DESIGN AND ANALYSIS OF HORIZONTAL AXIS WIND TURBINE BLADE USING DIFFERENT MATERIALS

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Abstract:
The wind turbine blade is a very important part of the rotor. To develop a low-cost horizontal axis wind turbine that will reduce energy costs and reduce reliance on non-renewable resources for power generation. There are many types of commercially available wind turbine designs are present currently but they require sophisticated manufacturing using composite materials that makes it very complex hence they are very costly. The horizontal axis wind blade profile has been chosen and it is modeled using the SW 2022 simulation package. The numerical analysis of the proposed wind blade is carried out using the ANSYS 2022R1 mechanical workbench. The structural and analyses of the proposed wind turbine under different loading conditions are performed. Through these analyses, maximum deflection occurs 100 N, 200 N loads at the wind blade, natural frequency (21.46 Hz for first resonant condition), and amplitude of different mode shapes are identified. Finally, the findings of the aforementioned evaluations of the proposed wind turbine are compared to the results of Kevlar49, Epoxy and Glass, Carbon/Epoxy composite-based wind turbines

Keywords: Horizontal Axis Wind Turbine Blade, SW 2022, ANSYS 2022R1

1.0 INTRODUCTION

Wind turbines are subjected to very specific loads and stresses. Due to the nature of wind, loads are highly variable. Varying loads are more difficult to handle than static loads because the material becomes fatigued. Moreover, as a working medium the air is of low density so that the surface required for capturing energy must be large. When designing a wind turbine, the aim is to attain the highest possible power output under particular atmospheric conditions and this depends on the shape of the blade. The change of the shape of blade is one of the methods to modify stiffness and stability, but it may influence aerodynamic efficiency of wind turbine. Other method to change dynamic and mechanical properties of wind turbine is modifying the composite material, which the blade is made of worked on structural analysis and numerical simulation of 34 m composite wind turbine blade, the material taken in his work is Glass- Epoxy. observed the opalization of the load carrying box girder in the full-scale test. A global non-linear FE-model of the entire blade was prepared and the boundaries to a more detailed sub-model were extracted. The FE-model was calibrated based on full-scale test measurements.

Horizontal Axis Wind Turbine (HAWT) Blades:

In wind turbine, blade is very important component, as the energy extraction from wind mainly depends on the structure of blade; wind are highly variable in nature and difficult to handle and also due to lower density of air larger surface area of blade has to be needed for higher efficiency. Therefore, the design and manufacturing processes have a dispersive influence on the structural performance on the blade the most widely used type of wind turbine in the wind energy industry today. The design of HAWT blades has undergone significant advancements to optimize aerodynamic performance, structural integrity, and overall energy conversion efficiency.

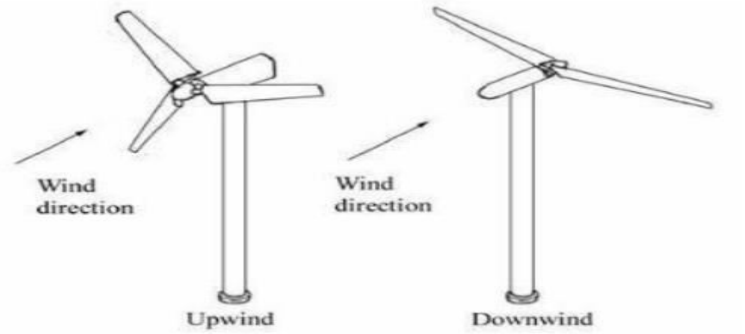

Figure 1: Horizontal Axis Wind Turbine (HAWT)

One crucial aspect of HAWT blade design is the distribution of twist along the length of the blade. The twist distribution helps regulate the angle of attack of the blade at different sections, ensuring optimal performance across varying wind speeds.

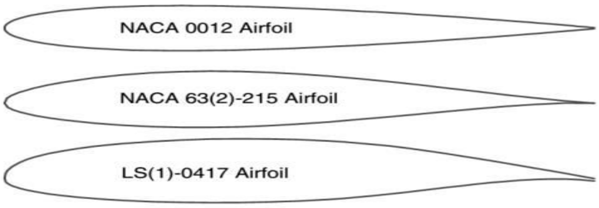

Figure 2: Sample airfoils used in wind turbine blade.

The material selection for HAWT blades is another critical consideration. Blades are typically made from lightweight yet robust materials such as fiberglass or carbon fiber composites. These materials offer high strength-to-weight ratios, allowing for efficient energy capture and durability. Advanced manufacturing techniques, such as resin infusion or vacuum-assisted molding, are employed to produce blades with precise geometries and consistent quality. To enhance efficiency, HAWT blades may feature additional design elements.

PROBLEM STATEMENT:

In the context of detailed and valuable literature review, the problem statement for the present research was devised. Due to the use of Nickel based super alloys there is a major problem such as cavitation occurs in the blade which leads to formation of rust on it. Due to the formation of rust the blades will fail. And Replacement of the blades cost high. Due to decreasing the thickness the stress carrying capacity of the blades get reduced which leads to failure of blades at very tough climates such as during storms. Due to usage of Glass reinforced epoxy polymer the blades are needed to be designed in a particular way that withstands those stresses, but the manufacturing of the blades needs a special process. The weight of the blades is also very high which need very high wind speeds to rotate; this leads to decrease in efficiency.

Objectives:

- To study the HAWT Blade profile using different materials
- To design the model done by using SW 2022 With different geometric conditions
- To Analyse the blade profile using structural and modal analysis using various boundary conditions

2.0 LITERATURE REVIEW

(Rehman et al., 2018) gave the overall picture of commonly used techniques, models, tools and approaches to enhance the efficiency of wind turbines. In this review work, specific emphasis is put on approaches that are used to design blades of wind turbines both experimentally and numerically. **(Fernandez-Gamiz et al., 2017)** presented the optimal location (position) to improve airfoil aerodynamic performance. Therefore, a dimensional and practical study of a mounted MT on the pressure surface of an airfoil is carried out. This study aims to know the optimal MT dimension and location to ascend airfoil aerodynamic performance and also investigate its effect on the power output of a 5 MW wind turbine. **(Pavese et al., 2017)** showed that justifying loads on a wind turbine rotor can result in a cost reduction of energy. Sweeping blades creates a structural coupling in amid flap wise torsion and bending, which can be used for load alleviation purposes. A multidisciplinary design optimization (MDO) challenge is framed including the blade sweep as a design variable. **(Rocha et al., 2016)** presented a standardization study of the k-ω SST turbulence model for gauge wind turbines. To achieve this, two distinct sets of blades were designed, constructed, experimented and simulated. The first set directed the NACA 0012 and the second the NACA 4412 airfoil. **(Hu, Choi and Cho, 2016)** explained reliability-based design optimization (RBDO) of a 5-MW wind turbine blade for designing dependable as well as cost-effective wind turbine blades. A different dynamic wind load uncertainty model has been created using 249 groups of wind data to contemplate wind load distinction over a huge spatiotemporal extent. **(Premkumar et al., 2015)** review of the existing state-of-art for wind turbine blade design, counting theoretical utmost efficiency, propulsion, hands-on efficiency, HAWT blade design, as well as blade loads. The evaluation provides an entire picture of wind turbine blade design along with the displays the supremacy of modern turbines nearly exclusive practice of horizontal axis rotors. The aerodynamic design notions for a modern wind turbine blade are described, including blade plan shape/amount, airfoil choice and optimal angles of attack. **(Han et al., 2015)** made an effort by designing single-stage horizontal axis wind turbine with a shroud and lobed ejector aimed at the efficient utilization of substandard wind energy by taking into concern the influence of the shroud and lobed ejector. The functioning of the proposed wind turbine was assessed using the commercial software CFX. **(Elfarra, Sezer-Uzol and Akmandor Sinan, 2015)** considered the foremost objectives of this report were to aerodynamically design and improve a winglet for a wind turbine blade by operating computational fluid dynamics (CFD) and to inspect its consequence on the power production. To validate and as a baseline rotor, the National Renewable Energy Laboratory Phase VI wind turbine rotor blade is exercised. **(Capuzzi, Pirrera and Weaver, 2014)** presented the use of a recent blade as the baseline for an aerodynamic analysis for maximizing the turbine's yielded power in part 1. These outcomes are then spent to detect ideal aeroelastic behavior. In Part II, they make use of material and structural bend-twist couplings in the key spar to bring appropriate differential blade twist, segment by segment, while bending flap-wise. **(Capuzzi, Pirrera and Weaver, 2014)** analyzed the essential elastically-induced twist from a structural viewpoint and acclimatized accordingly in part II. Additionally, a blade notion that realizes the desired adaptive behavior is projected and the surge of power harvested is evaluated by an interim structural design.

