Modal Analysis of Large E-Glass / Carbon Fibre HAWT Blade

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Abstract

In this paper, vibration modal analysis of a large horizontal axis wind turbine blade of two different materials is carried out by using the finite element analysis software ANSYS. The materials taken are E-glass fiber reinforced plastic and carbon fiber reinforced plastic. For analysis, RRB V-27 is taken as a model having a rotor diameter of 29 meters. Blade length is taken 14 meters with 1-meter hub diameter. The blade is modeled with and without the shear web. Modal analysis conducted as edgewise, flap wise and tensional deflection. Deformation characteristics of the blade for two mentioned materials with and without shear web at different frequencies are analyzed and compared.

Keywords: Horizontal Axis Wind Turbine; HAWT; ANSYS; Modal Analysis; Vibration analysis;

1. Introduction

Modal analysis has been till now the most usual approach used to describe the dynamics of mechanical systems, as well as it creates very illustrative and easy-going interpretable outcomes. Modal analysis delivers data on the dynamic characteristics of structural elements at resonances and therefore aids in the understanding of the thorough dynamic behavior of these. Modal analysis is used to classify natural frequencies, damping characteristics and mode shapes of wind turbine blades. Modal analysis has also been used to classify approximate mode shapes, related with the dominating deflection direction lone (i.e. mode shapes without structural coupling between torsion, flaps as well as edgewise deformations) of a horizontal wind turbine blade.

There are two basic classes of excitation techniques – transient excitation (free vibration) as well as continuous excitation (forced vibration). Continuous excitation is typically performed with electromagnetic or hydraulic based exciters able to produce, for example, swept-sine excitation, white noise excitation, pseudo-random excitation or periodic-random excitation. Usually, the excitation is subjected in only one point; however, for large or highly damped structures it might be advantageous to apply more exciters simultaneously. The transient type of excitation is usually associated with either an impulse force loading or an instantaneous release from an initial deflection of the structure (known as the snapback principle).

The major part of this study and research is to discover natural frequencies as well as natural vibration modes of the 14 m, E-glass/carbon fiber HAWT blade. For creating the model of wind turbine blade ANSYS design modular has been used. Further, this model is taken forward for meshing and then vibration modal analysis is performed. The outcomes of the analysis have been used to verify a structure's fitness for use.

2. Literature Survey

Abdel Hafeez and El-Badawy, (2018) presented a unique aeroelastic model that regulates the chord and flaps as well as torsional vibrations of an isolated HAWT blade. This model considers the sectional offsets among the shear, aerodynamic as well as the mass centers. A nonlinear strain was included to consider the centrifugal stiffening effects. For aerodynamic loads, an improved Theodorsen's theory is amended. The FEM approach is applied to discretize the resulting equations along with gaining an approximate solution to the blade's dynamic response, utilizing state-space techniques and complex modal analysis. Analysis of the blade's flutter stability limit was conducted. Effects of factors, for instance, wind speed and blade sectional offsets on the flutter limit as well as a dynamic response were also investigated. In stable air, blade experiences flutter at a rotor speed of 21.5 rpm. The oscillation is dominated by the first torsional mode [1].

The vibration produces the dynamic instability of components of the wind turbine. It was needed to analyze the vibration motion that hub shows to improve the endurance of parts of the wind turbine rotor. Ajayi, Agarana, and Animasaun (2017) adopted a sub-structuring technique in the investigation of the vibration motion. Primarily, the finite element equation was generated for the hub as well as shaft structures before coupling. Then suitable boundary condition was applied to reduce the system complexities. Further, the solution to the eigenvalue problem was developed using MATLAB software. The outcomes display a decent correlation among the dynamic behavior of the coupled hub as well as low-speed shaft using the MATLAB simulation. The hub, as well as the shaft due to their material as well as geometric properties, would not fail but the rotational speed of the blades does not surpass the least Eigen frequency [2].

Araújo et al. (2017) performed numerical/experimental analysis to find dynamic parameters of a twisted blade. Wind turbine VERNE555 of Brazilian Company ENERSUD, based at location Rio de Janeiro is taken for analysis. The experimental analysis conducted to find out modal parameters such as frequencies as well as the modal shape of 2.73 m blade length a wind turbine. Numerical modeling was created utilizing a Timoshenko beam element as well as conducted using the ANSYS software. The overall objective was to perform a comparative analysis of numerical as well as experimental outcomes [3].

In previous studies, the coupling between rotor rotational motion wind turbine blade as well as blade vibration was thoroughly examined. Ju and Sun, (2017) developed a dynamics model of a rotor-blade system meant for a HAWT, which defines the coupling terms between the blade elastic movement and rotor gross rotation. Lagrange's method was used to develop this model. To discretize the blade, the finite element method was employed. This model captures two-way interactions between aerodynamic wind flow as well as structural response. In the case of aerodynamic study, steady and unsteady flow conditions are pondered. On the structural side, blades are pondered flap and edgewise deflection while the rotor has been treated as a rigid body. The proposed model was compared with a model developed in the simulation software FAST. The coupling effects are excluded during the comparison since FAST does not include these terms. Once confirmed, the addition of coupling terms to our model to inspect the consequences of blade vibration on the rotor movement, which has a straight effect on the generator behavior, was done. It is exemplified that the addition of coupling effects could upsurge the sensitivity of blade fault detection ways. The planned model could be used to inspect the influence of different terms as well as analyze fluid-structure interaction. The observations in this study can help us comprehend the rotor vibrations and contribute to effective blade fault detection techniques. Apart from coupling effects, the planned model could be used to inspect the influence of different terms on system behavior [4].

