



STATIC STRUCTURAL ANALYSIS OF A DESIGNED WIND TURBINE MODEL

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Samuel, M., Muhammad, S. U., Solomon, W. C. and Japheth, G. C. (2022): Static Structural Analysis of a Designed Wind Turbine Model. *Journal of Engineering and Engineering Technology* /16(2), 97-106

Submission date: 02-07-2021

Accepted date: 22-04-2022

Abstract

A wind turbine is a machine which converts the power in the wind into electricity using the aerodynamic force of lift to rotate a shaft which in turn helps in the conversion of mechanical power to electricity by means of a generator. It is subjected to varying wind loads while in operation under different environmental conditions. In this paper, the structural analysis of a proposed model for scale assessment of 5 MW wind farm in Kaduna using Nigerian Defense Academy (NDA) as a case study was investigated. The design and assembly of the wind turbine components were done with the help of SolidWorks 2018 and the analyses were done in ANSYS 15.0 by constraining the model and applying equivalent environmental wind load on it. The designed turbine is made by different type of component materials such as i.e., cast alloy steel as the base, chromium stainless steel as the bearing, aluminum 2024 T361 as the blade, copper as the rotor; cast alloy steel as the housing, alloy steel as the tower and shaft. Alloy steel has a good strength but it contributes more weight to the turbine. The result showed that the maximum stress of the wind turbine structure is 33.80 MPa under maximum wind load of 120 N acting on the turbine which is lower than the yield strength of the turbine materials ranging from 241.28 MPa to 620.40 MPa. The tower, base and the blades are the most components of the system with the stress concentration.

Keyword: Wind load, turbine, deformation, model, structural analysis, design

Introduction

Energy has a major impact on every aspect of socio-economic life. It plays a vital role in the economic, social and political development of any nation especially in developing countries like Nigeria. Despite the abundance of energy resources in Nigeria, the country still battles with erratic supply of electricity from the national grid. Only about 40% of the nations of over 200 million people have access to grid electricity (Okedu *et al.*, 2015). There is, therefore, the need to harness renewable energy potentials (such as wind, solar etc.) to compliment the one supplied by the national grid.

Generally, wind is described as a natural phenomenon related to the movement of air masses caused primarily by the differential solar heating of the earth's surface (Aji *et al.*, 2015). Wind is a classic example of a stochastic variable; because of its stochastic nature, wind energy cannot be controlled, but can be managed. Thus, wind power is available only when the wind speed is above a certain threshold (Ohunakin, 2010). Methods to harvest renewable energy sources from the environment have been widely researched in recent years. Theoretically, they could be used to provide endless energy to drive large distributed, autonomous systems for various applications (Oyedepo, 2015).

A wind turbine is a machine which converts the power in the wind into electricity (Gizachew and Belete, 2019). It uses the aerodynamic force of lift to rotate a shaft which in turn is rotated in generator to generate electricity. This way the wind turbine generator converts the kinetic energy of the wind into mechanical energy and electrical energy through the generator. A wind turbine is made up of five main elements; the rotor made up of rotor blades that use aerodynamic lift to convert wind energy into mechanical energy, a rotor bearing fixed on a structure that causes a definite rotation of the rotor which converts aerodynamic wind energy into rotational shaft torque, a yaw system which maintains the horizontal rotor axis pointing upstream into the wind. In addition to the afore mentioned, the low rotational speed obtained from the turbine shaft is converted into the suitable shaft power to drive a generator in the power system as well as a tower and foundation structure to support the rotor and generator system at a height that produces the most amount of energy for an acceptable capital cost. Several factors are considered when designing wind turbine components, but most of them fall into two categories; mechanical (structural) and aerodynamics. However, the focus of this study is the structural analysis of the designed wind turbine.

