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Static analysis of wind blades based on weight loads to the gravitation and the centrifugal forces Using Finite Element

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Abstract

Static analysis of wind turbine blades that convert kinetic energy using wind to electrical power has been analyzed using Ansys model. The geometry was imported in ANSYS workbench 2020R1, where the material was changed to Epoxy E-Glass Wet. The mesh independence that occurred at 800 and 600 element sizes and an element size of 800 was chosen for subsequent static analysis. The static analysis shows that the total deformation and von Mises stress of the wind turbine blade was improved at both the vertical position and the horizontal position by 40.0% and 38.61%, respectively. Besides, the static analysis showed an almost linear mode shape increased from mode lines. Nevertheless, Campbell's diagram showed that resonance vibration occurred at an amplitude of 5.5x106Pa with a corresponding frequency of 5Hz, which gave a rotational speed of 262.4x106 rpm. This shows that the impulse force is better applied in wind turbine blade transient analysis at a lower von Mises stress to attain a quicker damping response steady-state, which favors wind turbine blade analysis. Overall, the wind turbine blade is better designed at a vertical position to allow better deformation stress at a static position. Conversely, the von Mises stress showed 44.64% and 38.61% at horizontal and vertical positions. This also agrees with static total deformation, since stress is better managed at a lower percentage range.

Keywords: Static; Wind-blade; Finite element; Loads Campell diagram

1 Introduction

In a wind turbine system, the blades play a very vital role. Kinetic energy is converted into electric energy when the blades of a wind turbine rotate. The blades are nice looking components of the wind turbine system and were designed by aero dynamical procedure for attaining maximum wind energy. The blade of a wind turbine system comprises three components: the rotor component which includes the blades for converting wind energy to low-speed rotational energy. The second component is the generator that controls the electrical generator and electronics. The third component is the structural support that houses the tower (Egwuagu *al.,* 2023).) The blade was intended to have low cut-in speed, and high power output, and was structurally strong for resilience and buckle. (Egwuagu *al.,* 2023).) Furthermore, the blades of a wind turbine were projected to generate the maximum power from the wind at a low cost. Basically, the design was driven by the aerodynamic requirements, but economics mean that the shape of the designed blade was a compromise to maintain the cost of construction sensible. In particular, a wind turbine blade was thicker than the aerodynamic optimal close to the root, where the stresses ascribable to bending were greatest (Onah. et al., 2023).. Researchers of engineering extraction created the wind turbine system to extract the energy inherent in the wind. Because the energy generated by the wind is converted to electric energy, the machine is sometimes called a wind generator. Locally, wind velocities are significantly affected by obstacles such as trees or (Onah. et al., 2023). A

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renewable energy source will be ideally suited to comply with these energy needs. The sources of energy available easily are wind, solar, biogas, etc. out of which energy of the wind was studied in length

Designing of the blades to get the maximum energy from the wind flow is an essential topic which is according to a refined aerodynamic science. Stiffness and strength-to-weight ratios are two important criteria used to design the blades of a wind turbine. Blades that are of horizontal axis are now completely built of composite materials that not only have smaller weight and appropriate stiffness, but also allow good resistance to the static, dynamic, and fatigue loadings. In other to achieve the maximal power output possible from the wind turbine under defined atmospheric conditions, we can change two parameters in the design. The first is to modify the overall mechanical properties and dynamics of the blade which modifies the composite material being used, which the blade is made of the material; the second aspect is that we can modify the shape of the blade. Confessedly, changing the physical shape of the blade affects the stiffness and stability in general; this may determine the aerodynamic efficiency of the wind turbine. Consequently, a crucial and complex problem has to do with defining the optimal shape of the blade and optimal composite material. Notwithstanding, how to select an airfoil and also determining the loading are two essential topics that would be used to design the appropriate composite blade (Ghasemi & Mohandes, 2016; Veludurthi & Bolleddu 2020). They analysed the response of the blade with different forces and frequencies using ANSYS 18.1 software. I will be analysing the blade of a wind turbine using ANSYS 2020 software for Static, Modal, Harmonic and Transient response. Krishnamurthy and Sesharao (2017), studied dynamic analysis of the wind turbine blades rotating with high speed. I would be analysing gravitational acceleration and rotational speed of wind turbine blades using ANSYS 2020 software.

Tenguria et al. (2011) designed a wind turbine blade with a horizontal axis using Glauert's optimal rotor theory. Campbell Diagram response theory will be used in this research. It was very hard to set up a model of a wind turbine blade in Finite Element software directly because of the complexity of the shape. To be able to eliminate this challenge, parameterized modeling and analyses program of wind turbine blades was formulated by use of ANSYS software. The procedures for establishing a finite element model, applying loads, and extracting post-processing data of the blade were talked about. This research work can be used to hasten the application of ANSYS modeling in the design and also analysis of wind turbine blades, providing references for parameterized modeling and analysis of similar engineering in the time to come. This study would also help to reduce the monetary value of production of the wind turbine blades. (Zhang *et al.,* 2013). This calls for the study analyses the properties of a blade based on static response using finite element analysis (FEA) Ansys model.