The tower is a key element for supporting the wind turbine components such as hubs, blades, and nacelles. Therefore, structural health monitoring has been essential to secure the structural safety and stability of wind turbine towers. Kim et al. (2017) investigated the dynamic characteristics of a wind turbine tower model with and without damage at various locations however indoor experimentations for the reason of damage assessment as well as structural health monitoring. Such results have been verified using a finite element method. A frequency-based damage detection method (FBDD) was applied on a 3 MW wind turbine tower operating in Jeju Island, Korea and found suitable for developing a vibration-based SHM system for wind turbine towers [5].

Li, Zhang, and Li (2016) studied the dynamic behavior of the HAWT blade, where the mode coupling among axial extension, flaps vibration, edgewise vibration and torsion is emphasized. A Green's function was used as a characteristic equation and further a system of integrodifferential equations was generated. The effect of centrifugal effect, mode coupling and rotational speed on natural frequencies as well as mode shapes were analyzed and concluded these findings (1) The effect of bending-torsion coupling on natural frequency is very small. (2) The rotation has a dramatic effect on bending frequency but less effect on torsion frequency. (3) The effect of bending coupling on dynamic behavior is considerably at a high rotational speed. (4) The influence of rotational speed on bending mode is very small [6].

Munteanu et al. (2018) performed modal vibration analysis on a wind turbine type WTB type GE 1.5sle, scale 1:5. Three-dimensional virtual models of the blade were prepared in modeling software Catia V5 and then imported in Abaqus software. The structure was made by a five-layer GFRP laminated composite. The materials properties were taken by conducting a tensile test. At the initial stage, the modes, as well as natural frequencies of the blade, have been modeled in the role of a composite structure reinforced with glass fiber fabric. Then the modal response from the blade was analyzed. The results emphasized the values of the natural frequencies change both in the analysis of the free structure as well as in the fixed structure [7].

Tan et al. (2019) conducted a modal analysis for a three-bladed HAWT (micro) blade at different rotor speeds. For this analysis FEA software, COSMOSWorks was used. The effect of the dynamic stiffening phenomenon on the vibration mode of the blade was also considered. This analysis ensures the reliability of system operation as well as improving the structural health of wind turbine rotor. It was concluded that providing dynamic stiffening, the resonance can be avoided effectively that confirms the reliable and safe operation of the rotor system [8].

Composite materials have different complex properties as per the use of constituent materials and boundary conditions. Therefore, it is not easy to analyze the characteristics of composite materials. Thus, it is needed to build up a tool that allows the designer to attain designs, covering the structural requirements and functional behavior. It is required to study the dynamic behavior that includes natural frequencies, mode shapes, etc. and it is necessary for proper use of composite materials. Taware et al. (2016) analyzed the behavior of small wind turbine blades made by composite materials. Two small wind turbine blades were manufactured from composite material Glass Fiber Reinforced Plastic (GFRP) as well as GFRP with steel wire mesh reinforcement. Finite Element Analysis (FEA) was performed by using FEM software ANSYS. The experimental free vibration test of fabricated blades was conducted to identify the mode shapes as well as natural frequencies. Finally, the comparison was done for the outcome found from the finite element analysis and experimental test of the blade. It was concluded that the natural frequencies for the first three modes of GFRP blade with steel mesh increase by 2-3 % than the GFRP blade. Also, the mode shapes for the first three modes displaying that there has been lesser variation in case of deformation of GFRP blade as well as GFRP blade along with steel wire mesh. The natural frequencies achieved, provide the resonant condition frequencies for both the blades [9].

In present work FEM modal analysis is carried out for airfoil NACA 63(4)-221 for redesigning the blade of RRB V27-225 kW HAWT. In this work, a model of the blade was first created in the design modeler of ANSYS and then mesh was generated in the next step. The set up was done in the ANSYS modal after mesh generation. Boundary conditions were applied at different frequencies. The analysis has been conducted on different frequencies.

3. Perform modal analysis

Following modal analysis, the result is find out for E-glass fiber and carbon fiber material with and without shear web at specified wind speed, nodes, and elements. There are five different forms of vibration at different frequencies that show different maximum deformation. Table 1 shows five maximum frequencies for both the materials while table 2 shows maximum deformation corresponding to frequencies given in table 1. Different deformation pattern along the blade at different specified frequencies are shown from fig 1 to fig 20 for both the materials with and without shear webs.

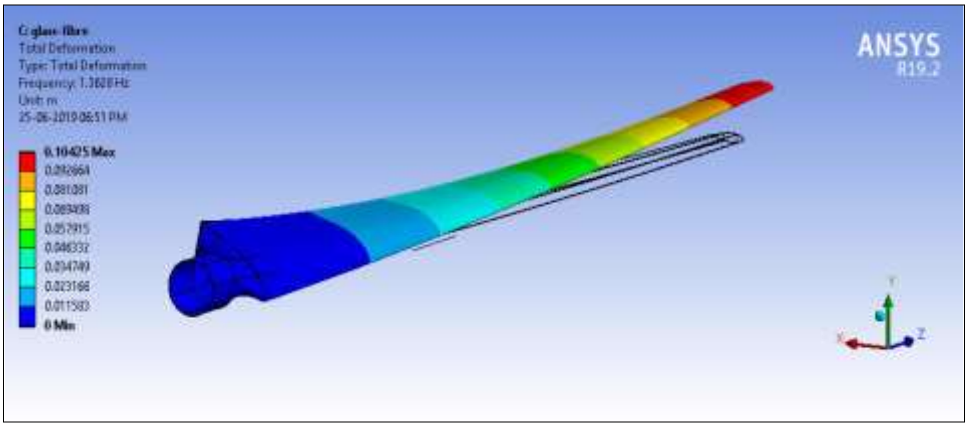

Fig 1 Deformation pattern along the glass fibre blade without shear web at frequency 1.3628 Hz

