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OPTIMAL DESIGN AND STRESS/STRAIN ANALYSIS OF WIND TURBINE BLADE FOR OPTIMUM PERFORMANCE IN ENERGY GENERATION VIA SIMULATION APPROACH

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ABSTRACT

The blade is a significant part of a wind turbine, due to its role in the conversion process of the wind energy into mechanical energy. The blade during operation is being acted upon by different forces and pressures on high humidity, which gives rise to a high rate of failure of the blade. There is a great need to study these forces and constraints on the design shape of the material blade via a simulation approach. This research focusses on the optimal design and stress/strain analysis of a wind turbine blade for sustainable power generation. This is to enable the manufacturer and end-users of the wind turbine blade to understand how the blade material withstand the forces and pressures acting on the blade during operation in the form of displacement, stress, and strain in high humidity. The design and simulation software employed in this study is Solid Works Visualize 2018. The wind turbine blade is made of AL6061 alloy material. The blade is simulated under two forces, 1 N and 5 N, with the pressure at zero degree. The result from this analysis shows the maximum stress that causes the blade to experience failure during operation, and this failure occurs at 285.377 N/m^2 and 1426.83 N/m^2, respectively. The result from the simulation analysis shows the specific area were the deformation process, and possible failure will occur on the blades. This paper also gives reasonable suggestion for reinforcement of the wind blade during the maintainer's section, which can be applied to achieve optimum performance of the wind turbine blade.

KEYWORDS: Optimal Design, Wind Turbine Blade, Simulation & Deformation Process

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Original Article

1. INTRODUCTION

Design analysis is one of the significant steps that must be put in place during the production of any mechanical component. The Optimal designs are design methodology employed to carry out the practical design of mechanical components with specific statistical measurement. In this case study, the optimal design is applied to design a wind turbine blade. Considering the environmental situation of the low wind speed region during the energy generation is very significant. And the wind energy conversion to electricity has been proven to be environmentally friendly and free from pollutions [1]. El Mouhsine et al. [2] study the aerodynamics analysis of wind turbine blade employing the element momentum method, considering the twist angle and the chord length. The Matlab software and Reynold Average Navier Stroke (RANS) were used to analyse the data obtained from the lift and drag simulation coefficients and fluid flow of the aerofoil unit. The developed model for the aerodynamic wind blade was employed to optimize the grid and the stepping time of the operations. Schubel and Crossley [3] carried out a review describing the principles of design of wind blade with the various gravitational, centrifugal, and gyroscopic force acting on the edge during operations.

Wang et al. [4] used the finite element analysis (FEM) to develop a model to analyse the power generation from the wind. The three-dimensional model was established using parameters from geometrical analysis and parameters from the aerofoil procedure. From the study, the authors discovered that the simulation process of the model is very significant as it helps to illustrate the displacement of the fluid flow on the blade. The performance rating of a wind turbine is strongly dependent on the structural characteristics of the wind blade, the relationship between the blade and the rotor. The optimization of the coefficient of the blade power and the rotor power will lead to an economical, proficient design of the wind blade [5-6]. Every mechanical component has a life span or duration for performance characterization, which creates the need for constant assessment of the blade and all engineering materials [7]. Okokpujie et al. [8] design a 0.5 kW capacity wind turbine for a low wind speed region and the wind turbine was able to generate the specific power. From the design study, the wind turbine was able to perform as design because of the application of the aerofoil shape of the wind blade. However, the design has some challenges during the operation of the wind turbine, which, as a result of the lack of simulation analysis of the stress/strain displacement factors [9-11].

Nada and Al-Shahrani [12] researched the shape of a small wind turbine blade optimization. The study employed the flexible multibody approach, and a logical approach is formed based on a floating frame of position preparation. That includes the dynamics of the bendable blades as well as the aerodynamic loads, as shown in Figure 1. Based on a flexible multibody approach, a technique of aerofoil shape optimization was carried out for low-speed wind turbines blades. The authors concluded that at low tip-speed ratio, the adaptation of inversely tapered edges could enhance the aero-dynamical performance of the turbines.

