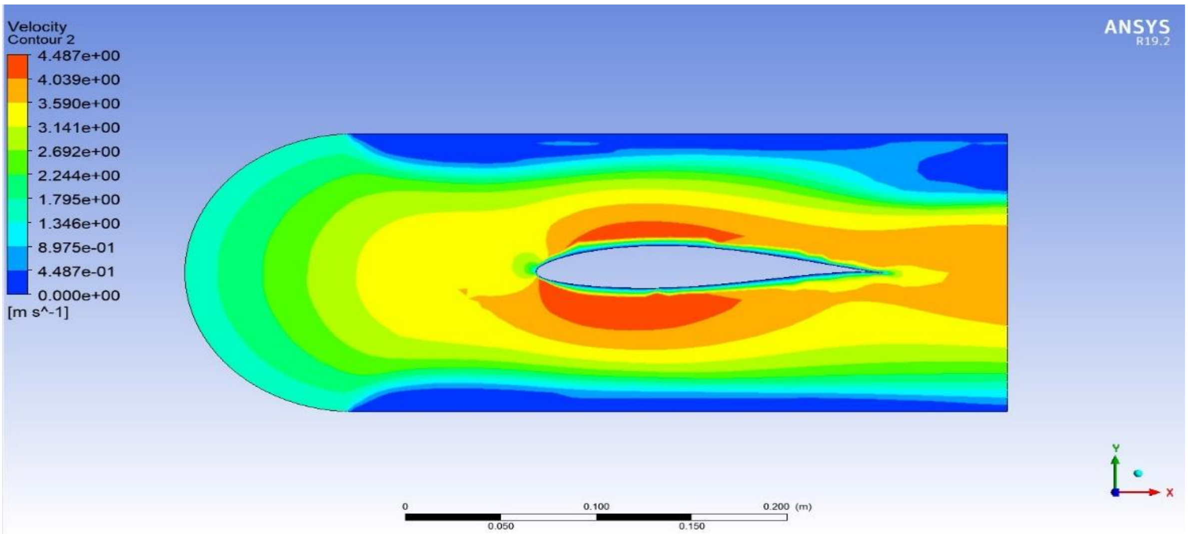


Fig 4.2: Flow Behaviour

The colour scale represents velocity magnitudes, with red indicating high velocity (approximately 4.487 m/s) and blue representing low velocity (near 0 m/s). The airflow accelerates over the upper surface of the air foil, creating a high-velocity, low-pressure region, while the lower surface experiences lower velocity and higher pressure. This difference

in pressure generates lift, which is essential for aerodynamic performance.
At the leading edge, the flow smoothly adheres to the air foil surface, while at the trailing edge, a wake region forms due to flow separation and turbulence. The x-axis represents the direction of airflow, while the y-axis shows the vertical dimension of the analysis domain.

