Modal and Structural Analysis of Wind Turbine Blade

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Abstract- *Wind power or wind energy is considered as a clean source of energy which produces no environmental harm during operation. The total wind power generation potential of India at a height of 50 m is 50000 MW. In recent years Indian Government has focused on this renewable source of energy. The main objective of this paper is to introduce a new composite material for wind turbine blades. Kevlar-Epoxy is selected for the suitability analysis. Finite element Method or Finite Element Analysis is an approximation techniques used for the analysis of Complex objects and geometries. The main part of this research is to identify structure's fitness of Kevlar fibre reinforced polymer wind turbine blade by structural and Modal analysis and also comparing with the analyses of glass fibre reinforced polymer and carbon fibre reinforced polymer wind turbine blade. Wind Turbine blade design is a complex procedure. For the design of wind turbine blade CATIA software is used and the model is imported in ANSYS 15.0 for analysis. For the suitability analysis of Kevlar-Epoxy it has done structural and Modal analysis to identify natural frequencies and natural vibration modes of the Kevlar-Epoxy wind turbine blade. So at first in this paper, validation of blade geometry in vibration analysis is taken up first to validate its first 3 natural frequencies with data available in open literature and then Structural analysis has been performed successively to evaluate the stresses and deformations produced for three different materials. The results of the analysis are used to verify a structure's fitness of Kevlar -Epoxy composite with the existence materials (E-glass and Carbon)-Epoxy.*

Index Terms- Modal, Structural, Analysis, Epoxy-E-glass, Epoxy-carbon and Epoxy-Kevlar.

1. INTRODUCTION

Wind energy is to be considered as one of the most viable sources of renewable energy when environmental issues such as acid rain, climate change, and imbalance of natural resources have been developed due to use of oil, gas and coal as fuel in power generation. Wind energy is considered as a clean source of energy. Wind power is an alternative to fuels.

In India wind power accounts for 6% of India's total installed power capacity, and it generates 1.6% of the country's power. A wind turbine is a rotary machine that extracts energy from the wind. There are two forces acting by wind on turbine blades known as Lift and drag force. The lift force is perpendicular to the direction of motion of wind whereas the drag force is parallel to the direction of motion of wind. For maximum power generation lift force should be large and drag force should be less.

A wind turbine consists of three elements known as Towers, Nacelles and Turbine blades. A wind turbine tower must be stiff and strong so that it can bear the load of turbine blades and generator/nacelles. The stiffness is most important factor to be considered because tower is also subjected to fluctuating wind loads due to rotation of blades. Nacelles are considered as a house of shafts, gearbox, generator and others supporting elements. In case of Nacelles weight is an important factor to be considering not the material. Turbine Blades are required to have an optimum cross section for aerodynamic efficiency to generate the maximum torque to drive the generators. The turbine blades are subjected to a wide range of loads like twisting, tension, and compression and flapping induced by variable wind loading. The blades must be stiff to avoid hitting the towers when deflected by the wind loads. For any given material the internal structure will determine the strength and stiffness of the turbine blades. At the same time when we are considering the strength and stiffness the weight of turbine blades play a important role to determine the cost and saving from fatigue failure. In general we require a material that is stiff as well as light also in order to minimize the overall weight of wind turbine system. Kevlar is stiff and strong having recycling sustainability. In all three elements of wind turbine, blades are the most critical component for design and analysis. The aerodynamics efficiency and weight of blades are two critical parameters for design and analysis. Blades are attached to rotor hub which rotates the generator shaft for producing electricity. All turbine blades have airfoil shaped cross sections which utilizes glass fibre reinforced plastics (GFRP) as a blade material. The wind turbine blades functions with principles of lift to transfer the wind energy into mechanical energy.

FEM is an approximation technique used for numerical solution of acoustic problems, electromagnetic problems, heat transfer, fluid problems and static and dynamic structural analysis. In finite element method, the geometry is divided into finite number of small elements and these elements are connected to each other at a point termed as nodes. Finite Element Method or Finite Element Analysis is a mathematical modelling and analysis tool used for finding the deformation, natural frequency and mode shape of the epoxy Kevlar wind turbine blades. The ANSYS workbench is a product of ANSYS software which has two interface areas such as toolbox and project schematic.

2. LITERATURE SURVEY

A detailed literature review was done on a lot of published research papers featuring in a wide range of journals. Some of those which have inspired this work in a more promising way have been critically analyzed and provided below.

Jitendra Kumar Sahu, Brijesh Patel [7] has done a modal Analysis on the turbine blade and turbine rotor disk to obtain its dynamic characteristic by subjecting the blade in CFFF boundary condition. The Analysis has carried by two methods i.e modelling and Modal Analysis. Firstly blade is modelled with the help of Pro E and imported in ANSYS 14.5, in modal Analysis FEA of blade has been carried out with adopting different case study such for different material. Results showed that both natural frequencies and mode shapes were almost identical and shows good agreement with the experimental data which is stated in literature.

V Manoj Kumar and B Nageswara Rao [1] carried out work on the improvement of wind turbine efficiency which depends on one of the important parameters as the speed of the blade. For a lighter blade a small wind force is enough to rotate it, where as a heavy blade will require large and steady wind loads. To improve the wind turbine performance the blade material is being changed from Epoxy-Glass to Epoxy-Carbon. The modelling was done in Pro-E and the static and dynamic structural analysis is carried out by using ANSYS software. The blade was subjected to FEA studies to demonstrate its ability to withstand the extreme loading conditions as defined in the international offshore wind standard. The results confirmed the design to have acceptable performance with regard to total deformation, directional deformation, Equivalent stresses, Normal stresses and Shear stresses. The work done in this paper gives better results for epoxy carbon material compared with epoxy glass.

Ashwani Kumara et.al [17] deals with the introducing a new material for wind turbine blades. Al 2024 is select for the suitability analysis. Finite element Method or Finite Element Analysis is a approximation techniques used for the analysis of complex objects and geometries. Wind energy or wind power is measured as a clean source of energy which produces no environmental harm during operation. This paper provides a detail study of Al 2024 wind Turbine blade using structural and modal analysis. Current analyzing trends are summarizing, and several analysis result of blade is presented. Preliminary blade design were developed for 25m heights, and work bench analysis were perform to investigate the potential benefits and options for inclusion of Al 2024 material and blade structure are discussed within the context of FEM analysis. In the current project also, the modal and structural analysis were done for the new material Epoxy-Kevlar and former materials Epoxy-E-glass and Epoxy-Carbon.

Sambit sarangi [5] deals with the validation of a beam (a geometrical approximation of a blade) in vibration analysis are taken up first. The natural frequencies are matched with a published research paper and then an actual blade geometry is taken up to validate its 1st 3 natural frequencies with a published research paper and then a CFD analysis is taken up to find the lift and drag forces on the blade and subsequently these forces are used to calculate the fatigue life of the blade. Suitable materials for different parts of the blade are taken to see which combination of materials gives better results.

