WIND IMPACT STRESS EVALUATION OF RECTANGULAR GEOMETRIC BLADES OF WIND TURBINE FOR MAXIMUM POWER DEVELOPMENT IN NIGERIA

EFOSA OBASEKI[1], NKWOR CHIMEZIE AGBAFOR[2], IKEGBULA SAMUEL OBI[3] , IFO CHIKE VALENTINE[4] & EWURUM TENNISON. I[5]

1, 2, 3&5 Department of Mechanical Engineering, School of Engineering Technology, Federal Polytechnic Nekede, Owerri, Nigeria

4, Maintenance Unit, Nigerian Breweries PLC, Enugu State, Nigeria

Corresponding author Email & phone number: tennymech@gmail.com, +2348161513849

ABSTRACT

The study, wind impact stress evaluation of rectangular geometric blades of wind turbine for maximum power development in Nigeria, was successfully achieved. Researchers created geometrical wind turbine rectangular blade models with rotor using Autodesk inventor. Rectangular blades retained dimensions of 30mm by 6mm with thickness of 5mm. The rotor hub and shaft diameters were 60mm and 35mm with rotor height of 50mm respectively and shaft length of 80mm. A fillet radius of 2mm was adopted to de-concentrate stress acting at the hub and shaft rims. . Maximum average wind speed was used to compute wind site pressure and wind site load acting on each blade and was found to be 0.030N. Finite element simulation was run with rectangular blade geometry, using wind site load and turning moment of 6 N mm. Results showed that the Von Mises stress was found to be 0.211202 MPa. Since, yield strength of the assigned material is 250 MPa; it suggested that failure of rectangular blade due to wind yielding load is not possible under the given conditions. In addition, the 1st and 3rd principal stresses were found to be 0.153905 MPa and 0.029736 MPa respectively. These results indicated that the rectangular blade would fail due to tensile stress on wind impact rather than compressive stress; these results, further suggested that to improve reliability and stability of operation, excessive attack of wind/impact on rectangular blades along horizontal axis must be avoided, since stress was much along the horizontal axis. Stress concentration was found to be much at the, bonded heads and tails of blades, as well as rotor circumference. Also, the maximum displacement/deformation of rectangular blades due to wind impact load of 0.03N was found to be 0.0000547862 mm. This suggested that the rectangular blade geometry used showed lower deformation response and could improve service life of wind turbines. It was also found that the maximum induced stress was 0.0452271 MPa where as the ultimate tensile strength of material used for the rectangular blade was 540 MPa. This suggested that the rotor and blade designs were safe and not over stressed.

Keywords* ---- *Impact stress, Wind, Rectangular geometry, Wind turbine, Wind load

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1. INTRODUCTION

Harnessing wind energy requires the use of a mechanical device known as wind turbine. The wind turbine, whether vertical axis or horizontal axis driven; requires a sub unit called rotor with freely revolving blades. The function of the blades is to convert the kinetic energy of winds through wind impact into mechanical energy of a revolving rotor shaft. According to Khurmi and Gupta (2012) as cited by Onyenobi et al., (2022) maintained that wind turbine blades experiences impact loads capable of causing stresses that could lead to vibration and subsequently deformation of blade material. Consequently, it is recommended that every reliable design of wind turbine rotor and blades must perform adequate wind impact stress evaluations.

According to Peng and Yan (2022), rotation of rotor and blades beyond rated speed of turbine, might set up blade resonance and vibration which would increase load on bearing elements, reduce operational performance and as well, chances of defects increases to lower service life.

In addition, reviewed literatures showed that wind impact load experienced on blades depends on the geometrical dimensions of the blade design and site wind pressure. Using the relevant site data such as wind pressure, blade geometrical area and drag coefficient, would give a reliable solution in the failure of blades due to wind impact stress. It is on this note that the researchers aimed to study wind impact stress evaluation of rectangular geometric blades of wind turbine for maximum power development in Nigeria.

2. METHODOLOGY

In this study, wind impact stress evaluation of rectangular geometric blades of wind turbine for maximum power development in Nigeria, researchers created geometrical wind turbine rectangular blade models with rotor using Autodesk inventor. Rectangular blades retained dimensions of 30mm by 6mm with thickness of 5mm. The rotor hub and shaft diameters were 60mm and 35mm with rotor height of 50mm respectively and shaft length of 80mm. A fillet radius of 2mm was adopted to de-concentrate stress acting at the hub and shaft rims.

The average monthly wind speed data from 1981 -2021 (40 years) for fourth-seven (47) study locations are sourced from National Aeronautics and Space Administration (NASA) website as cited by Njoku et al (2022) in Nkwor et al (2023). The major cities in Nigeria were covered by the study locations as shown in the table 1.0 below. Maximum average wind speed was used to compute wind site pressure and subsequently wind site load acting on each blade. Finite element simulation was run with blade geometry, using wind site load, turning moment of 6 N mm and the impact stresses were evaluated and reported as shown below.

