



An Investigation And Comparison Analysis Of Carbon Fiber Wind Turbine Blade

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Abstract: The optimal twist of a windmill blade is analyzed using fundamental blade element theory. It is demonstrated that, for a specific wind speed and blade angular velocity, the highest power efficiency is attained when the blade is twisted according to a scheme that reflects the changes in the sectional lift and drag coefficients relative to the angle of attack. Findings for a standard air foil cross-section indicate that the optimal angle of attack diminishes from the angle corresponding to the maximum lift coefficient at the blade root to more than eighty percent of this value at the blade tip. The materials employed in the study with Carbon fiber material with the NACA-63215 aerofoil profile

Index Terms - Carbon fiber, Wind turbine, NACA Air foil. Buckling load.

I. INTRODUCTION

The objective of this project is to fabricate a Horizontal Axis Wind Turbine Blade and to conduct an analysis of the buckling effects on the blade, which is a critical component of wind turbines. Wind turbine blades experience significant torque and buckling loads, which are primary contributors to blade failures. In this study, we examined the failures associated with buckling loads along the blade and determined that it can withstand loads of up to 6700N. Wind energy has the lowest relative greenhouse gas emissions and smallest water consumption demands, resulting in favorable social impacts compared to other energy sources like photovoltaic, hydro, geothermal, coal, and gas. This finding is instrumental in understanding the various failure modes of wind turbine blades [1, 2]. Renewable energy has become increasingly significant in global discussions surrounding climate change. These energy sources play a crucial role in mitigating greenhouse gas emissions, as they are not reliant on fossil fuels. Currently, over 75% of India's electricity is produced from coal-fired thermal power plants. In alignment with international commitments to reduce greenhouse gas emissions, the Government of India has enacted robust legal frameworks and policies to foster the growth of renewable energy. Notably, India has pioneered the establishment of a dedicated ministry—the Ministry of New and Renewable Energy (MNRE) to promote the advancement of power generation from renewable sources. The use of wind energy for electricity generation is gaining traction and is capturing a substantial share of the global electricity market.

1. Small-scale: Smaller wind turbines are used for auxiliary power applications, such as: Battery charging for boats or caravans powering traffic warning signs
2. Large-scale: Larger turbines contribute to domestic power supply and enable selling unused power back to the utility supplier via the electrical grid [3]

II. LITERATURE SURVEY

Dr. P.P.Ritapure et.al. [4] Proposed VAWT design demonstrated impressive performance, generating 50 watts of power at a wind speed of 4.5 m/s. This novel design showcases potential for improved efficiency and power output in VAWT. The method important parts including the shaft, UC 204 bearing, permanent magnet generator, gears, and aluminium sheet, using the NACA0018 air foil blade as a point of reference. P. Sakthivel et.al. [5] Proposed system was simulated using MATLAB, and the results were tabulated to demonstrate the effectiveness of the optimized control system in increasing wind power production. To achieve this objective, the study focuses on developing an optimized control system for an induction generator in conjunction with the Maximum Power Point Tracking (MPPT) of the wind turbine. The design aims to minimize resistive power loss. Yassine Charabi et.al. [6] Conducted a study to evaluate the wind power generation capacity in Northern and Southern Oman. The study aimed to identify the most economical, efficient, and reliable wind turbines for Oman's power needs. The researchers utilized HOMER Pro Software to analyze wind energy data in both regions. They evaluated six standard wind turbines, comparing their performance and cost of energy. T. Vishnuvardhan and Dr.B. Durga Prasad et.al. [7] Were presented a research paper on the development of small wind turbine blade models. The study focused on designing and fabricating blades with two distinct profiles, R21 and R22, using the NACA 63-415 airfoil. Ibrahim Alrowwad [8] proposed a study on utilizing numerical techniques to analyze and optimize wind blade performance. The research aimed to maximize design efficiency and enhance the overall performance of wind turbines.

WIND TURBINE

A Wind Turbine is a device shown in Figure 1 is that converts kinetic energy from the wind, also called wind energy, into mechanical energy a process known as wind power. If the mechanical energy is used to produce electricity, the device may be called a Wind turbine or Wind power plant. If the mechanical energy is used to drive machinery, such as for grinding grain or pumping water, the device is called a wind mill or wind pump. Similarly, it may refer to as a Wind charger when used for charging batteries. The modern wind turbine is a system that comprises three integral components with distinct disciplines of engineering science. The rotor component includes the blades for converting wind energy to an intermediate low speed rotational energy. The generator component includes the electrical generator, the control electronics, and most likely a gearbox component for converting the low speed rotational energy to electricity. The structural support component includes the tower for optimally situating the rotor component to the wind energy source. There are two basic sorts of wind turbines: Horizontal-axis turbines and Vertical-axis turbines. There are also sub types of vertical axis wind turbines namely Darrieus wind turbine, Giro mill turbines and Savinious turbines [2, 4]. The result of over a millennium of windmill development and modern engineering, today's wind turbines are manufactured in a wide range of vertical and horizontal axis types. The smallest turbines are used for applications such as battery charging or auxiliary power on boats: while large grid connected arrays of turbines are becoming increasingly important sources of wind power produced commercial electricity.