Dasari Thrinadh, Sateesh Bandaru, P H J Venkatesh[4] carried out the analysis by considering different geometrical and material parameters. Vibration analysis has been carried out and Natural frequency and mode shapes are calculated by the finite element analysis with commercial program (ANSYS). Structural analysis has been performed by considering wind speed in Visakhapatnam region and impact of pressure on the blade is observed through fluent analysis. Fatigue analysis also performed for all materials with 10 e9 cycles and results are compared with different materials to find out the optimum material body.

From above Literature survey it is concluded that previous research Scholars did the analysis of wind turbine blade on different materials like structured steel, aluminum alloy, and composites like E-glass/polyester, Flax/polyester, Epoxy/s-glass, Epoxy/carbon, Epoxy/E-glass, carbon fibers, glass fibers, boron fibers, Kevlar fibers and graphite fibers. There is usage of new materials every time, these new materials have better strengths and stiffness's compared to earlier used materials. The usage of the new materials is not only having better strengths and stiffness but also low density which in turn reduces the weight of the blade. Therefore the present paper considers a new material Epoxy/Kevlar for suitable analysis along with earlier used materials i.e., Epoxy/E-glass and Epoxy/Carbon. The Epoxy/Kevlar has low density and better material properties compared to earlier used materials. So in this current work, effort has been made towards modeling the same blade geometry in CATIA and carrying out vibration analysis in ANSYS to validate the natural frequencies to those published in the open literature. Further, the research paper does give insight into structural analysis where von misses stresses and deformations are obtained for the three materials. So the issue is obtaining the analyses results and comparing among the three materials to find if the Epoxy/Kevlar material can exhibit the better results.

3. COMPUTATIONAL ANALYSIS OF THE WIND TURBINE BLADE

CATIA is used to model the blade geometry as specified in [7]. The mini-wind turbine blade has the following sectional characteristics as specified in [7]. The wind turbine has the radius of the blade section along the blade span from the root of the stock. Chord is the end to end length of the blade cross section. Twist is the progressive rotation of the blade cross-section about its axis so as to increase surface area for lift and drag forces. Skin is the outer covering of the blade, the one that imparts the NACA shape to it

3.1 GEOMETRICAL MODEL

Geometrical model of the blade is generated based on cross section profiles by importing the co ordinates of NACA airfoil using CATIA software as shown in Figure 1 order to provide data for the finite element model then the surface model is analyzed by importing into ANSYS software.

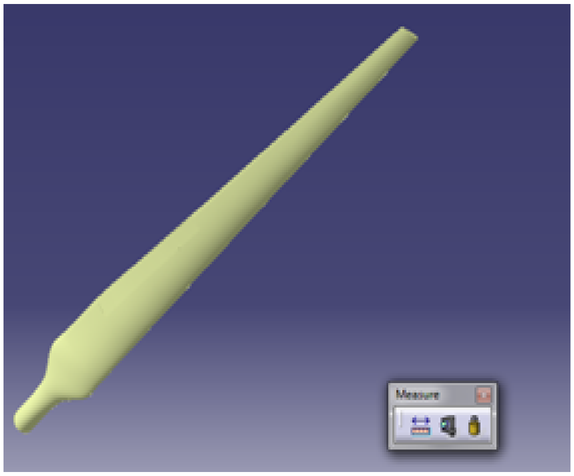

Figure 1 Blade geometry modeled in CATIA

The model shown in Figure 1 was created by the method of Multi-Sections Solid. Planes were created along the blade span and cross sectional geometries were created on these planes as per [7]. Then these sections were joined by a flow of solid by the multi-sections solid method using ratio coupling mode. Extreme care was taken to create proper closing points on the sections to avoid forming of cusps during solid flow. The normal procedure is to model a part in CATIA and then import it to ANSYS. But ANSYS takes up the geometry as a single body and hence separation of bodies in the blade becomes almost impossible if there are no clear dividing surfaces between the bodies.

3.2 MESHING

Analysis of the blade specified in [7] and modelled in CATIA was done in ANSYS workbench which is shown in figure 2. The meshed beam looked as shown in Figure 3. This FEM model consisted of 3186 nodes and 1511 elements. .

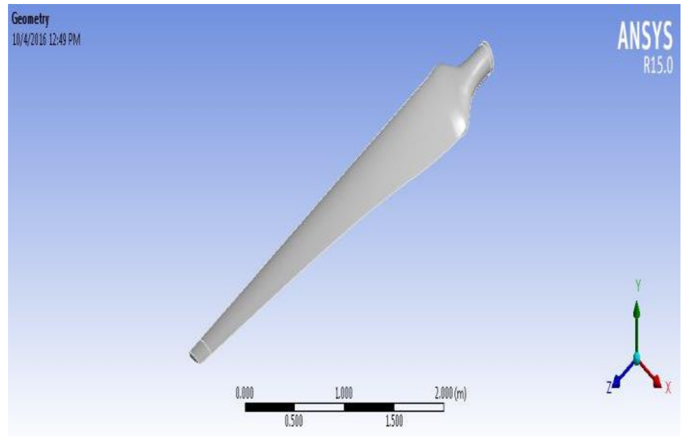

Figure 2 Blade geometry after importing to ANSYS

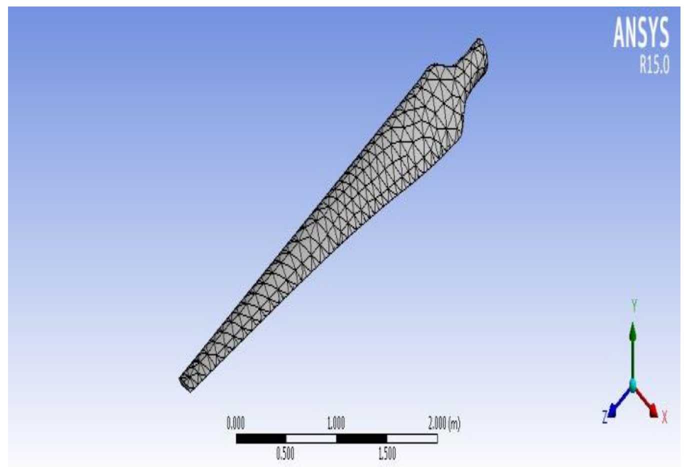

Figure 3 Meshed view of the wind turbine blade

3.3 APPLY BOUNDARY CONDITIONS

In this study the boundary condition is same as that of a cantilever beam, i.e. one end fixed and one end free. The root of the blade at the stock is fixed with 0 DOF as shown in Figure 4.