3.0 METHODOLOGY

Horizontal axis wind turbine goes from a process of steps for designing. Without having prior knowledge of these steps and requires the technical aspect of these things, it might get so fuzzy and complicated. A regular wind turbine design process is explained in Fig. where the aspects involved in the design process and their relationship are depicted. The design process is composed of three main models which are an aerodynamic model, a structure model and an economics model These three models form the mainframe of wind turbine design. Among the three models, the aerodynamic model is the most fundamental one which determines the power extracted and the loads underwent. As a result, the AEP, the Cost of Energy (CoE) and the lifetime of a wind turbine are all affected by the aerodynamic model used. In a word, the aerodynamic model has great importance on the design of wind turbine rotor blades and other components and subsystems. An accurate aerodynamic model is the first consideration in the wind turbine design process.

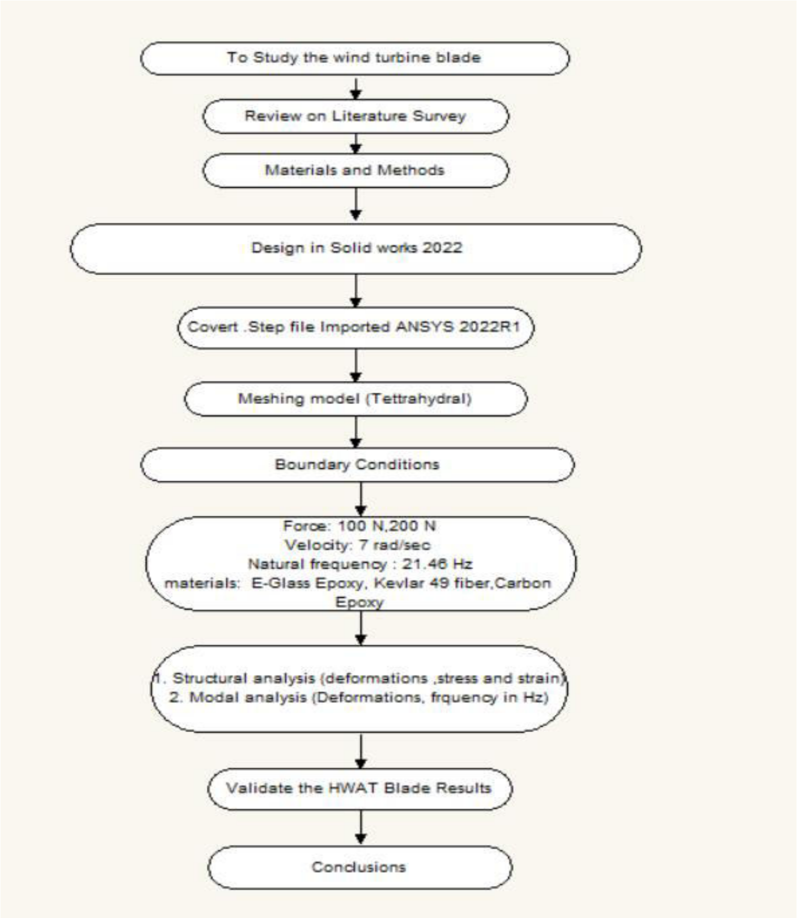

Figure 3: Design flow chart

Wind turbine design

It is the process of defining the form and specifications of a wind turbine to extract energy from the wind. A wind turbine installation consists of the necessary systems needed to capture the wind's energy, point the turbine into the wind, convert mechanical rotation into electrical power, and other systems to start, stop, and control the turbine.

Initial Boundary Condition

In the computational flow domain, the boundary condition of translational movement to the ground is given in the same direction and magnitude as the incoming air velocity, i.e. (7 m/s). The air foil is set to the wall's properties.

Using materials:

- Carbon epoxy
- E- Glass epoxy
- Kevlar 49 Fiber

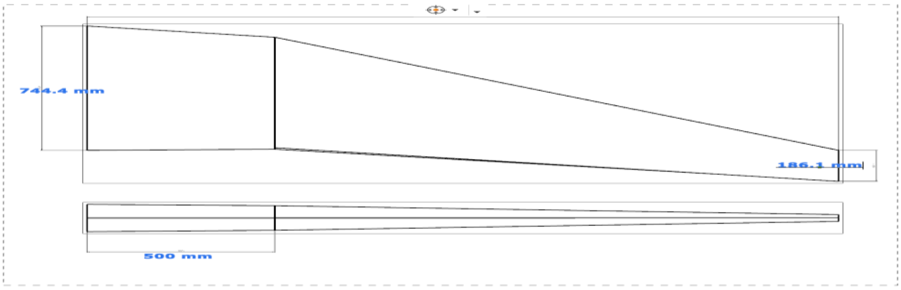

Figure 4: Geometric view

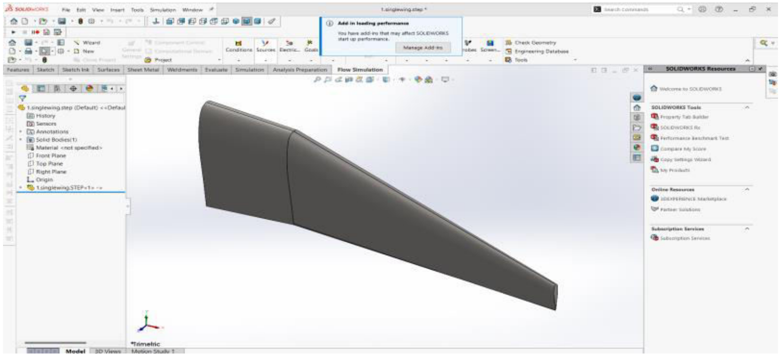

Figure 5: Design model

4.0 RESULTS AND DISCUSSIONS

Wind turbine blades are subjected to immense stress caused by turbulent winds, temperature variations, and regular wear and tear. These challenges demand materials that are not only lightweight but also possess high strength and durability. This is where advanced composites shine. Composed of a combination of materials such as carbon fibers and epoxy resins, they offer a unique set of properties that enable wind turbine blades to harness wind energy more efficiently.