2.1 TABLES AND FIGURES

Table 1:0 Average Monthly Wind Speed for Study Locations at 10m/s from 1981-2022 (NASA, 2023)

Locations	Lat. (ºN)	Long. (ºE)	Elev. (m)	Jan	Feb m/s	Mar	Apr m/s	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ave
Abakaliki	6.33	8.12	88.44	2.77	2.54	2.7	2.84	2.67	2.88	3.16	3.21	2.76	2.26	1.84	2.4	2.67
Abeokuta	7.15	3.37	80.92	2	2.23	2.44	2.44	2.26	2.42	2.84	2.94	2.45	1.99	1.65	1.73	2.28
Abuja	9.08	7.4	406.97	2.9	2.75	2.56	2.48	2.2	2.19	2.42	2.45	1.99	1.77	2.12	2.67	2.37
Ado-Ekiti	7.62	5.24	379.21	2.14	2.2	2.39	2.46	2.23	2.28	2.62	2.68	2.11	1.75	1.64	1.88	2.2
Akure	7.26	5.21	379.21	2.14	2.2	2.39	2.46	2.23	2.28	2.62	2.68	2.11	1.75	1.64	1.88	2.2
Asaba	6.21	6.7	103.94	2.53	2.43	2.56	2.64	2.5	2.79	3.19	3.28	2.81	2.3	1.86	2.14	2.59
Awka	6.23	7.09	103.94	2.53	2.43	2.56	2.64	2.5	2.79	3.19	3.28	2.81	2.3	1.86	2.14	2.59
Bauchi	10.31	9.83	518.79	4.11	4.18	3.83	3.47	3.28	3.01	2.59	2.3	2.3	2.63	3.28	3.82	3.23

Benin-City	6.34	5.61	93.92	1.76	1.71	1.74	1.74	1.64	1.8	2.06	2.13	1.83	1.5	1.29	1.5	1.73
Bida	9.08	6.01	126.59	2.26	2.21	2.23	2.35	2.17	2.14	2.34	2.36	1.89	1.66	1.71	2.05	2.11
Birinin Kebbi	12.44	4.2	241.96	3.64	3.64	3.24	3.08	3.27	2.99	2.43	1.96	1.75	1.89	2.54	3.29	2.81
Calabar	4.98	8.35	39.48	2.08	2.25	2.38	2.43	2.41	2.72	2.99	3.07	2.76	2.39	1.97	1.88	2.45
Damaturu	11.75	11.97	402.61	4.81	4.94	4.62	4.06	3.96	3.94	3.38	2.74	2.39	2.58	3.86	4.54	3.81
Duste	11.75	9.34	465.94	3.02	3.11	3.07	2.98	2.79	2.61	2.17	1.8	1.77	1.99	2.39	2.78	2.53
Enugu	6.46	7.55	151.33	2.78	2.61	2.74	2.85	2.67	2.91	3.28	3.32	2.81	2.3	1.88	2.37	2.71
Gombe	10.28	11.18	381.62	4.47	4.62	4.12	4	4.06	3.76	3.27	2.76	2.36	2.32	3.08	4.01	3.56
Gusau	12.17	6.68	529.87	4.92	4.82	4.28	3.84	3.61	3.51	3.08	2.61	2.31	2.68	3.74	4.53	3.66
Ibadan	7.38	3.95	188.89	2.17	2.31	2.6	2.71	2.52	2.65	3.08	3.16	2.53	2.03	1.71	1.89	2.45
Ijebu-Ode	6.83	3.92	90.82	1.77	1.94	2.12	2.14	2	2.17	2.54	2.63	2.2	1.78	1.46	1.54	2.02
Ikeja	6.61	3.36	25.49	2.48	2.9	3.24	3.21	2.98	3.36	3.92	4	3.54	2.88	2.29	2.15	3.08
Ikom	5.97	8.73	116.85	2.16	2.31	2.51	2.58	2.48	2.74	3.01	3.12	2.73	2.29	1.82	1.9	2.47
Ilorin	8.48	4.55	344.93	2.72	2.96	3.51	3.84	3.4	3.21	3.47	3.51	2.62	2.25	2.14	2.4	3
Jalingo	8.9	11.38	251.79	3.51	3.5	3.61	4.1	3.67	3.49	3.45	3.16	2.4	2.08	2.32	3.13	3.2
Jos	9.9	8.86	980.85	4.3	4.2	3.82	3.43	2.89	2.68	2.54	2.49	2.41	2.71	3.45	4.06	3.24
Kaduna	10.52	7.42	623.54	4.77	4.49	3.67	3.18	2.85	2.73	2.61	2.47	2.09	2.23	3.46	4.43	3.24
Kano	12.01	8.6	442.08	2.84	2.89	2.78	2.64	2.51	2.39	1.94	1.52	1.44	1.69	2.16	2.58	2.28
Katsina	12.97	7.63	474.54	5.05	4.93	4.54	4.03	3.77	3.85	3.46	2.72	2.45	2.94	4.02	4.7	3.86