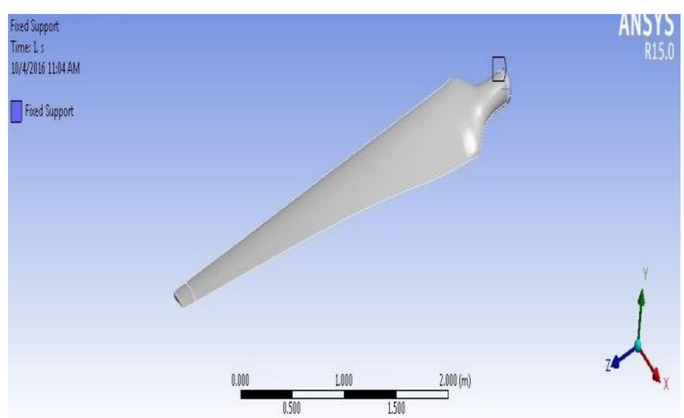

Figure 4 Boundary condition of the blade for analysis

3.4 APPLY MATERIALS

In this present work three types of composite materials are used viz., Carbon/Epoxy, E-glass/Epoxy and taken from the reference[5] and also Kevlar /epoxy composites taken mechanical properties from reference[6] and their corresponding properties is shown in table. The main advantage of composite materials is the high stiffness to weight ratio.

Table 1 material properties of composites

Material Properties	Epoxy/Carbon	Epoxy/E-Glass	Epoxy/Kevlar
Density (g/cm^3)	1.54	2	1.33
Young's Modulus in X-direction (Mpa)	209000	45000	87000
Young's Modulus in Y-direction (Mpa)	9450	10000	17000
Young's Modulus in Z-direction (Mpa)	9450	10000	17000
Poisson's ratio XY	0.27	0.3	0.31
Poisson's ratio YZ	0.4	0.4	0.34
Poisson's ratio XZ	0.27	0.3	0.31
Shear Modulus XY (Mpa)	5500	5000	2200
Shear Modulus YZ (Mpa)	3900	3846.2	1400
Shear Modulus XZ(Mpa)	5500	5000	2200

3.5 APPLYING LOADS AND ANALYSIS

The Modal and static structural analysis are done by using ANSYS 15.0 workbench. The boundary condition for the modal analysis is giving the one end of wind turbine blade as supported by the hub and another end is free in air as shown in figure 5. In this study for the structural analysis the hub end is provided two loading conditions i.e., constant angular velocities of 3rad/sec as shown in figure 6 and 4rad /sec as shown in figure 7 and different values of deformations and stresses are calculated.

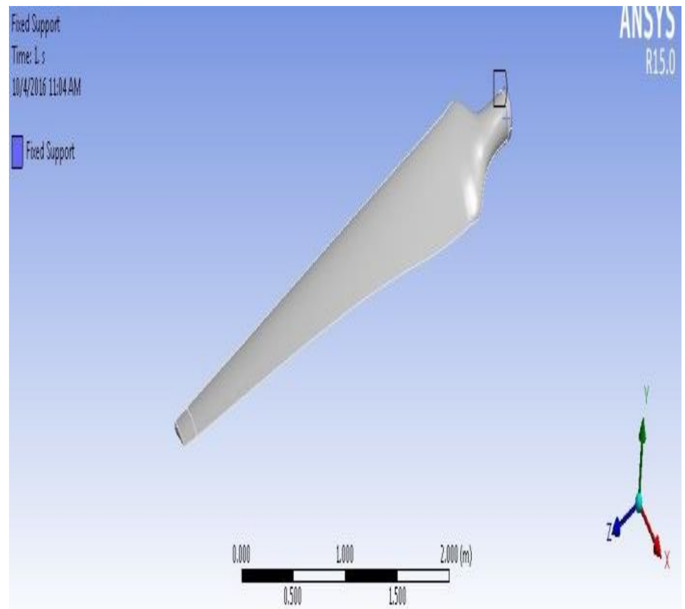

Figure 5 Loading condition of the blade for modal analysis.

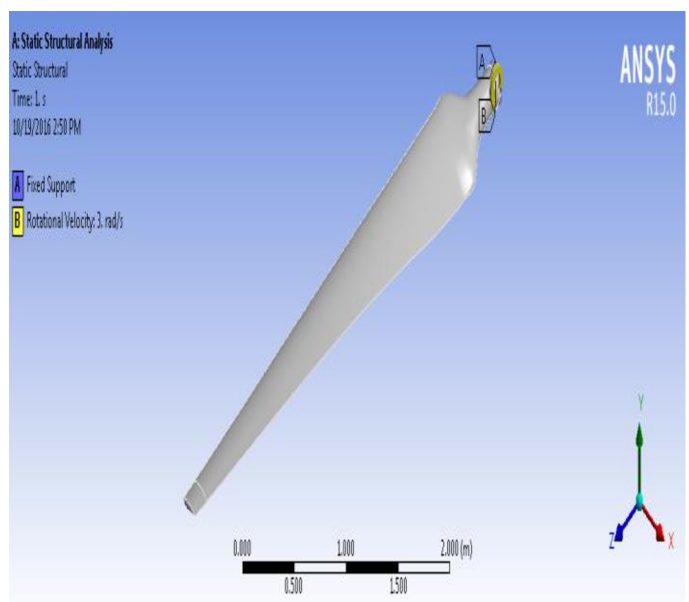

Figure 6 First loading condition of the blade for stress analysis.

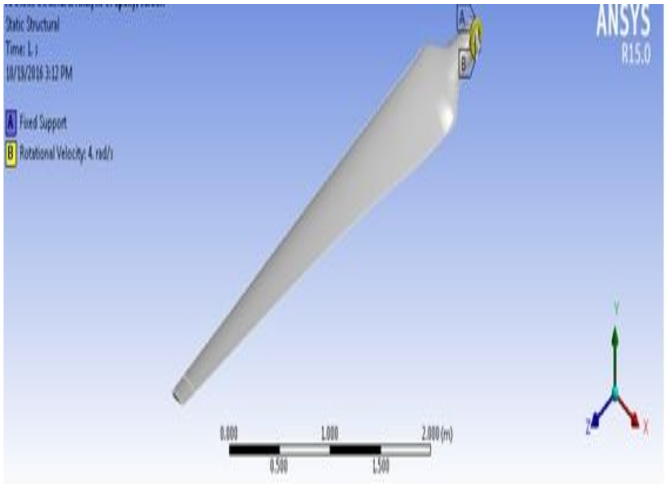

Figure 7 Second loading condition of the blade for stress analysis.

3.6 MODAL ANALYSIS

The blade model as taken from [7] was passed through a modal analysis in ANSYS workbench and the results were compared with that of the reference research paper [5]. The first three natural vibration frequencies are obtained. The corresponding mode shapes are shown in Figures 8-13. Comparison of frequency values from both ANSYS and [5] are tabulated in Table 3.