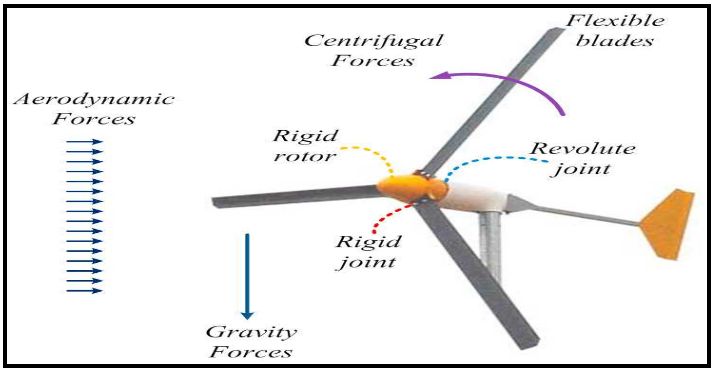


Figure 1: The Multi-Body System showing the Load Analysis on a Small Scale Wind Turbine [12]

Hosseini and Moetakef-Imani [13] design the horizontal wind turbine blades using computer-aided design. The design was split into two parts the structural and the aerodynamic surface, and this is to ensure excellent compatibility of the system curves. The importing functionality of the IGES standard compared with commercial CAD and FE software shows an outstanding performance of the innovative approach. And the authors recommended that this method should be employed for MW wind turbine blades designs

The deformation process of the wind blade is one of the critical aspects that need to be put into consideration [14]. Blades deformation occurs due to the forces and pressures the blade encountered during operations. The interaction between the surrounding air and the wind turbine blades is scribed by the fluid-structure interaction (FSI), which is employed to meshed the analysis together to form the model [15-18]. This process will also affect the engineering materials of the wind turbine blades during operations [19-21]. However, one significant way to study the deformation process of a wind turbine blade is to analysis the displacement, stress, and strain of the various force acting on the blade, which is the major focus of this study. This study employs the optimal design method to design the blade and carry out the deformation analysis via solid work software to understand the effects of the forces acting on the blade.

2. DESIGN METHODOLOGY

The optimal design of the AL6061 alloy wind turbine blade in this study is divided into three sections, such as the tip speed ratio, the aerodynamic shape, and performance efficiency. The power derived from the wind is given in equation (1). And the tip speed ratio, which defines the relative velocity of the wind and the velocity of the blade is also presented in equation (2).

$$P = \frac{1}{2}\rho A V^3 \quad (1)$$

$$\lambda = \frac{\Omega r}{V_w} \quad (2)$$

Where, V= air velocity, A= swept area, ρ = air density, $\lambda = tip\ speed\ ratio$, Ω = rotational velocity (m/s), $r = radius$, V_w = wind speed.

The analysis of the force acting on the aerodynamic shape of the blade from the profile point of view is shown in Figure 2.

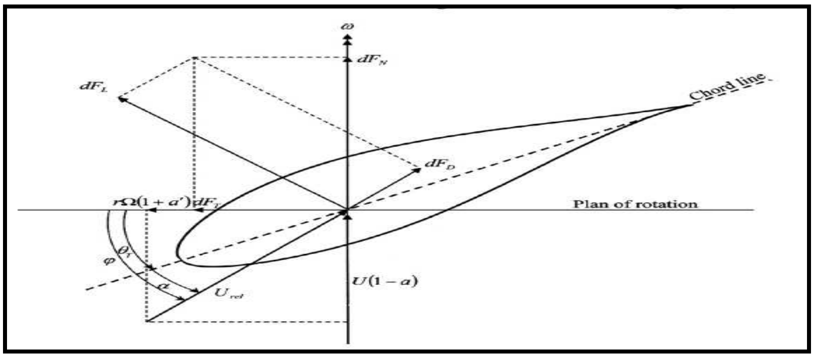


Figure 2: The Analysis of the Forces Acting on the Wind Turbine Blade via the Wind Speed