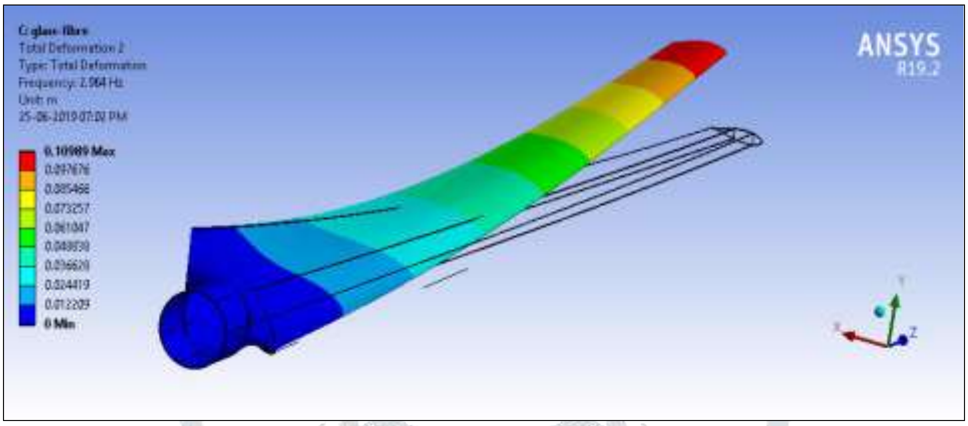

Fig 2 Deformation along the glass fibre blade without shear web at frequency 2.964 Hz

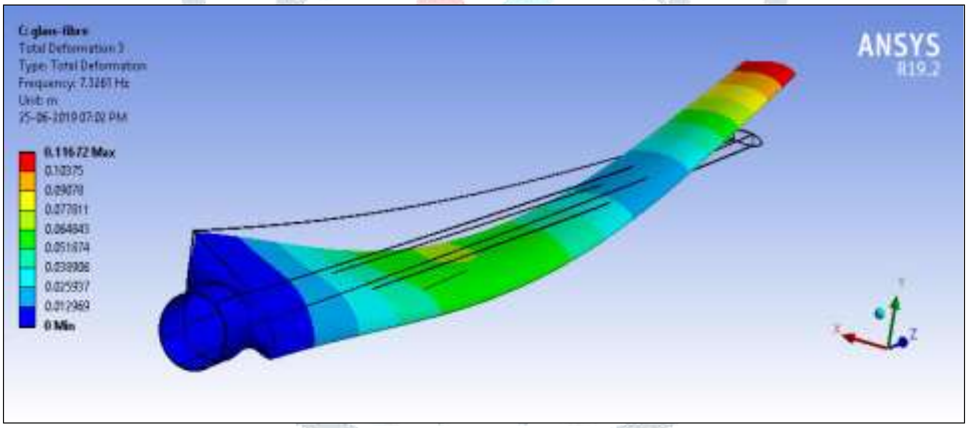

Fig 3 Deformation along the glass fibre blade without shear web at frequency 7.3261 Hz

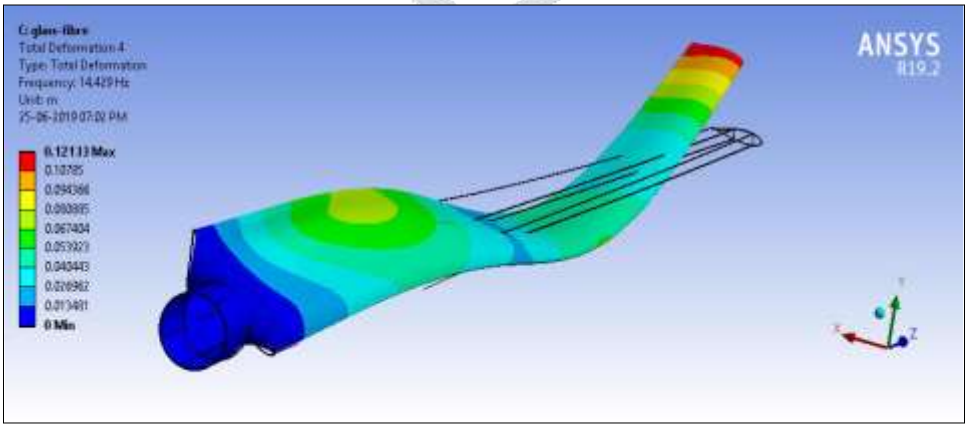

Fig 4 Deformation along the glass fibre blade without shear web at frequency 14.429 Hz

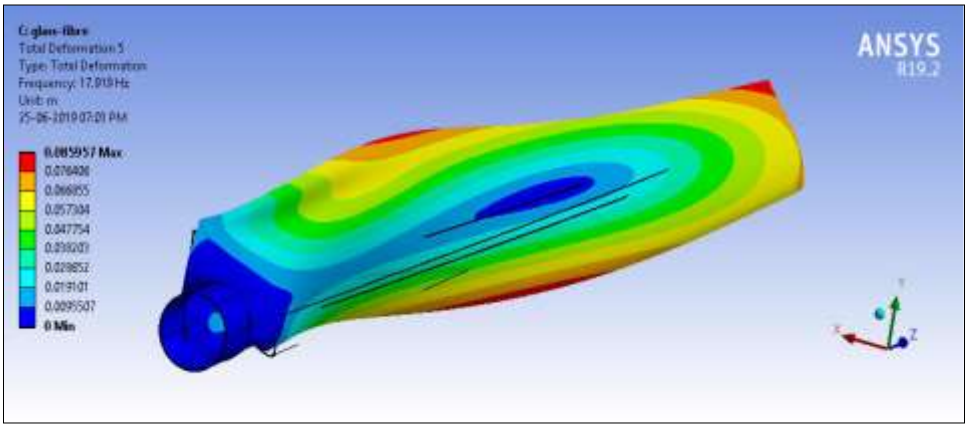

Fig 5 Deformation along the glass fibre blade without shear web at frequency 17.919 Hz