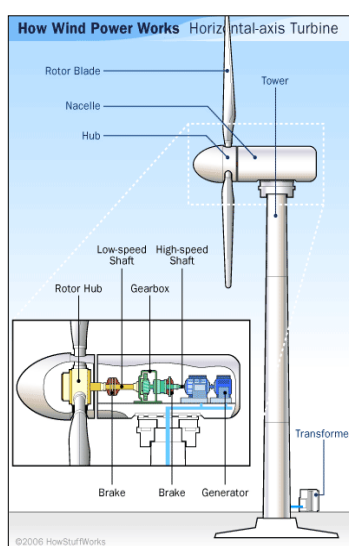


Fig. 2, 3 Horizontal Axis Wind Turbines HAWT)

Fig. 4 Vertical axis wind turbines

TYPES OF WIND MILLS

Horizontal Axis Wind Turbine (HAWT)

Horizontal-axis wind turbines (HAWTs) have their main rotor shaft and electrical generator located at the top of a tower as shown in Figures 2 and 3. These turbines must be oriented to face into the wind to operate efficiently. For small turbines, a simple wind vane is used to adjust the orientation, while larger turbines typically rely on a wind sensor coupled with a servo motor for more precise control. To maximize energy production, most HAWTs are equipped with a gearbox, which converts the slower rotation of the blades into a faster rotation suitable for driving an electrical generator. However, because the tower produces turbulence in the air behind it, the turbine is usually positioned slightly upwind to minimize the impact of this turbulent airflow on performance. This ensures optimal wind capture and enhances the turbine's efficiency.

Vertical Axis Wind Turbine (VAWT)

Vertical-axis wind turbines (VAWTs) have their rotor shaft oriented vertically, as opposed to the horizontal orientation found in traditional turbines as shown in Fig.4 one of the key advantages of this design is that VAWTs do not require alignment with the changing wind direction, allowing them to capture wind energy from any direction. This feature makes them well-suited for locations where wind direction is highly variable. Another benefit is that the generator and gearbox can be placed close to the ground, simplifying maintenance and reducing the need for complex tower structures. The direct connection between the rotor assembly and the ground-level gearbox allows for easier servicing, repair, and replacement of components, making VAWTs a potentially more accessible and cost-effective option for certain applications. However, while they offer these advantages, VAWTs generally have lower efficiency and are less common than horizontal-axis wind turbines in large-scale power generation.

3. Composites

Composite materials are engineered materials created from two or more constituent materials with distinct physical or chemical properties. When combined, these materials produce a material with characteristics different from the individual components. Classification of Composite Materials

Composite materials can be classified based on

1. Matrix material: polymers, metals, or ceramics
2. Reinforcement phase: fibers, particulates, or whiskers (short fibers) Importance of bonding. The bonding between particles, fibers, or whiskers and the matrix is crucial. In structural composites, polymeric molecules known as coupling agents are used to enhance bonding.

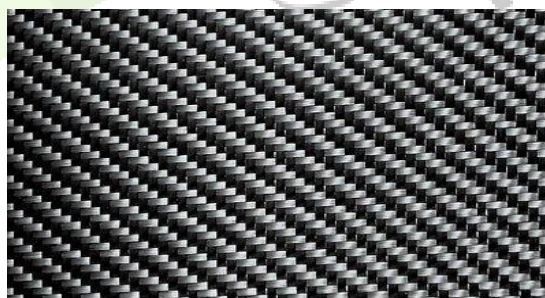


Fig.5 Carbon fibre (Google)

Types of Composite Materials

Among composite materials, fiber-reinforced polyester composites are the most popular. These include: 1. Glass Fiber Reinforced Polyester (GFRP) 2. Carbon Fiber Reinforced Polyester (CFRP) 3. Natural Fiber Reinforced Polyester (NFRP) Objectives of Composite Materials the primary goal of these composites is to improve: 1. Strength 2. Stiffness 3. Fatigue resistance 4. Strength-to-weight ratio

Aerodynamics of Airfoils

When an airfoil-shaped body moves through a fluid, it generates an aerodynamic force. This force can be broken down into two components:

- Lift: The component perpendicular to the direction of motion, which provides the upward force that counteracts weight and keeps the airfoil flying.

- Drag: The component parallel to the direction of motion, which opposes the forward motion of the airfoil.

Characteristics of Subsonic Flight Airfoils:

- Rounded leading edge
- Sharp trailing edge
- Asymmetric curvature of upper and lower surfaces
- Hydrofoils: Airfoils designed to operate in water instead of air are called hydrofoils. These foils use the same principles of aerodynamics, but with water as the working fluid, to generate lift and propel watercraft forward.