In order to design the proper shape of the wind turbine blade, the Betz method is used, which is given in equation (3) and (4). The power analyses the performance of the aerodynamic lift it yields during the generation process and is shown in equation (5) base on the drag and lift ratio.

$$C_{OPT} = \frac{2\pi r}{n}\frac{8}{9C_L}\frac{U_{wd}}{\lambda V_r} \quad (3)$$

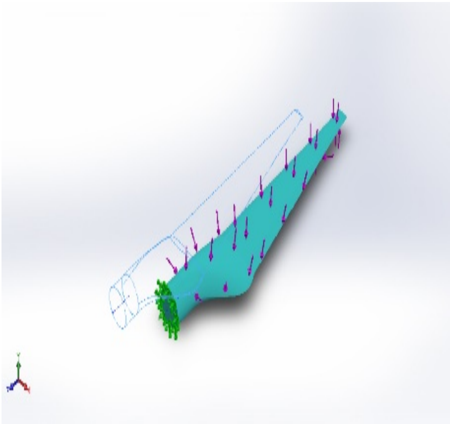
Knowing that: $V_r = \sqrt{{V_W}^2 + U^2}$ (4)

Where $r = radius\ (m)$, n = Blade Quantity, $C_L = Lift\ coefficient, \lambda = Local\ tip\ speed\ ratio,\ V_r = Local\ resultant\ air\ velocity\ (\frac{m}{s})$, U = wind speed (m/s), $U_{wd} = Design\ wind\ speed\ \left(\frac{m}{s}\right) C_{opt} = Optimum\ chord\ length$

$$\text{Lift to drag ratio} = \frac{Coefficient\ of\ lift}{coefficient\ of\ drag} = \frac{C_L}{C_d} \quad (5)$$

The optimal design was used to determine the design parameters of the wind blade. Which includes the length of the blade of 2 m, the total length of the entire model is 2.76 m, the area of the blade 1.2 m, and the design perimeter is 1.27 m. Table 1 shows the volumetric and the material property of the AL6061 alloy used for this research. Table 2 gives the mass property of the design of the wind turbine blade analysis, and Figure 3 shows the various view for proper interpretation of the wind turbine blade.

Table 1: The Volumetric Material Properties of the AL 6061 Alloy Employed for the Simulation Study.

Blade Reference	Properties		Components
	Material:	6061 Alloy	Solid-Body 1(Boss-Extrude1)(HAWT BLADE)
	Simulation type:	Linear Flexible Isotropic	
	Yield strength:	5.61485e+007 N/m^2	
	Tensile strength:	1.2484e+008 N/m^2	
	Adaptable modulus:	6.9e+010 N/m^2	
	Poisson's ratio:	0.33	
	Density of the material:	2700 kg/m^3	
	Volume	0.0509958 m^3	
	Shear modulus:	2.6e+010 N/m^2	
	Weight	1349.35 N	
	Thermal coefficient:	2.4e-005 /Kelvin	
	Mass	137.689 kg	

The Design Mass Property for the Assembly

Configuration: Default

Coordinate systems: ---default

Mass = 137688.67 grams

Volume = 50995803.06 cubic millimeters

Surface area = 2049264.54 square millimeters

Center of mass: millimeters

X = 999,48

Y = 1476.25

Z = 2797.90

The principal axes of the inertia and moments of inertia: (grams*square millimeter) of the design of the wind turbine blade are express below.

Taken at the center of mass

Ix = (0.00, 0.00, 1.00) Px = 1770269738.96

Iy = (1.00, 0.02, 0.00) Py = 41498114138.54

Iz = (-0.02, 1.00, 0.00) Pz = 42796165149.01

Moments of inertia: (grams*square millimeter),

Taken at the center of mass and aligned with the output coordinate system of the design.

Lxx = 41498106046.35 Lxy = 20701743.55 Lxz = 117064077.96

Lyx = 20701743.55 Lyy = 42795708985.38 Lyz = -70023098.88

Lzx = 117064077.96 Lzy = -70023098.88 Lzz = 1770733994.78

Moments of inertia: (grams*square millimeter)

Taken at the output coordinate system.