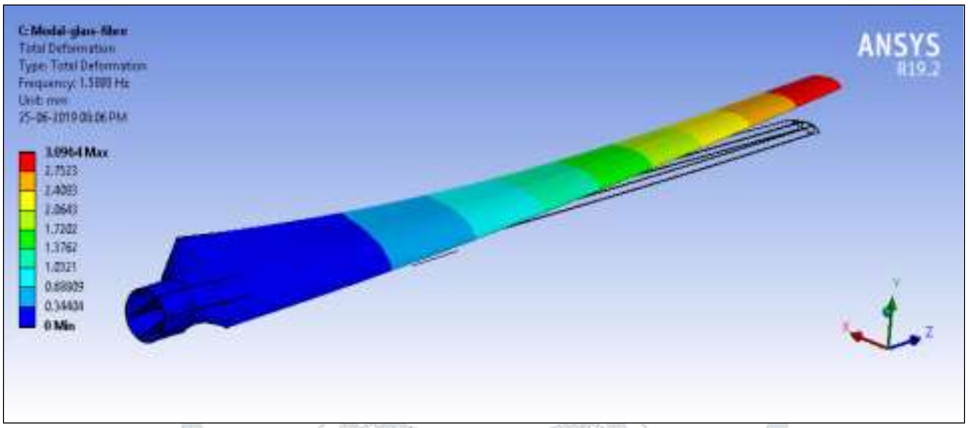

Fig 6 Deformation along the glass fibre blade with shear web at frequency 1.5893 Hz

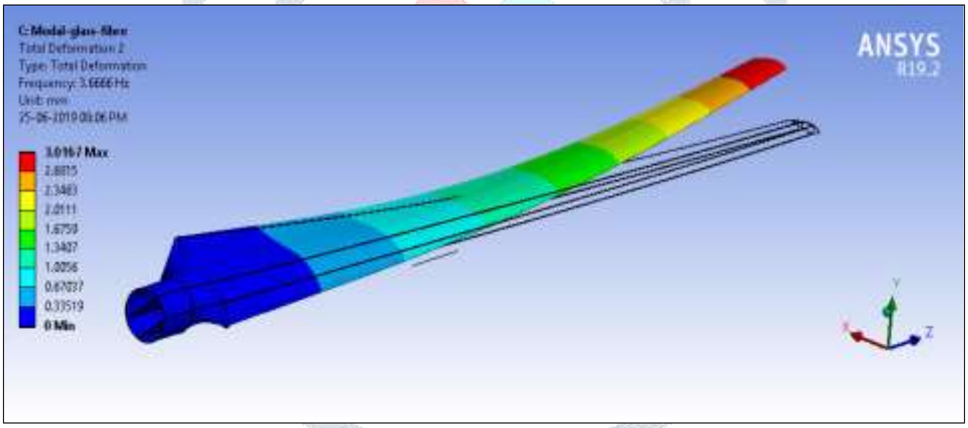

Fig 7 Deformation along the glass fibre blade with shear web at frequency 3.6666 Hz

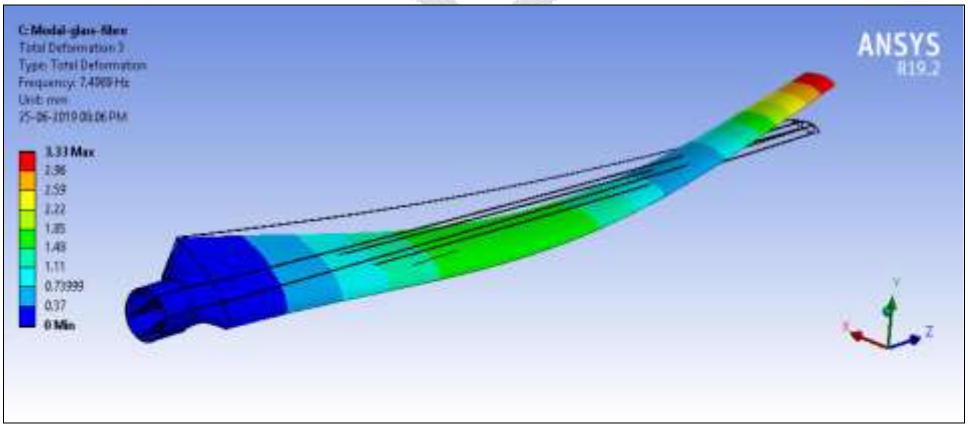

Fig 8 Deformation along the glass fibre blade with shear web at frequency 7.4989 Hz

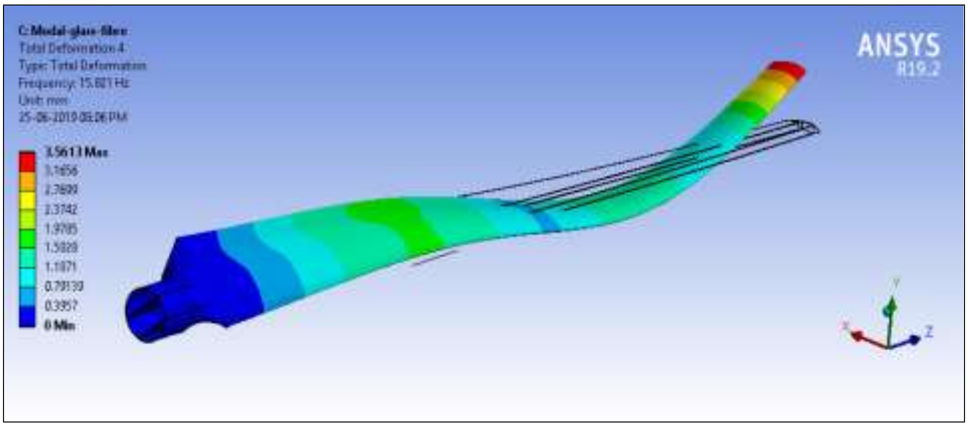

Fig 9 Deformation along the glass fibre blade with shear web at frequency 15.821 Hz