Youness, (2009) examined the structural dynamics of a 5-kW vertical axis wind turbine through the use of finite element method. A finite element model of turbine was developed using the commercial software MSc Patran in order to define the mode shape and natural frequencies that will withstand the varying external loads over its lifespan. The Lagrangian method was used to establish the equation of motion for the system. The geometry of the turbine was partitioned into many groups so as to achieve good mesh for the finite element analysis. The investigation was also conducted analytically and the result compared with those obtained by the software. The obtained results revealed a significant agreement between those of the analytical method and software. It was concluded that the first Eigen frequencies determined were sufficient to design the turbine structure for dynamic loads. Zhang *et al.* (2013) investigated the reason for turbine shaft failure by conducting a series of experiments to determine the chemical composition and mechanical properties of the shaft. In addition, a theoretical calculation of equivalent stress at the shaft's conducted. The results of the investigation revealed that the cracks developed, developed easily under the influence of impact loads. Iov *et al.* (2002) reported on a novel simulation platform for modeling, optimizing, and designing wind turbines using Matlab/Simulink especially for the modelling dynamic loads. The study deployed the Matlab/Simulink develop an integrated simulation platform for wind turbine modeling, optimization, and design. The platform includes a HAWC, DIgSilent, and Saber. Mouhsine *et al.* (2018) worked on the aerodynamics and structural analysis of wind turbine blade and their ultimate objective was to increase the reliability of wind turbine blades through the development of the airfoil structure. They used airfoil sections of horizontal axis wind turbines in NREL phase 2 and phase 3 of S818, S825 and S862. Finite-element method (FEM), commercial arable software FLUENT were employed and for the calculation of the flow field, they used the Reynolds – average Nervier stokes (RANS) in conjunction with the K-omega shear stress transport (SSI). The grid and time step were optimized to reach independent solutions and they finally developed an accurate three dimensional horizontal – Axis wind turbine (HAWI) model which can be used to support wind tunnel experiments. Zemmouri *et al.* (2018) studied the static structural analysis of a pointed tip wind turbine blade using fluid structure interaction techniques (FSI). They carried out a static structural analysis using ANSYS at a 10 m/s wind speed, where they utilized National Renewable Energy laboratory (NREL) phase VI wind turbine blade dimension. The 10% of the blade span was changed from a standard tip shape to a pointed one, finite element structural analysis was done using aerodynamic force distribution as an input and the pressure distribution around the blade was obtained separately through computational fluid Dynamics (CFD) Simulations and applied as surface

load input for the structural analysis. It was successfully transferred from the fluid domain to structural one through an interface and mapping process. They finally obtained the deformation and equivalent stress distribution for both NREL original Shape and the pointed shape for comparison and concluded that the maximum deformation was more on the pointed tip blade but the equivalent stress difference was not significant. Ozdemir *et al.* (2017) carried out the static analysis of different type of wind turbine towers. They studied three different wind turbine towers (steel, reinforced concrete and hybrid) under the effect of static loads using finite element analysis with 10 m Height. ABAQUS was used for the analyses. They compared the deformations and stresses for the different types of towers and concluded that the reinforced concrete tower has the lowest displacement, the effect of torsion is dominant in steel and the hydric tower is venerable in connection to concrete and steel parts.

For decades, Nigeria has been be devilled by incessant and erratic power supple from the national grid. This is not unconnected with vandalization of gas pipelines, low water, generation and will transmission problems. In recent times, the supply has deuterated to a level that even the government in looking at the possible of taking over distribution companies arises the nation. Also, most of thermal generating plant used conventional source of fuel for powering the power plants. Therefore, if the use of renewable energy could be imbibed and subsequently integrating these sources of renewables into the national grid, to have an integrating energy mix system, this may lessen the burden placed on conventional fuels. Therefore, this paper presents the structural analysis of a proposed model for scale assessment of 5 MW wind farm in Kaduna using Nigerian Defense Academy (NDA) as a case study.

Materials and Methods

The monthly mean wind speed data used for this work was obtained from Nigeria Meteorological Agency (NiMet) Abuja specifically for Afaka, were the permanent site of the Nigerian Defence Academy Kaduna is located. The acquired data was for a period of twelve (12) years, from 2009 to 2020.

i. Design Consideration

The design of the wind turbine in this study was based on the following considerations:

- i. Annual average wind speed of NDA Afaka, Kaduna.
- ii. A blade profile that captures highly efficient wind energy.
- iii. Material selection for light weight, fatigue resistance, wears resistance, and availability.
- iv. A machine with a low beginning torque and a high speed that is suited for generating electricity.