2 Overview of Wind turbine blade

Veludurthi and Bolleddu (2020b) worked on modal and harmonic analysis of wind turbine blades that are small in size taken from the NACA 63415 series. The sandwich structure type composite blade was constructed from GFRP and epoxy with Uni-vinyl hard foams of different alignments as stiffeners. In this research, the modal and harmonic analysis of different types of blades like solid, hollow, and rectangular alignment blades was carried out by the Finite Element Method employing ANSYS 18.1 software. From Finite Element Analysis, the natural frequencies, amplitudes, and mode shapes were obtained. Based on the operating principle of wind turbine blades, the boundary considerations were applied. The experimental investigation was also done using a vibration test rig with specially designed fixtures. The forced vibration approach was used to examine the responses of the blade with different forces and frequencies which gives the feasible study to define the effective blade structure. After the modal analysis, the harmonic analysis was also carried out for different materials to find the amplitude at different frequencies. The outcome of this analysis can be used as a source for improving the structure and material attributes of the blade.

Yi and Teoh (2018) examined a wind turbine blade (Aeolos-V 1k) design already existing with a focus on the modal properties utilizing a computational approach (ANSYS Workbench) and redesigned it. The modal analyses were modeled to observe the natural frequency and corresponding mode shape of the system under free vibration. The flow accelerated vibration could cause blade failure due to resonance or fatigue. Fluid Structural Interaction (FSI) ANSYS was used to ascertain the interaction between the wind flow and the blade. Harmonic Response ANSYS was the tool used to test the frequency reaction of the blade under wind-accelerated vibration. After adjustment, the first mode has increased from 91.42 Hz to 102.12, since it was more than 50.92 Hz (Turbine maximum operating frequency), resonance would not occur during operating conditions. The Aeolos-V's blade was altered by using teak wood material and redesigned the blade for weight reduction to achieve lower blade cost. The weight of the altered blade was reduced by 72.8 % after using teak wood and the efficiency of the wind turbine increased. The modified blade was dependable, efficient, and more economical.

Bin and Dongbai (2013) surveyed the testing, inspecting, and supervising technologies for wind turbine blades, including mechanical property testing, non-destructive testing, full-scale testing, structural health monitoring, and condition supervising. Then, the development trends and some propositions for testing, inspecting, and supervising technologies for wind turbine blades were discussed.

Ehsan *et al.,* (2013) investigated the noise generation and tower vibration characterization. He designed the tower in such a way that the noise emission was minimized. In his research work, the operational modal analyses were done using 24 accelerometers placed on the tower in two orthogonal lines for measurement. For detecting operational deflection shapes and natural frequencies he used FDD technology. It was observed that when the turbine produces power, the initial three natural modes vibrate significantly with great magnitude.

Larsen *et al.,* (2002) worked on identifying the natural frequencies, damping characteristics and the mode shapes of the blades of a wind turbine using modal analysis. For getting mode shapes, they adopted different experimental procedures on blade LM 19 m and considered the right method for analysis. The selected experimental procedure was quantified by estimating the unsystematic variations. The results were received satisfactorily for natural frequencies, damping characteristics, and the prevailing deflection direction of investigated mode shapes. The blade LM19 m was experimentally analyzed and cross-checked with the results obtained from the FEA modeling of the same blade. For a few higher modes, significant variances between the natural frequencies arising from modal analysis and FE modeling were observed.

Rao & Venkatesh (2015) carried out the modal and harmonic analysis for multi-leaf springs for different materials using ANSYS 12.1 and compared them with theoretical values. Using the graphs generated from the harmonic analysis done, the researcher noticed that E-glass/epoxy and carbon/epoxy had prominent amplitude of response compared to other materials and Kevlar/epoxy, graphite/epoxy, and steel had low amplitude of response. For E-glass/epoxy, the maximal amplitude value that was obtained was 2.5 mm at a frequency of 23 Hz. For carbon/epoxy, the maximal amplitude value obtained was 1.11 mm at a frequency of 9 Hz.

Chaudhary *et al.,* (2018) optimized the pattern of the blade and designed a vital part called a micro wind turbine blade with the aid of SG 6043 airfoil cross-section. Finite element analysis software was used to model the blade and the results were received for deformations and stress distributions were equated with analytical results. The researcher found out that the unique design of the blade was dependable at 5.37 factor of safety when analyzed by use of an analytical method and at 6.72 factor of safety when analyzed by use of a structural method.

Krishnamurthy and Sesharao (2017) researched the dynamic analysis based on wind turbine blades that were rotating at a high speed. Studies on transient and modal analysis were done using six degrees of freedom for 10 beam elements with freedom per node. The blades were fastened at the center with five degrees of freedom constrained. The researcher found that the natural frequencies of the blades were changing at different rotational speeds. The researcher also noticed that the increase in acceleration resulted in variation of torsional modes as equated to both flap-wise and edgewise modes.