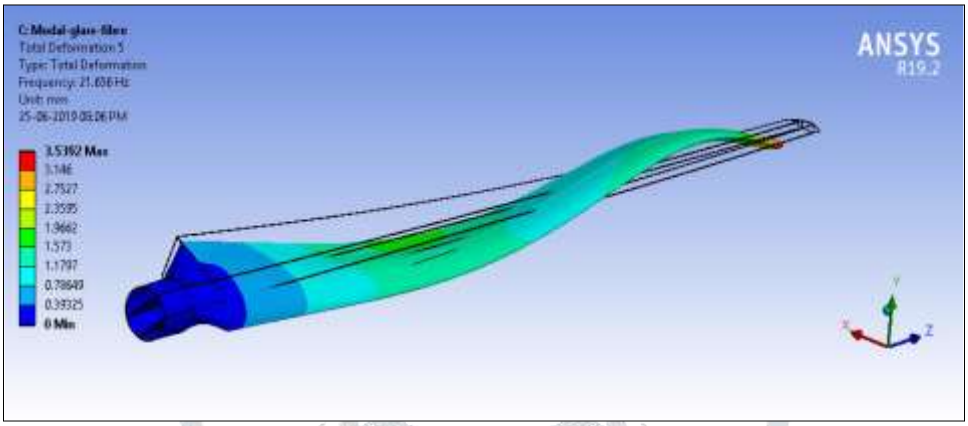

Fig 10 Deformation along the glass fibre blade with shear web at frequency 21.636 Hz

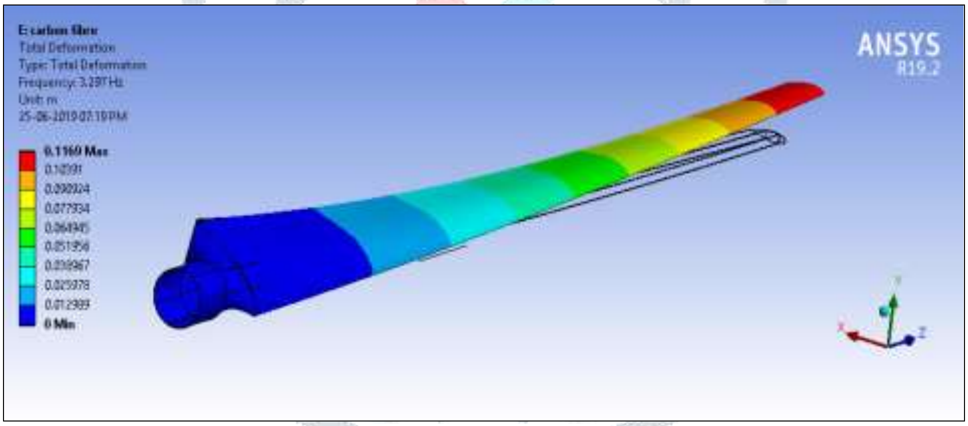

Fig 11 Deformation along the carbon fibre blade without shear web at freq. 3.297 Hz

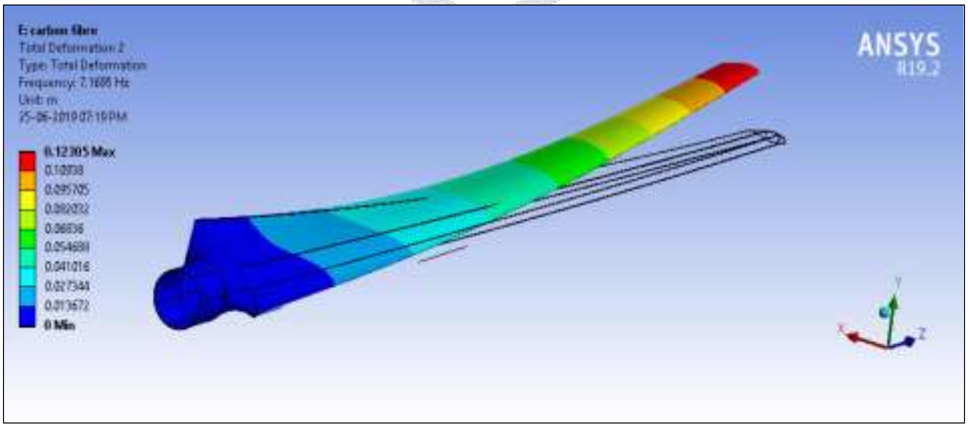

Fig 12 Deformation along the carbon fibre blade without shear web at freq. 7.1695 Hz

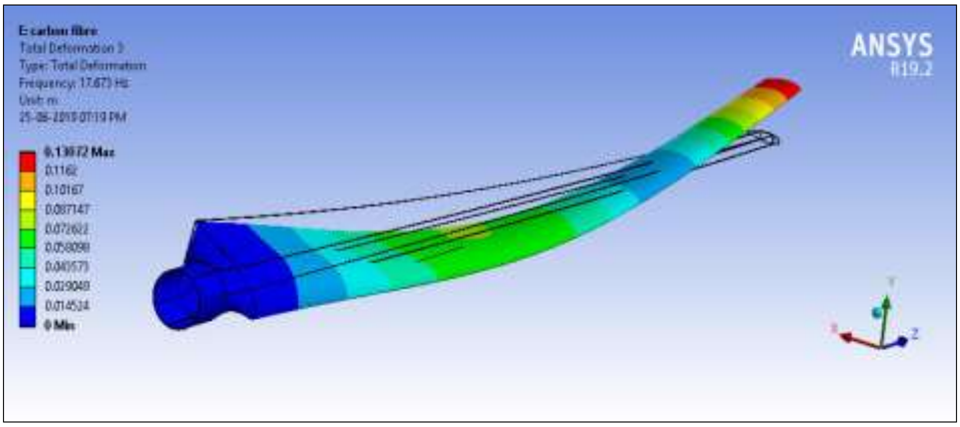

Fig 13 Deformation along the carbon fibre blade without shear web at freq. 17.673 Hz