- v. Blade count for dynamic stability and cost reduction.
- vi. Horizontal axis, lift-based, upwind, onshore, gearless wind turbine.

Figure 1 presents the flow chart of the design process. It shows the design, analysis and implementation strategies adopted in this work. After

initiating the design model concept of the turbine, a 3D modelling of the turbine was carried out using solid works. This was followed by mechanical and aerodynamic designs for the monthly mean wind speed obtained from analyzed NiMet data and finally, the structural analysis of the modeled turbine was conducted on ANSYS software.

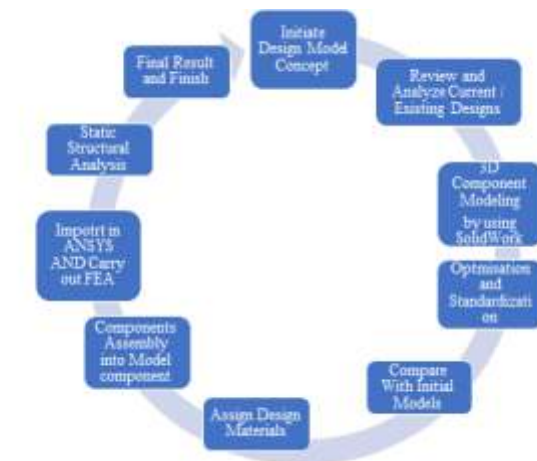


Figure1: The Model Design and Analysis Implementation Strategy

i. The Wind Turbine Model

Figure 2 shows the CAD model of the wind turbine developed using SolidWorks and ANSYS software

package. The study is only focused on the performance of the model under static structural loading.



Figure 2: The Wind Turbine Model

i. Finite Element Analysis (FEA)

Finite Element Analysis FEA provide solutions to problems through mesh operations which represents a discrete representation of geometry that is involved in the problems. It partitions a space into elements (or cells or zones) over which the analysis solution can be approximated. The FEA of the wind turbine was

imported into the ANSYS static structural schematic window. Automatic generated mesh was used. The elements order and sizes were specially set to program controlled and default respectively. This smart controlled mesh approach generated a fine mesh since the wind turbine geometry is complex. Figure 3 shows the meshed model.

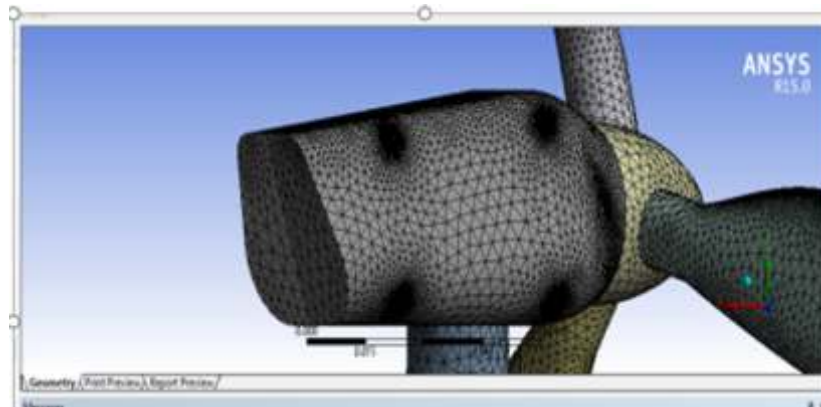


Figure 3: The Model Meshing

i. **Governing Equations**

- i. **Wind Loading:** This load act on the turbine due to the inertia of the moving parts. The inertia load can be found out using Equation (1), (Schmitz, 2019).

Wind Load (P)

$$P = mR\omega^2 \left(\cos\theta + \frac{\cos(2\theta)}{n} \right) \quad (1)$$

where; $n = L/R$, is the rotational wind speed, R is the blade position from rotor tip, L is the length of the blade and θ is the angle of attack.

v. Stress Due to Wind Speed Loads; The force of wind resistance per unit area, offered by a body against deformation is known as stress. This is given by Equation (2), (Schmitz, 2019)

$$\text{Stress}(\sigma) = P/A \quad (2)$$

vi. Material selection of wind turbine components

The designed turbine is made by different type of component materials such as i.e., cast alloy steel as the base, chromium stainless steel as the bearing, aluminum 2024 T361 as the blade, copper as the rotor, cast alloy steel as the housing, alloy steel as the tower and shaft. Alloy steel has a good strength but it contributes more weight to the turbine. Steel is one of the most widely used materials in wind turbine fabrication. Steel is used for many structural components including the tower, base, hub, main frame, shafts, gears and gear cases, fasteners as well as the reinforcing in concrete (Manwell et al., 2009).