Advantages of NACA 63-215 Aerofoil Profile

- Low Drag: Designed to maintain laminar flow over a significant portion of the chord, reducing skin friction drag and improving overall aerodynamic efficiency.
- High Lift-to-Drag Ratio: Optimized for a lift coefficient around 0.5, providing an excellent balance between lift and drag, making it efficient for various flight conditions.
- Efficient at Moderate Speeds: Ideal for subsonic flight regimes, suitable for general aviation, UAVs, and other moderate-speed applications.
- Structural Integrity: The 15% maximum thickness offers a good compromise between aerodynamic performance and structural strength, making it suitable for wing and control surface designs.
- Versatility: Can be applied in different areas such as aircraft wings, stabilizers, and wind turbines due to its efficient aerodynamic profile.
- Fuel Efficiency: The reduced drag helps improve fuel efficiency, lowering operational costs and minimizing environmental impact.
- Stable Handling: Contributes to smooth and stable handling characteristics, enhancing Performance for both piloted and unmanned vehicles. These advantages make the NACA 63-215 aerofoils a popular choice for designs where low drag and efficient lift are paramount.

The NACA 63-215 airfoil shown in Fig.5 is a part of the 6-series family of airfoils designed for achieving laminar flow and good lift characteristics. Here's a breakdown of its key features based on the given parameters:

- Max Thickness: 15% of the chord length.
- Max Thickness Location: Occurs at 34.9% of the chord length from the leading edge.
- Max Camber: 2.2% of the chord length.
- Max Camber Location: Occurs at 50% of the chord length from the leading edge.

This profile is designed to optimize laminar flow over a significant portion of the airfoil, reducing drag while maintaining lift, making it suitable for applications requiring efficient cruising performance, such as in certain aircraft wings. The "63" indicates it's from the 6-series, with "2" representing the mean line, "1" the maximum camber, and "5" the maximum thickness (multiplied by 10). When creating a basic drawing of a blade using the NACA 63-215 airfoil profile, several key aspects need to be carefully considered and illustrated to ensure accuracy and functional representation:

Airfoil Shape: The NACA 63-215 airfoil has a maximum thickness of 15% at 34.9% of the chord



Fig. 5 NACA 63-215 Airfoil (Google)

3.1 Buckling in Wind Turbines

Wind turbine blades are prone to buckling due to the compressive loads imposed by wind forces, gravity, and centrifugal forces. Buckling can lead to catastrophic failure, resulting in significant economic losses and potential safety risks. Understanding and mitigating buckling is crucial for ensuring the structural integrity and reliability of wind turbines. Engineers use advanced analysis techniques, such as finite element analysis, and design optimization methods to minimize the risk of buckling and ensure the safe operation of wind turbines.