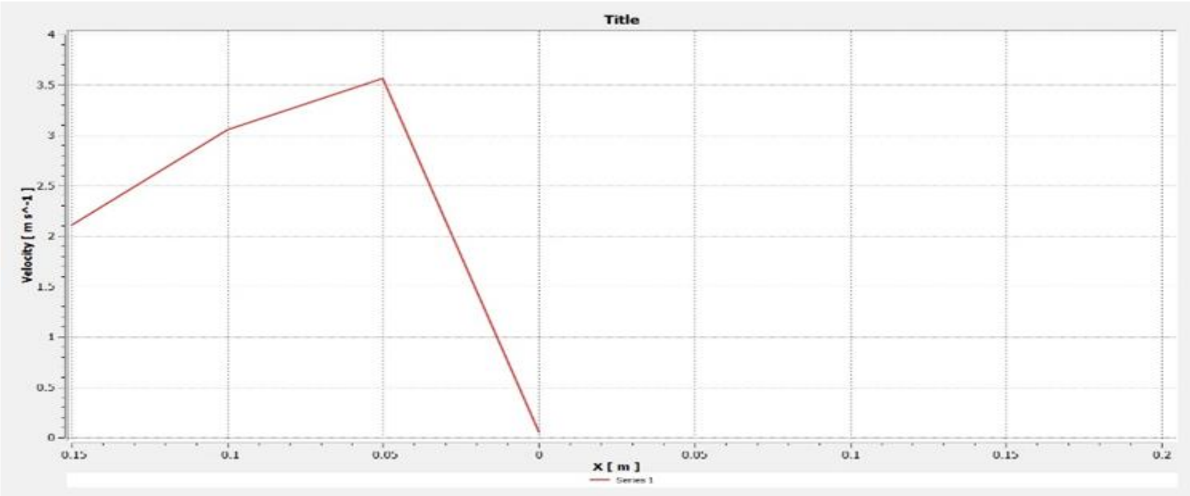


Fig 4.3: Velocity

4.2 CFD ANALYSIS RESULT TABLE

S.NO	MATERIAL NAME	Velocity
1	NACA63-415	4.487e+00

Table 6.1 CFD analysis result

4.2.1 Discussion on CFD Analysis Result

Computational Fluid Dynamics (CFD) analysis plays a vital role in evaluating the aerodynamic performance of air foil profiles used in wind turbine blades. In this study, a CFD simulation was conducted to assess the airflow characteristics over the NACA 63-415 air foil. The key parameter extracted was the velocity magnitude, which is critical for understanding the aerodynamic efficiency and lift potential of the blade design.

Velocity Analysis

The CFD simulation revealed a velocity of 4.487 m/s for the NACA 63-415 air foil under the defined boundary conditions. This value represents the flow acceleration around the air foil surface, which is closely associated with the generation of lift and the efficiency of energy conversion in wind turbines.

The NACA 63-415, being part of the 6-series air foils, is specifically designed for laminar flow control, providing a high lift-to-drag ratio which is essential for wind energy applications. The recorded velocity suggests a favourable pressure distribution over the air foil surface, promoting efficient lift generation with minimized flow separation and drag.

Implications for Wind Turbine Design

A velocity magnitude of 4.487 m/s around the air foil indicates:

- Good aerodynamic performance at the tested angle of attack and flow conditions.
- Effective air foil shaping, suitable for low-to-medium wind speed regions.
- Potential for optimized power output when implemented in horizontal axis wind turbines (HAWTs).

This velocity also serves as a foundation for calculating other aerodynamic parameters like pressure coefficient, lift and drag forces, and ultimately, the blade's torque and power coefficient.

4.3 STATIC STRUCTURE ANALYSIS RESULT TABLE

S.NO	MATERIALS NAME	Total Deformation IN MM	Equivalent Elastic Strain	Equivalent stress (N/MM^2)
1	GFRP+ Polyester+ Graphene fillers	1.4815e-003	1.3e-006	2.5991
2	UV Hard Foam	1.9388e-002	5.0185e-006	0.24357

3	GFRP+ Epoxy + Graphene fillers	1.4094e-003	1.266e-006	2.7091
4	GFRP +Polyester + CFRP	1.2834e-003	1.1512e-006	2.7029
5	GFRP+ Epoxy +CFRP	1.2185e-003	1.0978e-006	2.7043
6	GFRP + Polyester+ MWCNT	1.3323e-003	1.1963e-006	2.7134
7	GFRP+ Epoxy +MWCNT	1.3323e-003	1.1963e-006	2.7134

Table 4.2 Static Structural analysis result

4.3.1 Discussion on Static Structural Analysis Results

The static structural analysis conducted using ANSYS 19.2 offers valuable insights into the mechanical performance of various hybrid polymer composite materials proposed for wind turbine rotor blades. The results, including total deformation, equivalent elastic strain, and equivalent stress, allow for comparative evaluation of stiffness, strength, and deformation resistance among the tested materials.

Total Deformation

The total deformation values indicate the extent of displacement under the applied loads. Among all tested materials, UV Hard Foam exhibited the highest deformation of 1.9388e-002 mm, reflecting its relatively low stiffness and poor load-bearing capability. In contrast, the GFRP + Epoxy + CFRP combination showed the least deformation (1.2185e-003 mm), suggesting superior rigidity and structural integrity.

