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# Thermal and Structural Performance Analysis of wind Turbine Blades Using Advanced Composite Materials: A FEA Simulation Study

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**ABSTRACT**

Wind turbine blades are critical additives that at once influence the performance, reliability, and service lifestyles of wind strength systems. As turbine sizes increase to fulfill growing strength needs, the need for advanced substances with advanced mechanical and thermal houses becomes crucial. This look at affords a comprehensive finite element evaluation (FEA)-primarily based investigation into the structural and thermal overall performance of horizontal-axis wind turbine blades product of advanced composite substances, particularly epoxy-glass and epoxy-carbon. The blade geometry become modeled using Pro/ENGINEER (Creo Parametric), and static structural, modal, and consistent-state thermal analyses have been conducted the use of ANSYS Workbench beneath operational loading situations described by using worldwide requirements (IEC 61400-1). The results of the simulation showed that the total deformation of epoxy-carbon composite blades was significantly lower (729 mm) than that of epoxy-glass blades (955.33 mm), which indicates better stiffness and aerodynamic hundreds resistance. Moreover, epoxy-carbon exhibited a marginally reduced von Mises stress (10.51 MPa vs. 10.82 MPa) and a more evenly distributed stress, indicating a progress in fatigue resistance. Directional deformations in the flap-smart (Y) and area-wise (Z) directions were further reduced by approximately 24% and 24% respectively in the carbon-bolstered layout. Epoxy-carbon composites were found to have lower thermal expansion and better dimensional stability under temperature gradients, which is important for offshore and arid-climate applications.These results confirm that epoxy-carbon composites provide superior specific electricity, stiffness-to-weight ratio and thermal stability compared to conventional epoxy-glass making them tremendously appropriate for next generation wind turbine blades notwithstanding better preliminary fees. The study demonstrates that the integrated CAD/CAE workflows can speed up the optimisation of the blade design and validate the overall performance under multi-physical loads.

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## 1. INTRODUCTION

Wind electricity has been one of the fastest growing renewable power resources over the past two many years, driven by means of global efforts to reduce dependence on fossil fuels, reduce operating costs, and improve the best and reliability of power generation (Hau, 2006; Burton, 2011). Today thousands of wind turbines are whirling around the world, producing clean, renewable energy to meet the growing needs of modern life. From 2000 to 2016, wind electricity experienced exponential increase, with global established capacity greater than quadrupling. The United States presently leads the arena in wind electricity technology, accounting for a significant share of general wind-derived power output (Johnson, 2001; Hau, 2006).

Compared to traditional energy sources, wind power gives vast environmental benefits. It produces no greenhouse gas emissions or air pollution in the course of operation and calls for no fuel enter past the herbal kinetic strength of the wind (Burton, 2011). The primary environmental footprint stems from the producing, transportation, and installation of turbine components. A regularly mentioned situation is the capability chance to avian and bat populations; but, research indicate that chicken mortality as a result of wind generators is notably lower than that resulting from air pollution and habitat degradation associated with fossil fuel-based power generation (Johnson, 2001; Habali & Saleh, 2000).

Wind generators function on the same aerodynamic concepts that permit airplane wings to generate elevate (Abbott & Doenhoff, 1949). When the wind blows past the turbine blades, the difference in pressure produces turning forces that spin the generator. Most modern generators are equipped with anemometers that continuously record wind speed. When the wind speed reaches a certain minimum—typically about 4 m/s, called the cut-in speed—the control system starts the rotor and electricity is generated at low speeds. The power output is unexpectedly increasing in wind velocity, with a cubic courting with wind speed. When the turbine reaches its design capacity at a rated wind speed of around 15 m/s, the control machine limits the output to the rated energy to prevent damage to the mechanical components. If the wind speed exceeds a critical level, in the order of 25 m/s, the so called cut-out velocity, the turbine is usually shut down completely in order to prevent structural damage (Fuglsang & Madsen, 1999; Stol et al., 2006).

The strategic importance of wind electricity has increased with the rising demand for a transition to sustainable energy systems. With fossil fuels becoming more costly and less sustainable to the environment, wind electricity is expected to provide 1.1 trillion kilowatt-hours (kWh) of the 3.3 trillion kWh of renewable electricity expected to be provided globally by 2030 (Maalawi & Badr, 2003; Van Kuik, 2007). Wind and solar electricity are the most economically viable and scalable of all renewable technologies. Other developing renewable sources are either too expensive or not proven enough for massive scale-up, suggesting that wind power will be crucial in the future global power mix.

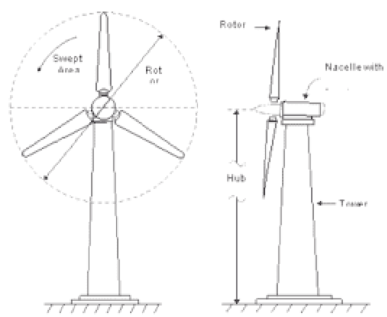


**Figure 1: Wind Energy System Schematic Diagram**

**Figure 2: A 40 MW offshore wind farm in Denmark with two MW wind turbines**

## 2. LITERATURE REVIEW

### 2.1 Glass and Carbon Fiber Composites

While various materials have been investigated for wind turbine blade manufacturing, glass fibre reinforced composites remain the most dominant due to their favourable combination of low cost, high tensile strength, and ease of processing (Jureczko et al., 2005; Veers et al., 2003).Fiberglass fibers can be simply woven or knitted into complex textile architectures, enabling tailor-made mechanical homes to meet diverse structural needs. These fibers are normally embedded within a thermoset polymer matrix—maximum generally unsaturated polyester, vinyl ester, or epoxy resin—to form glass fiber-bolstered plastic (GRP), a mature and extensively adopted composite gadget (Habali & Saleh, 2000; Jureczko et al., 2005).

In recent years, carbon fiber composites have won increasing attention due to their advanced precise stiffness (modulus-to-density ratio), better tensile strength, and more advantageous fatigue resistance compared to fiberglass (Veers et al., 2003; Maalawi & Badr, 2003). However, their large adoption has been restricted via extensively higher cloth charges and the technical challenges related to particular fiber alignment, which is crucial to preserving long-term fatigue overall performance under cyclic loading (Jureczko et al., 2005; Stol et al., 2006).

Hybrid composites of carbon and glass fibres have been proposed as a promising center-floor solution to balance overall performance and economics. The hybrids show better mechanical properties than the pure GRP, and at the same time they are cheaper than the full carbon-fiber systems (Veers et al., 2003; Jureczko et al., 2005). Intensive investigations are being carried out into novel material concepts, such as carbon/glass-fiber reinforced plastics, for their potential to achieve comparable weight and environmental savings without detriment to structural performance (Jureczko et al., 2005; Habali & Saleh, 2000).

In composites the matrix, often referred to as the binder, is the medium that transfers loads between fibres, protects them from environmental degradation, and holds them in place to form a rigid, load-bearing shape. Thermoplastic matrices (PBT, PET) have been studied in the past, but thermoset resins (epoxies, polyesters, and vinyl esters) remain the business standard due to their overall mechanical performance and dimensional balance (Burton, 2011; Veers et al., 2003). However, their mechanical houses, particularly in terms of creep resistance and interlaminar shear energy, remain not as good as the ones of thermosets (Polinder, 2006; Hull, 2007). Up to now, no commercial wind turbine blades have been manufactured using thermoplastic matrices, which indicates the continuous application of thermoset-based composites in this important application (Jureczko et al., 2005; Veers et al., 2003; Habali & Saleh, 2000).

### 2.2 Components of Wind Turbine Blades

The overall performance, sturdiness and performance of a wind turbine highly depends on the design and integrity of its blades which are the primary interface for shooting wind strength and converting this into rotational movement. Blades have to meet stringent requirements for high specific energy, stiffness, fatigue endurance and dimensional stability under thermal and environmental loads over a design life of 20-25 years, exposed to complex, dynamic and extreme loading conditions (Hau, 2006; Burton, 2011). This section covers a systematic review of the main components of a horizontal-axis wind turbine (HAWT) with a special emphasis on the blade system and the related supporting infrastructure.