Lafia	7.81	6.74	167.21	2.38	2.54	3.01	3.23	2.82	2.71	2.88	2.84	2.32	2.03	1.89	2.12	2.57
Lokoja	7.81	6.74	167.21	2.38	2.54	3.01	3.23	2.82	2.71	2.88	2.84	2.32	2.03	1.89	2.12	2.57
Maiduguri	11.84	13.16	318.25	4.57	4.78	4.65	4	3.77	3.98	3.64	2.88	2.57	2.79	3.91	4.34	3.82
Makurdi	7.74	5.54	373.17	2.53	2.65	3.01	3.16	2.83	2.82	3.14	3.19	2.52	2.12	1.97	2.23	2.68
Mbaise	5.54	7.29	92.75	2.34	2.28	2.35	2.41	2.33	2.6	2.92	3.02	2.65	2.21	1.79	1.98	2.41
Minna	7.61	8.09	149.83	3.02	3	3.3	3.42	2.98	2.97	3.18	3.14	2.57	2.17	1.98	2.59	2.86
Nguru	12.88	10.46	345.61	4.94	4.95	4.75	4.07	3.57	3.62	3.39	2.7	2.52	3.1	4.33	4.75	3.89
Onitsha	6.14	6.8	103.94	2.53	2.43	2.56	2.64	2.5	2.79	3.19	3.28	2.81	2.3	1.86	2.14	2.59
Oshogbo	7.79	4.55	337.39	2.43	2.6	3.03	3.23	2.91	2.9	3.31	3.38	2.55	2.06	1.89	2.13	2.7
Owerri	5.47	7.02	62.54	2.26	2.18	2.22	2.25	2.16	2.44	2.77	2.87	2.52	2.1	1.72	1.9	2.28
Port-Harcourt	4.34	7.05	6.8	1.65	1.77	1.76	1.66	1.62	1.86	2.17	2.29	2.03	1.71	1.5	1.45	1.79
Potiskum	11.7	11.09	411.77	4.36	4.47	4.13	3.56	3.43	3.33	2.8	2.27	2.06	2.25	3.38	4.06	3.34
Sokoto	13.01	5.25	276.18	4.51	4.42	3.94	3.59	3.8	3.71	3.12	2.44	2.19	2.38	3.3	4.14	3.46
Umuahia	5.53	7.5	92.75	2.34	2.28	2.35	2.41	2.33	2.6	2.92	3.02	2.65	2.21	1.79	1.98	2.41
Uyo	5.04	7.92	39.48	2.08	2.25	2.38	2.43	2.41	2.72	2.99	3.07	2.76	2.39	1.97	1.88	2.45
Warri	5.55	5.57	9.6	1.36	1.41	1.4	1.3	1.2	1.36	1.64	1.79	1.58	1.28	1.07	1.15	1.38
Yelwa	10.84	4.75	257.74	3.94	3.89	3.36	3.35	3.15	2.9	2.65	2.48	2.07	2.05	2.81	3.54	3.01
Yenegoa	4.93	6.28	17.26	2.08	2.15	2.23	2.19	2.09	2.37	2.72	2.87	2.56	2.14	1.78	1.77	2.25
Yola	9.04	12.5	344.13	2.48	2.82	3.36	3.55	2.94	2.68	2.59	2.36	1.91	1.91	2.05	2.21	2.57

Zaria	11.13	7.73	646.9	4.86	4.67	3.97	3.5	3.23	3.11	2.82	2.53	2.2	2.39	3.51	4.45	3.43
			Ave	3.01	3.05	3.04	2.97	2.77	2.82	2.88	2.76	2.36	2.18	2.33	2.71	2.74
			Max	5.05	4.95	4.75	4.1	4.06	3.98	3.92	4	3.54	3.1	4.33	4.75	3.89
			Min	1.36	1.41	1.4	1.3	1.2	1.36	1.64	1.52	1.44	1.28	1.07	1.15	1.38

2.2 EQUATIONS AND CALCULATIONS

The mathematical formulas for calculating the wind site load are shown below.

$$Wind\ pressure\ per\ square\ foot = 0.00256 \times square\ of\ the\ wind\ speed \ldots\ldots (1.0)$$

$$Drag\ coefficient, C_d = a\ measure\ of\ wind\ resistance \ \ldots\ldots. (2.0)$$

$$Drag\ coefficient, C_d = 2.0 \text{ For rectangular surface}$$

$$Drag\ coefficient, C_d = 1.2 \text{ For cylindrical or cone surface}$$

$$Wind\ site\ load, L_w = Geometrical\ Area \times Wind\ Pressure \times C_d \ldots\ldots (3.0)$$

$$Geometrical\ Area\ of\ Rectangle = Length \times Width \ldots. (4.0)$$

$$Geometrical\ Area\ of\ cone = \pi r(r + \sqrt{h^2} + r^2) \ldots.. (5.0)$$

$$Geometrical\ Area\ of\ Cylinder = 2\pi rh + 2\pi r^2 \ldots\ldots (6.0)$$

From table 1.0, the maximum average wind speed in Nigeria is 3.89 m/s

Since 1m/s is equivalent to 2.24miles per hour, 3.89m/s = 8.7136mph

$Wind\ pressure\ per\ square\ foot = 0.00256 \times 8.7136^2$ = 0.1898psf

1psf is equivalent to 47.88N/m^2

Then, 0.1898psf = 9.088N/m^2

For the two chosen geometries; we have

$$Drag\ coefficient, C_d = 2.0 \text{ For rectangular surface}$$

$$Drag\ coefficient, C_d = 1.2 \text{ For cylindrical or cone surface}$$

$$Wind\ site\ load, L_w = Geometrical\ Area \times Wind\ Pressure \times C_d$$

$$Geometrical\ Area\ of\ Rectangle = Length \times Width$$

$$Length = 30mm = 0.030m$$

$$Width = 6mm = 0.006m$$

$$Geometrical\ Area\ of\ Rectangle = 0.030 \times 0.006 = 0.00018m^2$$

$$Wind\ site\ load, L_w = 0.00018 \times 9.088 \times 2 = 0.00327168\ N$$

3.0 RESULTS

Table 2.0: Project

Part Number	TURBINE BLADE RECT
Designer	Ewurum Tennison
Cost	$57.00
Date Created	5/4/2024

Table 3.0 : Physical

Material	Stainless Steel
Density	8 g/cm^3
Mass	0.732753 kg
Area	15700.4 mm^2
Volume	91594.2 mm^3
Center of Gravity	x=-0.00607343 mm y=0.0141332 mm z=16.9535 mm

Table 4.0: General objective and settings

Design Objective	Single Point
Study Type	Static Analysis
Last Modification Date	5/4/2024, 4:39 PM
Detect and Eliminate Rigid Body Modes	No