Therefore, the materials selected in this study for the wind turbine components were based on their properties. Presented in the Figure 4 are the materials.

Model Type:	Linear Elastic Isotropic	
Units:	SI - N/m ² (Pa)	
Category:	Steel	
Name:	Alloy Steel	
Description:		
Source:		
Sustainability:	Defined	

Property	Value	Units
Elastic Modulus	2.1e+011	N/m ²
Poissons Ratio	0.28	N/A
Shear Modulus	7.9e+010	N/m ²
Density	7700	kg/m ³
Tensile Strength	723825600	N/m ²
Compressive Strength in X		N/m ²
Yield Strength	620422000	N/m ²
Thermal Expansion Coefficient	1.3e-005	/K
Thermal Conductivity	50	W/(m.K)
Specific Heat	460	J/(kg.K)

Model Type:

Units:

Category:

Name:

Description:

Source:

Sustainability:

Property	Value	Units
Poisson's ratio	0.28	N/A
Shear modulus	79000	N/mm ²
Mass density	7700	kg/m ³
Tensile strength	723.83	N/mm ²
Compressive Strength in X		N/mm ²
Yield strength	620.42	N/mm ²
Thermal expansion coefficient	1.3e-005	/K
Thermal conductivity	50	W/(m·K)
Specific heat	460	J/(kg·K)
Material Damping Ratio		N/A

Model Type:

Units:

Category:

Name:

Description:

Source:

Sustainability:

Property	Value	Units
Elastic Modulus	190000	N/mm ²
Poissons Ratio	0.26	N/A
Shear Modulus	78000	N/mm ²
Density	7300	kg/m ³
Tensile Strength	448.08	N/mm ²
Compressive Strength in X		N/mm ²
Yield Strength	241.28	N/mm ²
Thermal Expansion Coefficient	1.5e-005	/K
Thermal Conductivity	38	W/(m·K)
Specific Heat	440	J/(kg·K)

Model Type:	Linear Elastic Isotropic	
Units:	SI - N/m ² (Pa)	
Category:	Aluminium Alloys	
Name:	2024-T361	
Description:		
Source:		
Sustainability:	Defined	

Property	Value	Units
Elastic Modulus	7.24e+010	N/m ²
Poissons Ratio	0.33	N/A
Shear Modulus	2.8e+010	N/m ²
Density	2780	kg/m ³
Tensile Strength	495000000	N/m ²
Compressive Strength in X		N/m ²
Yield Strength	395000000	N/m ²
Thermal Expansion Coefficient	2.32e-005	/K
Thermal Conductivity	120	W/(m·K)
Specific Heat	875	J/(kg·K)

Figure 4: Material Properties of Alloy Steel, Cast Steel and Aluminum alloy

Results and Discussion

The various results comprising of wind force loading, equivalent von-Mises stress, deformations and equivalent elastic strain were evaluated. The simulation results are shown in Figures 5–9.