STATIC STRUCTURAL ANALYSIS

Engineering analysis relies heavily on numerical simulation-based methods, which are characterized by low costs, accurate, results and quick processes. the numerical simulation techniques are being increasingly implemented, partly as a result of technological advancements. Numerical simulations are becoming significantly more advanced due to the flexibility of its implementation

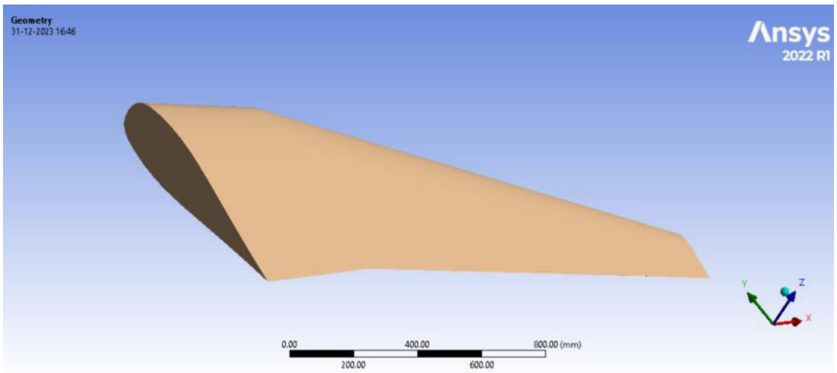

Figure 6: Geometric model

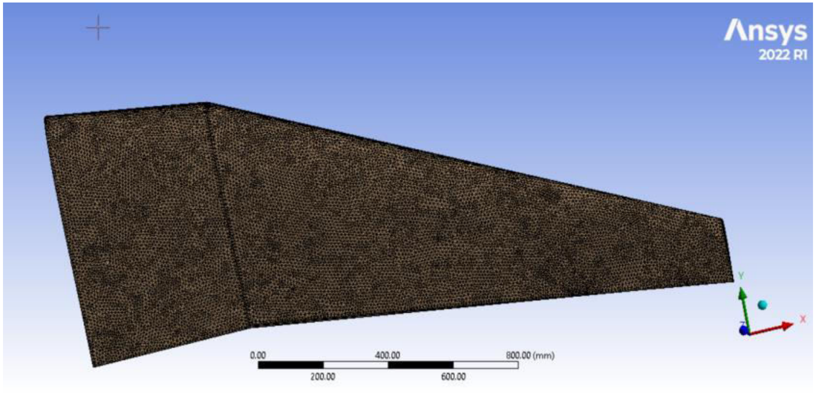

Figure 7: Meshed model (Tettra)

Static structural analysis of horizontal axis wind turbine blade Using Kevler 49 material

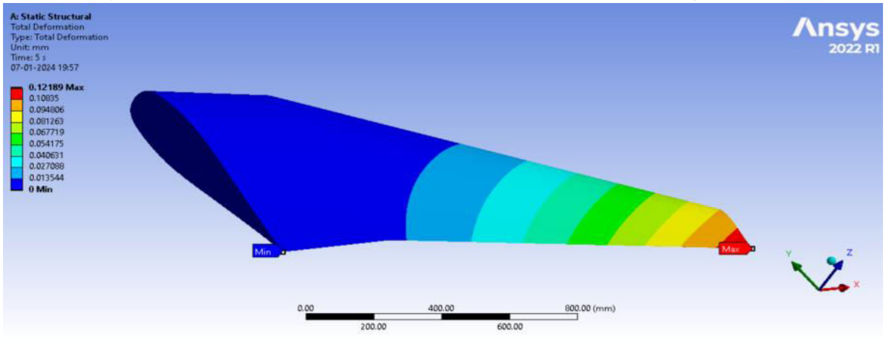

Figure 8: Total Deformation

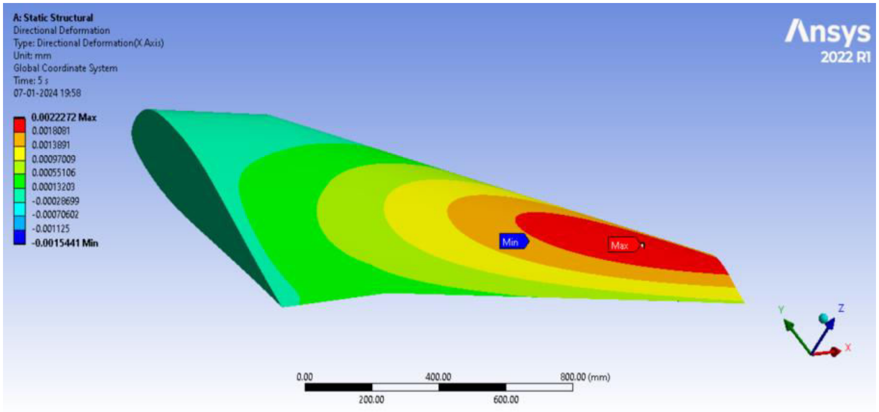

Figure 9: Directional deformation

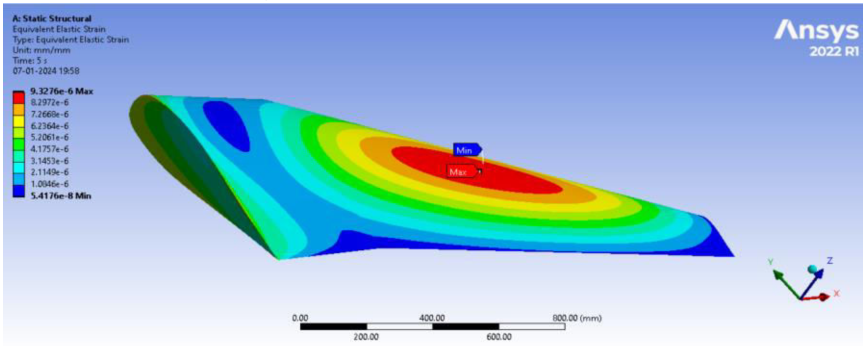

Figure 10: Equivalent elastic strain

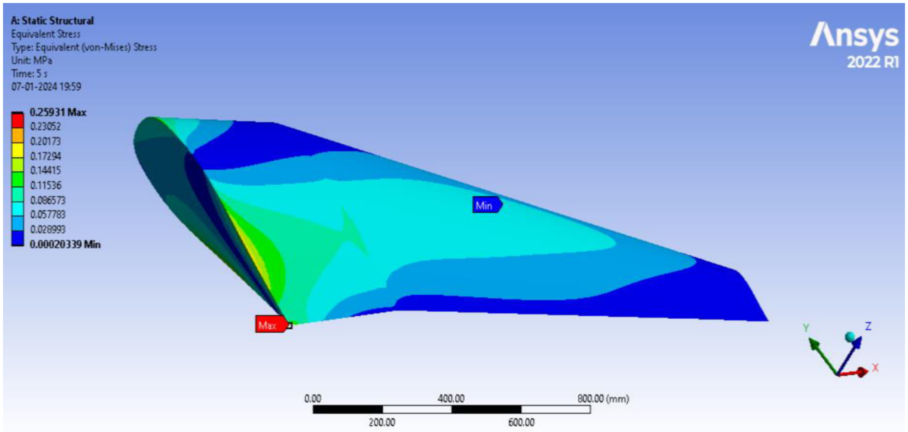

Figure 11: Equivalent stress

Static structural analysis of horizontal axis wind turbine blade Using Carbon/epoxy material