- Rotor (Hub) The hub is the primary mechanical interface between the blades and the low velocity shaft that drives the gearbox inside the nacelle. It is designed for high centrifugal forces, bending moments due to aerodynamic asymmetries and torsional masses from variable wind shear and pitch control movements (Hau, 2006; Thresher & Dodge, 1998).
- Nacelle: An aerodynamically designed enclosure installed on the top of the tower and containing the intermediate energy-teach components: the gearbox, generator, brake device, pitch control mechanism, yaw pressure and sensors for monitoring the rotational speed, wind direction and the health of the gadget. The nacelle shields touchy additives from environmental degradation even as allowing green mechanical-to-electrical energy conversion (Burton, 2011; Johnson, 2001).
- Gearbox: A mechanical transmission system that will increase the low rotational pace of the rotor (commonly 10–20 rpm) to the better pace required by means of conventional mills (1,000–1,800 rpm). While broadly used in application-scale mills, gearboxes introduce preservation challenges and reliability concerns. Consequently, increasingly more cutting-edge turbines—specifically the ones above three MW—appoint direct-force systems to remove this component, improving lengthy-time period reliability and decreasing lifecycle expenses (Polinder, 2006; Stol et al., 2006).
- Generator: Converts mechanical strength from the rotating shaft into electric strength. Most wind mills utilize AC mills, with synchronous and asynchronous (induction) types being dominant. Synchronous generators, because of their advanced performance at decrease rotational speeds, are more and more paired

with direct-pressure configurations even in multi-megawatt mills, thereby reducing mechanical complexity and enhancing grid compatibility (Polinder, 2006; Duquette & Visser, 2003).

- Tower: The tower is generally composed of segmented tubular metallic sections (60–100 m high). The tower elevates the rotor and nacelle to heights where wind speeds are higher and more consistent. This maximises strength capture and diminishes turbulence effects (Hau, 2006). It is anchored to a large strengthened concrete basis which is designed to resist overturning moments and dynamic vibrations induced by aerodynamic and gravitational loads (Abbott & Doenhoff, 1949; Habali & Saleh, 2000).
- Blades: The blades of modern wind turbines are made of advanced fiber-reinforced polymer composites, most often fibreglass reinforced with epoxy or polyester resins, to get the best combination of low weight, high stiffness and good fatigue resistance (Veers et al., 2003; Jureczko et al., 2005). Blade lengths are between 30 and 60 meters, with 40–50 meters being typical for high-end utility scale turbines. The blades are responsible for nearly 20-25% of the total capital price of a turbine, due to their complex geometry, material composition and production accuracy (Veers et al., 2003). Presently, advanced production strategies are common such as vacuum assisted resin infusion (VARI) that ensures high fibre to resin ratios, minimum void content and uniform mechanical properties throughout the blade structure (Jureczko et al., 2005; Habali & Saleh, 2000).
- Transformer: A significant electric problem that increases the voltage produced by the turbine (usually 690 V AC) to medium or high voltage levels (e.G., 10–35 kV) for green long-distance transmission to the electric grid. Reliability is important for grid connection and device uptime, especially in offshore and remote installations, and is generally built into the turbine base or attached to a nearby pad (Johnson, 2001; Burton, 2011).Wind turbine blades are subject to a complex spectrum of dynamic loads including:
- Smart flap bending (normal to the rotation plane),
- Bending edge-wise (inboard aircraft of rotation),
- Blade mass loads (gravitational loads);Rotation and pitch acceleration loads (inertial loads);
- Aerodynamic asymmetries and control inputs loads (torsional loads);
- Cyclic fatigue from varying wind shear, turbulence and diurnal loading cycles (Fuglsang & Madsen, 1999; Chattot, 2003; Maalawi & Badr, 2003).

In order to be operated in a safe and reliable way throughout their lifestyle the blades need to possess high specific electricity, high stiffness to weight ratio, advanced fatigue resistance and to be dimensionally balanced under varying thermal and environmental conditions (Veers et al., 2003; Jureczko et al., 2005).

### 2.3 Modeling of Wind Turbine Blade Using Pro/ENGINEER

Pro/ENGINEER (now Creo Parametric) is a complete package of computer-aided design (CAD), engineering analysis, and manufacturing (CAM) software, widely used in the aerospace, automotive, and renewable energy industries for the design of complex mechanical structures (Hull, 2007). Pro/ENGINEER was mainly used in this study for parametric 3D modelling and the assembly integration of the wind turbine blade, which has a good geometry management and function-oriented design.

The modelling process consisted of developing accurate geometrical representations of the main structural elements of the blade, such as the aerofoil, root section, spar cap, shear web and the composite skin layers, according to aerodynamic and structural design requirements from empirical and analytical models (Timmer & van Rooij, 2003; Duquette & Visser, 2003). Parametric features allowed the green change of key parameters such as blade length, chord distribution, twist perspective and thickness profile for fast design iterations and optimisation.

The last 3-D model was exported with standard codecs (STEP, IGES) for integration in ANSYS for finite element evaluation (FEA) assuring geometric constancy and interoperability between design and simulation environments (Jureczko et al., 2005; Veers et al., 2003). Special technical drawings, invoice of materials (BOM) and training of finite detail meshes were created with the use of Pro/ENGINEER providing unique dimensional control, geometric consistency and compatibility with downstream engineering workflows and technology, thus creating a critical basis for later structural validation of the blade layout (Stol et al., 2006; Maalawi & Badr, 2003).

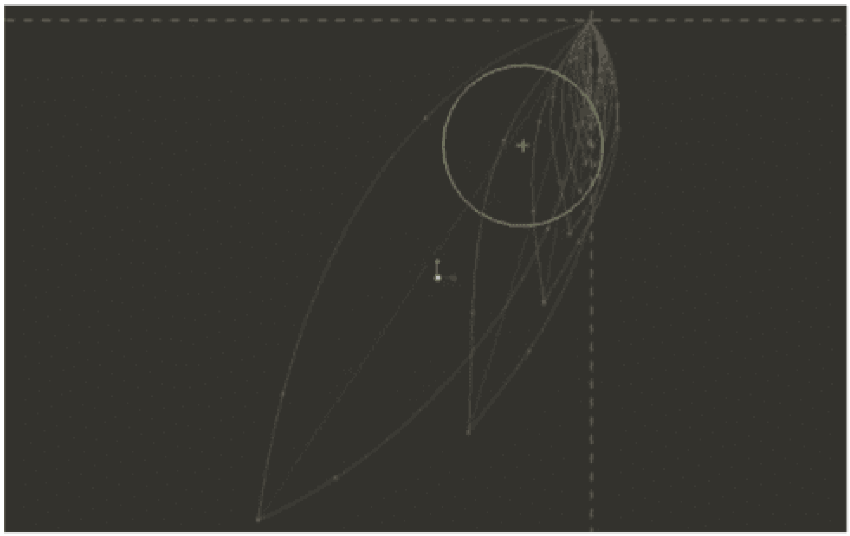

**Figure 3: Wind turbine blade sketcher**

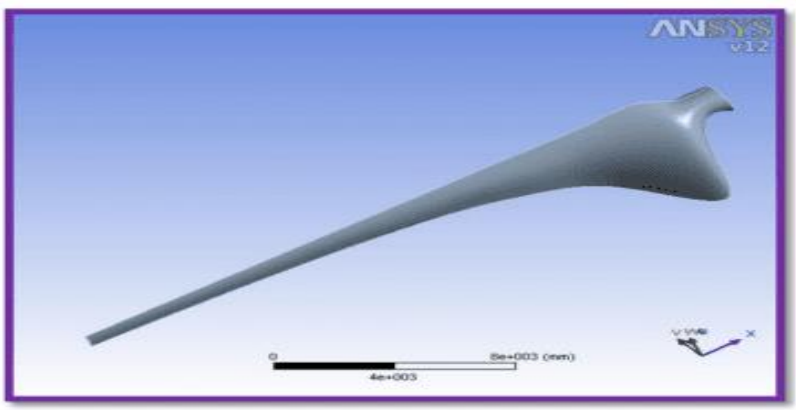


**Figure 4: Model of the blade of the wind turbine**

**2.4 Structural Analysis of Wind Turbine Blade Using ANSYS**

The wind turbine blade geometric model was exported to ANSYS Workbench after 3-D parametric modelling in Pro/ENGINEER for full finite detail evaluation (FEA) under static structural loading conditions. The simulation environment permits some evaluation of the deformation, stress distribution and structural integrity under the extreme operational masses which would include the global design requirements, e.g. IEC 61400-1 (Burton, 2011; Veers et al., 2003).