Tenguria *et al.,* (2010) used Glauert's optimal rotor theory to design a turbine blade that had a horizontal axis. A computer program (ANSYS) was formulated to find the thickness, the chord, and twist distribution on the blade, which helps to maintain the lift coefficient fixed all-round the blade. The researcher divided the blade into nineteen sections and each section had an equal length. Using ANSYS software that had aerofoil NACA coordinates and had blade material as E Glass-Epoxy, the modeling and analysis of the blade being analyzed were carried out. The results generated were equated with the experimental values and it was discovered that the blade behavior was not symmetric.

Kumar & Rajakumar (2015) modeled the wind turbine by use of CATIA and then imported the modeled blade to ANSYS software workbench for extensive modal analysis. The models that were developed included some sort of approximations. From the modal analysis that was carried out, the deformations of the blade ascribable to the impact of the wind were created on some parts like the blade, tail, tower, and base. The modal analyses were used to discover the frequency of the modal in other to avert experimental vibration measurement. Vibrations are common in wind turbines of small size because of the impingement by the wind on the blades. By implementing of necessary vibration dampers on the subsisting wind turbine, the vibration levels were cut down. The researcher used the ANSYS workbench modal analysis method to find out very crucial properties like natural frequencies, damping, and mode shapes.

Mathew *et al.,* (2018) and (Onah. et al., 2023), designed a composite windmill blade for which was used for static analysis and under similar loading conditions; the operation of different composite blade materials used were equated. Finite Element Analysis software was used to validate attributes such as strain, stress, and deformations. From the results generated, the researcher discovered that the blades that were formed of epoxy carbon and structural steel had experienced less distortion with less stress values but structural steel blades had shown uttermost variations. The researcher concluded the study by saying that epoxy carbon was a lot more suitable material for a windmill blade. Researchers did not study and analyze the properties inherent in the blade that was discussed based on static response using Finite Element Analysis ANSYS Model, hence the need for this study.

3 Materials and Methods

3.1 Materials

The materials that were used in this study include the geometry of the blade that was provided in the file "WindTurbineBlade.stp" downloaded from the wind turbine design model 2019 workbench file. It was manufactured from a composite material "**Epoxy E-Glass Wet**", but its material characteristics were found in the "Composite Materials" library of ANSYS Workbench "Engineering Data Sources". For the analysis types, the blade deformation was accounted for in the rotating frame of reference Fig. 1 based on the coordinate system attached to the blade that is revolving and the blade cross-section attached to the wind turbine hub. This rotating frame of reference was created to have a Z-axis coinciding with the blade rotation axis.

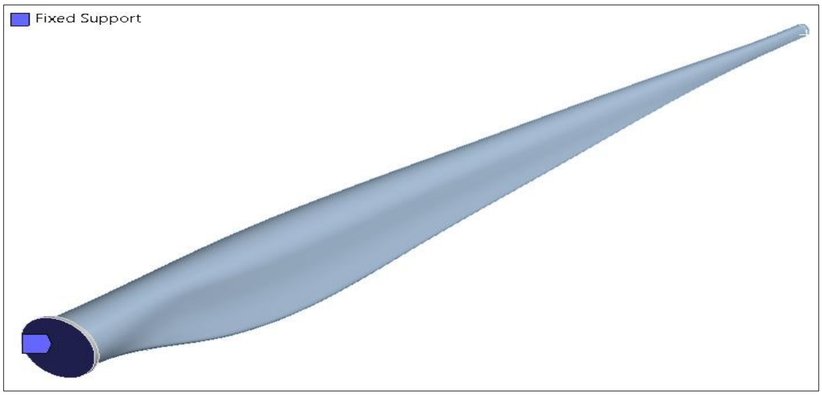


Figure 1 Displacement constraints for the wind turbine blade[30]

3.2 Procedure

Wind turbine blade that converts kinetic energy using wind to electrical power is to be examined in the following four (4) procedures in this particular study.

3.2.1 *The Static Analysis*

The static analysis involved the application of two loads by weight loads ascribable to the gravitation and centrifugal forces that occurred ascribable to the rotation of the blade around the wind turbine axis Z-axis with the rotation speed of 12 rpm. The blade orientations for vertical and also horizontal applications are shown in Figs. 2 and 3, with the positions of the gravitational acceleration of 9.81m/s^2.