Ixx = 1419422618924.34 Ixy = 203177765539.65 Ixz = 385154816648.52

Iyx = 203177765539.65 Iyy = 1258198207373.43 Iyz = 568638702874.96

Izx = 385154816648.52 Izy = 568638702874.98 Izz = 439383091538.45

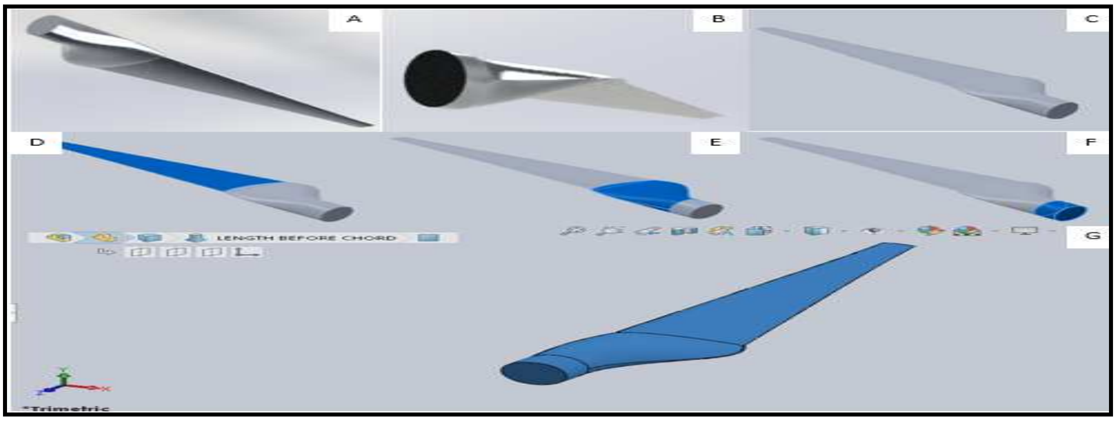


Figure 3: Shows the Different views of the AL6061 Alloy Wind Turbine Blade with some Selected Part. (a) The 3D Rendered View, (b) Bottom/Hallow View, (c) The Front View, (d) The Length of the Blade before the Chord, (e) Blade Chord, (f) The Extruded Hub, (g) The Complete Section of the Blade

3. RESULT AND DISCUSSIONS

The simulation analysis is carried out on two forces applied, such as 1 N and 5 N, and the resultant force for 1N and the 5 N is displayed in Table 2a-2c. Having a reaction moments of zero N/m. Table 3 and Figure 4 shows the mesh information and the model of the wind turbine blade.

Table 2a: Loads and Fixtures of the Simulation Analysis

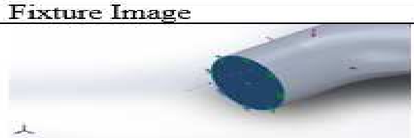
Fixture name	Fixture Image	Fixture Details	
Fixed-1		Entities	1 face(s)
		Type	Fixed Geometry

Table 2b: Resultant Forces for 1 N

Components	X	Y	Z	Resultant
Reaction force(N)	-0.0115309	0.873136	-0.0529517	0.874816
Reaction Moment(N/m)	0	0	0	0

Table 2c: Resultant Forces for 5 N

Components	X	Y	Z	Resultant
Reaction force(N)	-0.0573635	4.36583	-0.264575	4.37422
Reaction Moment(N/m)	0	0	0	0

Table 3: Presenting the Mesh Information in Details

Total Nodes	15915
Total Components	9045
Maximum Characteristic Ratio	1797.8

% of components with Aspect Ratio < 3	79.3
% of components with Aspect Ratio > 10	9.21
% of inaccurate components(Jacobian)	0
Time to complete mesh (hh;mm;ss):	00:00:02
Tolerance:	0.00185432 m
Component Size:	0.0370863 m
Mesh Superiority:	High
Jacobian points:	4 Points