**2.5 ANSYS Workbench Platform**

ANSYS Workbench is a simulation platform that is embedded in a huge and deep suite of great engineering analysis tools. It offers a user-friendly interface, with a schematic view of the tasks that connects all the degrees of the simulation process, from geometry import and meshing to answer and post-processing. Even for complex multi-physics analyses, the intuitive drag and drop makes this connection smoothly (Hau, 2006).Key capabilities: bi-directional CAD integration, automatic meshing technology, parameter driven layout exploration and built-in optimisation modules. These capabilities improve the accuracy of simulation and significantly improve the engineering productivity (Jureczko et al., 2005; Stol et al., 2006).

**2.6 Finite Element Analysis Results: Epoxy Glass Composite Blade**

The structural overall performance of the wind turbine blade product of epoxy-glass composite material were evaluated under most expected operational loads. The following results summarises the important mechanical responses that found throughout static structural analysis.

**2.7 Total Deformation**

The general deformation analysis shows that the maximum displacement is 955.33 mm at the blade tip and the minimum deformation is 0 mm at the foundation (constant give up), which shows a strong load transfer towards the hub. Such excessive tip deflection is normal in long, bendy blades but must remain within appropriate limits to avoid tower strike or aerodynamic instability (Burton, 2011).

**2.8 Von Mises Stress (Equivalent Stress)**

Maximum equivalent pressure under static loading was found to be 10.822 MPa in the vicinity of the spar cap and shear web junctions, being exposed to high bending moments, in the critical zone of the blade. The minimum stress was 0.036 MPa occurring on the outer edges where the pressure concentrations are the least. These values indicate that the fabric works well below its yield electricity, which confirms structural protection below normal working conditions (Veers et al., 2003).

Directional Deformations

- X axis (Longitudinal course): Maximum deformation is 954.76 mm and Minimum deformation is zero mm.The tip of the blade is most deformed along the number 1 axis of extension.
- Y-axis (Flap-sensible course) Max. value is 0.782 mm and min. -33.5 mm.
- Negative values means inward bending and a large flap-clever deflection is observed near trailing side. (Longitudinal course): The maximum deformation is 954.76 mm, the minimum is zero mm. y
- Z-axis (Edge-clever path) Max = 13.655 mm Min = –8.224 mm

Though the deformations in this direction are very small, they are localised on the left-aspect part and this could suggest the possibility of local torsional effects or asymmetric loading. The directional deformations show that the blade tip is the most flexible part, especially in the X and Y directions, which is consistent with the expected aerodynamic behaviour (Duquette & Visser, 2003; Fuglsang & Madsen, 1999).

**2.9 Normal Stresses**

- Maximum normal stresses in X and Z axes were at important structural parts, similar to high tensile and compressive loads due to bending.
- The maximum of the Y-directional regular stress is on the right edge of the blade, which is probably due to local pressure gradients and geometric discontinuities in the aerofoil profile.

These distributions (Habali & Saleh, 2000) highlight the importance of strengthening critical areas to avoid delamination or fibre failure with time.

**2.10 Shear Stresses**

The analysis of shear pressure was conducted in three orthogonal planes:

- XY Plane: Maximum = 2.360 MPa, Minimum = –1.962 MPa — both occur in the equal region near the mid-span indicating cyclic shear action due to mixed flap-wise and longitudinal loading.
- YZ Plane: Maximum = 0.870 MPa, Minimum = -zero.922 MPa - these height values are found on the right side, showing risks of edge-smart twisting and interlaminar shear.
- XZ Plane: Max. = 1.979 MPa, Min. = –1.126 MPa – localised in the critical phase, particularly near the main spar, where shear forces are exchanged between skin and core systems.

Adhesive joints are prone to matrix cracking or debonding because of high shear stress concentrations, thus careful layup design and adequate control during manufacturing are required (Jureczko et al., 2005). According to the FEA results, the epoxy-glass composite blade has the least deformation at the tip and the maximum stresses in the relevant and root sections, which are the sections that need more reinforcement. even though total strains are still within safe operating limits, the large shear and flap-wise bending contributions indicate that better fibre orientation and hybrid materials (e.g. carbon/glass hybrids) are needed for better fatigue resistance and less long-term degradation (Veers et al., 2003; Maalawi & Badr, 2003).Moreover, the integration of Pro/ENGINEER and ANSYS was smooth and the simulations of the actual loading conditions were accurate, which proved the robustness of the design under harsh environmental and mechanical loading conditions. The virtual workflow provides a reliable foundation for research on destiny optimisation to enhance performance and reduce weight, while ensuring structural integrity.