Table 5.0: Mesh settings

Avg. Element Size (fraction of model diameter)	0.1
Min. Element Size (fraction of avg. size)	0.2
Grading Factor	1.5
Max. Turn Angle	60 deg
Create Curved Mesh Elements	Yes

Table 6.0: Material(s) Properties

Name	Stainless Steel	
General	Mass Density	8 g/cm^3
	Yield Strength	250 MPa
	Ultimate Tensile Strength	540 MPa
Stress	Young's Modulus	193 GPa
	Poisson's Ratio	0.3 ul
	Shear Modulus	74.2308 GPa
Part Name(s)	TURBINE BLADE RECT	

Table 7.0: Operating conditions, Force

Load Type	Force
Magnitude	0.030 N
Vector X	-0.030 N
Vector Y	0.000 N
Vector Z	0.000 N

Table 8.0: Operating conditions, Moment

Load Type	Moment
Magnitude	6.000 N mm
Vector X	0.000 N mm
Vector Y	0.000 N mm
Vector Z	-6.000 N mm

The tables 2.0 to 8.0 above indicated the setting conditions in finite element software, physical and mechanical properties of the assigned material, with the operating conditions generated by finite element software used.

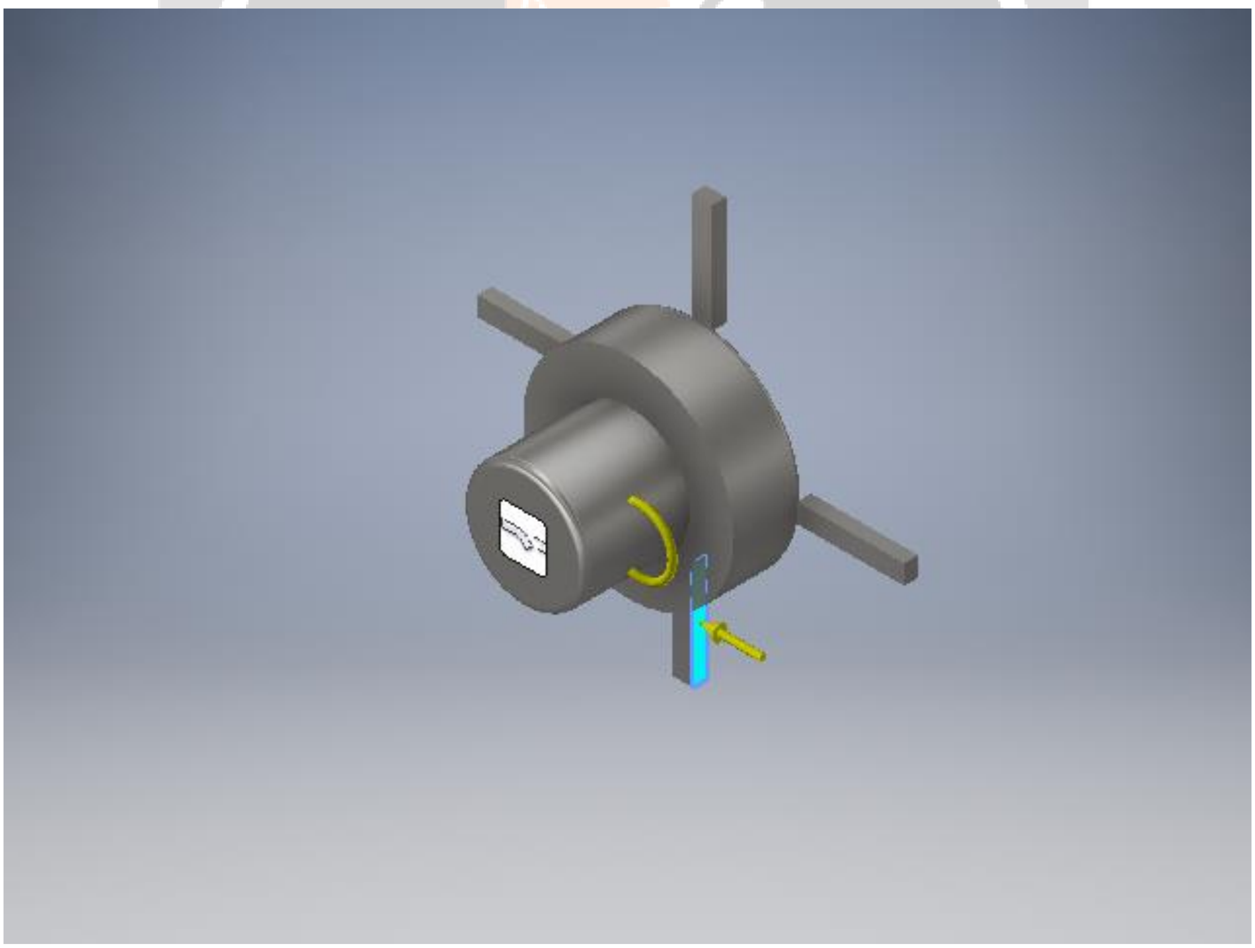

Fig 1.0: Wind Turbine Rotor, Blade, Load and Constraint

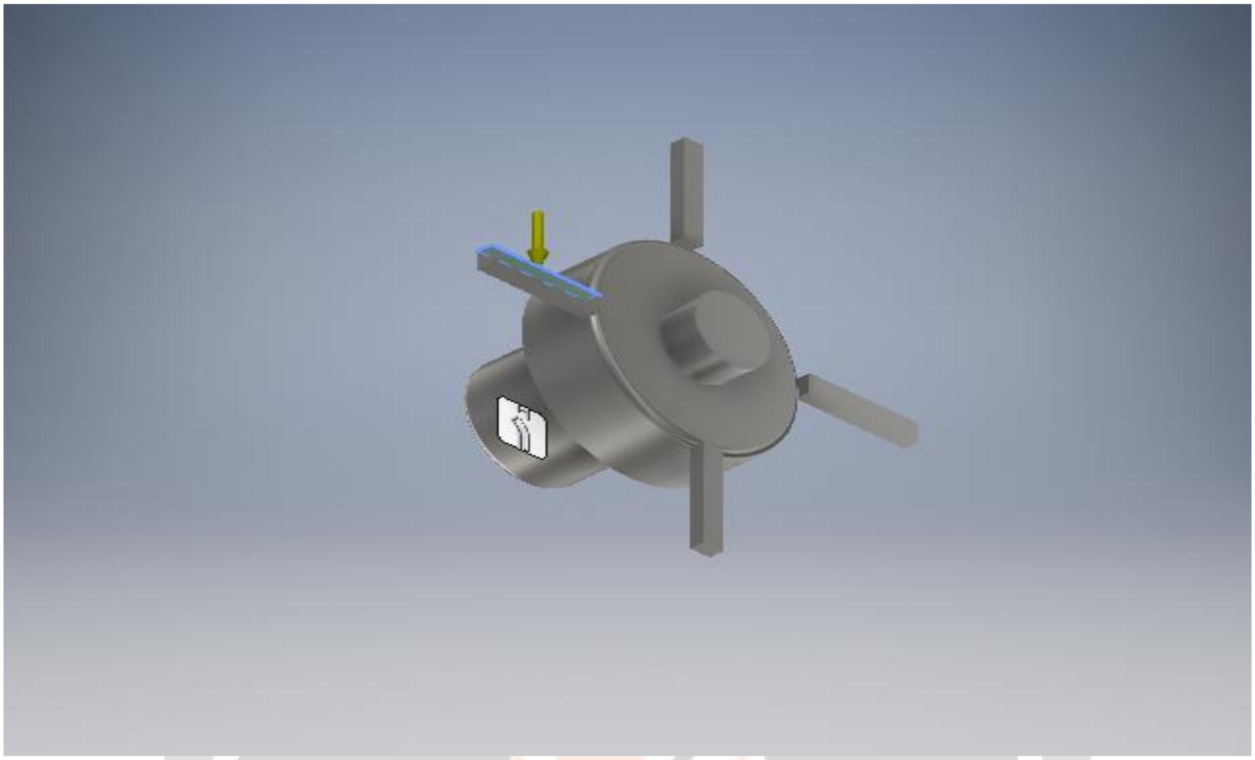

Fig 2.0: Wind Turbine Rotor, Blade, Load and Constraint

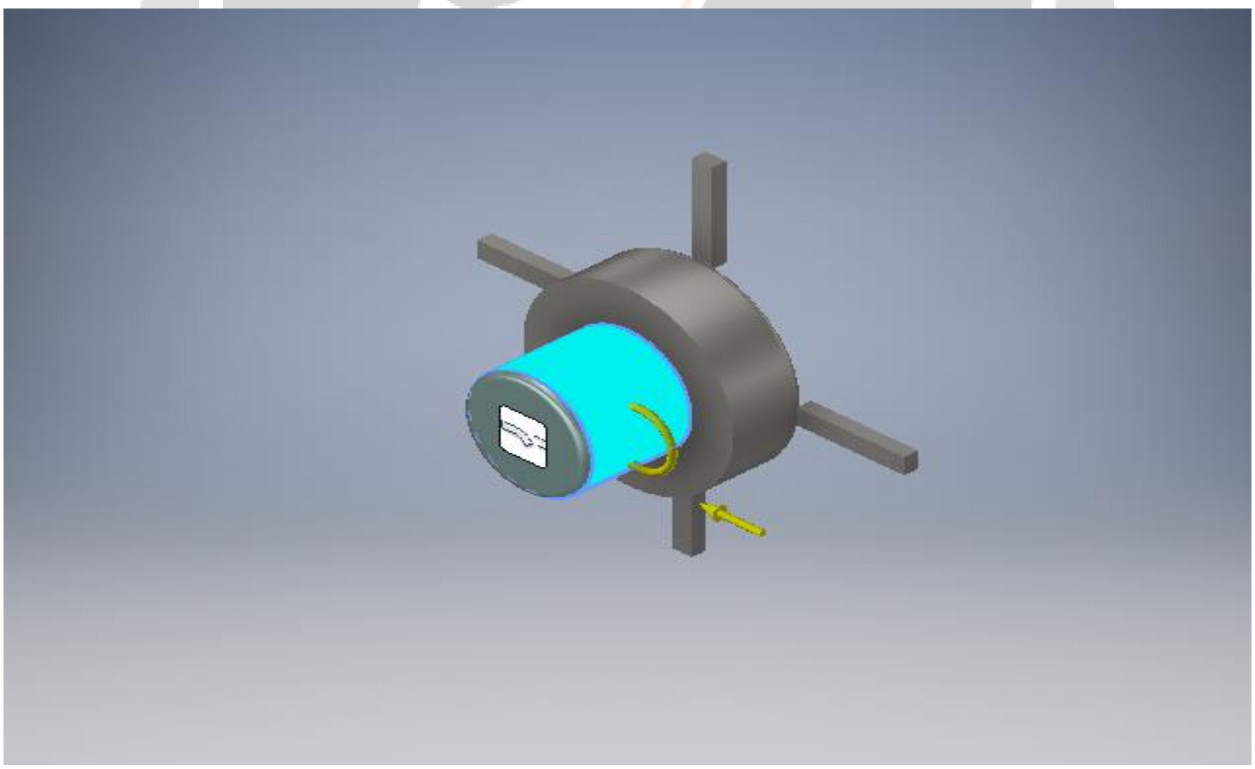

Fig 3.0: Wind Turbine Rotor, Blade, Load and Constraint

Table 9.0: Reaction Force and Moment on Constraints

Constraint Name	Reaction Force		Reaction Moment	
	Magnitude	**Component (X,Y,Z)**	**Magnitude**	**Component (X,Y,Z)**
Fixed Constraint:1	0.03 N	0.03 N	0.00751001 N m	0 N m
		0 N		-0.00149995 N m
		0 N		0.0073587 N m

According to table 9.0, the rectangular blade under bonded fixed constraints was subjected to wind load of 0.03N. It was observed that the maximum reaction moment and force at the fixed points was 0.00751001 N m and 0.03N, these results suggested that the wind turbine rotor and blades would require a fastening support bolt whose nominal diameter is not less than 12mm to achieve effective stability during rotation.