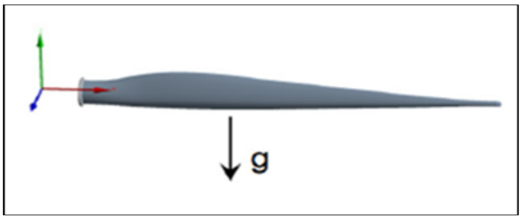


Figure 2 Horizontal oriented blade

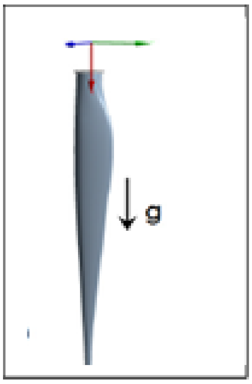


Figure 3 Vertical oriented blade

After that, total displacements and Von Mises stresses for these two orientations under action of only weight forces, with the blade not rotating and under action of the weight and centrifugal force are to be analyzed and compared.

3.3 Parameters and conditions

Table 1 shows the parameters and considerations of the analysis in the wind turbine blade

Table 1 Parameters and considerations of the analysis in the wind turbine blade

Type of analysis	Parameters and conditions	Values
Static	Rotation speed	.12rpm
	Gravitational acceleration	9.81m/s^2
Modal	First natural frequencies	6 Hz
	Centrifugal forces at the rotation speed	12 rpm.
	Rotation speed range	0 to 30 rpm
Harmonic	Amplitude of acceleration free- fall out.	9.81m/s^2
	Structural damping coefficient value	0.01.
	Frequency response curves	@ X, Y and Z components
Transient	Impulse force at the blade tip along Y-axis.	5000N
	Time interval with transient vibrations	0.1s
	Total interval transient vibration	5 s,
	Stiffness damping coefficient controlled ratio and frequency	0.02 ans 1.8Hz
	Time interval	0 to 5 s for Y and Z coordinates

3.4 Finite Elements and Material Properties

By way of the wind forces, impact forces of birds and other vibrations the blade is manufactured from a composite material “Epoxy E-Glass Wet” that can withstand these impacts. The procedure was done by importing the geometry from C:\Users\44730\OneDrive-WindTurbineBladeFiniteElements\AnsysProfile\Turbineblade_files\dp0\SYS-1\DM\SYS-1.agdb into Model (D4), the material was changed to Epoxy E-Glass Wet. Its coordinate was followed to mesh. The meshing was done under a static structure. The process was from static structural analysis to setting/sub-modeling/fixed support/ standard earth gravity/ rotational speed/ solution. The resolution then gave solution information/total deformation/equivalent stress.

3.5 Mesh independence

The number of elements that were chosen for the mesh independence that started from default element size of 2131.94 to 2000, 1800, 1600, 1400, 1200, 1000, 800, 600 and 400, respectively. These finest meshes for the convergences, based the maximal stress and convergence plot were conducted after meshing could not go further.

4 Results and discussion

4.1 Results of mesh convergence

The results of the two finest meshes that converged were presented in fig. 4 and 5. Besides fig.4 and Table 2 show the values and convergence at element sizes of 800 and 600. Hence mesh of fig. 4 of element size 800 was chosen for subsequent upon determinations of static analysis by application of weight loads ascribable to the gravitation and the centrifugal forces occurring by the rotation of the blade around the wind turbine axis for total and equivalent stress. Besides the results so obtained was later transferred to modal analysis by way of natural frequencies and pre-stressed loading of centrifugal forces at the rotation speed for its analysis. However, harmonic forced response analysis by the gravitational forces consideration and transient response analysis by impulse for loading at the blade tip along Y-axis over time interval were later carried out based on the parameters in Table 2.

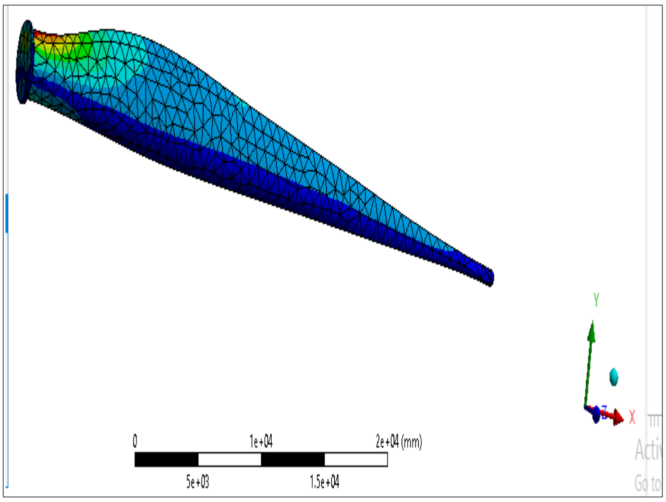


Figure 4 Mesh of 800-element size[30]