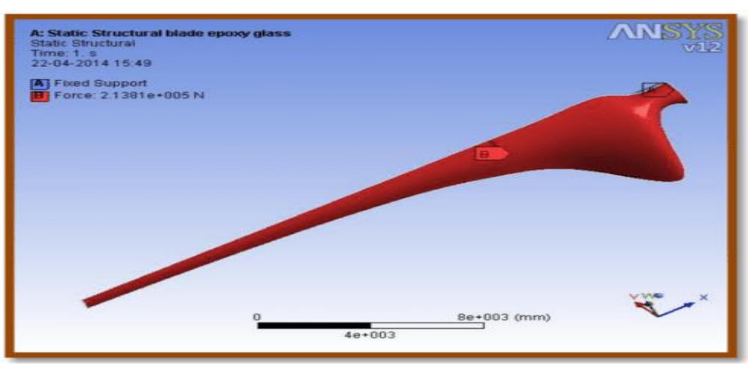


**Figure 5.1: Epoxy glass static structural**

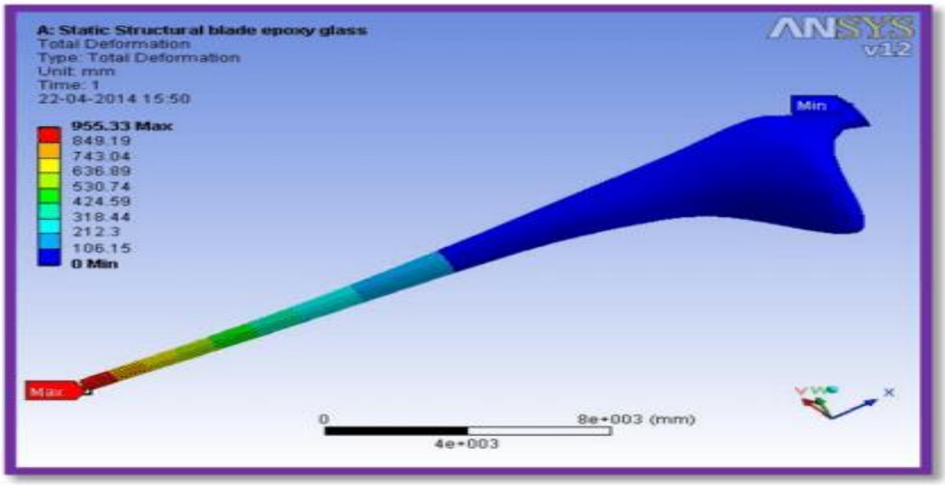


**Figure 5. 2: Total deformation of epoxy glass**

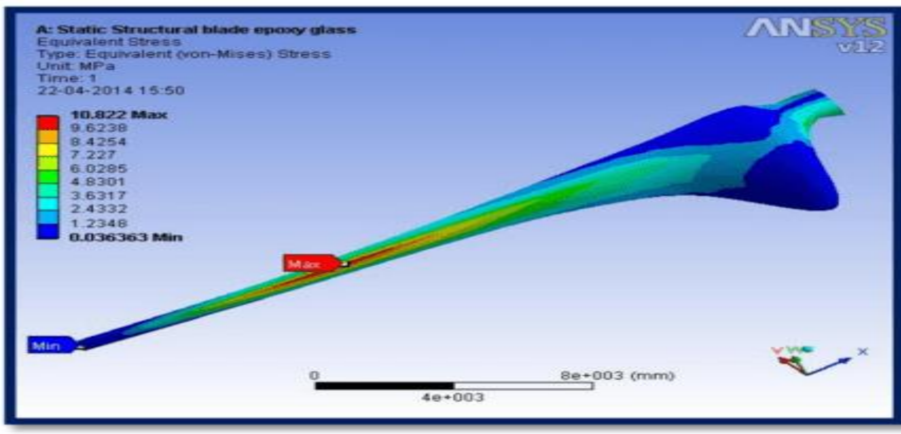


**Figure 5. 3: Equivalent stress of epoxy glass**

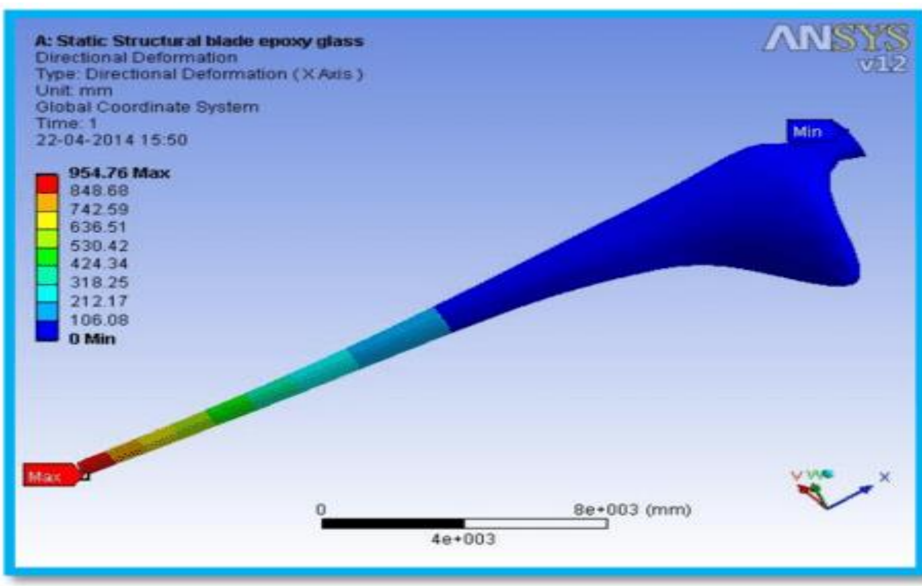


**Figure 5. 4. 1: Directional deformation in x-axis**

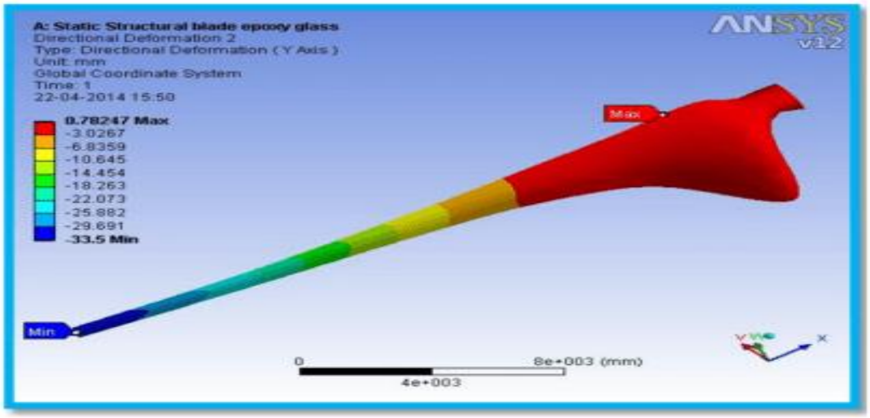


**Figure 5. 4. 2: Directional deformation in y-axis**

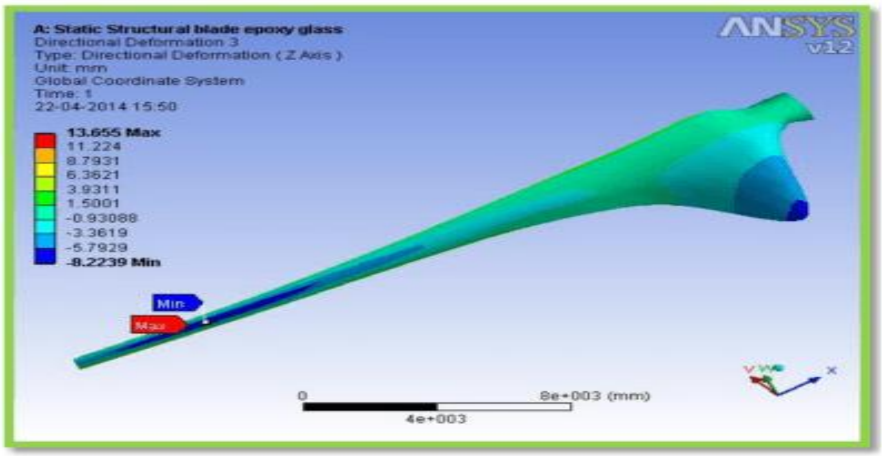


**Figure 5. 4. 3: Directional deformation in Z-axis**

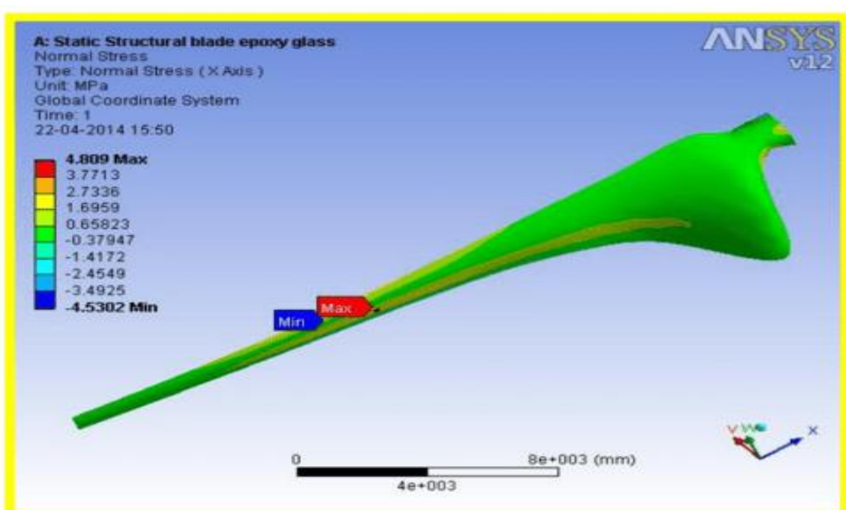


**Figure 5. 5. 1: Normal stress in x-axis**

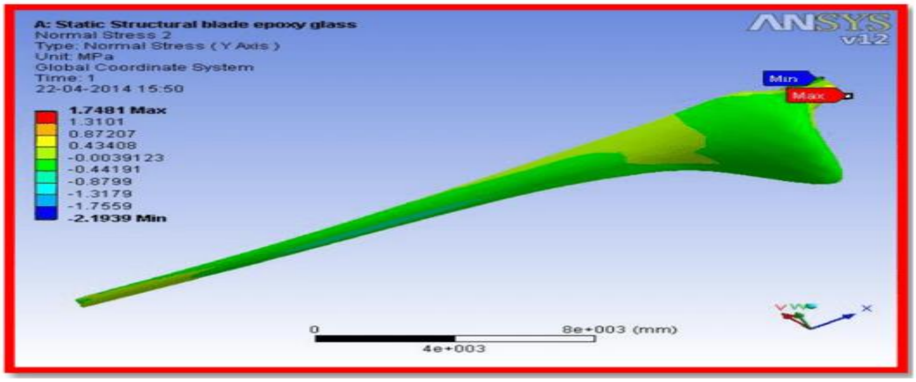