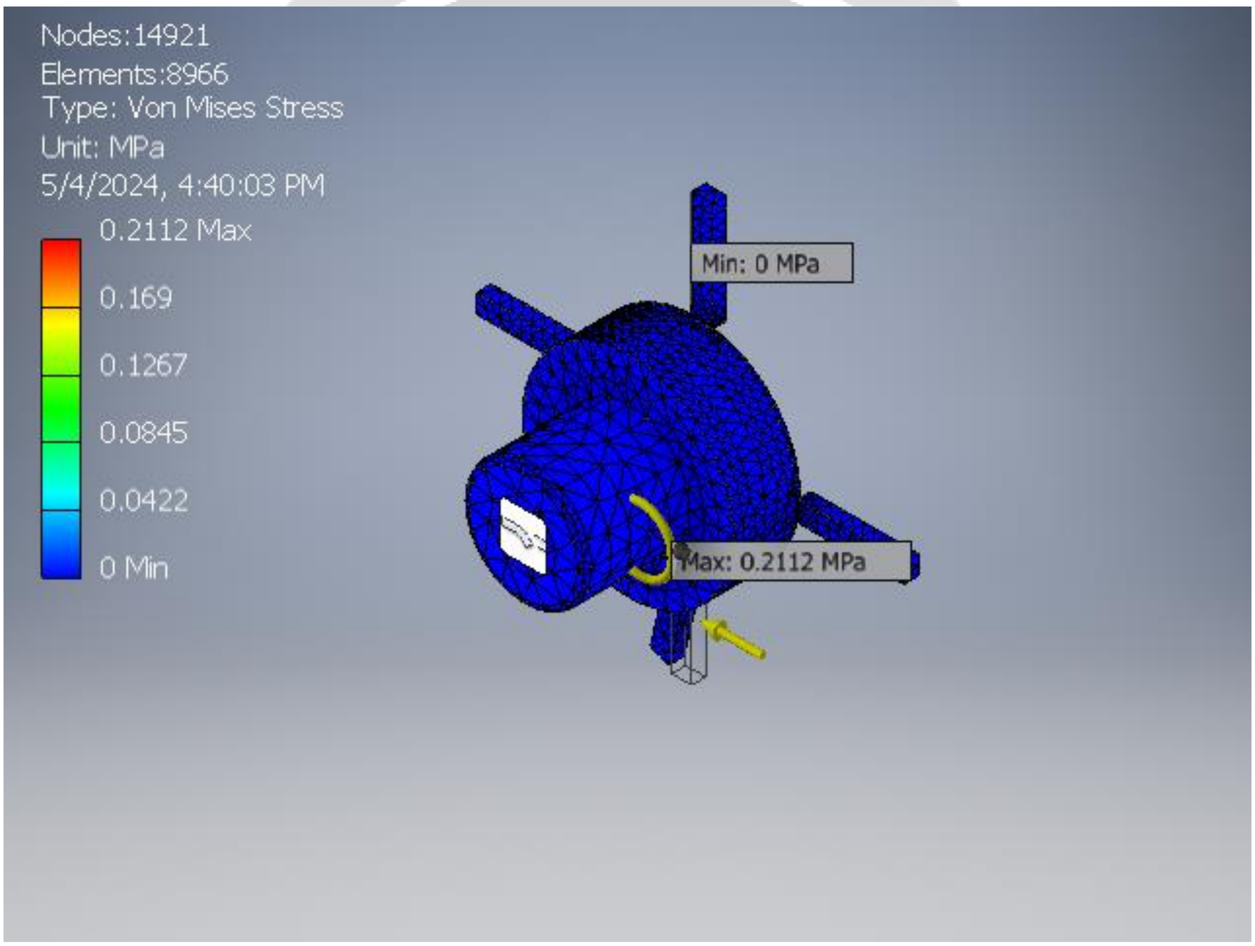

Fig 4.0: Von Mises Stress

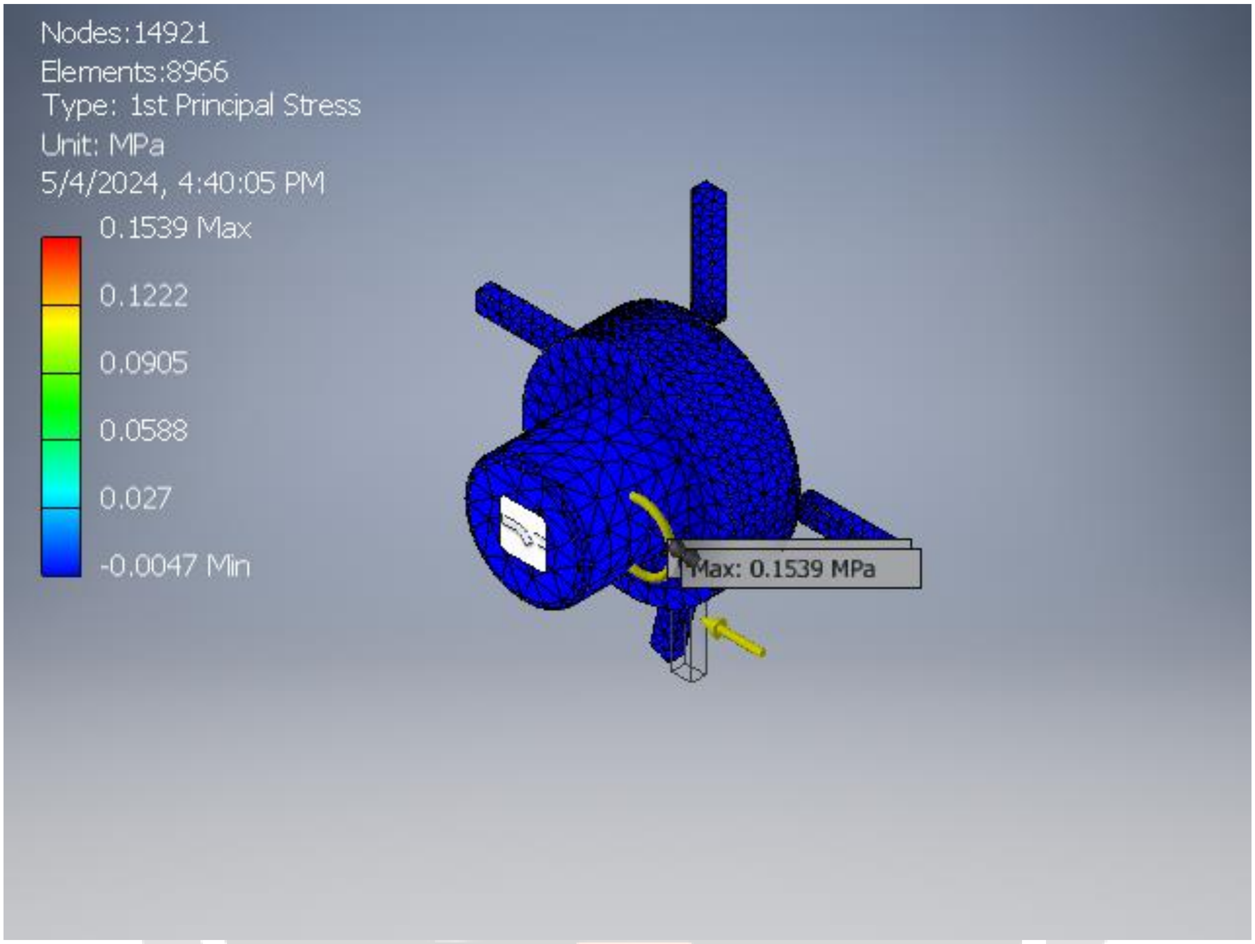