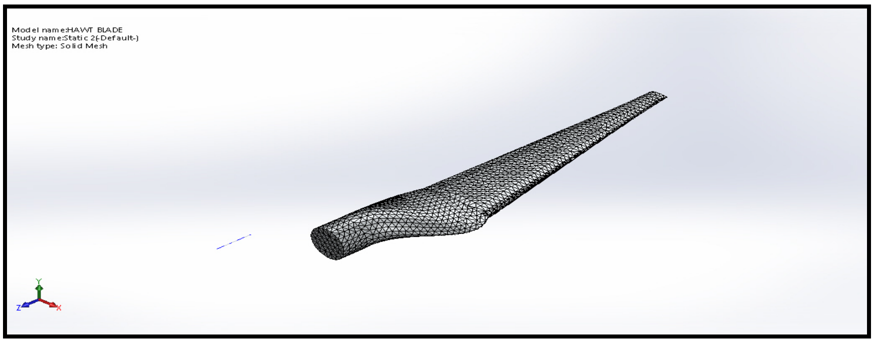
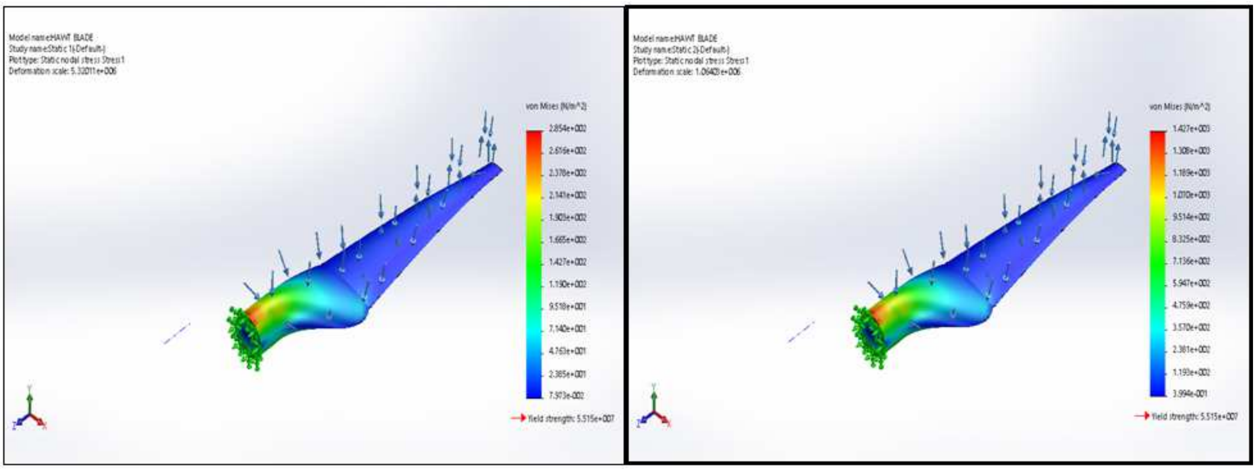