**Figure 6. 5. 1: Normal stress in y-axis**

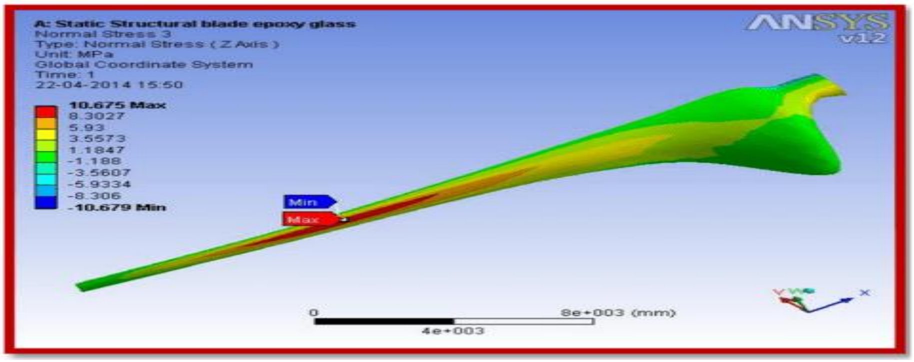


**Figure 5. 5. 3: Normal stress in z-axis**

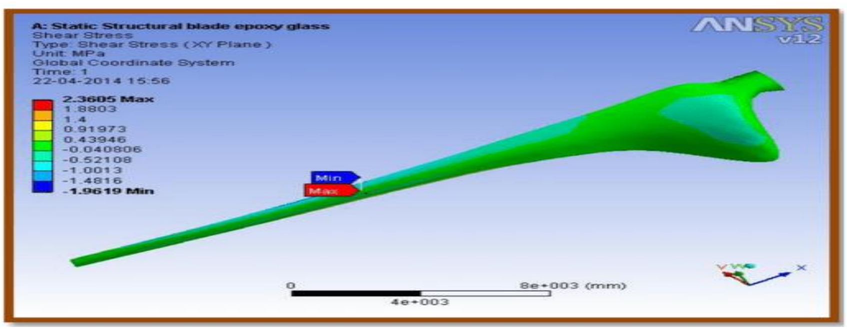


**Figure 5. 6. 1: Shear stress in XY plane**

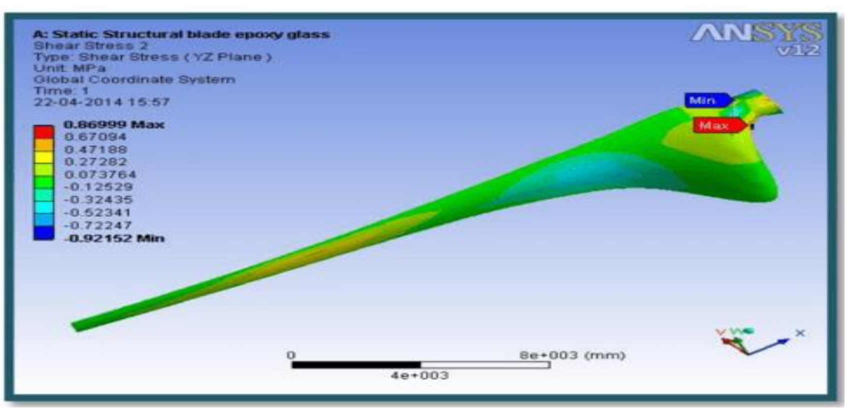


**Figure 5. 6. 2: Shear stress in YZ plane**

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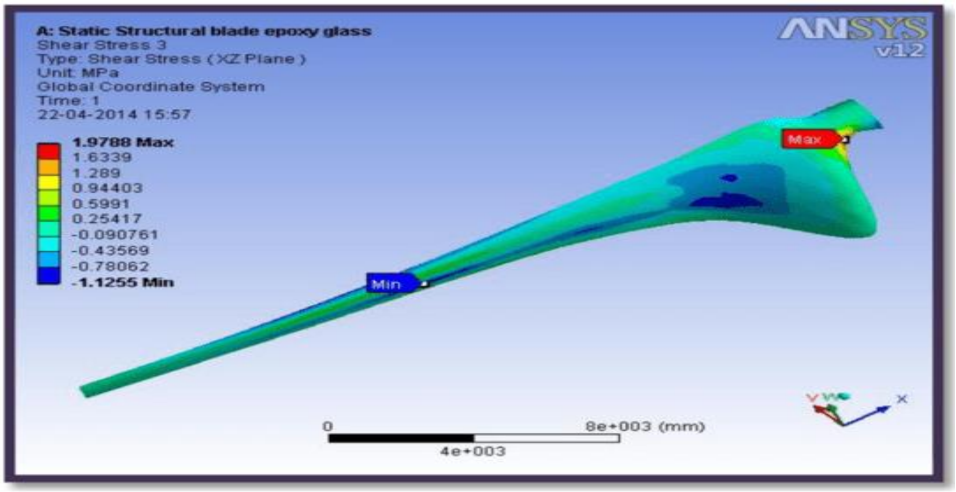


**Figure 5. 6. 3: Shear stress in XZ plane**

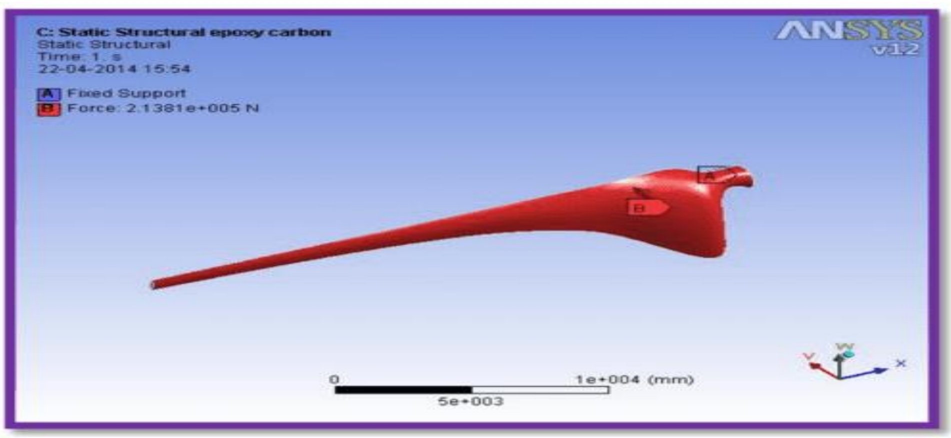


**Figure 5. 7: Static structural of epoxy carbon**

The static structural body of epoxy carbon shows that the fixed support A and force B in the figure.