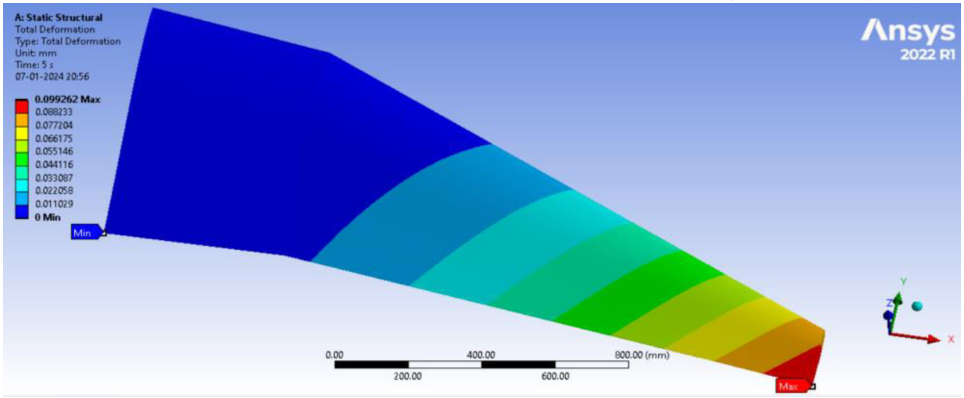

Figure 12: Total Deformation

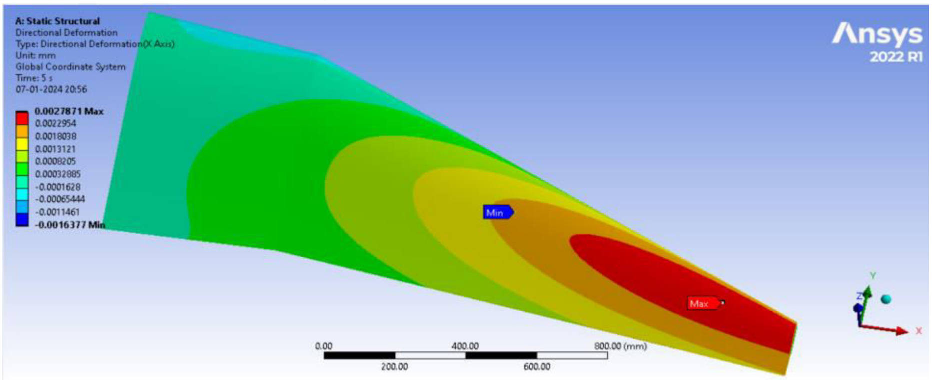

Figure 13: Directional deformation

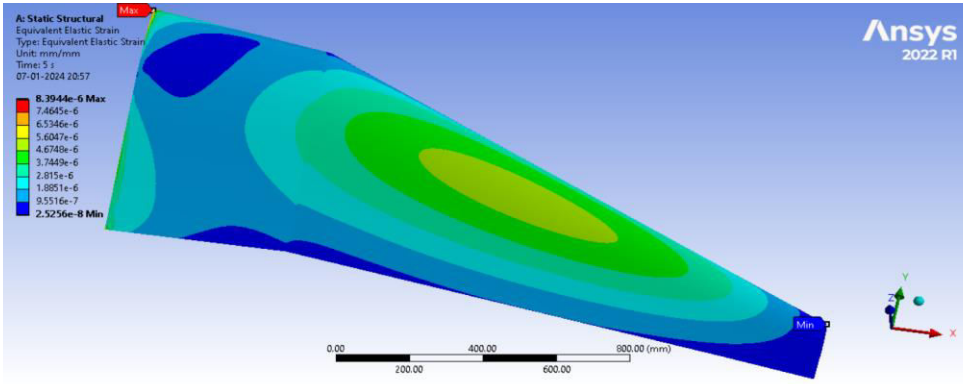

Figure 14: Equivalent elastic strain

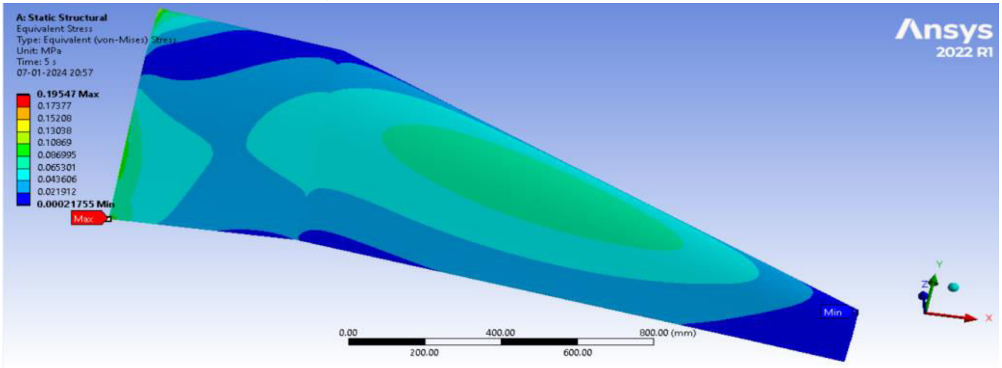

Figure 15: Equivalent stress

Static structural analysis of horizontal axis wind turbine blade Using Glass/Epoxy material