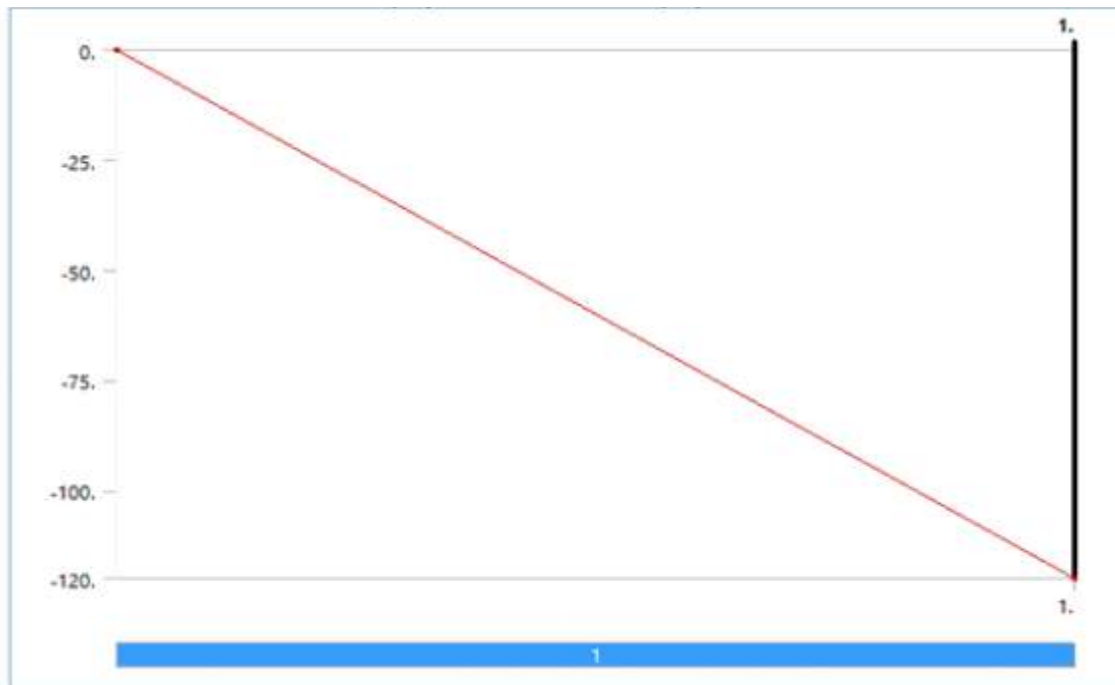


Figure 5: Loading Forces Acting on the Wind Turbine (120 N maximum)