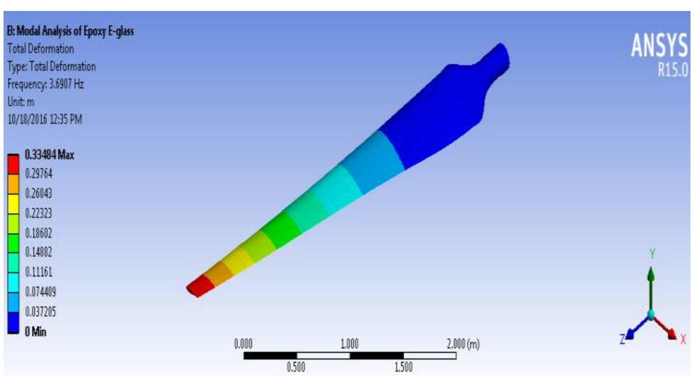

Figure 8 Mode shape of Epoxy/E-glass blade corresponding to 1st modal frequency

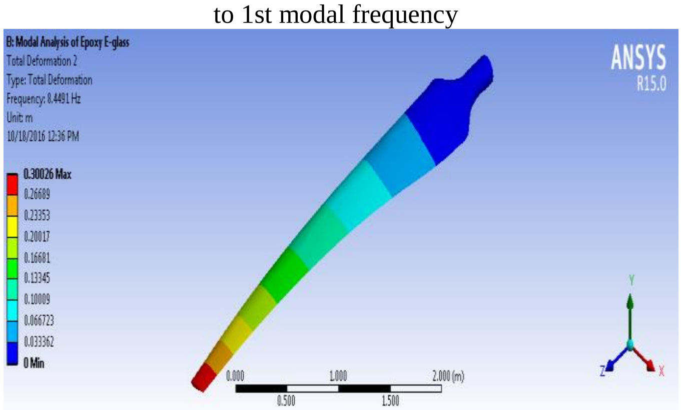

Figure 9 Mode shape of Epoxy/E-glass blade corresponding to 2nd modal frequency

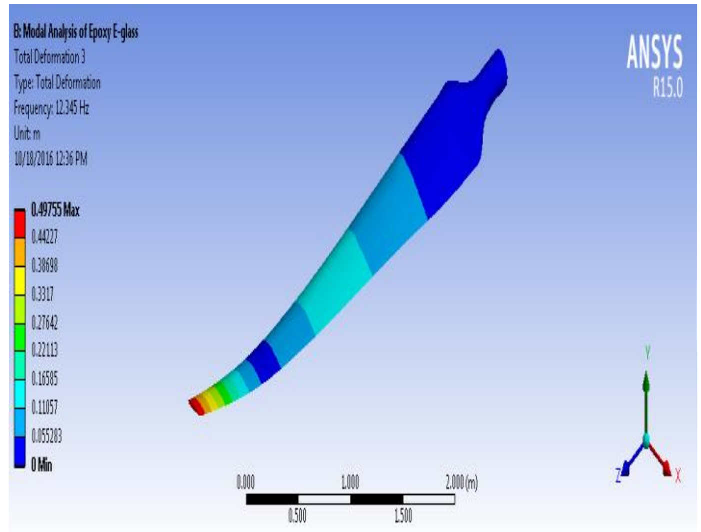

Figure 10 Mode shape of Epoxy/E-glass blade corresponding to 3rd modal frequency

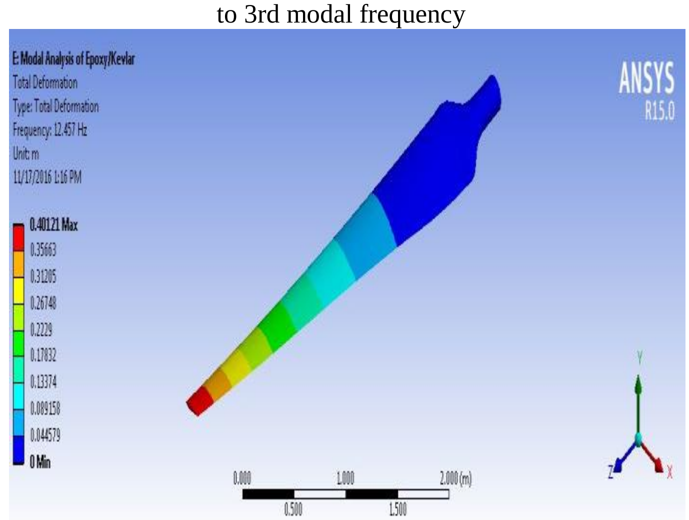

Figure 11 Mode shape of Epoxy/Kevlar blade corresponding to 1st modal frequency

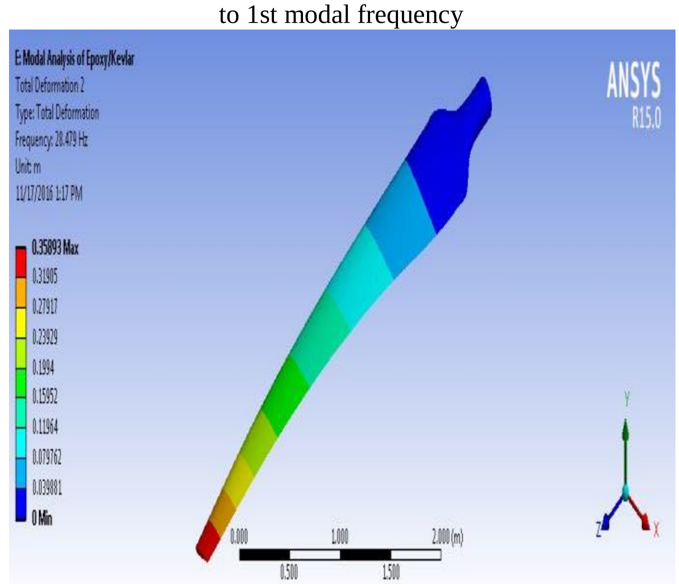

Figure 12 Mode shape of Epoxy/Kevlar blade corresponding to 2nd modal frequency

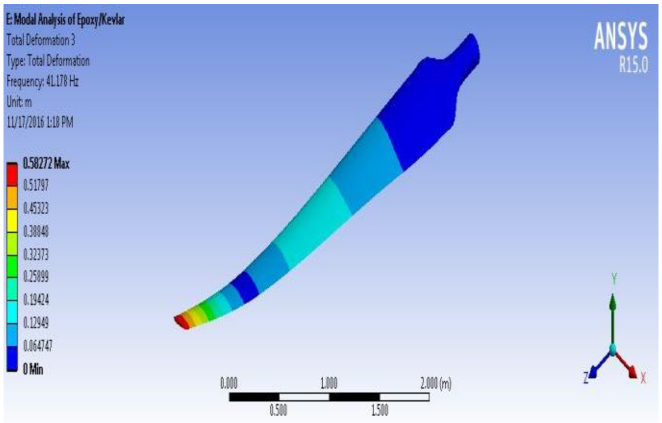

Figure 13 Mode shape of Epoxy/Kevlar blade corresponding to 3rd modal frequency

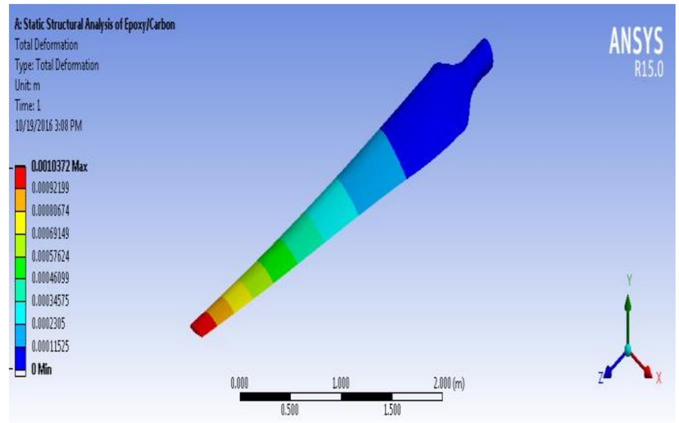

Figure 16 Showing Total deformation of the Epoxy/carbon wind turbine blade

3.7 STRUCTURAL ANALYSIS

The blade model passed through a Static structural analysis for two loading conditions in ANSYS workbench and the results that are found is Von misses stresses, Equivalent elastic strain and Total deformation for three different materials i.e., Epoxy/carbon, Epoxy/E-glass, Epoxy/Kevlar

Case I: The following figures shows the static structural analysis of all the three materials for the first loading condition i.e., angular velocity of 3m/s