The three hybrid configurations that included carbon-based fillers—GFRP + Epoxy + MWCNT, GFRP + Polyester + MWCNT, and GFRP + Epoxy + Graphene fillers—also demonstrated minimal deformation, each in the range of 1.3e-003 mm, showing that the addition of nanomaterials effectively enhances the stiffness of the composite.

Equivalent Elastic Strain

The elastic strain values further validate the material behaviour under load. Again, UV Hard Foam presented the highest strain (5.0185e-006), consistent with its high deformation. The lowest strain was seen in GFRP + Epoxy + CFRP (1.0978e-006), followed closely by other nanomaterial-infused composites, confirming their superior resistance to elastic deformation.

This implies that CFRP and nanofillers like graphene and MWCNT (Multi-Walled Carbon Nanotubes) contribute significantly to minimizing the internal strains within the material, which is crucial for the fatigue performance of wind turbine blades.

Equivalent Stress

The equivalent stress values represent the von Mises stress distribution and are critical in understanding the failure potential of the materials. All composite configurations with GFRP, CFRP, and nanofillers showed relatively higher stress values (around 2.6 – 2.71 N/mm²), indicating their capacity to withstand higher loads without failure. Among these, GFRP + Epoxy + MWCNT and GFRP + Polyester + MWCNT exhibited the highest stress capacity (2.7134 N/mm²), marking them as optimal choices in terms of load resistance.

In contrast, UV Hard Foam displayed a significantly lower stress value (0.24357 N/mm²), underscoring its unsuitability for high-load applications like wind turbine blades.

A velocity magnitude of 4.487 m/s around the air foil indicates:

- Good aerodynamic performance at the tested angle of attack and flow conditions.
- Effective air foil shaping, suitable for low-to-medium wind speed regions.
- Potential for optimized power output when implemented in horizontal axis wind turbines (HAWTs).

This velocity also serves as a foundation for calculating other aerodynamic parameters like pressure coefficient, lift and drag forces, and ultimately, the blade's torque and power coefficient.

V. CONCLUSION

The modeling and simulation of wind turbine rotor blades using FEA and CFD provided valuable insights into their structural and aerodynamic performance. Hybrid polymer composites reinforced with nanofillers like MWCNT and Graphene significantly improved mechanical properties. Among the materials tested, GFRP + Epoxy + MWCNT and GFRP + Polyester + MWCNT exhibited minimal deformation and strain, along with high stress capacity, indicating superior stiffness. CFRP-based composites also performed well, while UV Hard Foam showed high deformation and poor stress resistance, making it unsuitable structurally. CFD analysis confirmed the aerodynamic efficiency of the NACA 63-415 airfoil, with favorable velocity distribution (4.487 m/s), indicating effective laminar flow and lift generation. Overall, the combined structural and aerodynamic analysis highlights GFRP-based composites with nanofillers and the NACA 63-415 airfoil as optimal choices for high-performance wind turbine blades. Future work may focus on experimental validation and further optimization.

REFERENCES

[1] Tartibu, L.K., Kilfoil, M., & van der Merwe, A.J. (2012). Vibration Analysis of a Variable Length Blade Wind Turbine. International Journal of Advances in Engineering & Technology, 4(1), 630-639

[2] Ganesh B. Taware, Sham H. Mankar, V. B. Ghagare, G. P. Bharambe, and Sandip A. Kale (2016). Vibration Analysis of a Small Wind Turbine Blade. International Journal of Engineering and Technology, Vol. 8, Issue 5, October-November 2016.

[3] Deepak J. N., Chandan R., Doddanna K. (2017). Design and Optimization of a Small Wind Turbine Blade for Low Wind Speed Conditions. International Journal of Innovative Research in Science, Engineering and Technology, Vol. 6, Issue 9, September 2017.