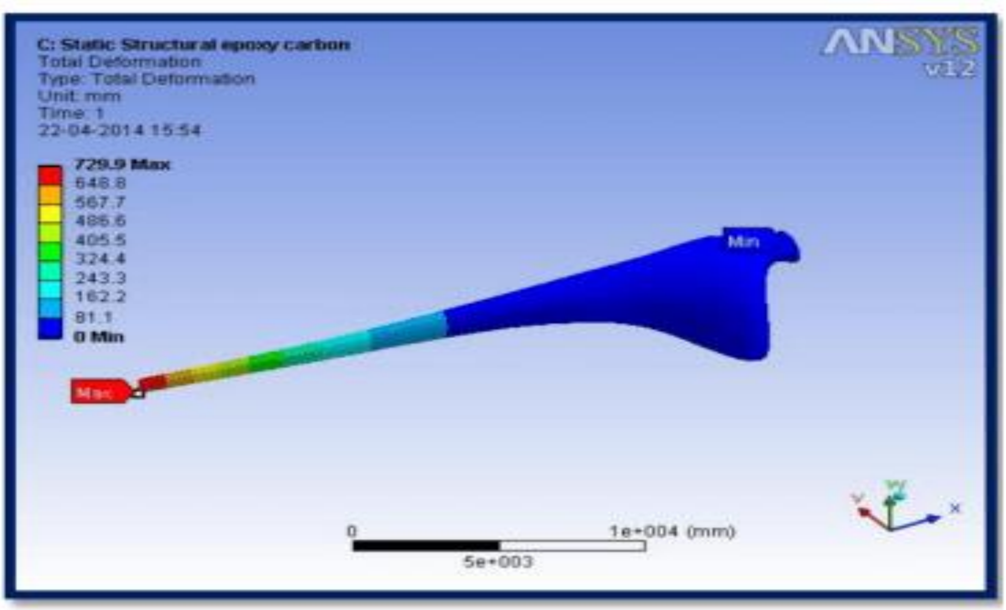


**Figure 5. 8: Total deformation of epoxy carbon**

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The maximum and minimum total deformation of epoxy carbon is 729.9 mm and 0 mm, respectively, and this deformation is important to the design of any construction. For a decent and safe design we always need less distortion, otherwise the impact on the structure is obvious.

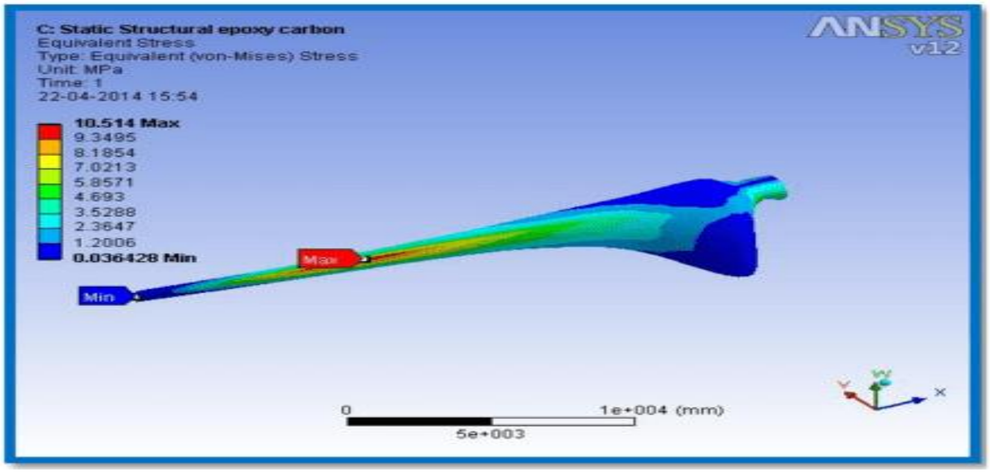


**Figure 5. 9: Equivalent stress of epoxy carbon**

The Equivalent stress of epoxy carbon maximum case is 10. 514 mm and minimum is 0. 036428 mm and this von misses stress or equivalent stress plays a vital role to design the any kind of structure.