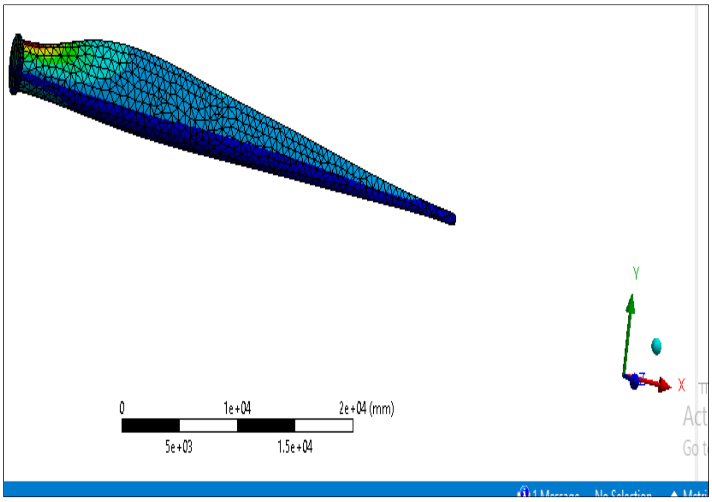


Figure 5 Mesh of 600 element size

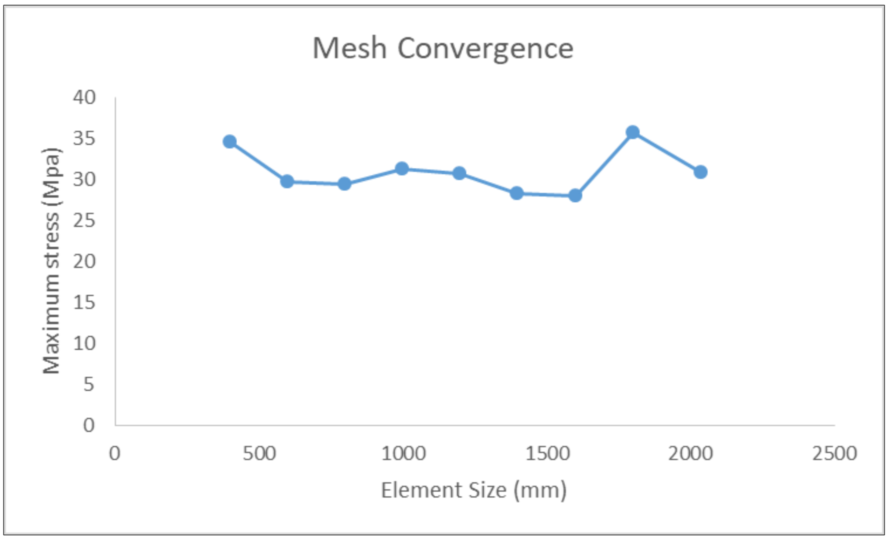
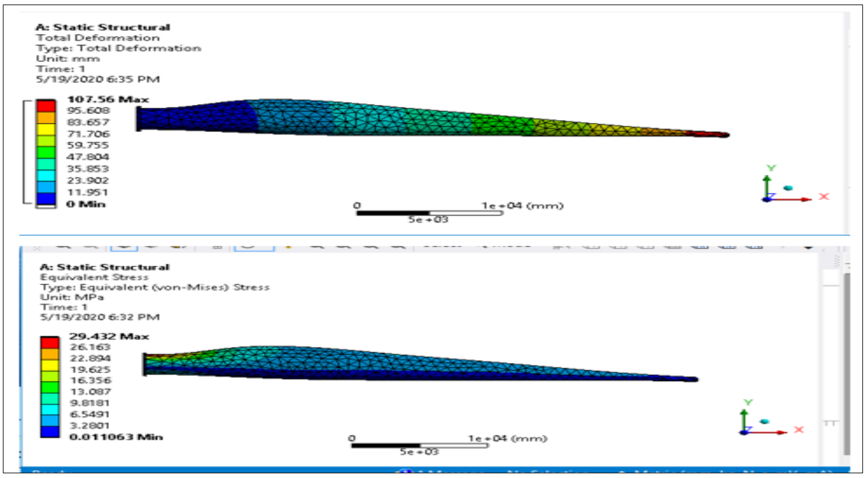


Figure 6 Mesh convergence

Table 2 Mesh sizes and maximum stresses

Mesh size (mm)	Maximum stress (Mpa)
2039.1	30.818
1800	35.623
1600	27.961
1400	28.271
1200	30.693
1000	31.313
800	29.432
600	29.641
400	34.482

4.2 Result of Static Analysis


A: Static Structural
Total Deformation
Type: Total Deformation
Unit: mm
Time: 1
5/19/2020 6:35 PM

A: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 1
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Figure 7 First position with rotational velocity of only gravitational load for orientation: (Total deformation and Von Mises Stress)

The generated results of the static analysis by way of first positions (horizontal blade) with rotational velocity for the total deformation and Von Mises Stress were shown in fig. 7 and without rotational speed in fig. 8, but figs.9 and 10 are the second positions (vertical blade), with and without rotational velocity for the total deformation and Von Mises Stress respectively.