4. Ansys geometry and Meshing details of Wind Turbine

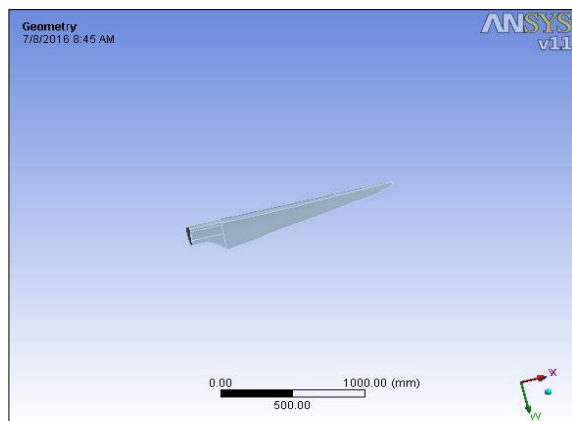


Fig.6 Ansys- Imported geometry

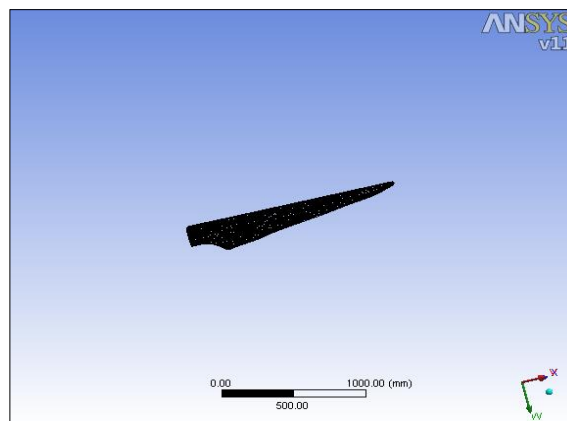


Fig.7 Ansys Meshing

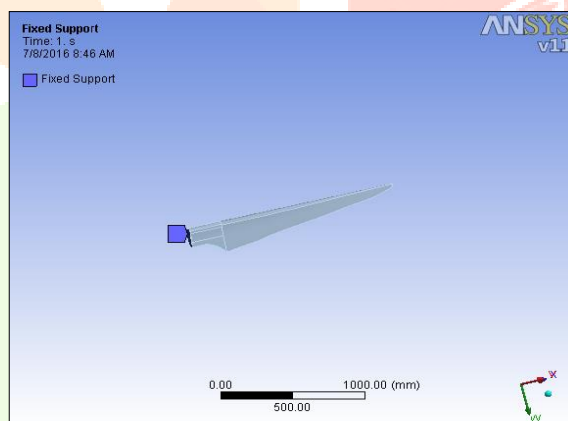


Fig.8 Ansys Fixed support

The Fig.6 explained the Imported Geometry the 3D geometry of the Vertical Axis Wind Turbine was imported into ANSYS software for analysis. The geometry consisted of the turbine blades, hub, and shaft. Fig.7 explained the ANSYS Meshing to perform finite element analysis; the imported geometry was meshed using ANSYS Meshing tool. The meshing process involved: Dividing the geometry into smaller elements (mesh) - Defining element types and sizes - Ensuring mesh quality for accurate results. The meshed model was then used for further analysis, including structural and fluid dynamics simulations, to evaluate the performance and behavior of the Vertical Axis Wind Turbine. Fixed Support Boundary Condition is explained in Fig.8 the Ansys analysis of the Vertical Axis Wind Turbine, a fixed support boundary condition was applied to the base of the turbine shaft. This boundary condition simulates the real-world scenario where the turbine is anchored to the ground. Fixed Support Details: - Location: Base of the turbine shaft - Type: Fixed support (no displacement or rotation allowed) - Purpose: To replicate the anchored condition of the turbine and analyze the structural behavior under various loads. This boundary condition helps to accurately analyze the stress, strain, and deformation of the turbine components under different operating conditions.

4.1 Analysis of Wind Turbine with a Load of 10000 N

The Fig.9 mentioned about the total Deformation results under a 10,000 N load are summarized below: Maximum Deformation: 30.741 mm Mid-point Deformation: 13.663 mm Minimum Deformation: 3.4156 mm. These results provide valuable insights into the structural behavior under varying loads.

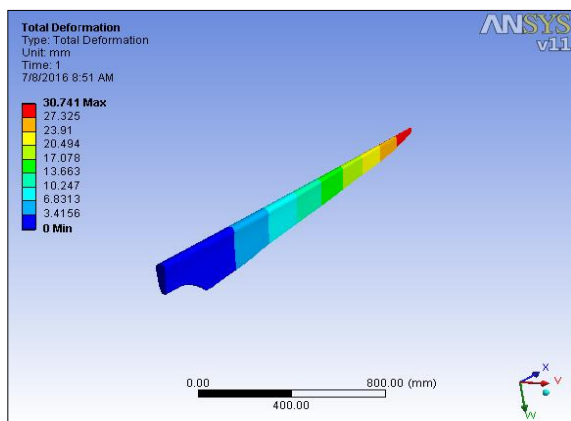


Fig. 9 Total Deformation

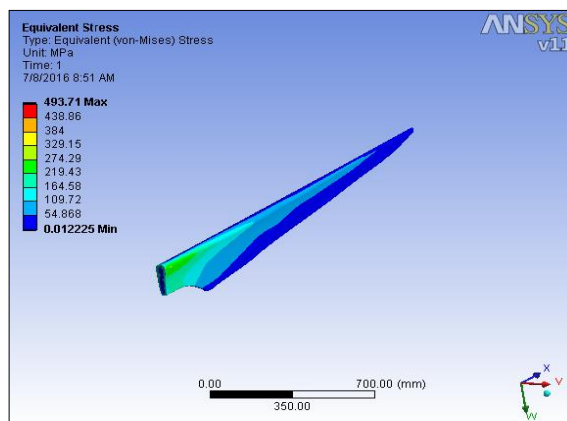


Fig. 10 Equivalent stress

The mentioned Fig.10 about the Equivalent Stress and Deformation Results under 10,000 N Load The equivalent stress and total deformation results under a 10,000 N load are summarized likewise Maximum Deformation: 493.71 MPa, Mid-point Deformation: 219.43 MPa and Minimum Deformation: 0.012225 MPa. These results offer valuable insights into the equivalent stress behavior of the structure under varying loads, providing essential data for further analysis and optimization.

4.2 Analysis of Wind Turbine blade with a Load of 6000N

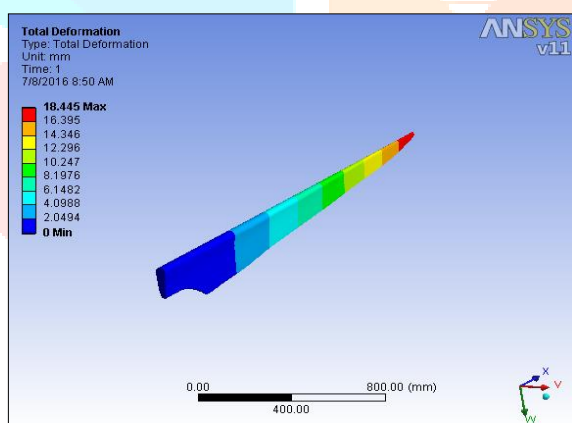


Fig.11 Total Deformation

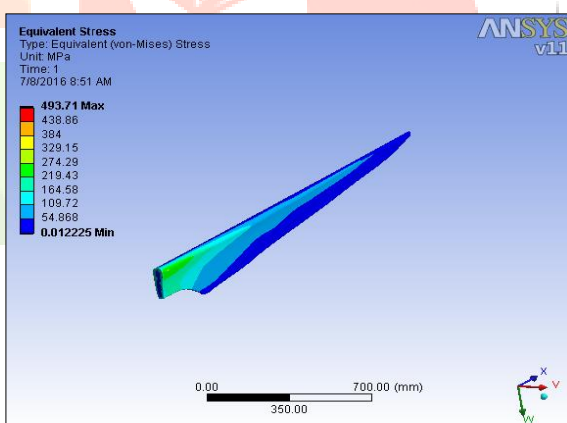


Fig.12 Equivalent stress

The above Fig.11 mentioned about the total Deformation results under a 6,000 N load are summarized below: Maximum Deformation: 18.44 mm Mid-point Deformation: 8.197 mm Minimum Deformation: 2.0494 mm. These results provide valuable insights into the structural behavior under varying loads. The above Fig.12 mentioned about the Equivalent Stress and Deformation Results under 6,000 N Load The equivalent stress and total deformation results under a 6000N load are summarized likewise Maximum Deformation: 246.86 MPa, Mid-point Deformation: 109.72 MPa and Minimum Deformation: 32.92 MPa. These results offer valuable insights into the equivalent stress behavior of the structure under varying loads, providing essential data for further analysis and optimization.