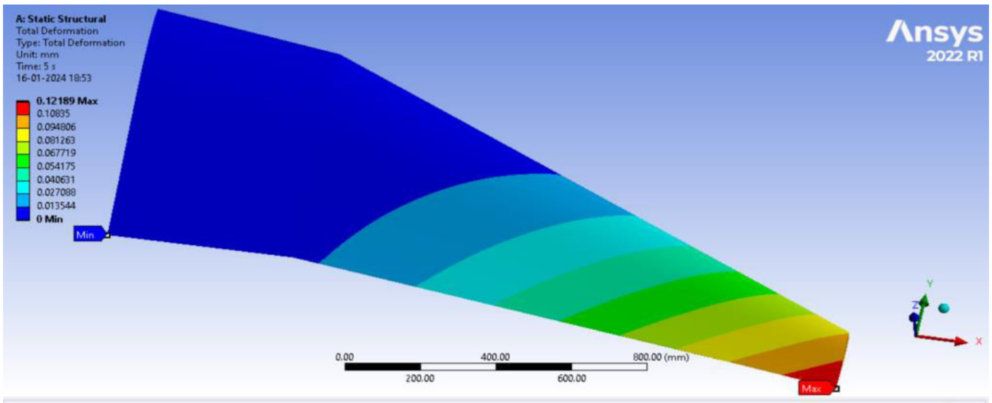

Figure 16: Total Deformation

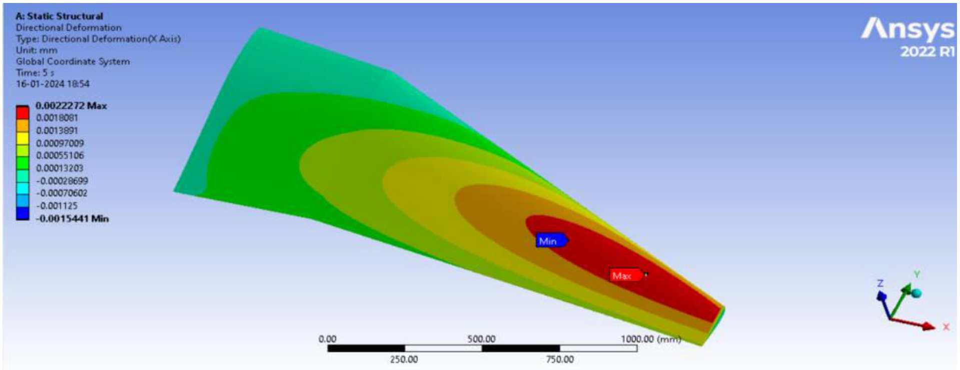

Figure 17: Directional deformation

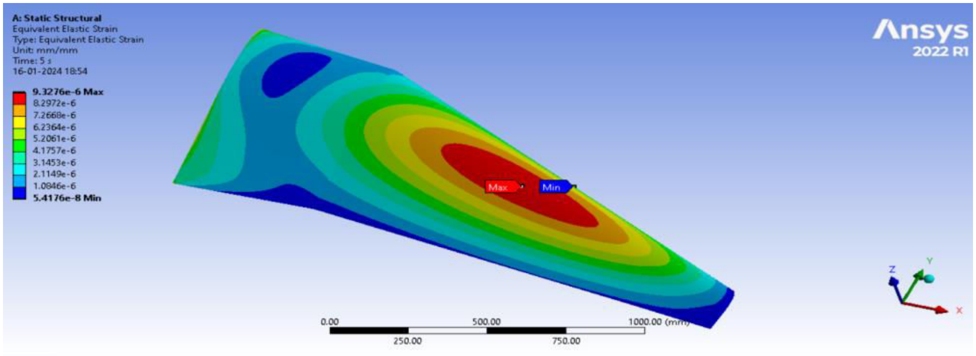

Figure 18: Equivalent elastic strain

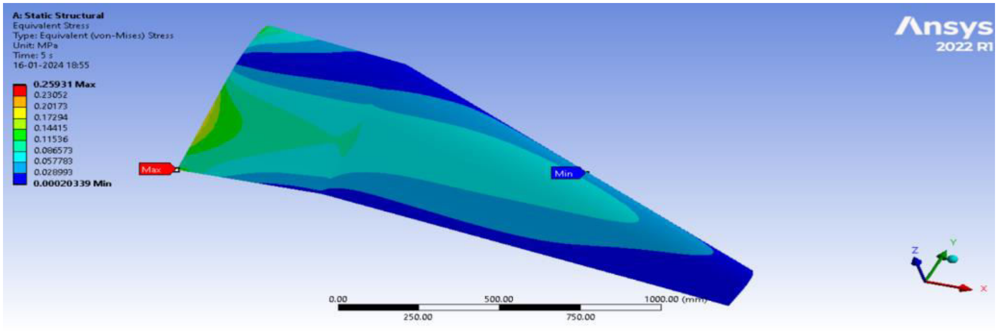

Figure 19: Equivalent stress

Table 1: Static structural analysis of HAWT Blade Total deformations (mm) at different materials

LOAD (KN)	Kevlar fiber	Glass Epoxy	Carbon Epoxy
100	0.12	0.12	9.9
200	0.22	0.22	0.18

Table 2: Static structural analysis of HAWT Blade Directional deformations (mm) at different materials

LOAD (KN)	Kevlar fiber	Glass Epoxy	Carbon Epoxy
100	2.22	2.22	2.78
200	3.85	3.8	4.51

Table 3: Static structural analysis of HAWT Blade equivalent elastic strain (mm/mm) at different materials

LOAD (KN)	Kevlar fiber	Glass Epoxy	Carbon Epoxy
100	9.32	9.32	8.39
200	1.63	1.63	1.24

Table 4: Static structural analysis of HAWT Blade equivalent stress (MPa) at different materials

LOAD (KN)	Kevlar fiber	Glass Epoxy	Carbon Epoxy
100	0.25	0.25	0.19
200	0.37	0.37	0.21

- The 'LOAD (KN)' values range from 100 to 200, with an average of 150 KN. This may indicate a balanced distribution of load across the three models.
- 'Kevlar fiber' and 'Glass Epoxy' share the same average, minimum, and maximum values (avg: 0.17, min: 0.12, max: 0.22). This suggests a comparable performance between the two material types.
- 'Carbon Epoxy' shows the greatest variance, ranging from 0.18 to 9.9. This large range signifies a high level of variability in the energy retained after data transmission across different load concentrations.

MODAL ANALYSIS OF HAWT

Modal analysis is the process of determining the inherent dynamic characteristics of a system in forms of natural frequencies, damping factors and mode shapes, and using them to formulate a mathematical model for its dynamic behaviour.

Modal analysis of HAWT blade using Kevlar material

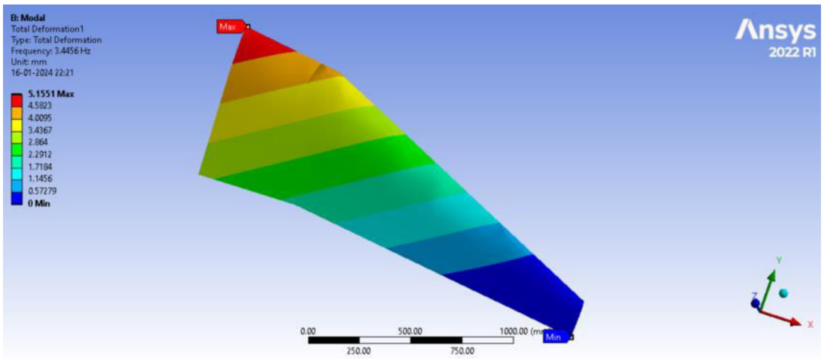

Figure 20: Frequency modal-1

In this figure clearly observed that applied the frequency 3.4456 HZ with assignment material was Kevlar and the deformation moment was 5.1551 max

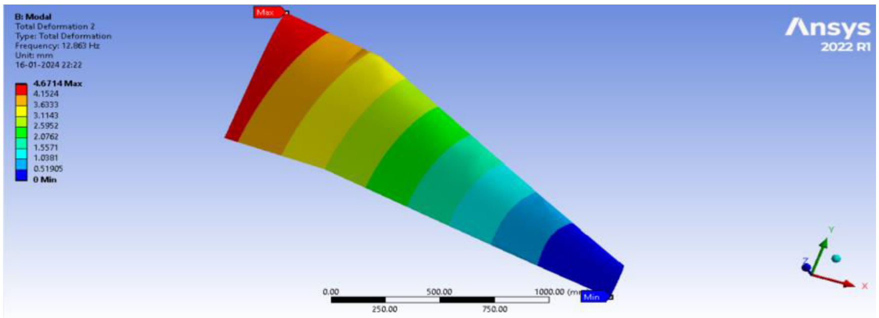

Figure 21: Frequency modal-2

The second mode of the Blade design was clearly observed that applied the frequency 12.863 HZ with assignment material was carbon fiber and the deformation moment was 4.6714 max