Figure 4: The Model of the Wind Turbine Blade

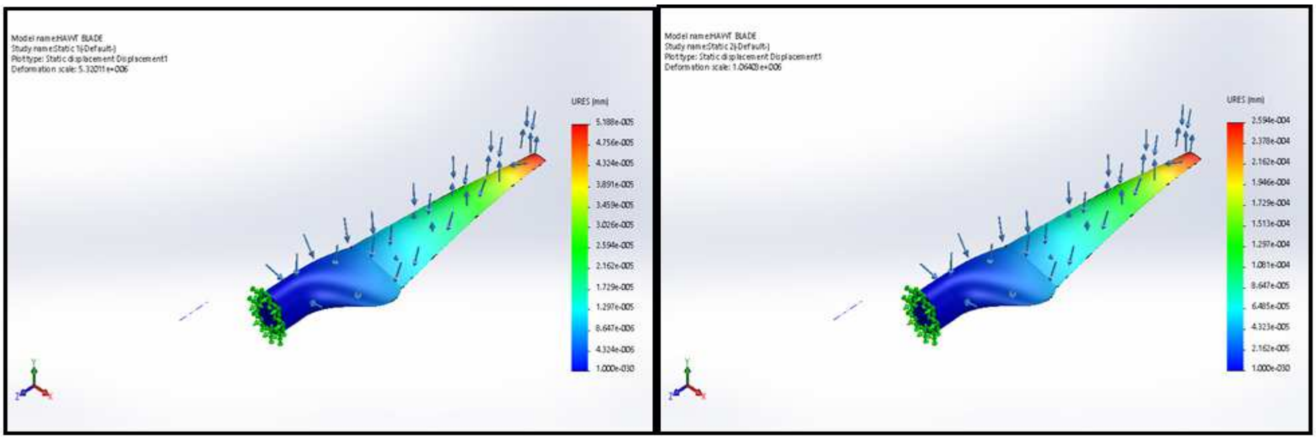
Figure 5 shows the analysis of the stress via the simulation approach. The stress effect of the 1 N and 5 N loads applied on the wind blade, it can be seen that the maximum stress of 285.377 N/m^2 occurs at the root of the wind blade. This has proven that the thermal and mechanical load affects the wind turbine blade during its operations. Figure 6 also presents the displacement analysis. From the result, the maximum displacement for the 1 N force applied is 0.0000518 mm and 0.000259 mm for the 5 N, which occurs at the tip of the wind blade. The displacement analysis is very significant in wind blade analysis due to the high humidity experienced by the wind blade during operations.

From this analysis, it can be noted that as the forces and pressures increase, the failure rate of the blade increases. The wind blade design must be carried out with caution and with high safety of factor. The model most considered the environmental conditions of the site where the wind turbine will be installed and also with suitable materials.



(a) **(b)**

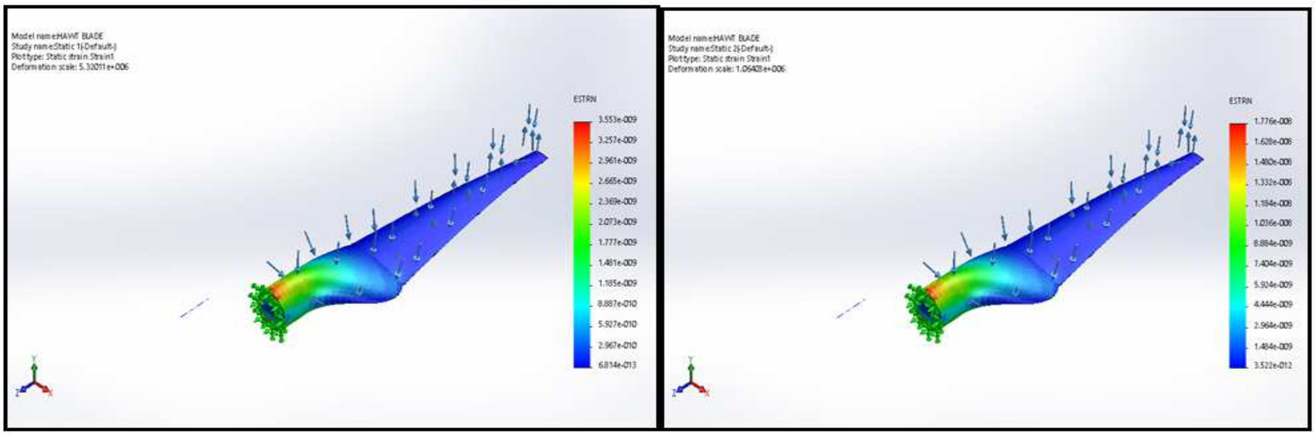
Figure 5: The Stress Analysis of the Wind Turbine Blade (a) 1 N and (b) 5 N



(a) **(b)**

Figure 6: The Displacement Analysis of the Wind Turbine Blade (a) 1 N and (b) 5 N

Figure 7(a-b) and 8(a-b) shows the simulation analysis of the von Mises and the ESTRN. It is seen that the strain effect on the wind turbine blade causes elongation, which is attributed to the different force and pressure affecting the wind blade. This force and pressure are vibration, high temperature, contraction, and thermal expansion process. In this analysis, the maximum strain for both forces applied is 3.55281e-009 and 1.77642e-008, respectively. Figure 8a and 8b presents the wind blade experience massive displacement, stress, and strain at the centre region of the blade. This has shown that the maximum failure occurs in this region due to various elemental factors faced by the wind blade.