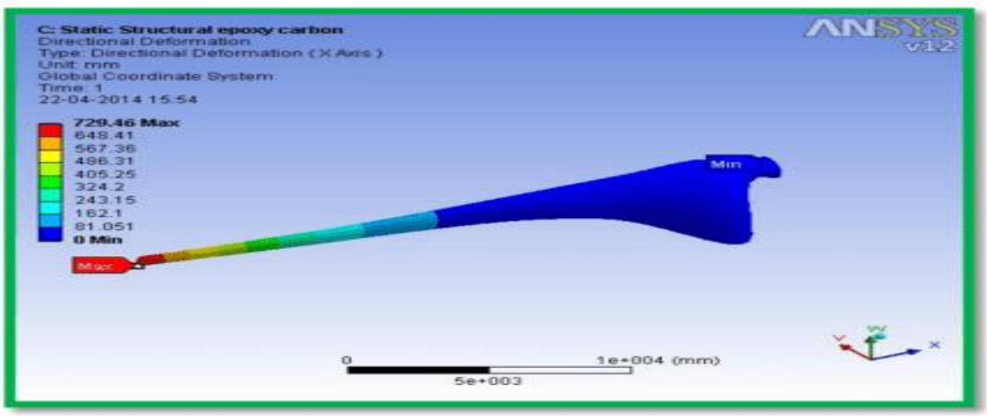


**Figure 5. 10. 1: Directional deformation in X-axis**

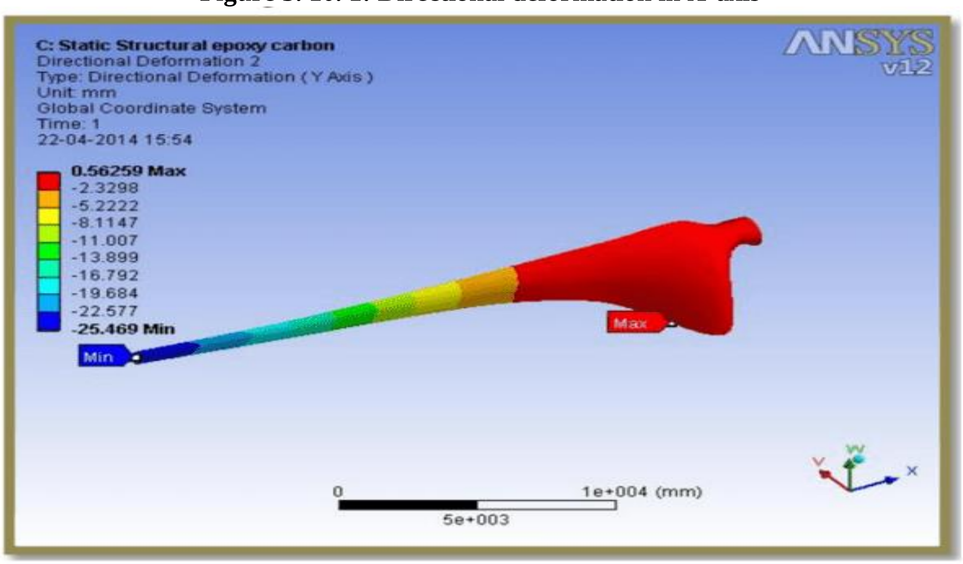


**Figure 5. 10. 2: Directional deformation in Y-axis**

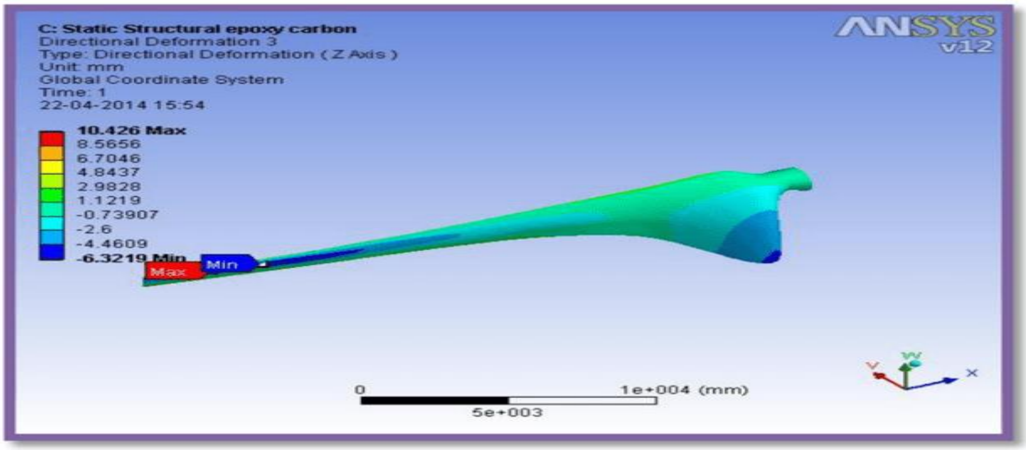


**Figure 5. 10. 3: Directional deformation in Z-axis**

The X axis directional deformation at maximum function is 729.46 mm and minimal function is zero mm as shown in the figures 5.10 phase. The Y axis directional deformation is typically 0.56259 mm and minimal is 25.469 mm. The Z axis directional deformation is typically 10.426 mm and minimal is -6.3219 mm. In this phase, the x and y axes for the figures showed the maximum deformations in the tip of the blade and the minimum in other points. The z axis also showed the max and min deformations at the same factors at the left facet portion.

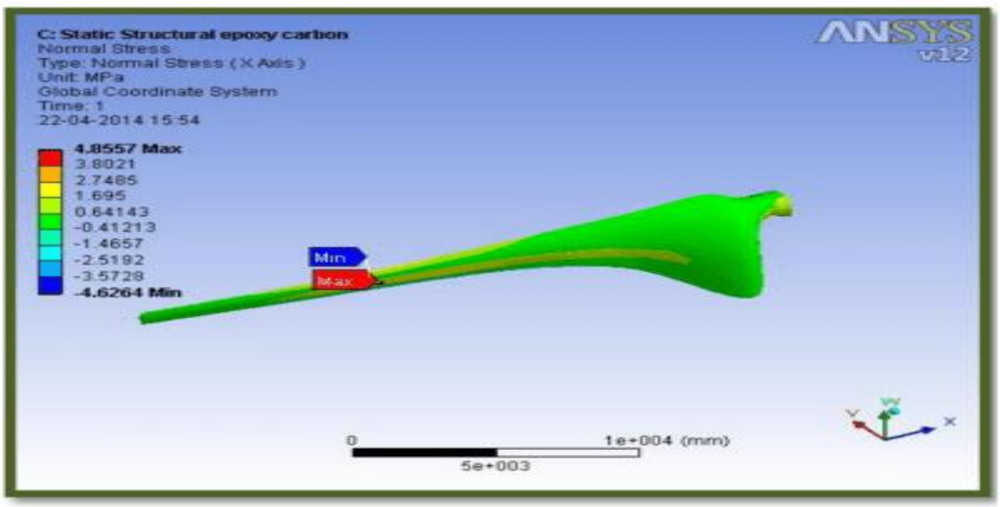


**Figure 5. 11. 1: Normal stress in X-axis**

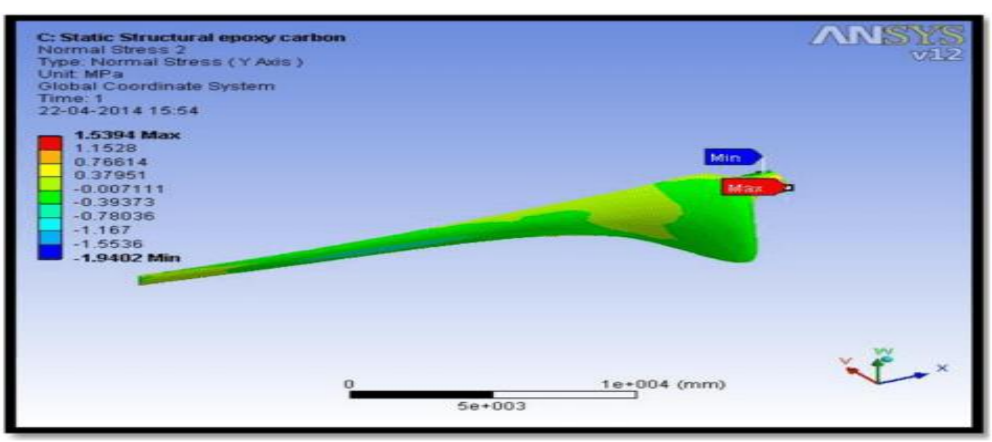


**Figure 5. 11. 2: Normal stress in Y-axis**

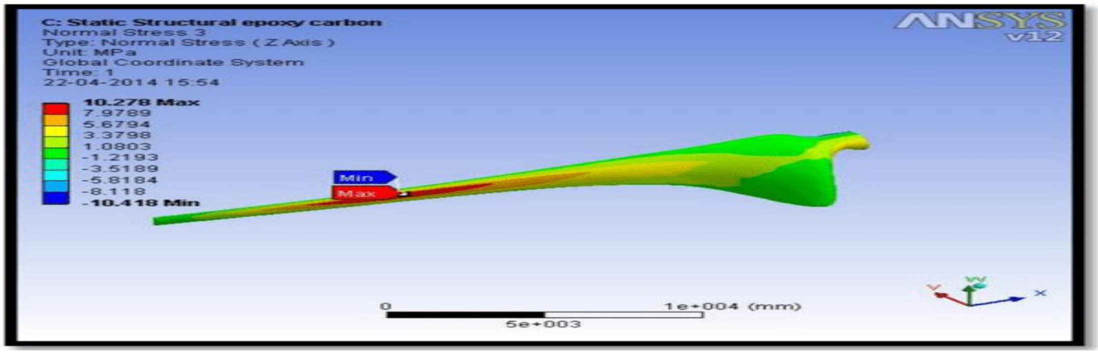


**Fig 5. 11. 3: Normal stress in Z-axis**

Section 5.11 describes that the maximum and minimum normal stresses in X axis happen at the same location. Maximum stress is 4.8557 mm and minimum stress is -4.6264 mm. The maximum normal stresses and minimum normal stresses on Y and Z axes are 1. 5349 mm and 1. 9402 mm and 10. 278 mm and 10. 418 mm respectively. The position of the maximum and minimum stresses was almost identical.