[4] T. Krishnamurthy, Y. Sesharao (2017). Design and Dynamic Analysis of a Wind Turbine Blade Using NACA 63415 Aerofoil Profile. International Journal of Engineering Research and Applications, Vol. 7, Issue 5, 2017.

[5] Chaudhary M.K., Anindita Roy (2015). Design and Optimization of Small Wind Turbine Blades for Low Wind Speed Conditions. International Journal of Advanced Mechanical Engineering, Vol. 5, Issue 7, 2015.

[6] Selvan Nambi, Joselin Herbert (2018). Design and Analysis of Wind Turbine Blades Considering Aerodynamic and Structural Integrity. International Journal of Mechanical and Production Engineering Research and Development, Vol. 8, Issue 1, February 2018.

[7] Aditya Arvind Yadav, L. Mishnaevsky, Wei T. (2020). Material Selection, Finite Element Analysis (FEA), and Monitoring Systems for Wind Turbine Blades. International Journal of Engineering Research and Applications, Vol. 10, Issue 12, December 2020.

[8] Benhadda Yamina et al. (2023). Modeling and Stress Analysis of a 61.5-Meter Wind Turbine Blade Using COMSOL Multiphysics 6.0. International Journal of Renewable Energy Research, Vol. 13, Issue 2, 2023.

[9] Mishnaevsky L. et al. (2017). Composite Materials for Wind Turbine Blades: Fatigue Failure, Delamination, and Impact Resistance. Materials, Vol. 10, Issue 11, 2017.

[10] Christ & Abeykoon (2015). Wind Turbine Modelling and Numerical Simulations for Performance Optimization. International Journal of Sustainable Energy, Vol. 34, Issue 4, 2015.

[11] Wang et al. (2019). Structural Optimization of Wind Turbine Towers Using Finite Element Analysis and Genetic Algorithms. Wind Energy Science, Vol. 4, Issue 3, 2019.

[12] Fakada et al. (2021). Fatigue and Stress Distribution in Horizontal Axis Wind Turbine Blades Under Cyclic Loading Conditions. Journal of Renewable and Sustainable Energy, Vol. 13, Issue 5, 2021.

[13] Shiv N. Prajapati & Manish Kumar (2023). Finite Element Structural Analysis of Horizontal Axis Wind Turbine (HAWT) Blades Using ANSYS 14.5. International Journal for Research Trends and Innovation, Vol. 2, Issue 7, July 2023.

[14] Kim et al. (2011). Static, Dynamic, and Modal Tests on 750 kW Composite Wind Turbine Blades Using Fiber Bragg Grating Sensors. International Journal of Aeronautical and Space Sciences, Vol. 12, Issue 4, December 2011.

[15] Curtu et al. (2014). Evaluation of NACA 44XX Wind Turbine Blades Under Gravitational, Aerodynamic, and Gyroscopic Forces. Pro Ligno, Vol. 11, Issue 4, December 2014.

[16] Wang et al. (2014). Finite Element Analysis (FEA) of NACA 0012 Aerofoil Blades Under Static and Dynamic Loading Conditions. Journal of Mechanical Engineering Science, Vol. 228, Issue 10, 2014.

[17] Mathew et al. (2015). Analysis of Wind Turbine Blades Made from Aluminum Alloys, Structural Steel, and Carbon Fibers. International Journal of Engineering Science and Technology, Vol. 7, Issue 6, 2015.

[18] Kumar et al. (2017). Comparative Study of Natural Fiber Composites (Banana, Sisal, and Jute) for Small Wind Turbine Blades. Journal of Composite Materials, Vol. 51, Issue 20, 2017.

[19] Benham et al. (2013). Structural Analysis of Wind Turbine Blades Made from E-glass, Carbon Fiber, S-glass, and Kevlar Under Aerodynamic Loading. Journal of Wind Engineering, Vol. 37, Issue 2, 2013.
[20] Amano, R.S., & Malloy, R.J. (2009). CFD Analysis on Aerodynamic Design Optimization of Wind Turbine Rotor Blades. World Academy of Science, Engineering and Technology, 60, 71–75.