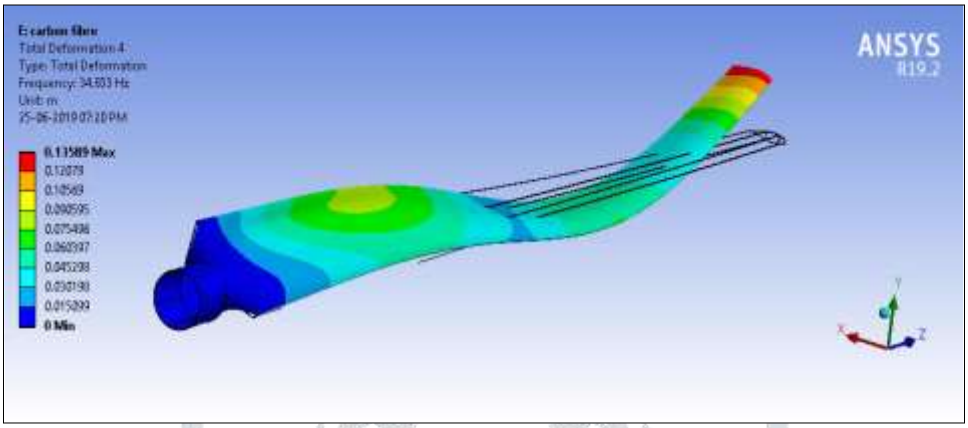

Fig 14 Deformation along the carbon fibre blade without shear web at freq. 34.833 Hz

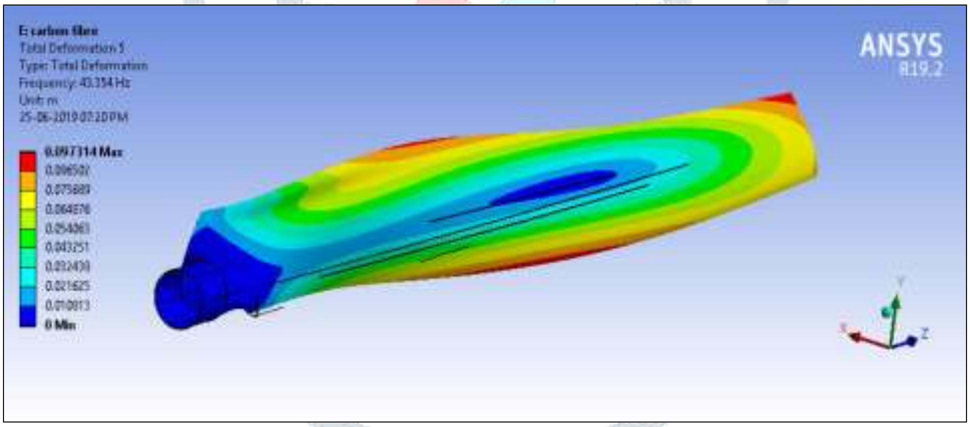

Fig 15 Deformation along the carbon fibre blade without shear web at freq. 43.354 Hz

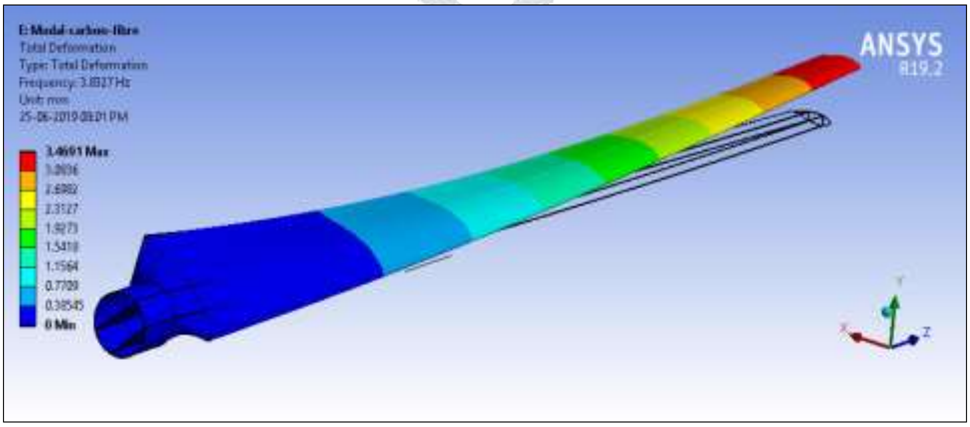

Fig 16 Deformation along the carbon fibre blade with shear web at frequency 3.8327 Hz