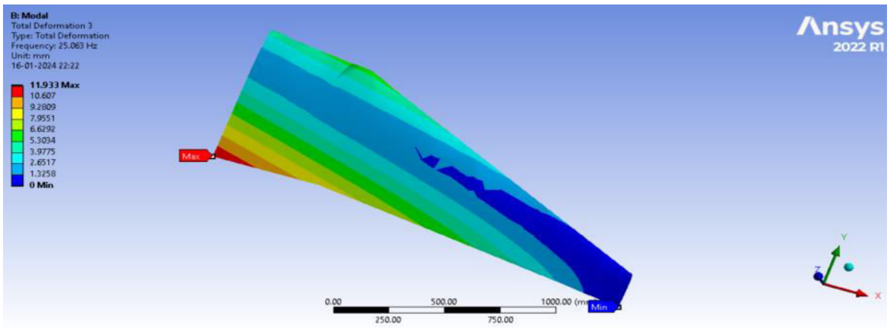

Figure 22: Frequency modal-3

In this figure observed that the second mode Blade design' for which the assigned frequency was 25.063 Hz, the material was Kevlar and the maximum deformation moment was 11.933 max, was clearly detected.

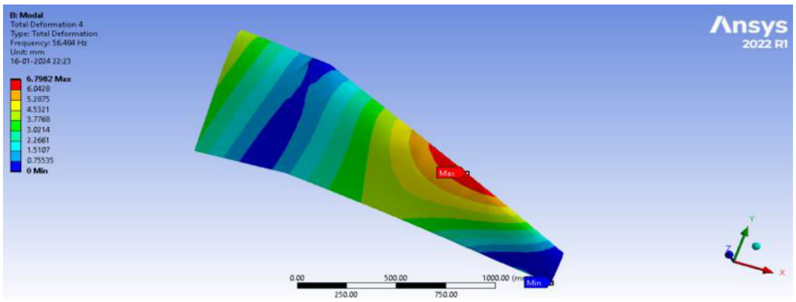

Figure 23: Frequency modal-4

The fourth mode of the blade frequency was 56.484 Hz, and the applied model deformation was 6.7982 Max, as determined by modal analysis, which examines the blade inherent vibration characteristics and their dynamic features.

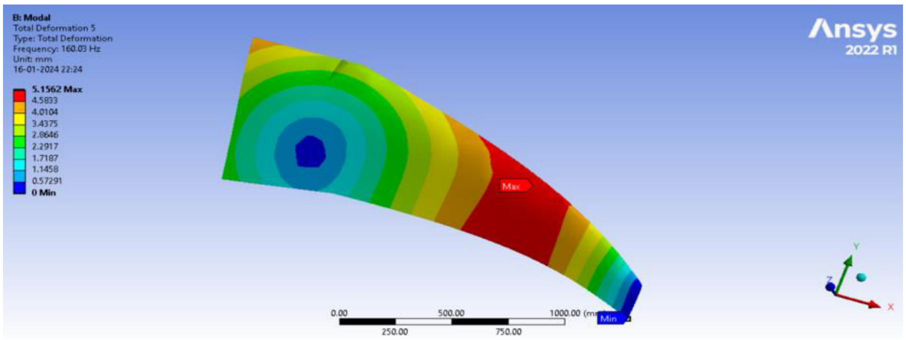

Figure 24: Frequency modal-5

The above figures show the results of the modal analysis of blade according to the Kevlar material applied the natural frequencies 713.99 Hz and the blade deformation after load condition was 246.81 Max

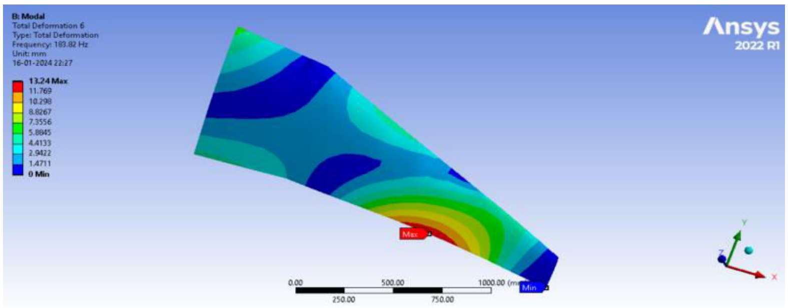

Figure 25: Frequency modal-6

The above figures show the results of the modal analysis of blade according to the Kevlar material applied the natural frequencies 183.82 Hz and the blade deformation after load condition was 13.24 Max

Modal analysis of HAWT using Glass Epoxy material

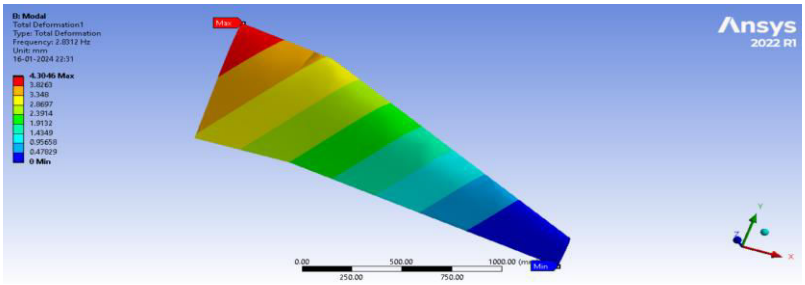

Figure 26: Static stress concentration of modal-1

In this figure clearly observed that applied the frequency 2.8312 HZ with assignment material was carbon fiber and the deformation moment was 4.3046 max

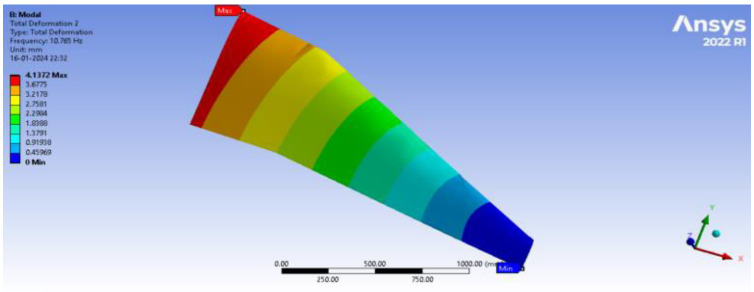

Figure 27: Static stress concentration of modal-2

The second mode of the Blade design was clearly observed that applied the frequency 10.765 HZ with assignment material was carbon fiber and the deformation moment was 4.1372 max

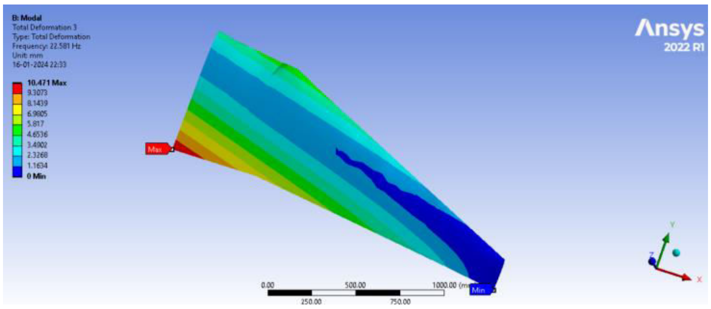

Figure 28: Static stress concentration of modal-3

In this figure observed that the second mode Blade design' for which the assigned frequency was 22.58 Hz, the material was carbon fiber, and the maximum deformation moment was 10.471 max, was clearly detected.