4.3 Analysis of Wind Turbine blade with a Load of 5000N

The above Fig.13 mentioned about the total deformation results under a 5,000 N load are summarized below: Maximum Deformation: 15.37 mm Mid-point Deformation: 6.83 mm Minimum Deformation: 1.7078 mm. These results provide valuable insights into the structural behavior under varying loads.

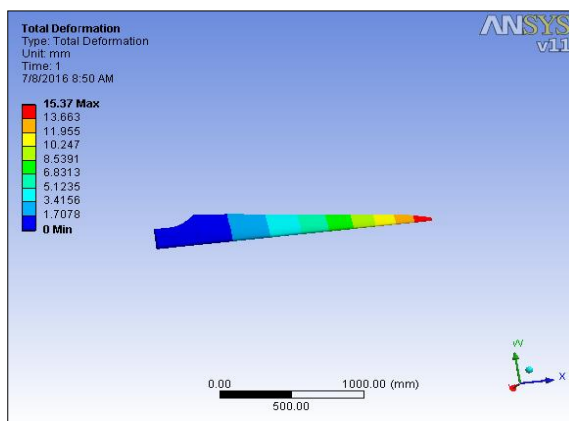


Fig.13 Total Deformation

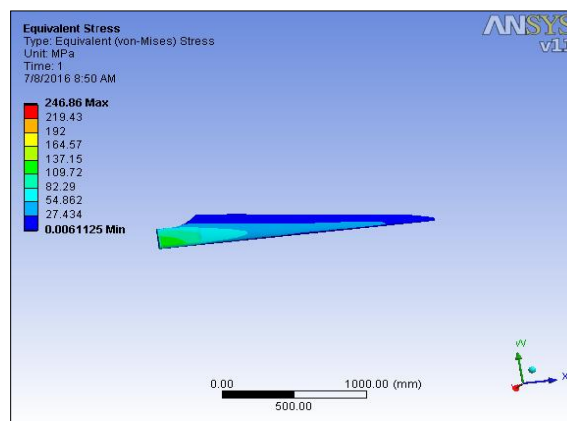


Fig.14 Equivalent stress

The above Fig.14 mentioned about the Equivalent Stress and Deformation results under 5,000 N Load. The equivalent stress and total deformation results under a 5,000 N load are summarized likewise Maximum Deformation: 246.86 MPa, Mid-point Deformation: 137.15 MPa and Minimum Deformation: 0.006 MPa. These results offer valuable insights into the equivalent stress behavior of the structure under varying loads, providing essential data for further analysis and optimization.

4.4 Analysis of Wind Turbine blade with a Load of 4000N

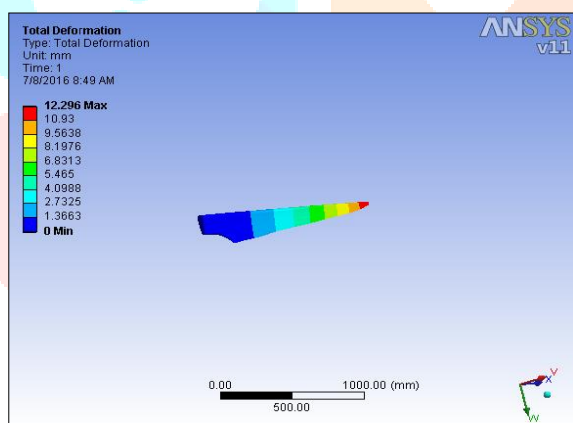


Fig. 15 Equivalent stress

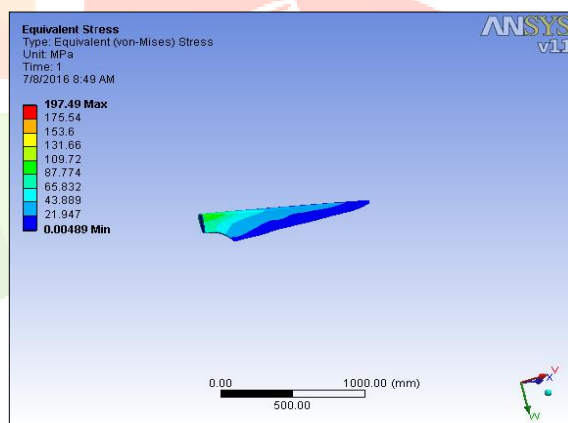


Fig. 16 Total Deformation

The above Fig.15 mentioned about the Equivalent Stress and Deformation Results under 4,000 N Load. The equivalent stress and total deformation results under a 4,000 N load are summarized likewise Maximum Deformation: 246.86 MPa, Mid-point Deformation: 137.15 MPa and Minimum Deformation: 27.434 MPa. These results offer valuable insights into the equivalent stress behavior of the structure under varying loads, providing essential data for further analysis and optimization.