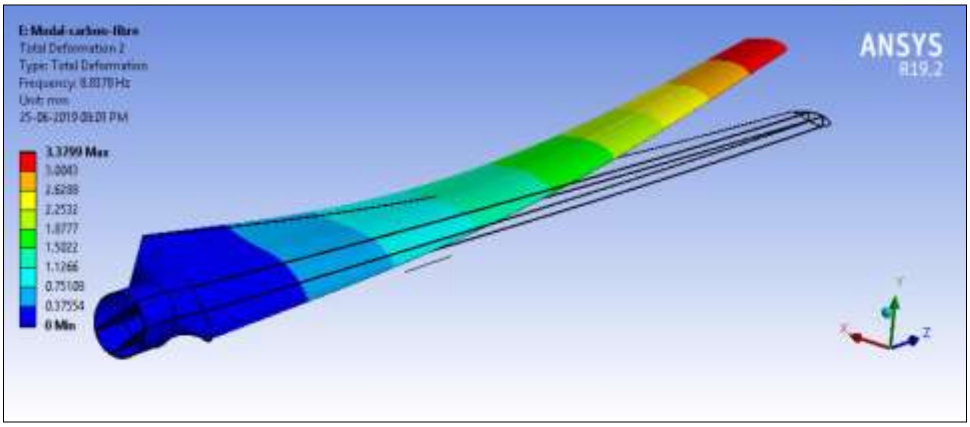

Fig 17 Deformation along the carbon fibre blade with shear web at frequency 8.8378 Hz

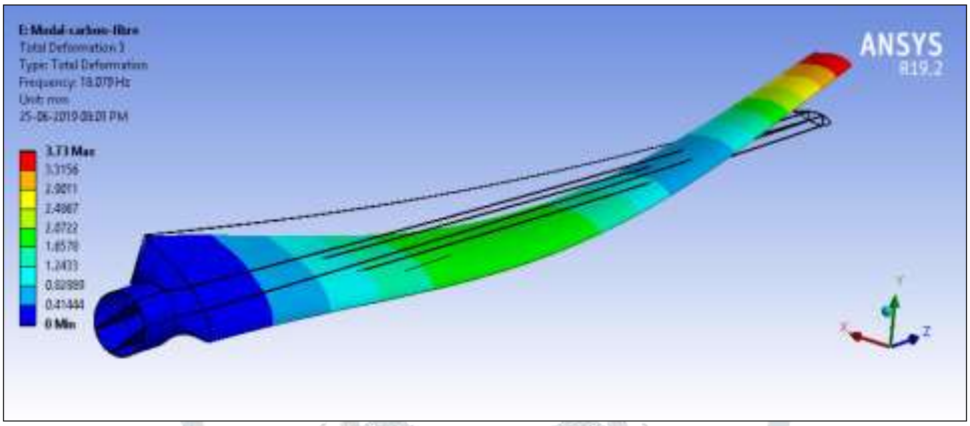

Fig 18 Deformation along the carbon fibre blade with shear web at frequency 18.079 Hz

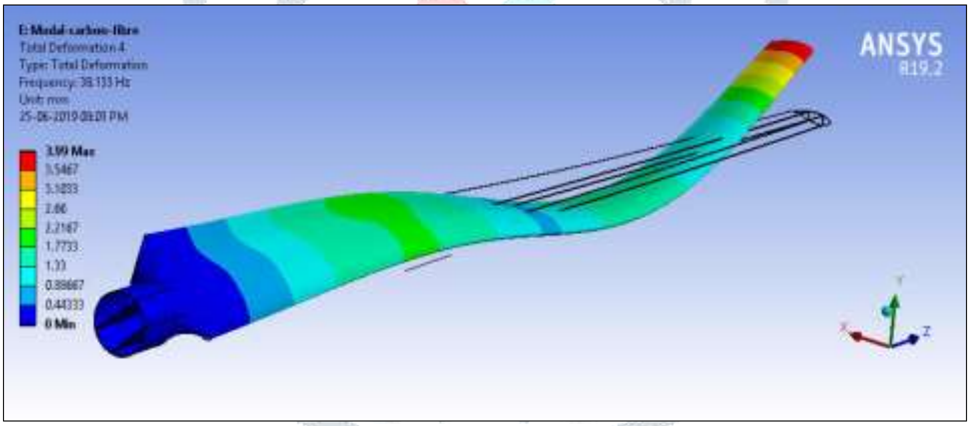

Fig 19 Deformation along the carbon fibre blade with shear web at frequency 38.133 Hz

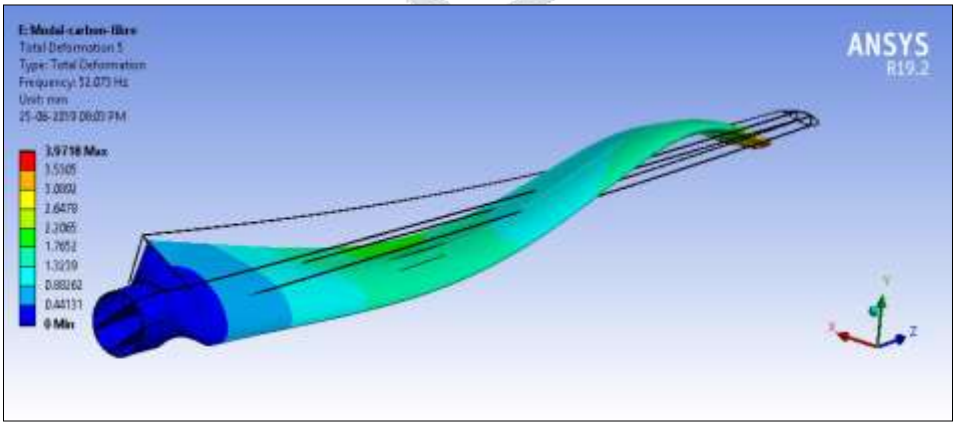

Fig 20 Deformation along the carbon fibre blade with shear web at frequency 52.073 Hz

Table 1 Frequency of blade of glass fibre and carbon fibre with and without shear web