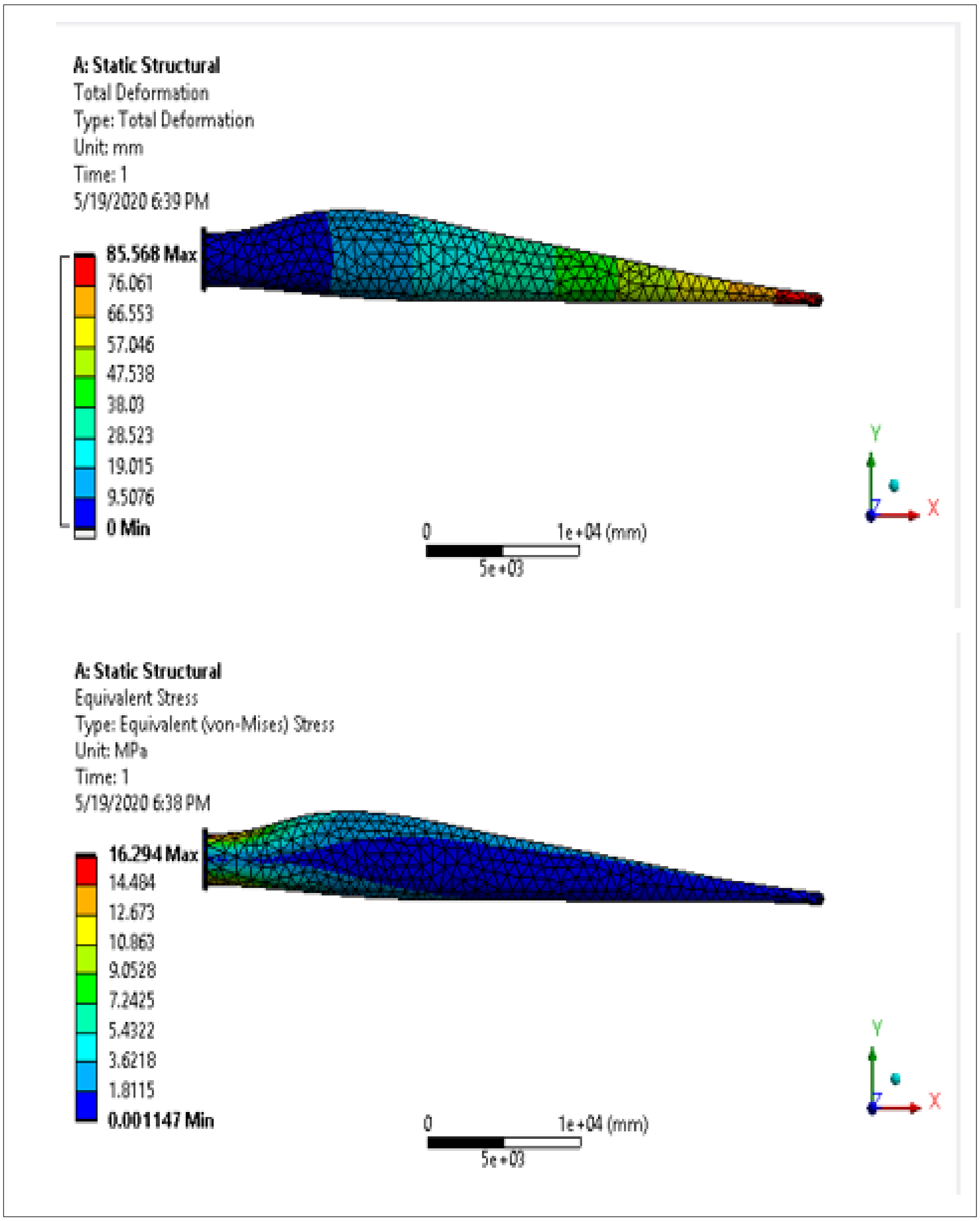

Figure 8 First position without rotational velocity of only gravitational load for orientation: (Total deformation and Von Mises Stress)