(a) **(b)**

Figure 7: The Analysis of the Strain (a) 1 N (b) 5 N Forces Applied

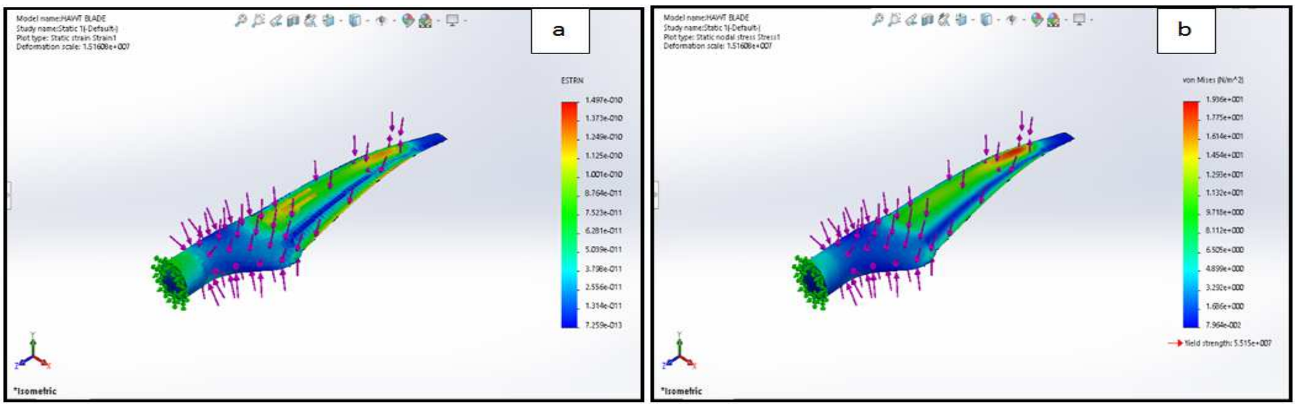


Figure 8: The Simulated Result showing the Possible area where the Failure of the Wind Turbine Blade can Occur during Operations (a) at 1 N and (b) at 5 N

4. CONCLUSIONS

The optimal design and the simulation analysis of stress/ strain of the wind turbine blade was carried out to study the effects of different forces and pressure on the wind turbine blade via a simulation approach. The design and simulation software employed in this study is Solid Works Visualize 2018. The wind turbine blade is made of AL6061 alloy material. The blade is simulated under two forces, 1 N, and 5 N and pressure at zero degree, the maximum stress that causes the blade to experience failure during operation occurs at 285.377 N/m^2 and 1426.83 N/m^2 respectively. The result from the simulation analysis shows that high failure rate occurs at the tip of the wind blades, due to the displacement force acting on it. The simulation result also shows that the wind blade experiences elongation at the middle of the blade due to the strain forces been acted upon the blade. From this study, the blade maintenance can also be carried out if the failure is detected on time, by using an additive manufacturing process in restructuring the material of the blade, which help to prolong the lifespan of the blade for optimal performance during energy generation.

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Mr. Aladegbeye Iyanuoluwa O., is a mechanical engineering graduate from Covenant University. He has vital knowledge of foundational areas in mechanical engineering such as machine drawing, mechanics of machines, manufacturing technology, fluid mechanics, and automotive engineering. He also possesses a wide range of soft skills which include but are not limited to active listening, communication adaptability and empathy. And also have intermediate-level proficiency in product design software like SolidWorks and Autodesk Inventor. He is a graduate member of the Nigerian Society of Engineers (NSE) and Nigerian Institute of Mechanical Engineers (IMechE).

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