The above Fig.16 mentioned about the total deformation results under a 4,000 N load are summarized below: Maximum Deformation: 12.29 mm Mid-point Deformation: 5.465 mm Minimum Deformation: 1.366 mm. These results provide valuable insights into the structural behavior under varying loads.

4.5 Analysis of Wind Turbine blade with a Load of 3000N

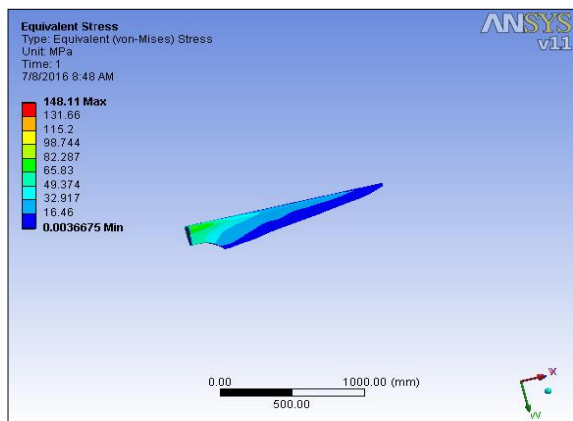


Fig. 17 Equivalent stress

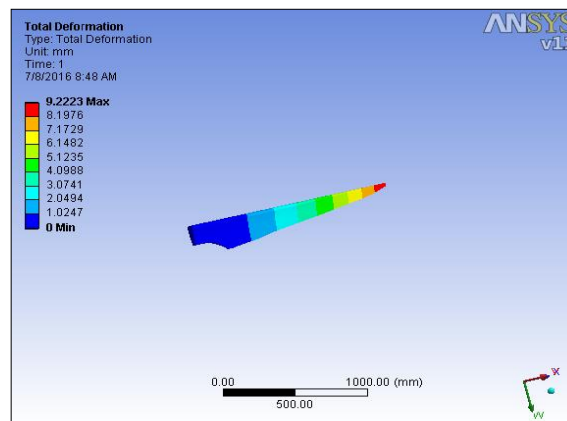


Fig. 18 Total Deformation

The below Fig.17 mentioned about the Equivalent Stress and Deformation results under 3,000 N Load. The equivalent stress and total deformation results under a 3,000 N load are summarized likewise Maximum Deformation: 148.11 MPa, Mid-point Deformation: 65.83 MPa and Minimum Deformation: 0.00366 MPa. These results offer valuable insights into the equivalent stress behavior of the structure under varying loads, providing essential data for further analysis and optimization.

The below Fig.18 mentioned about the total deformation results under a 4,000 N load are summarized below: Maximum Deformation: 9.22 mm Mid-point Deformation: 4.09 mm Minimum Deformation: 0. mm. These results provide valuable insights into the structural behavior under varying loads.

4.6 Total Deformation Frequency

In ANSYS, the total deformation frequency is a result of a modal analysis that shows the total deformation of a wind turbine object at various mode frequencies. This analysis provides valuable insights into:

1. Natural Frequencies: The inherent frequencies at which the wind turbine structure tends to vibrate.
 2. Mode Shapes: The deformation patterns or shapes that the structure assumes at each natural frequency.
 3. Total Deformation: The combined effect of all mode shapes, providing a comprehensive understanding of the wind turbines dynamic behaviour. By analyzing the total deformation frequency, engineers can:
 1. Identify potential resonance issues
 2. Optimize turbine design for reduced vibrations
 3. Improve overall structural integrity and reliability
 4. Enhance wind turbine performance and efficiency.
- ANSYS enables detailed modal analysis, allowing engineers to simulate various loading conditions, such as wind loads, gravitational loads, and rotational loads. This helps ensure that wind turbines are designed to withstand dynamic loads and operate efficiently over their lifespan.