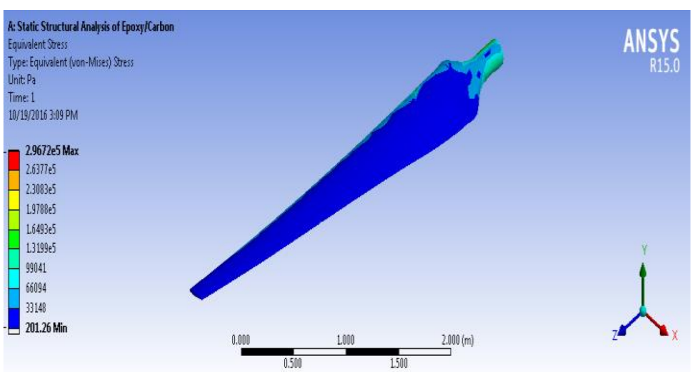

Figure 14 Showing Stress Analysis of the Epoxy/carbon wind turbine blade

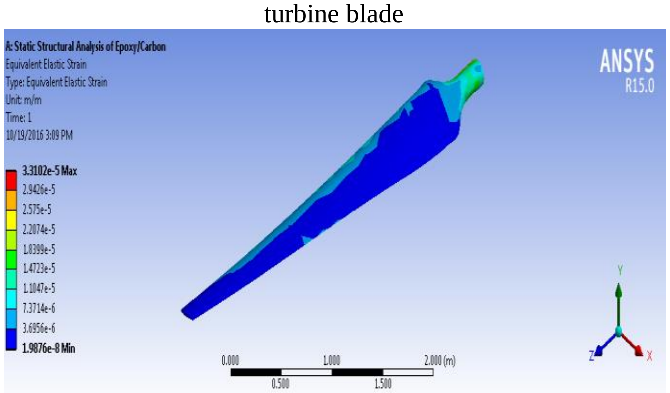

Figure 15 Showing Strain Analysis of the Epoxy/carbon wind turbine blade

Stress analysis of the part model showed that maximum stresses of 0.2Mpa are generated around the root of the blade and at the joining point of blade to stock as seen in Figure 14. Figure 15 shows the maximum strain 0f 3.3×10^{-5} is developed around the root and deformation contour along the blade span due to the applied loads. As evident, the tip of the blade has a maximum deformation of 1.03 mm is seen in figure 16

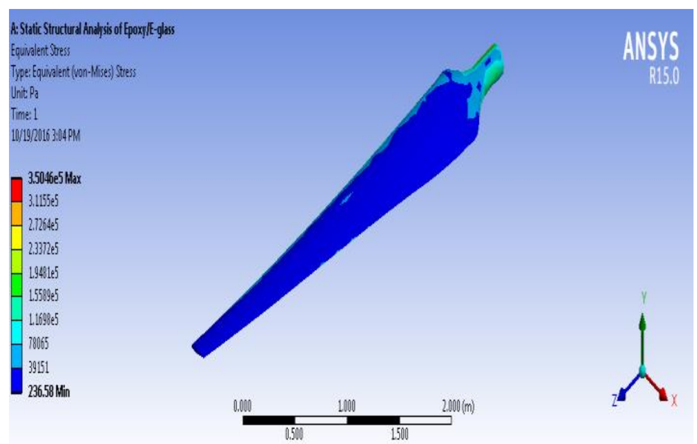

Figure 17 Showing Stress Analysis of the Epoxy/E-glass wind turbine blade

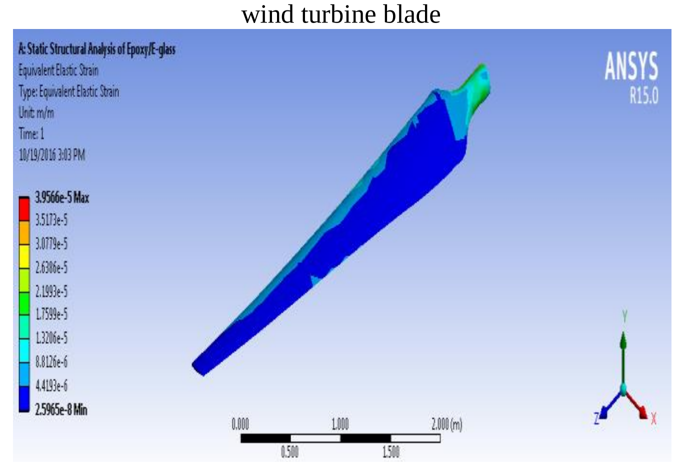

Figure 18 Showing Strain Analysis of the Epoxy/E-glass wind turbine blade

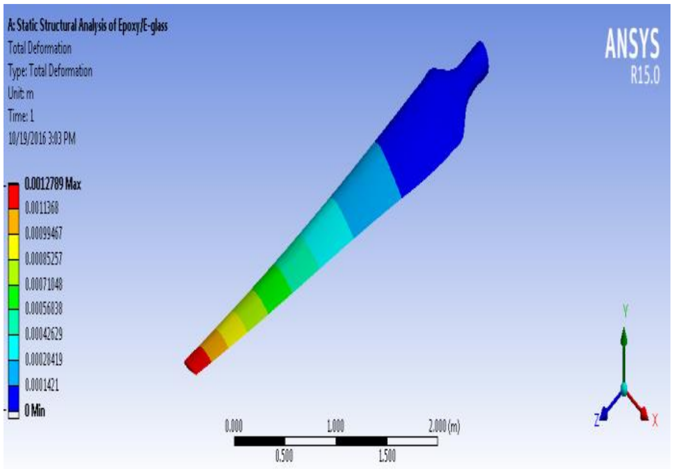

Figure 19 Showing Total Deformation of the Epoxy/E-glass wind turbine blade

Stress analysis of the part model showed that maximum stresses of 0.35Mpa are generated around the root of the blade and at the joining point of blade to stock as seen in Figure 17. Figure 18 shows the maximum strain 0f 3.9×10^{-5} is developed around the root and deformation contour along the