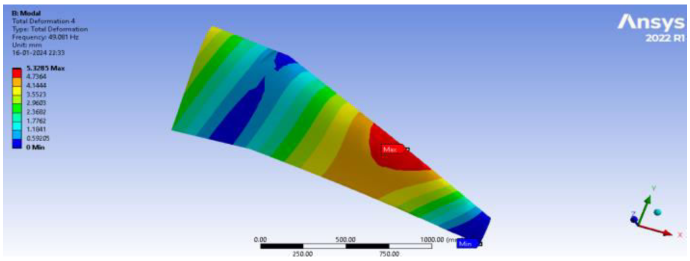

Figure 29: Static stress concentration of modal-4

The fourth mode of the blade frequency was 49.081 Hz, and the applied model deformation was 5.3285 Max, as determined by modal analysis, which examines the blade inherent vibration characteristics and their dynamic features.

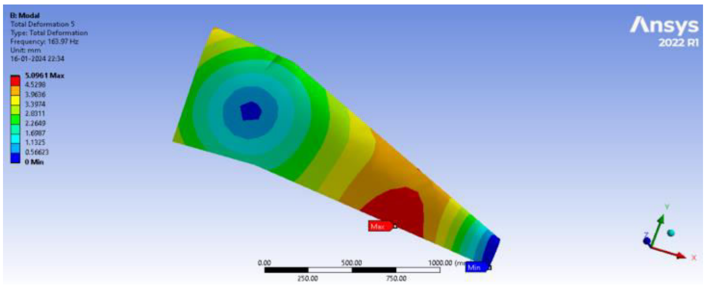

Figure 30: Static stress concentration of modal-5

The above figures show the results of the modal analysis of blade according to the Carbon fibre material applied the natural frequencies 163.97 Hz and the blade deformation after load condition was 5.0961 Max

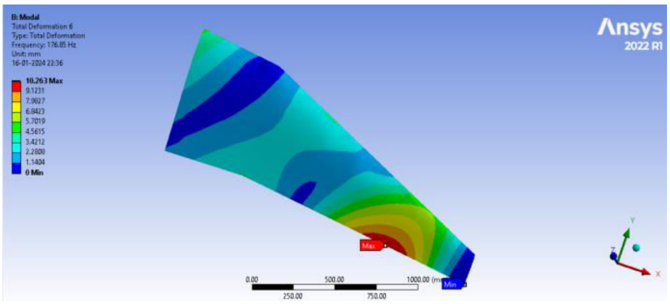

Figure 31: Static stress concentration of modal-6

The above figures show the results of the modal analysis of blade according to the Carbon fibre material applied the natural frequencies 176.85 Hz and the blade deformation after load condition was 10.263 Max

Modal analysis of HAWT using Carbon Epoxy material

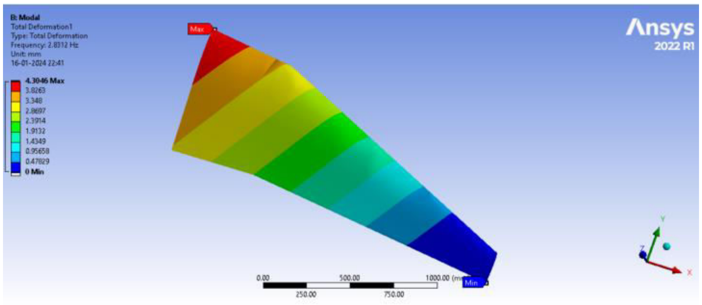

Figure 32: Static stress concentration of modal-1

In this figure clearly observed that applied the frequency 2.8312 HZ with assignment material was Glass Epoxy and the deformation moment was 4.3046 max

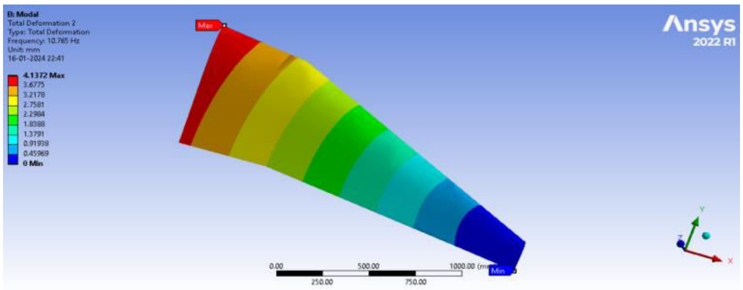

Figure 33: Static stress concentration of modal-2

The second mode of the blade design was clearly observed that applied the frequency 10.765 HZ with assignment material was Glass Epoxy and the deformation moment was 4.1372 max

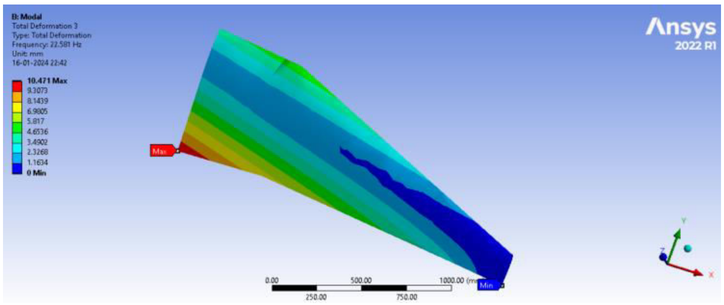

Figure 34: Static stress concentration of modal-3

In this figure observed that the second mode Blade design' for which the assigned frequency was 22.581 Hz, the material was Glass Epoxy, and the maximum deformation moment was 10.471 max, was clearly detected.

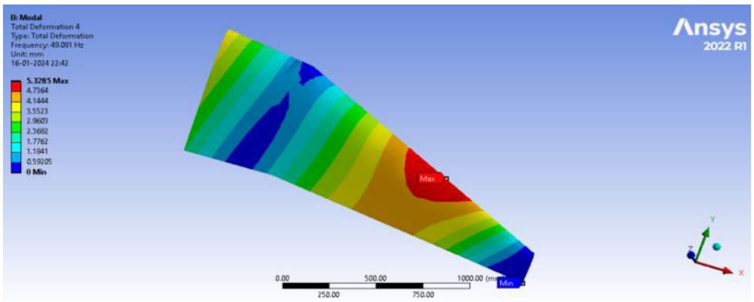

Figure 35: Static stress concentration of modal-4

The fourth mode of the blade frequency was 49.081 Hz, and the applied model deformation was 5.3285 Max, as determined by modal analysis, which examines the blade inherent vibration characteristics and their dynamic features.