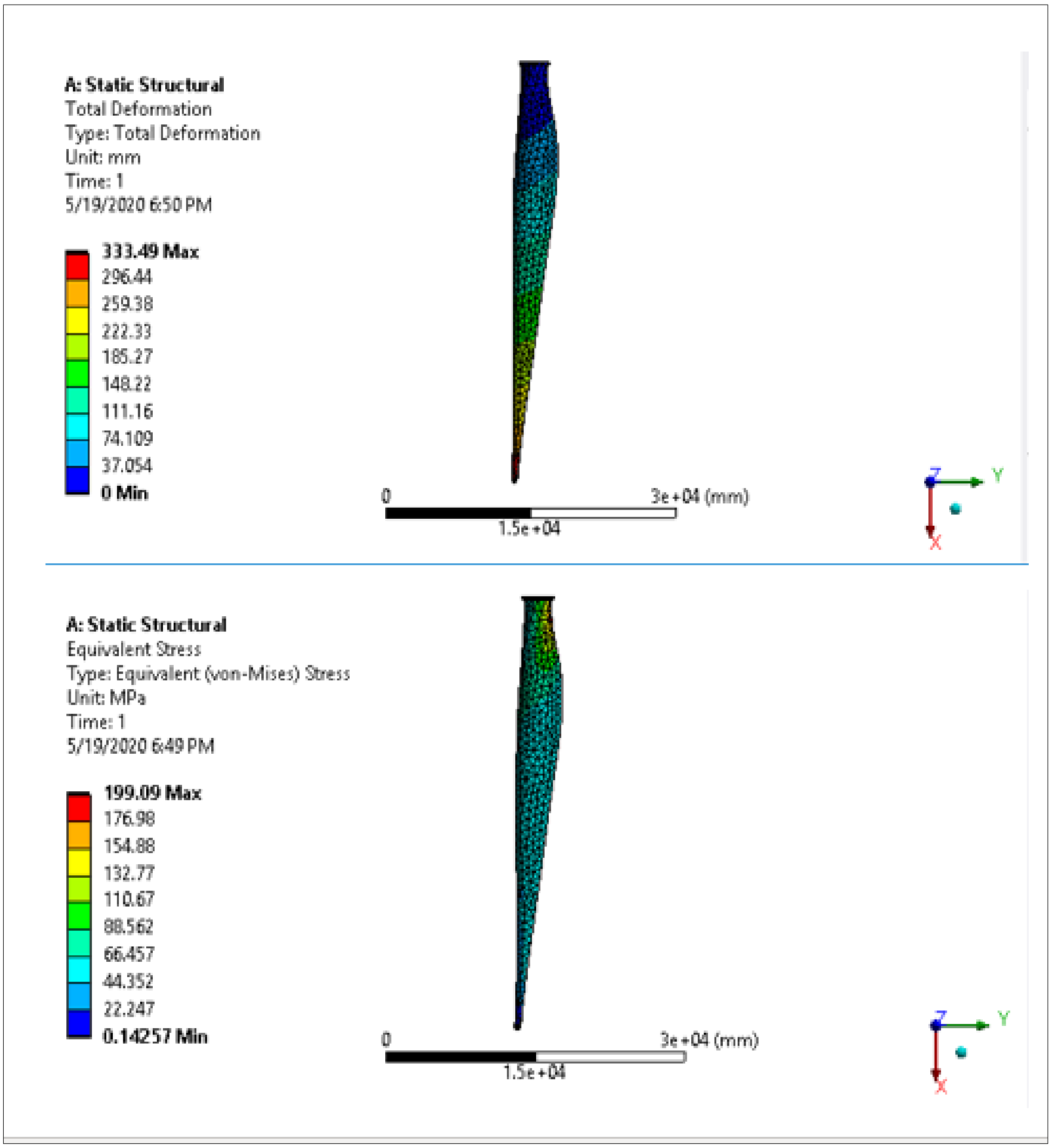

Figure 9 Second position with rotational velocity for centrifugal forces + gravitational load for orientation (Total deformation and Von Mises stress)