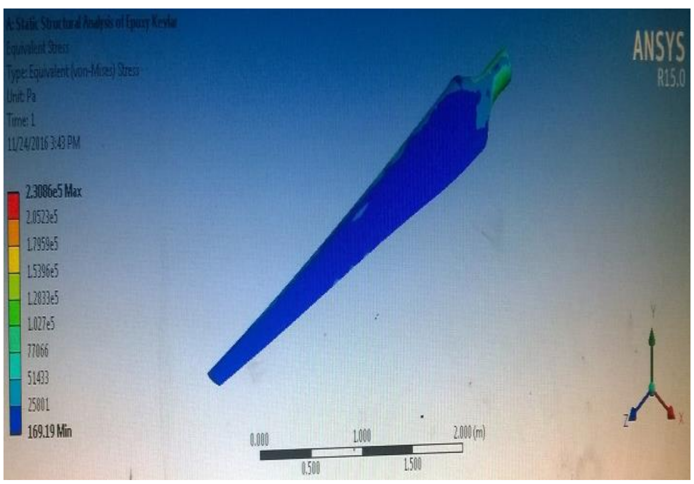

Figure 20 Showing Stress Analysis of the Epoxy/Kevlar wind turbine blade

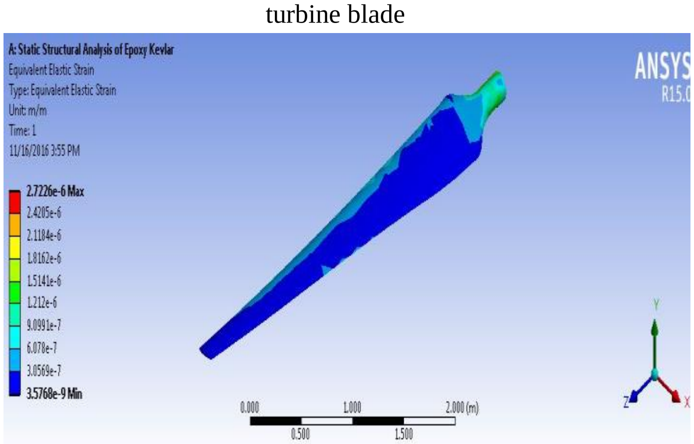

Figure 21 Showing Strain Analysis of the Epoxy/ Kevlar wind turbine blade

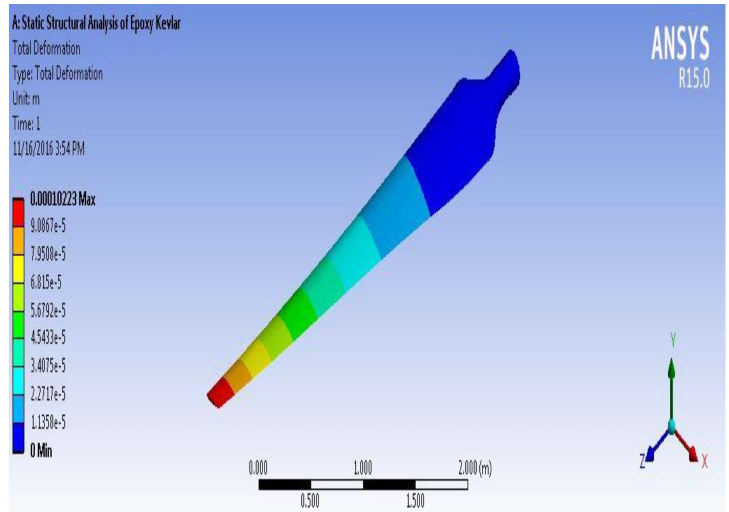

Figure 22 Showing Total deformation of the Epoxy/ Kevlar wind turbine blade

Stress analysis of the part model showed that maximum stresses of 0.23Mpa are generated around the root of the blade and at the joining point of blade to stock as seen in Figure 20. Figure21 shows the maximum strain 0f 2.72×10^{-5} is developed around the root and deformation contour along the blade span due to the applied loads. As evident, the tip of the blade has a maximum deformation of 0.102 mm is seen in Figure 22

Case II: The following figures shows the static structural analysis of all the three materials for the first loading condition i.e., angular velocity of 4m/s