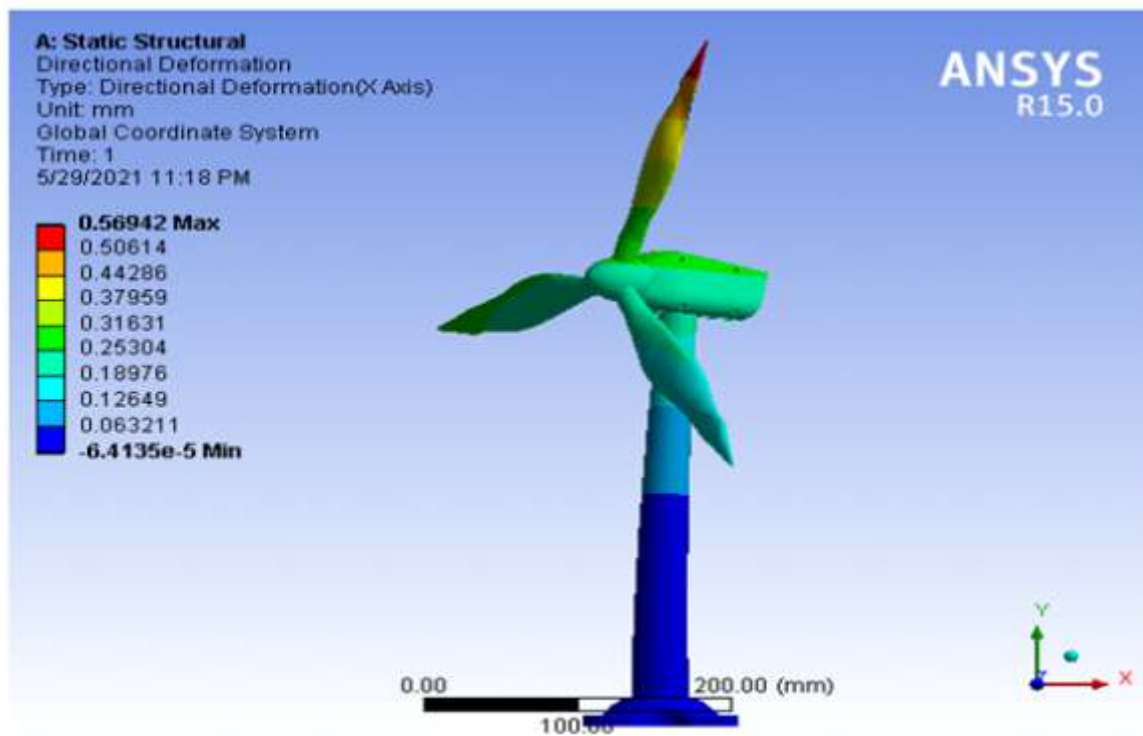


Figure 6: Directional Deformation of the Wind Turbine

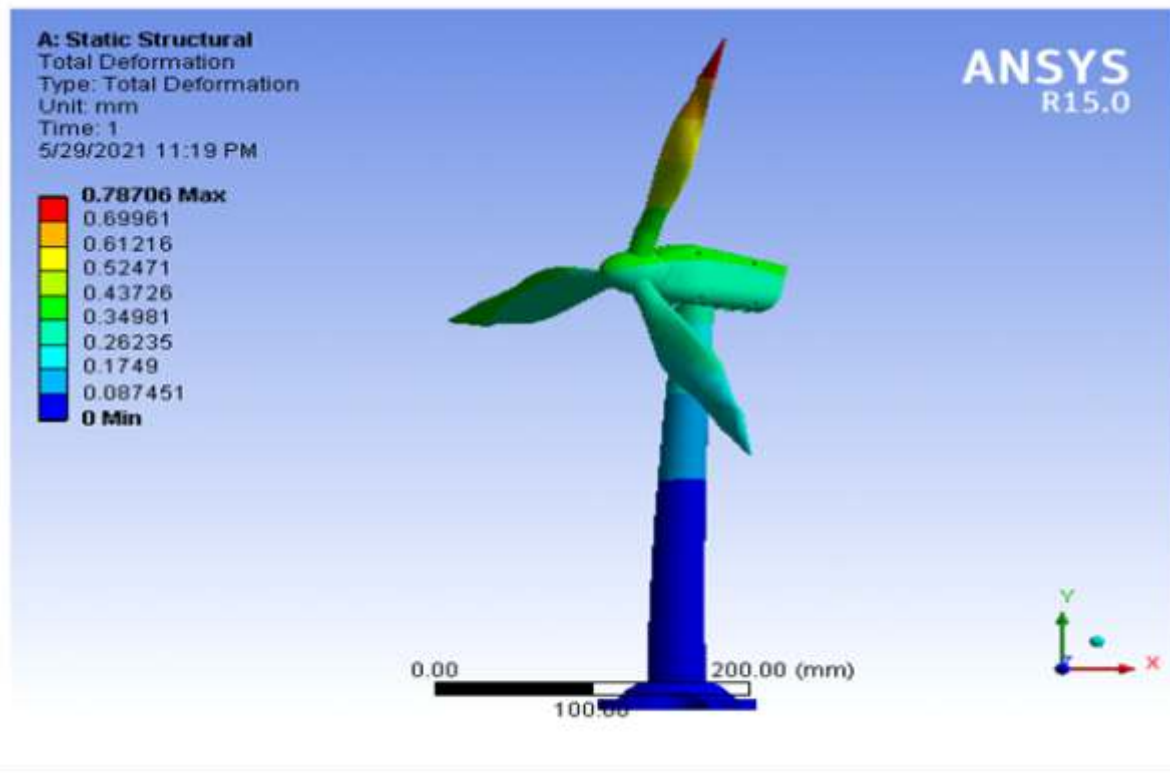


Figure 7: Total Deformation of the Wind Turbine Model

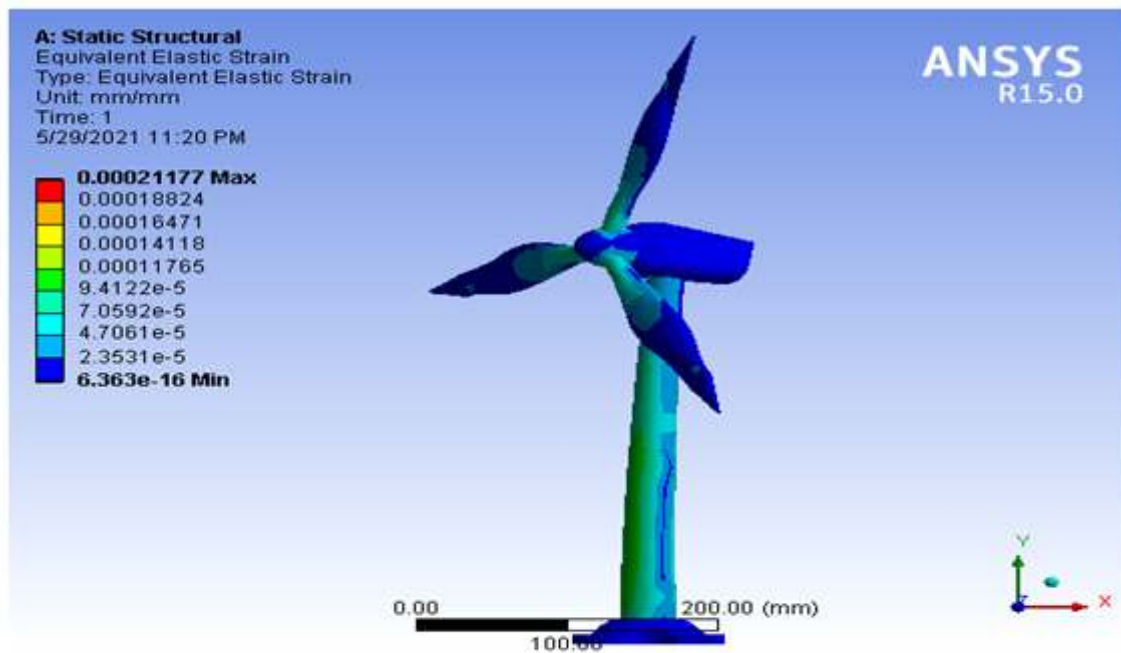


Figure 8: Equivalent Elastic Strain of the Wind Turbine Model

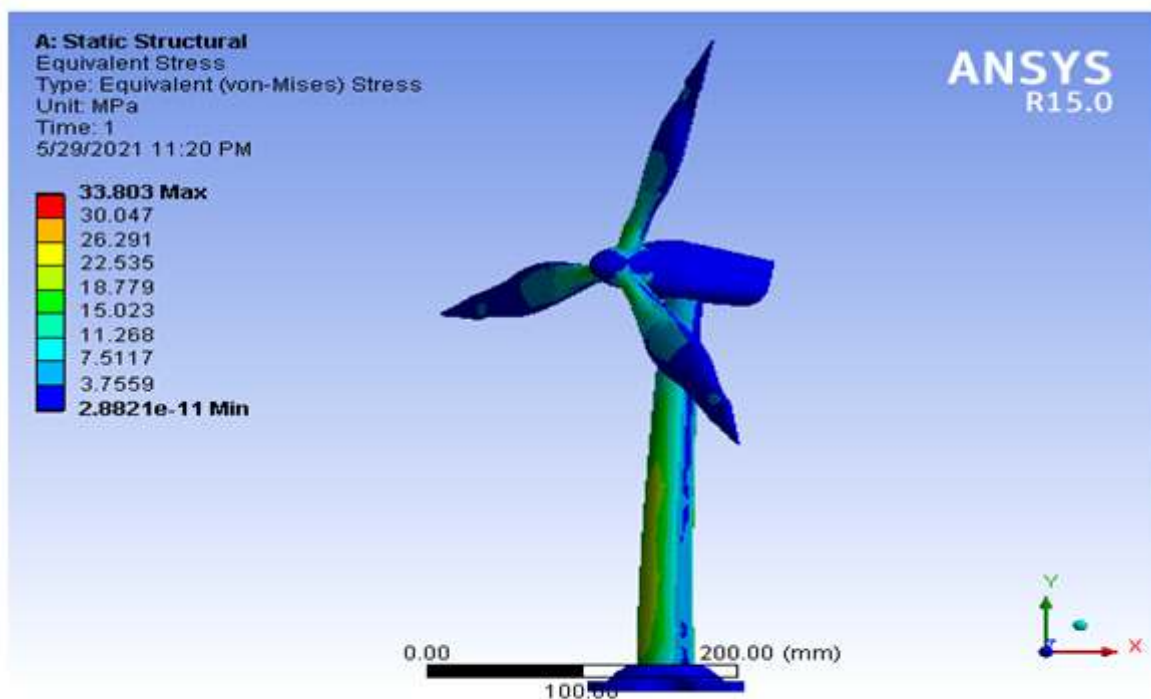


Figure 9: Equivalent (von-Mises) Stress of the Wind Turbine Model

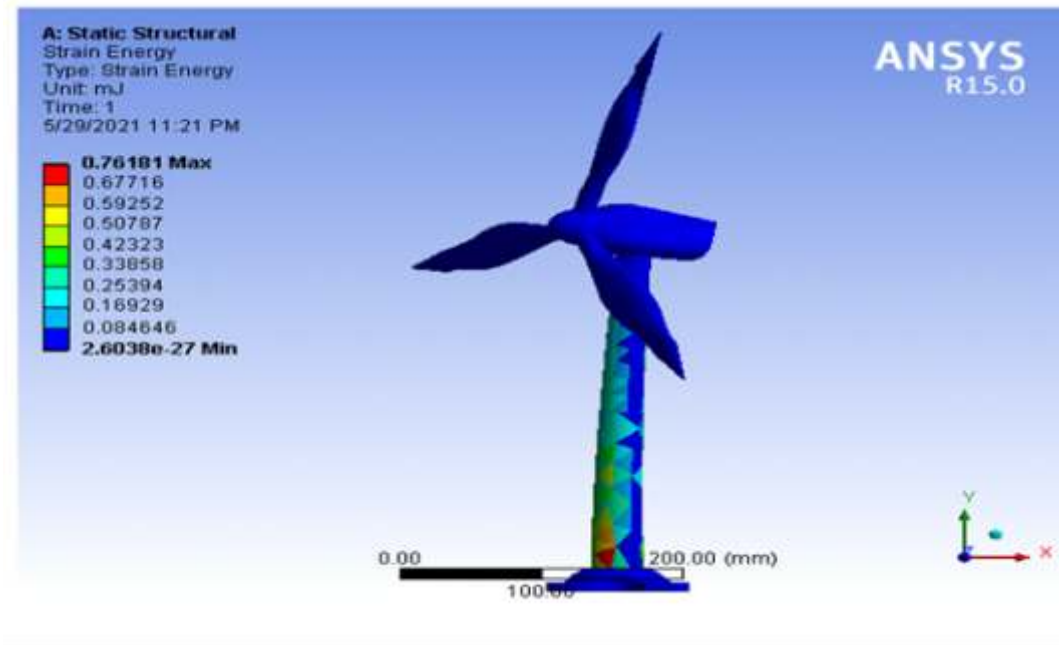


Figure 10: Strain Energy of the Wind Turbine Model

The materials used for each of the components are shown in the Figure. The simulation results revealed a slight change in total deformation of the turbine blade. It experienced the highest static stress at the base and tower components of the wind turbine. However, the maximum static stress was found to be less than the yield strength of the materials which shows that it is unlikely that plastic deformation will take place, considering that the maximum static stress 33.80 MPa is less than the yield strength of the turbine materials ranging from 24.28 to 620.40 MPa. Therefore, even after taking into consideration the presence of non-homogeneity in material properties the wind turbine will withstand the static wind loads and therefore good for application within the NDA environmental limits of wind speed specified in the NiMet data. Also, after putting weight and manufacturability into consideration, the simulation results still suggest adequate ability to withstand static wind loads in service with very low possibility of failure.

Conclusion

A wind turbine for the proposed Nigerian Defence Academy Wind Farm has been modelled using SolidWorks software and the structural analysis done using ANSYS software. The following conclusion can be drawn from the results:

- The maximum total deformation is located at the blade of the turbine due to wind loading.
- Maximum stress concentrations were found at the model base and tower area but these are still below the yield stress of the base and tower materials as expressed in Figure 4
- The model is therefore found suitable for

application within the specified NDA environmental wind speed limits.

Acknowledgement

The Department of Mechanical Engineering, Nigeria Defence Academy is acknowledged, Nigerian Metrological Agency (NiMet) and all the authors cited in this work. We are grateful

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