Blade material	**Wind speed in m/s**	**Weight of blade in kg**	**Freq.-1 (Hz)**	**Freq.-2 (Hz)**	**Freq.-3 (Hz)**	**Freq.-4 (Hz)**	**Freq.-5 (Hz)**	**Nodes/ Elements**
E-Glass fibre reinforced plastic without shear web	24	530.15	1.3628	2.964	7.3261	14.429	17.9191	51603/ 51568
E-Glass fibre reinforced plastic with shear web	24	699.77	1.5893	3.6666	7.4989	15.821	21.636	64823/ 63448
Carbon fibre reinforced plastic without shear web	24	422.42	3.297	7.1695	17.673	34.833	43.354	51603/ 51568
Carbon fibre reinforced plastic with shear web	24	557.57	3.8327	8.8378	18.079	38.133	52.073	64823/ 63448

Table 2 Maximum deformation of blade of E-glass fibre reinforced plastic (E-GFRP) and carbon fibre reinforced plastic (CFRP), with and without shear web

Blade material	**Max. deformation at freq.-1**	**Max. deformation at freq.-2**	**Max. deformation at freq.-3**	**Max. deformation at freq.-4**	**Max. deformation at freq.-5**
E-GFRP without shear web	104.250	109.890	116.720	121.330	85.957
E-GFRP with shear web	3.0964	3.0167	3.3300	3.5613	3.5392
CFRP without shear web	116.900	123.050	130.720	135.890	97.314
CFRP with shear web	3.4691	3.3799	3.7300	3.9900	3.9718

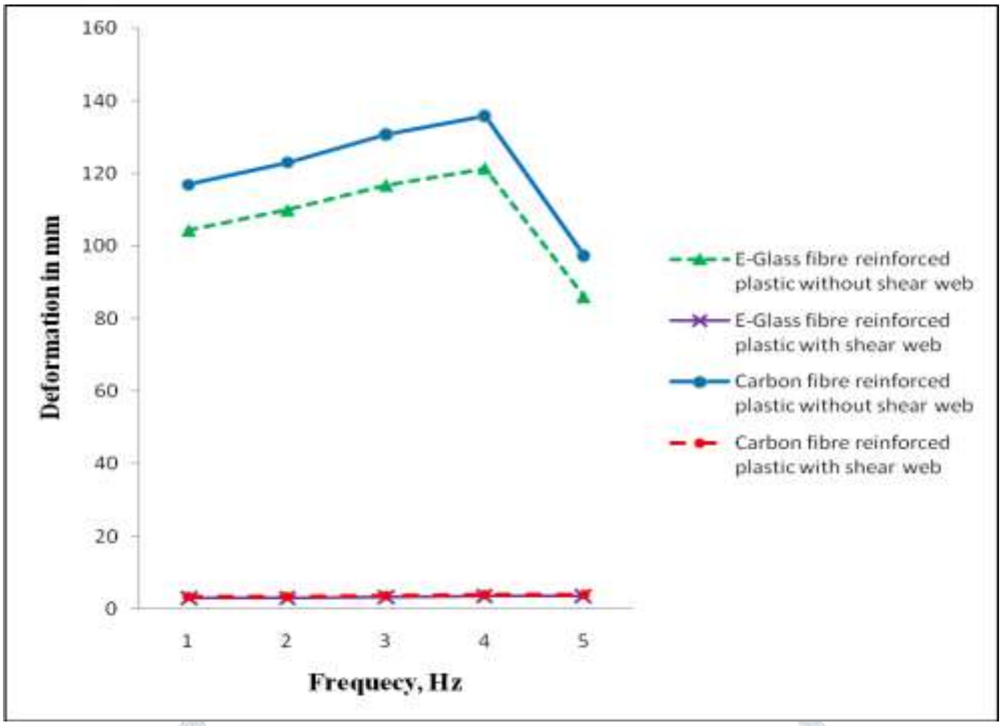

Fig. 21 Deformation characteristics of blade for two different materials with and without shear web at different frequencies

4. Conclusion

Figure 21 shows the graph for deformation at different frequencies for both materials with and without shear webs. The analysis shows E-glass fiber has more deformation at all frequencies than carbon fiber. It is also seen that providing shear web inside the structure of the blade gives sufficient strength than without the shear web. Hence carbon fiber with shear web provides a better choice than E-glass fiber for a 14m horizontal axis wind turbine blade.

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References

1. Abdel Hafeez, M. and El-Badawy, A., *J. of Vibration and Acoustics* 140(4), 1 (2018). https://doi.org/10.1115/1.4039402
2. Ajayi, O., Agarana, M. and Animasaun, T., *Procedia Manufacturing* 7, 602 (2017). https://doi.org/10.1016/j.promfg.2016.12.090
3. Araújo, D., e Castro, L., Shzu, M., Ávila, S. and de Morais, M., *Procedia Engineering*, 199, 2250 (2017). https://doi.org/10.1016/j.proeng.2017.09.479
4. Ju, D. and Sun, Q., *J. of Vibration and Acoustics* 139(5), 1 (2017). https://doi.org/10.1115/1.4036633
5. Kim, W., Yi, J., Kim, J. and Park, J., *Procedia Engineering*, 188, 333 (2017). https://doi.org/10.1016/j.proeng.2017.04.492
6. Li, L., Zhang, X. and Li, Y., *Acta Mechanica Solida Sinica* 29(6), 620 (2016). https://doi.org/10.1016/S0894-9166(16)30332-9
7. Munteanu, M., Stanciu, M., Năstac, S. and Savin, A., *IOP Conference Series: Materials Science and Engineering* 444, 062 (2018). https://doi.org/10.1088/1757-899X/444/6/062004
8. Tan, X., Tan, X., Guo, X., Wang, L., Li, Q. and Li, B., *Vibro engineering PROCEDIA* 22, 87 (2019). *https://doi.org/10.21595/vp.2019.20593*
9. Taware, G., Mankar, S., V. B., G., G. P., B. and Kale, S., *Inter. J. of Engg. and Techn.* 8(5), 2121 (2016). https://doi.org/10.21817/ijet/2016/v8i5/160805431