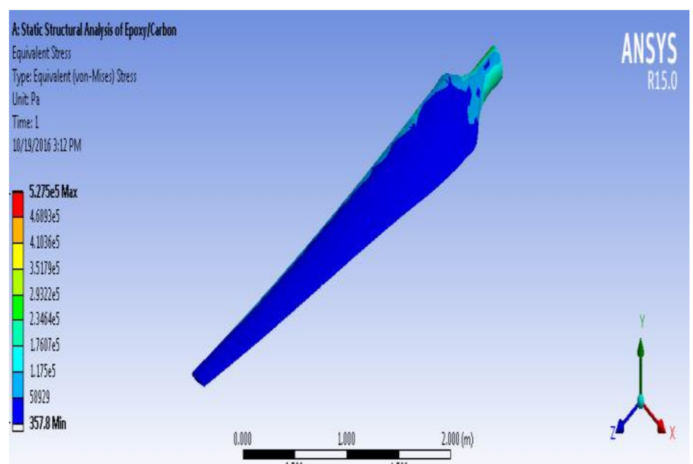

Figure 23 Showing Stress Analysis of the Epoxy/carbon wind turbine blade

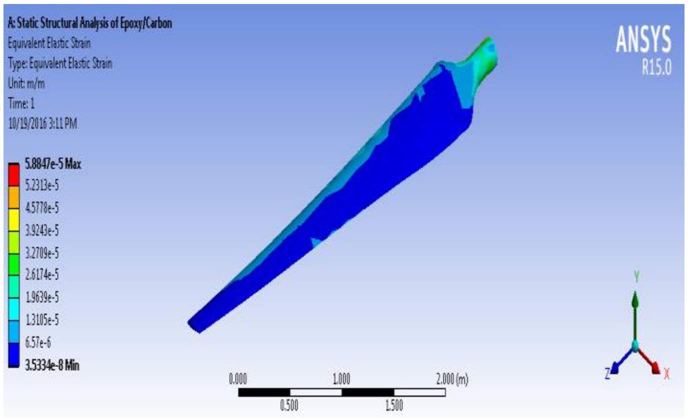

Figure 24 Showing Strain Analysis of the Epoxy/carbon wind turbine blade

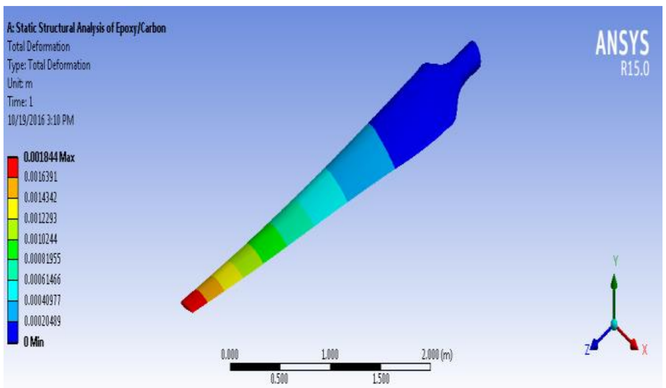

Figure 25 Showing Total deformation of the Epoxy/carbon wind turbine blade

Stress analysis of the part model showed that maximum stresses of 0.5 Mpa are generated around the root of the blade and at the joining point of blade to stock as seen in Figure 23. Figure 24 shows the maximum strain 0f 5.88×10^{-5} is developed around the root and deformation contour along the blade span due to the applied loads. As evident, the tip of the blade has a maximum deformation of 1.8 mm is seen in figure 25.

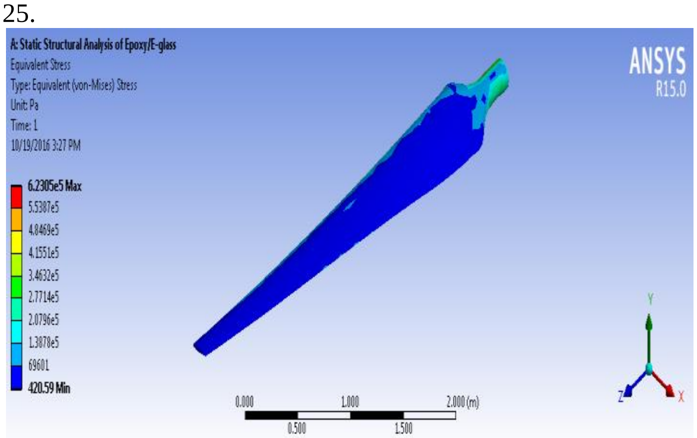

Figure 26 Showing Stress Analysis of the Epoxy/E-glass wind turbine blade

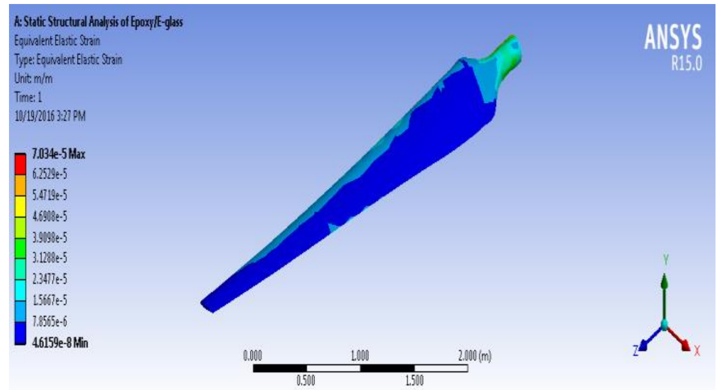

Figure 27 Showing Strain Analysis of the Epoxy/E-glass wind turbine blade

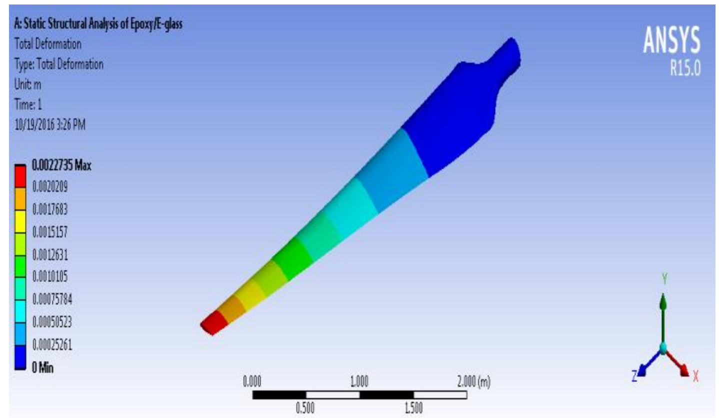

Figure 28 Showing Total deformation of the Epoxy/E-glass wind turbine blade

Stress analysis of the part model showed that maximum stresses of 0.6Mpa are generated around the root of the blade and at the joining point of blade to stock as seen in Figure 26. Figure 27 shows the maximum strain 0f 7.08×10^{-5} is developed around the root and deformation contour along the blade span due to the applied loads. As evident, the tip of the blade has a maximum deformation of 2.2 mm is seen in figure 28