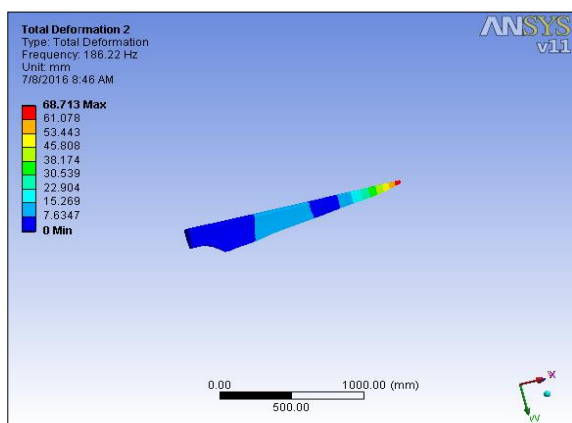


Fig.19 Mode 1

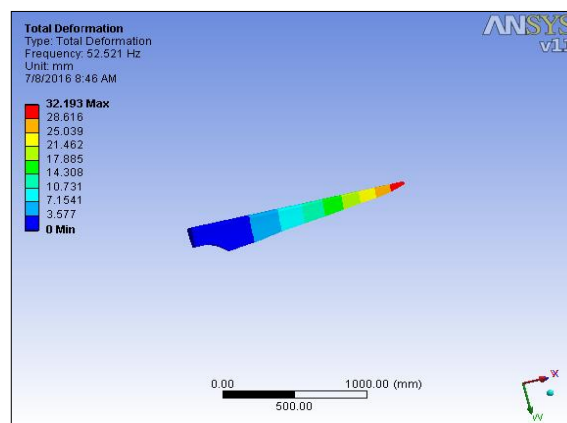


Fig.20 Mode 2

Fig.19 presents the results of the modal analysis, which examined the dynamic behavior of the wind turbine structure. The analysis revealed the following key findings: Total Deformation Frequency: 52.521 Hz, indicating the frequency at which the structure exhibits maximum deformation. Maximum Deformation: 32.193 mm, representing the largest displacement of the structure from its equilibrium position. Mean Deformation: 14.3 mm, signifying the average displacement of the structure over the analyzed frequency range. Minimum Deformation: 0 mm, indicating that the structure returns to its equilibrium position at certain points during the vibration cycle. Fig.20 presents the results of the modal analysis, providing further insights into the dynamic behavior of the wind turbine structure. The analysis revealed the following key findings:

Total Deformation Frequency: 186.22 Hz, indicating a higher frequency at which the structure exhibits maximum deformation. Maximum Deformation: 68.72 mm, representing a significant displacement of the structure from its equilibrium position. Mean Deformation: 30 mm, signifying a higher average displacement of the structure over the analyzed frequency range. Minimum Deformation: 0 mm, indicating that the structure returns to its equilibrium position at certain points during the vibration cycle.

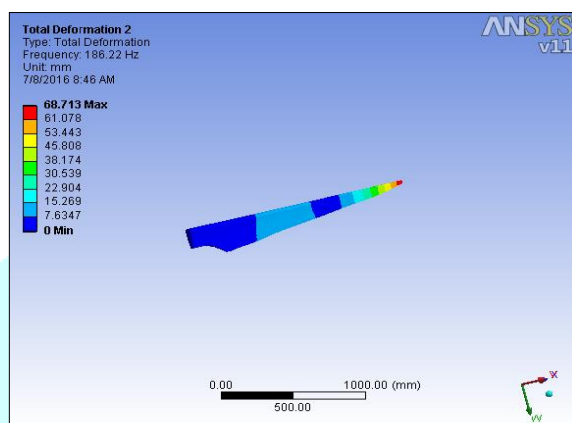


Fig.21 Mode 3

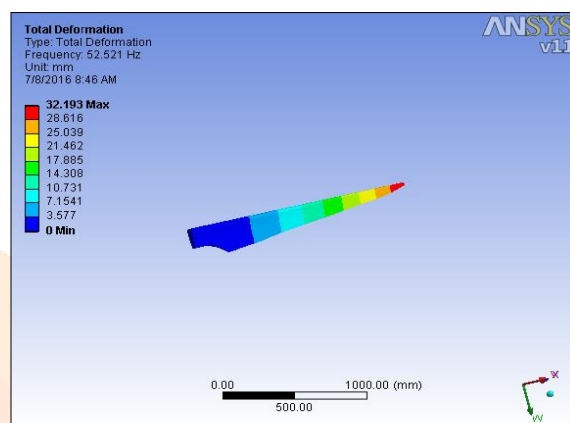


Fig.22 Mode 4

Fig. 21 presents the results of the modal analysis, providing additional insights into the dynamic behavior of the wind turbine structure. The analysis revealed the following key findings: Total Deformation Frequency: 199.2 Hz, indicating a high-frequency vibration mode. Maximum Deformation: 39.2 mm, representing a significant displacement of the structure from its equilibrium position. Mean Deformation: 17.42 mm, signifying a moderate average displacement of the structure over the analyzed frequency range. Minimum Deformation: 0 mm, indicating that the structure returns to its equilibrium position at certain points during the vibration cycle. Fig. 22 presents the results of the modal analysis, providing additional insights into the dynamic behavior of the wind turbine structure. The analysis revealed the following key findings: Total Deformation Frequency: 659.25 Hz, indicating a high-frequency vibration mode. Maximum Deformation: 67.628 mm, representing a significant displacement of the structure from its equilibrium position. Mean Deformation: 30.05 mm, signifying a moderate average displacement of the structure over the analyzed frequency range. Minimum Deformation: 0 mm, indicating that the structure returns to its equilibrium position at certain points during the vibration cycle.

Fig. 23 presents the results of the modal analysis, providing additional insights into the dynamic behavior of the wind turbine structure. The analysis revealed the following key findings: Total Deformation Frequency: 677.43 Hz, indicating a high-frequency vibration mode. Maximum Deformation: 119.75 mm, representing a significant displacement of the structure from its equilibrium position. Mean Deformation: 53.22 mm, signifying a moderate average displacement of the structure over the analyzed frequency range. Minimum Deformation: 0 mm, indicating that the structure returns to its equilibrium position at certain points during the vibration cycle.