Fig 5.0: 1st Principal Stress

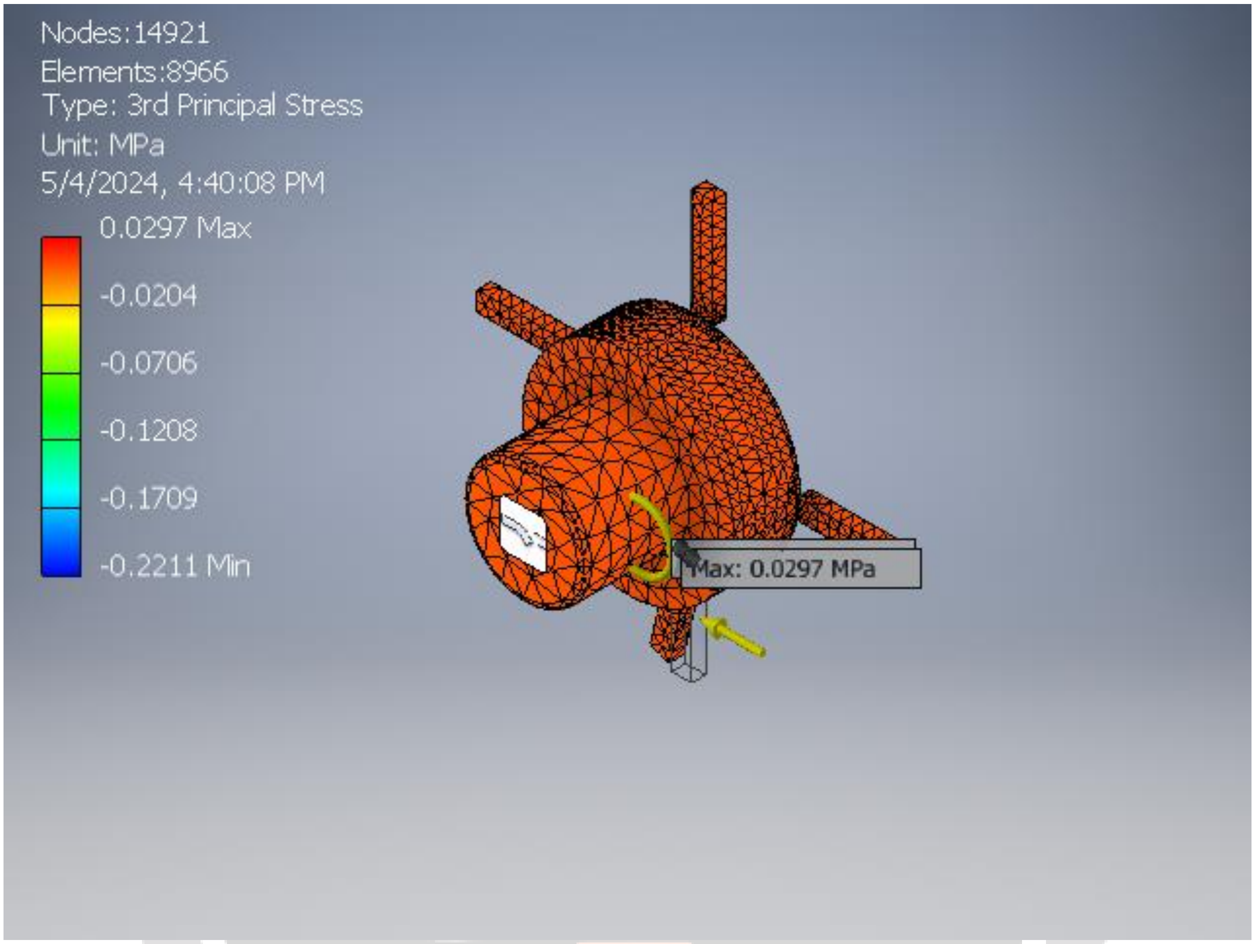