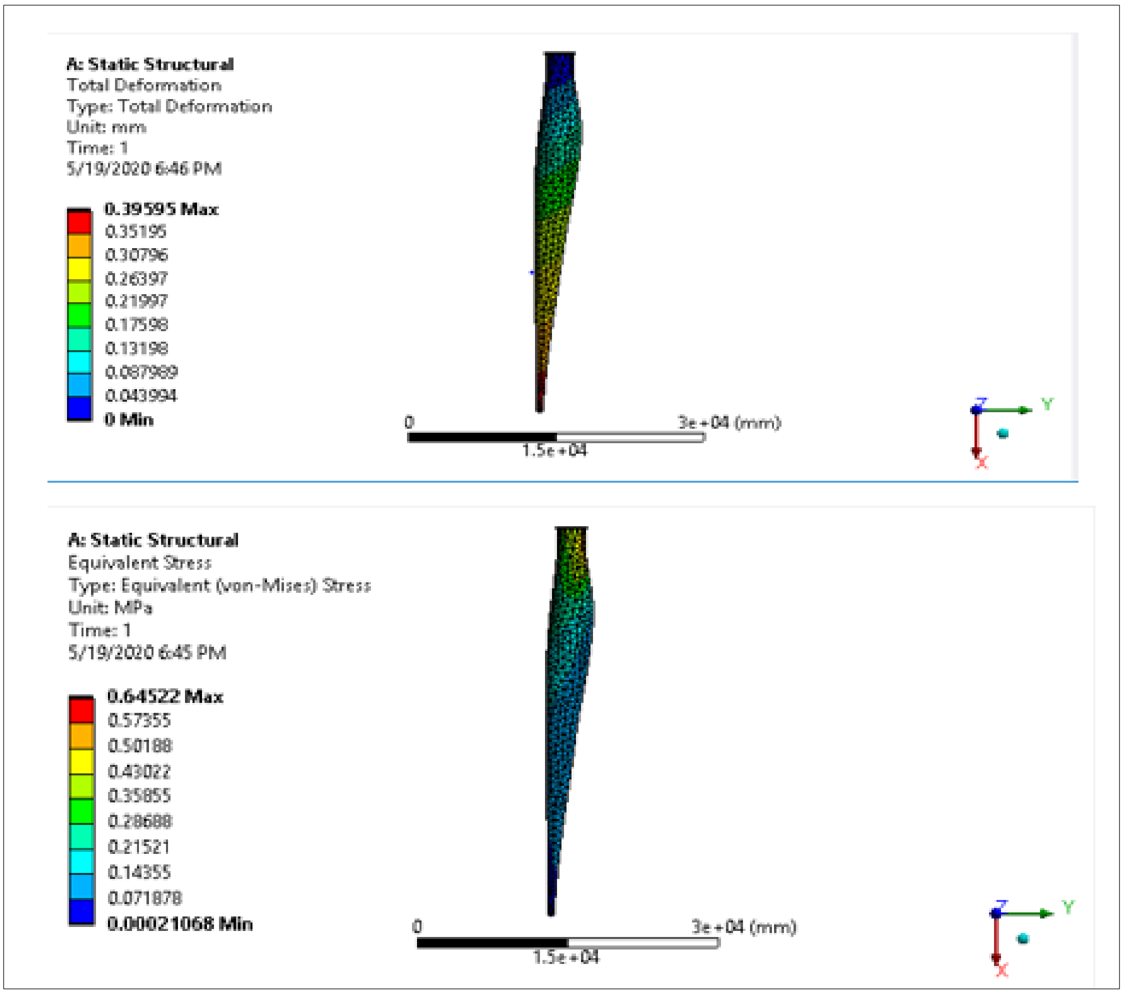

Figure 10 Second position without rotational velocity for centrifugal forces + gravitational load for orientation (Total deformation and Von Mises stress)

4.3 Findings based on static analysis.

At the first positions (horizontal blade), figs .7 and 8 show maximum total deformation and equivalent von Mises stresses of 107.56Mpa and 29.43Mpa with rotational velocity, but 85.56Mpa and 16.291Mpa without rotational velocity. Also figs. 9 and 10 at the second position (vertical blade), gave 333.49Mpa and 199.09Mpa at total deformation, and 0.39595Mpa and 0. 6452Mpa at equivalent von Mises stress.

Nevertheless, the total deformation in the horizontal direction showed 20% while the equivalent von Mises stress was 44.64%. In the vertical blade direction, the total deformation showed 40.09% while equivalent von Mises stress showed 38.61%, all calculated from Equs.4.1 to 4. 4 as;

$$\%\ \text{total deformation(Horizontal blade)} = \frac{107.56 - 29.43}{107.56} = 20\% \quad \dots\dots\ (4.1)$$

$$\%\ \text{Von mises stress(Horizontal blade)} = \frac{85.56 - 16.291}{85.56} = 44.64\% \quad \dots\dots.(4.2)$$

$$\%\ \text{total deformation(Vertical blade)} = \frac{333.49 - 199.09}{333.49} = 40.09\% \quad \dots\dots\dots.(4.3)$$

$$\%\ \text{Von mises stress(Vertical blade)} = \frac{0.6452 - 0.3959}{0.6452} = 38.61\% \quad \dots\dots\dots..(4.4)$$

Thus, the total deformation is better with vertical position at higher percentage of 40.09% than 20% at horizontal position. Thus, Wind turbine blade is better designed at vertical position to allow better deformation stress at static position. Conversely, the von Mises stress showed 44.64% and 38.61% at horizontal and vertical positions. This also agrees with static total deformation, since stress is better managed at lower percentage range. Consequently, static analysis proposes that both wind turbine blade total deformation and von Mises stress are improved at vertical position than horizontal position with 40.0% and 38.61%.

5 Conclusion

The mesh independence occurred at 800 and 600 element sizes and element size 800 was chosen for subsequent upon determinations of static analysis by application of weight loads ascribable to the gravitation and the centrifugal forces occurring by the revolution of the blade around the wind turbine axis for total and equivalent stress. Thus, the static analysis at the first positions (horizontal blade) gave maximum total deformation and equivalent von Mises stresses of 107.56Mpa and 29.43Mpa with rotational velocity, but 85.56Mpa and 16.291Mpa without rotational velocity. Also, at second position (vertical blade), 333.49Mpa and 199.09Mpa were obtained as total deformation, and 0.39595Mpa and 0. 6452Mpa as equivalent von Mises stress. At end, static analysis proposes that both wind turbine blade total deformation and von Mises stress are improved at vertical position than horizontal position with 40.0% and 38.61%.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that there are no conflicts of interest

Statement of ethical approval

Ethical clearance was not required at the analysis and optimization phase of engineering design model of improved dental chair design, hence, was unnecessary.

Author contribution

All authors contributed equally to this work.

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Data availability statement

The data that supports the findings of this study are available on request from corresponding author.

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