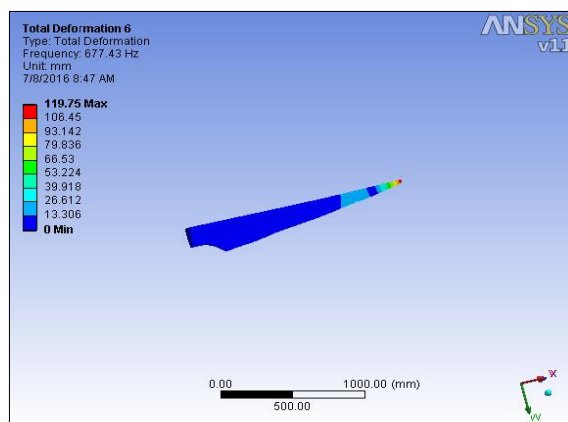


Fig.23 Mode 5

5. Results and Discussions

This graph illustrates the correlation between the applied vertical load and the resulting total deformation of the wind turbine blade. The graph provides insight into the blade's structural behavior, showcasing how the deformation increases with the applied load. This graph offers a comprehensive view of the blade's response to varying loads, displaying both the equivalent stress and total deformation. The equivalent stress represents the combined effect of different stress components, while the total deformation indicates the overall displacement of the blade. This graph enables the evaluation of the blade's structural integrity and its ability to withstand Various Loading Conditions.

5.1 Conformation Test

A comparative analysis was conducted to evaluate the performance of different materials for wind turbine blades, including Carbon Fibres, Gray Cast Iron, Stainless Steel (SS), and Epoxy Glass. The analysis focused on the deformation behavior of these materials under a load of 3000N. The present analysis results were compared with the findings of Mada Rukmini et.al. [9], who conducted a similar study with a load of 2000N. The comparison revealed that the Carbon Fiber material performed consistently well in both studies, validating its suitability for wind turbine blades.

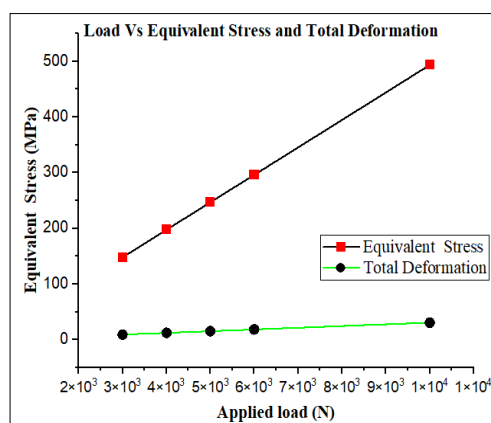
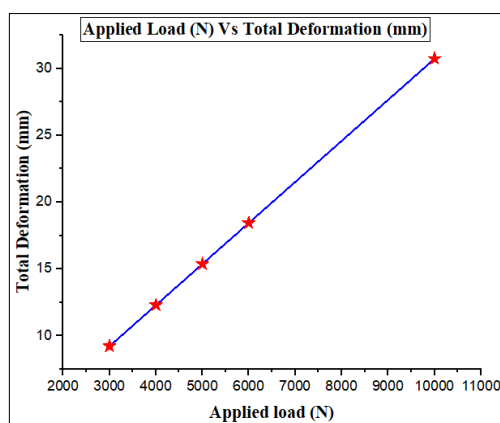


Fig. 24 Applied Load (N) Vs Total Deformation (mm) Fig. 25 Applied Load (N) Vs Total Deformation

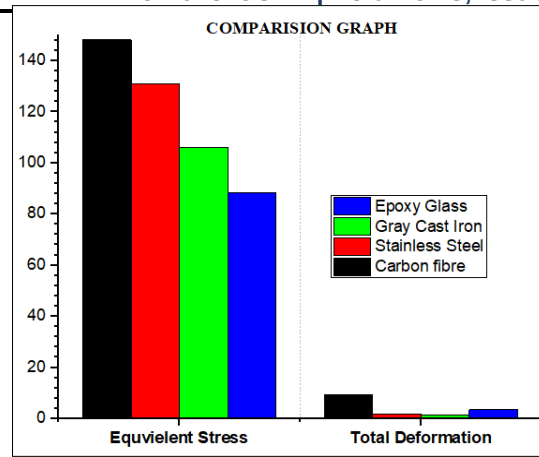


Fig. 26 Conformation Test on Applied Load (N) Vs Total Deformation

6. Conclusion

The analysis provides insight into the structural integrity and deformation characteristics of the wind turbine blade under specified loads, using carbon fiber as the material. A horizontal axis wind turbine blade has been analyzed using carbon fiber material, focusing on its static structural and modal behavior. The blade, designed with the NACA-63215 aerofoil profile, was modeled in Pro-E and analyzed in Ansys. The analysis involved applying vertical loads of 3000N, 4000N, 5000N, 6000N, and 10000N to evaluate the structural response and deformation. The results indicate a proportional increase in both equivalent stress and total deformation with the applied load. This analysis is critical in understanding the performance and structural integrity of the wind turbine blade under various loading conditions, highlighting its capability to withstand different stresses and deformations.

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