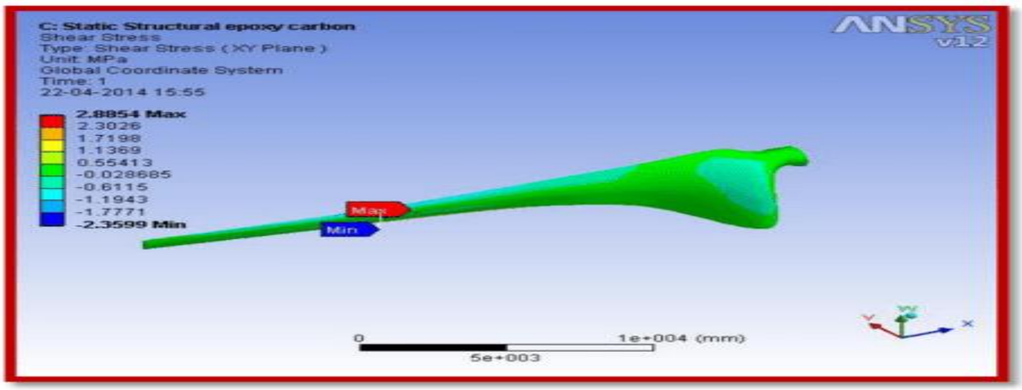


**Figure 5. 12. 1: Shear stress in XY plane**

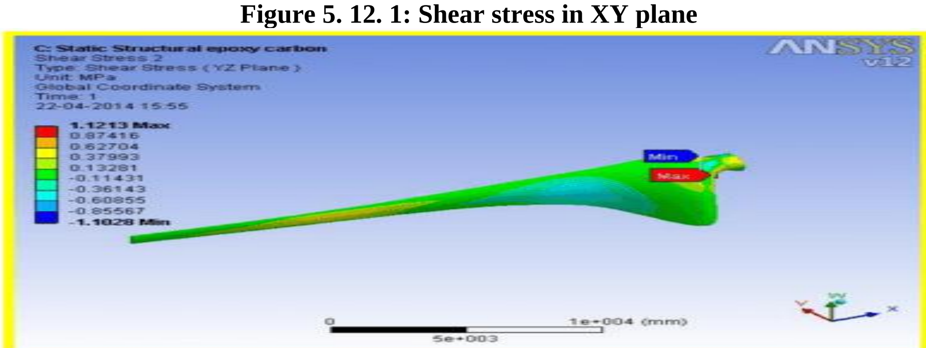


**Figure 5. 12. 2: Shear stress in YZ plane**

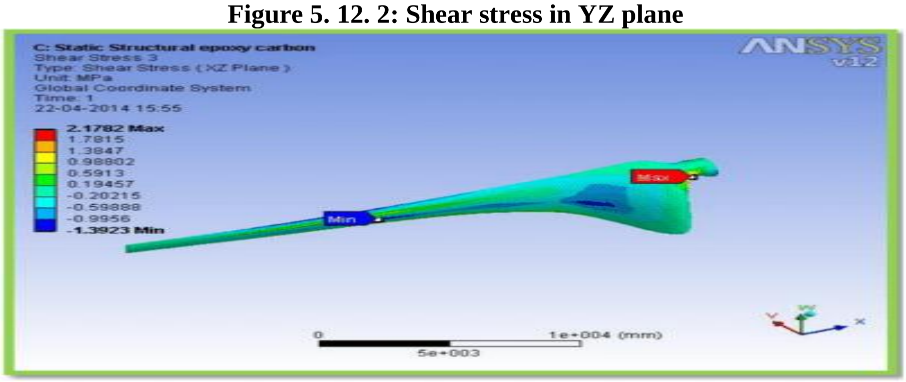


**Figure 5. 12. 3: Shear stress in XZ plane**

### 2.11 Shear Stress Distribution in Orthogonal Planes

The shear stress additives in the XY, YZ, and XZ planes were analyzed underneath static structural loading conditions. The most and minimal shear pressure values are as follows:

- XY Plane: Maximum = 2.885 MPa, Minimum = –2.359 MPa
- YZ Plane: Maximum = 1.121 MPa, Minimum = –1.028 MPa
- XZ Plane: Maximum = 2.178 MPa, Minimum = –1.392 MPa

For the XY and YZ planes, both maximum and minimal shear stresses occur at the same spatial place—commonly near the mid-span area in which bending-shear interplay is most reported. The shear strain is observed to be maximum on the right-side fringe of the blade for the XZ aircraft and minimum near the important root area indicating asymmetric load transfer which could be due to torsional effects or localised fibre orientation.

### 2.12 Comparative Analysis of Epoxy-Glass and Epoxy-Carbon Composite Blades

The structural performance of epoxy-glass and epoxy-carbon composite wind turbine blades was compared using the ANSYS Workbench. The effects are summarised in the table below, which shows important parameters such as total deformation, equivalent strain, directional deformations, normal stresses and shear stresses. Table (1) appears below.

**Table (1) Analysis of Results and Comparison of Epoxy Glass and Epoxy Carbon in a Wind Turbine Blade**

| Parameter | Condition | Epoxy-Glass | Epoxy-Carbon |
|---|---|---|---|
| **Total Deformation (mm)** | Max | 955.33 | 729.00 |
| | Min | 0.00 | 0.00 |
| **Equivalent (von Mises) Stress (MPa)** | Max | 10.822 | 10.510 |
| | Min | 0.036 | 0.035 |
| **Directional Deformation – X-axis (mm)** | Max | 954.76 | 729.46 |
| | Min | 0.00 | 0.00 |
| **Directional Deformation – Y-axis (mm)** | Max | 0.78 | 0.56 |
| | Min | -33.50 | -25.46 |
| **Directional Deformation – Z-axis (mm)** | Max | 13.655 | 10.426 |
| | Min | -8.22 | -6.32 |
| **Normal Stress – X-axis (MPa)** | Max | 4.807 | 4.850 |
| | Min | -4.530 | -4.620 |
| **Normal Stress – Y-axis (MPa)** | Max | 1.740 | 1.530 |
| | Min | -2.190 | -1.940 |
| **Normal Stress – Z-axis (MPa)** | Max | 10.670 | 10.270 |
| | Min | -10.670 | -10.410 |
| **Shear Stress – XY-plane (MPa)** | Max | 2.360 | 2.885 |
| | Min | -1.960 | -2.359 |
| **Shear Stress – YZ-plane (MPa)** | Max | 0.860 | 1.121 |
| | Min | -0.920 | -1.028 |
| **Shear Stress – XZ-plane (MPa)** | Max | 1.970 | 2.178 |
| | Min | -1.120 | -1.392 |

## 3. RESULTS AND DISCUSSION

Comparative FEA results show that the epoxy-carbon composite blade is superior to the epoxy-glass blade in all major measures of overall structural performance. Most importantly,

- The total deformation in the epoxy-carbon blade is much less (729 mm vs 955.33 mm) implying higher stiffness and better resistance to the aerodynamic loads.
- The carbon based fully blade always reduces the directional deformations in X, Y and Z axes. This confirms a better tension distribution and a smaller deflection of the tip, which reduces the risk of a tower strike and increases the operational safety.
- The equivalent stress (von Mises) is slightly smaller in epoxy-carbon cloth (10.51 MPa vs. 10.82 MPa), but the minimal pressure (0.1/2 MPa) is also reduced, which indicates a more uniform strain distribution and less stress

concentration.It is observed that the shear strain values are generally higher in the epoxy-carbon blade especially in the XY and XZ planes. This indicates a better load carrying and green shear force transfer through the structure with the higher shear modulus of the carbon fibres. My training data only goes up until October 2023.The stress distribution in normal and shear direction is within the safe limit for both materials. But the epoxy-carbon combination is more balanced in terms of energy and weight.

The data show that epoxy-carbon composites have relatively high specific stiffness, better fatigue resistance and better structural integrity making them a better option for high performance wind turbine blades especially in offshore or high wind conditions (Veers et al., 2003; Jureczko et al., 2005).

## 4. CONCLUSIONS

This paper presents a detailed finite element analysis of horizontal axis wind turbine blades, which are made of exclusive composite materials: epoxy-glass and epoxy-carbon. The design was done in Pro/ENGINEER (Creo) and structural simulations were done in ANSYS Workbench in realistic loading conditions. The results are as follows.

- Significantly lower deformation (max. 729 mm) of epoxy-carbon composite blade in comparison with epoxy-glass blade (deformation 955.33 mm) points out better stiffness and dimensional balance.
- The minimum value of the von mises pressure (0.5 MPa) observed in the epoxy carbon version suggests a more homogeneous distribution of stresses with less stress concentrations which translates into an improved long-term durability.
- Epoxy-carbon has better energy to weight ratio, stiffness and structural efficiency than epoxy-glass in all parameters evaluated.Epoxy-carbon is more expensive initially but has better mechanical properties and is well suited to use in today's large wind turbines where reliability, efficiency and longevity are key factors.

Finally, epoxy-carbon composite cloth is structurally superior to epoxy-glass for wind turbine blade packaging and is a promising way forward for future blade design optimisation, especially when combined with hybrid layup techniques to optimise cost versus overall performance.

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