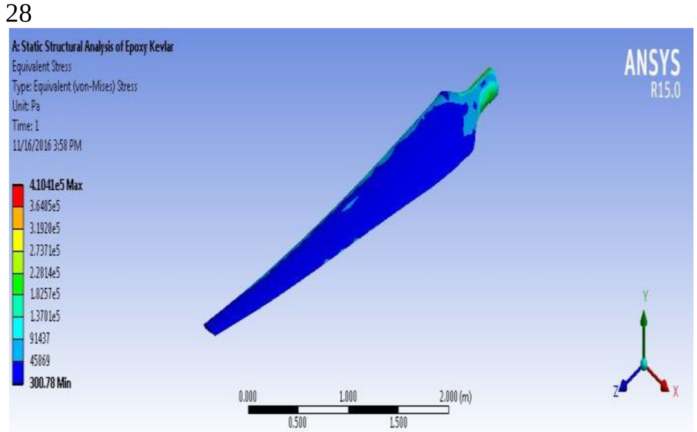

Figure 29 Showing Stress Analysis of the Epoxy/ Kevlar wind turbine blade

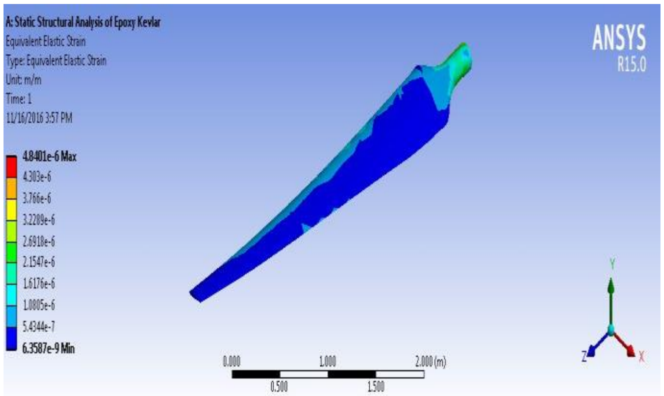

Figure 30 Showing Strain Analysis of the Epoxy/ Kevlar wind turbine blade

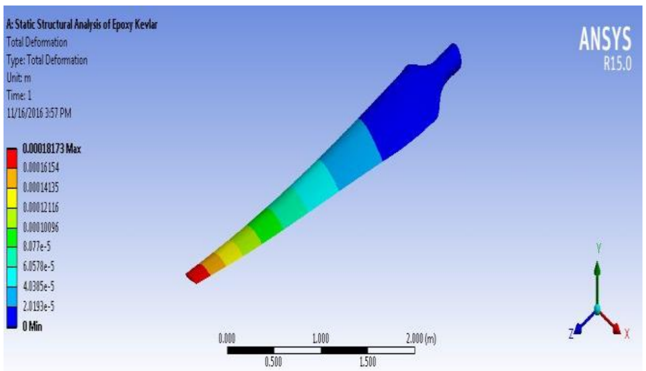

Figure 31 Showing Total deformation of the Epoxy/ Kevlar wind turbine blade

Stress analysis of the part model showed that maximum stresses of 0.410Mpa are generated around the root of the blade and at the joining point of blade to stock as seen in Figure 29. Figure 30 shows the maximum strain 0f 4.84×10^{-6} is developed around the root and deformation contour along the blade span due to the applied loads. As evident, the tip of the blade has a maximum deformation of 0.181 mm is seen in figure 31.

4. RESULTS AND DISCUSSIONS

4.1 MODAL ANALYSIS RESULTS

Table 2 Comparison of blade's modal frequencies

Mode Shape	**Measured natural frequency ref. [5] in Hz**	**Obtained natural frequency in Hz Epoxy/E-glass**	**Obtained natural frequency in Hz Epoxy/Kevlar**
1	3.98	3.69	12.45
2	8.917	8.44	28.47
3	13.375	12.34	41.17

From the analysis of the above Table we can infer that the values of obtained natural frequencies and measured natural frequencies are quite in good agreement with each other. Thus the blade model is validated with the existing open literature.

4.2 STRUCTURAL ANALYSIS RESULTS

FEA models using ANSYS are employed to calculate maximum tensile stresses for the wind turbine blade for the two loading conditions. The following tables shows the results of the two loading conditions i.e., angular velocities of 3m/s, 4m/s that are applied at the root end of the turbine blade.

Table 3 shows results of case I loading condition

Results	**Epoxy/Carbon**	**Epoxy/ E-glass**	**Epoxy/Kevlar**
Stress (Mpa)	0.29	0.35	0.23
Strain (mm/mm)	3.3×10^{-5}	3.9×10^{-5}	2.72×10^{-5}
Total Deformation(mm)	1.03	1.2	0.102

From the above table the maximum stresses that is developed for the epoxy/carbon is 0.29Mpa, for epoxy/E-glass is 0.35Mpa and for Epoxy/ Kevlar is 0.23Mpa. It is found that the maximum stresses for the Epoxy/ Kevlar is lowest among the three materials. The maximum equivalent elastic strains from the table 2 for the Epoxy/Carbon are 3.3×10^{-5}, for Epoxy/E-glass is 3.9×10^{-5}, for Epoxy/ Kevlar is 2.72×10^{-5}.The maximum total deformations developed for Epoxy/Carbon is 1.03mm, for the Epoxy/E-glass is 1.2mm and for the Epoxy/ Kevlar is 0.102mm. The total deformation for the Epoxy/Kevlar is very less among the three materials.

Table 4 Shows results of case II loading condition

Results	**Epoxy/Carbon**	**Epoxy/E -glass**	**Epoxy/Kevlar**
Stress (Mpa)	0.527	0.623	0.410
Strain (mm/mm)	5.88×10^{-5}	7.08×10^{-5}	4.84×10^{-6}
Total Deformation (mm)	1.8	2.2	0.181

From the above table the maximum stresses that is developed for the Epoxy/carbon is 0.527Mpa, for Epoxy/E-glass is 0.623Mpa and for Epoxy/ Kevlar is 0.410Mpa. It is found that the maximum stresses for the Epoxy/ Kevlar is lowest among the three materials. The maximum equivalent elastic strains from the table 4 for the Epoxy/Carbon are 5.88×10^{-5}, for Epoxy/E-glass is 7.08×10^{-5}, for Epoxy/ Kevlar is 4.84×10^{-6}.The maximum total deformations developed for Epoxy/Carbon is 1.8mm, for the Epoxy/E-glass is 2.2mm and for the Epoxy/ Kevlar is 0.181mm. The total deformation for the Epoxy/ Kevlar is lowest from the three materials.

5. CONCLUSIONS

The wind turbine blade was modeled and its natural frequencies were computed computationally using CAE software .The values of natural frequencies were validated with thesis results [5] available in literature and good agreement was found between the values suggesting that the modeling and analysis of the blade is correct. Then structural analysis of the blade model and regions of high stress concentration were observed from the CAE results. The deformation along the blade span was also studied.

After completing the successful analysis of the turbine blade for the different materials at two different loading cases the following conclusions are derived:

- Among the three materials the weight of the Kevlar reinforced epoxy blade is lowest among the three materials since Kevlar reinforced epoxy has low density 1.33gm/cm^3. So the weight of the blade can be reduced with Kevlar fibers.
- From the analysis among the three materials Epoxy/Kevlar exhibits less stresses i.e., 0.23Mpa so strength of the Epoxy-Kevlar is good.
- Through the analysis among the three materials Epoxy/Kevlar exhibits lower stresses compared with Epoxy-E-glass i.e., 0.35Mpa. So it can be concluded that from the strength wise Kevlar fiber is having strength higher than carbon and glass fiber.
- It is derived from the analysis that total deformation of the Epoxy-Kevlar i.e., 0.102mm which is lower than the two materials (Epoxy-E-Glass is 1.2mm and Epoxy-Carbon is 1.03mm) and so the stiffness of the Kevlar fibers is higher than two materials.
- It is clear that throughout the analysis Kevlar fibers reinforced Epoxy is found better results than the Glass fibers reinforced Epoxy and Carbon fibers reinforced Epoxy and can conclude that it can be used as turbine material for low power wind turbine blades

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