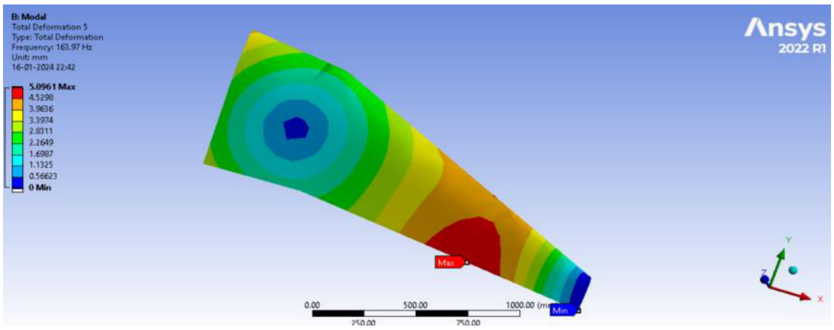

Figure 36: Static stress concentration of modal-5

The above figures show the results of the modal analysis of blade according to the glass fibre epoxy material applied the natural frequencies 163.97 Hz and the blade deformation after load condition was 5.0961 Max

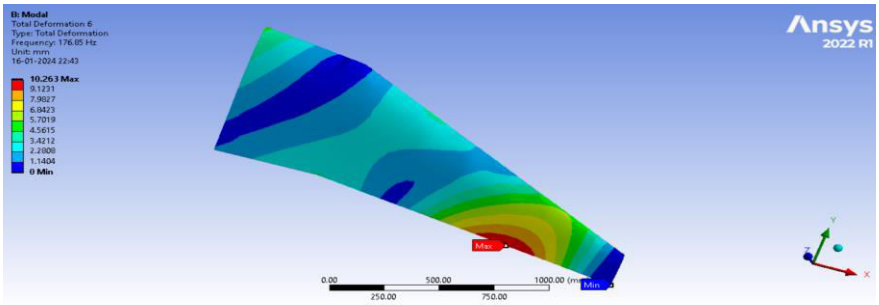

Figure 37: Static stress concentration of modal-6

The above figures show the results of the modal analysis of blade according to the glass fibre epoxy material applied the natural frequencies 176.85 Hz and the blade deformation after load condition was 10.263 Max

Table 5: Modal analysis of HAWT with different materials values in Hz from ANSYS

S. No	Modals	Kevlar	Glass	Carbon
1	Modal-1	3.4456	2.6733	2.8312
2	Modal-2	12.863	10.091	10.765
3	Modal-3	25.063	23.299	22.581
4	Modal-4	56.484	47.096	49.081
5	Modal-5	160.03	153.34	163.97
6	Modal-6	183.82	170.56	176.85

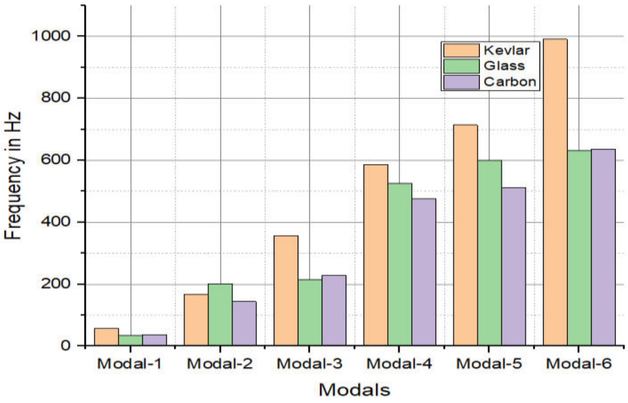

Figure 38: Validation of HAWT with different materials values in Hz from ANSYS

Discussions:

- Kevlar has the highest average energy after data transmission at 73.6, with Carbon close behind at 71.0 and Glass trailing at 67.8. This suggests Kevlar may be the most efficient material.
- Kevlar also shows the highest maximum energy at 183.82. This might indicate that Kevlar has the greatest potential to achieve peak performance in energy transmission.
- Carbon and Kevlar's energy ranges are quite similar (174.0 and 180.3 respectively), slightly greater than Glass's (167.9). This could imply that Kevlar and Carbon are more versatile across varying conditions.

Conclusion:

In this thesis, the wind turbine blade modeling in Solid works parametric software and analyzed for its strength using Finite Element analysis software ANSYS. Structural, modal and fatigue analysis will be done in ANSYS on the different materials wind turbine blade material galvanized iron replace with carbon epoxy, Kevlar and e-glass epoxy at different speeds of the turbine rotor. By observing the static Analysis, the stress, deformation and strain values are increased by increasing the speed of the wind turbine rotor. The stress values are less for used e-glass epoxy material. By observing the frequency analysis, the stress values are less for Kevlar 49 material than other materials. Kevlar-49 fiber composites are usually strong composites materials compared to others glass and carbon composite materials. So, it can be conclude be Kevlar 49 material is the better material for wind turbine blade.

REFERENCES

[1] S. Rehman, M. Mahbub Alam, L. M. Alhems, and M. Mujahid Rafique, “Horizontal AxisWind Turbine Blade Design Methodologies for Efficiency Enhancement A Review,” Energies, vol. 11, no. 3, 2018.

[2] U. Fernandez-Gamiz, E. Zulueta, A. Boyano, J. A. Ramos-Hernanz, and J. M. Lopez-Guede, “Microtab design and implementation on a 5MW wind turbine,” Appl. Sci., vol. 7, no. 6, 2017.

[3] C. Pavese, C. Tibaldi, F. Zahle, and T. Kim, “Aeroelastic multidisciplinary design optimization of a swept wind turbine blade,” Wind Energy, vol. 20, no. 12, pp. 1941–1953, 2017.

[4] P. A. C. Rocha, H. H. B. Rocha, F. O. M. Carneiro, M. E. V. da Silva, and C. F. de Andrade, “A case study on the calibration of the k-ω SST (shear stress transport) turbulence model for small scale wind turbines designed with cambered and symmetrical airfoils,” Energy, vol. 97, pp. 144–150, 2016.

[5] W. Hu, K. K. Choi, and H. Cho, “Reliability-based design optimization of wind turbine blades for fatigue life under dynamic wind load uncertainty,” Struct. Multidiscip. Optim., vol. 54, no. 4, pp. 953–970, 2016.

[6] P. S. Premkumar et al., “Uncertainty and Risk Assessment in the Design Process for Wind,” J. Adv. Res. Dyn. Control Syst., vol. 9, no. February, p. V07AT30A013, 2015.

[7] W. Han, P. Yan, W. Han, and Y. He, “Design of wind turbines with shroud and lobed ejectors for efficient utilization of low-grade wind energy,” Energy, vol. 89, pp. 687–701, 2015.

[8] M. Elfarra, N. Sezer-Uzol, and I. Akmandor Sinan, “NREL VI rotor blade: numerical investigation and winglet design and optimization using CFD,” Wind Energy, vol. 18, no. 11, pp. 1875–1891, 2015.

[9] M. Capuzzi, A. Pirrera, and P. M. Weaver, “A novel adaptive blade concept for large-scale wind turbines. Part I: Aeroelastic behaviour,” Energy, vol. 73, pp. 15–24, 2014.

[10] M. Capuzzi, A. Pirrera, and P. M. Weaver, “A novel adaptive blade concept for large-scale wind turbines. Part II: Structural design and power performance,” Energy, vol. 73, pp. 25–32, 2014.