Fig 6.0: 3rd Principal Stress

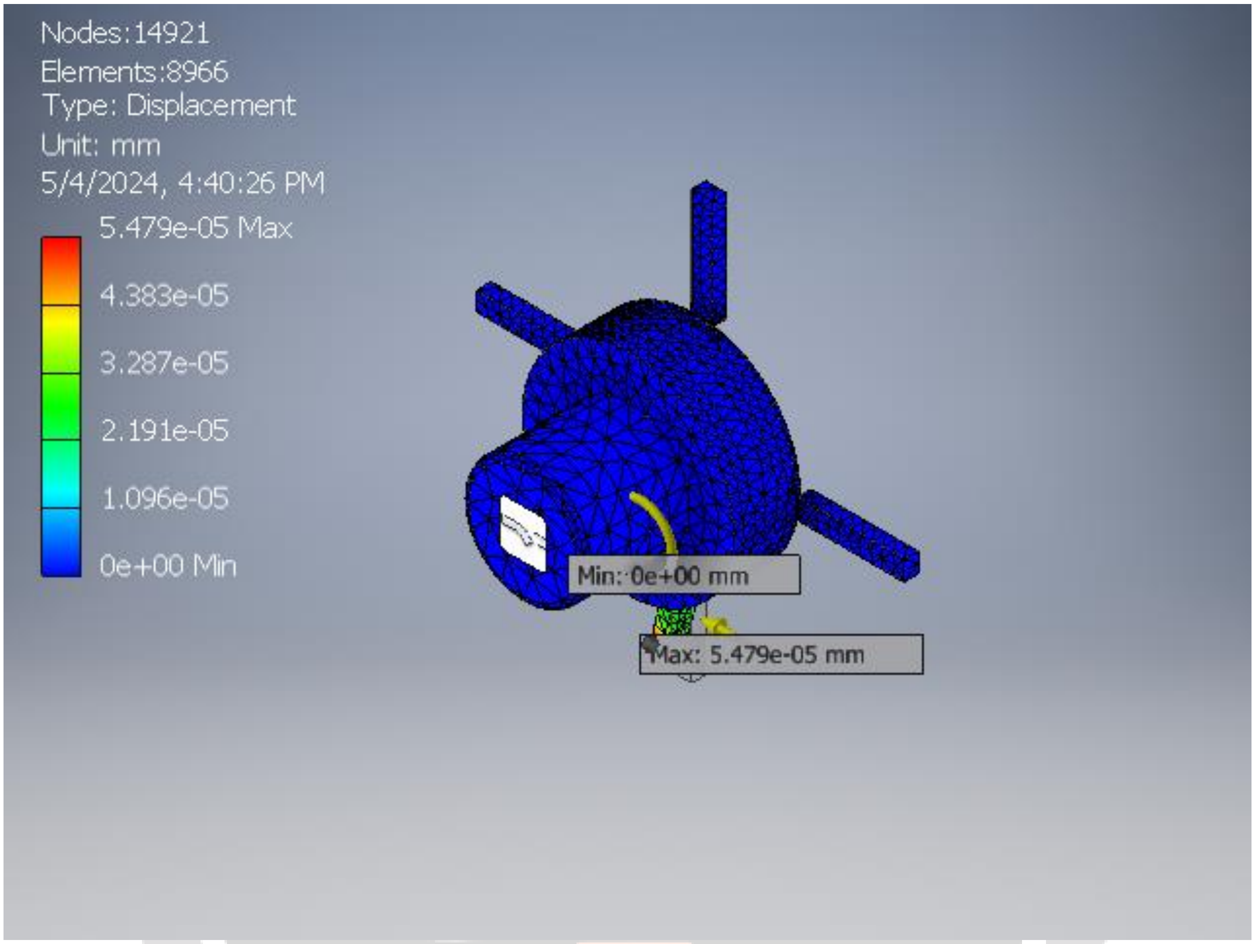

Fig 7.0: Deformation on Blades

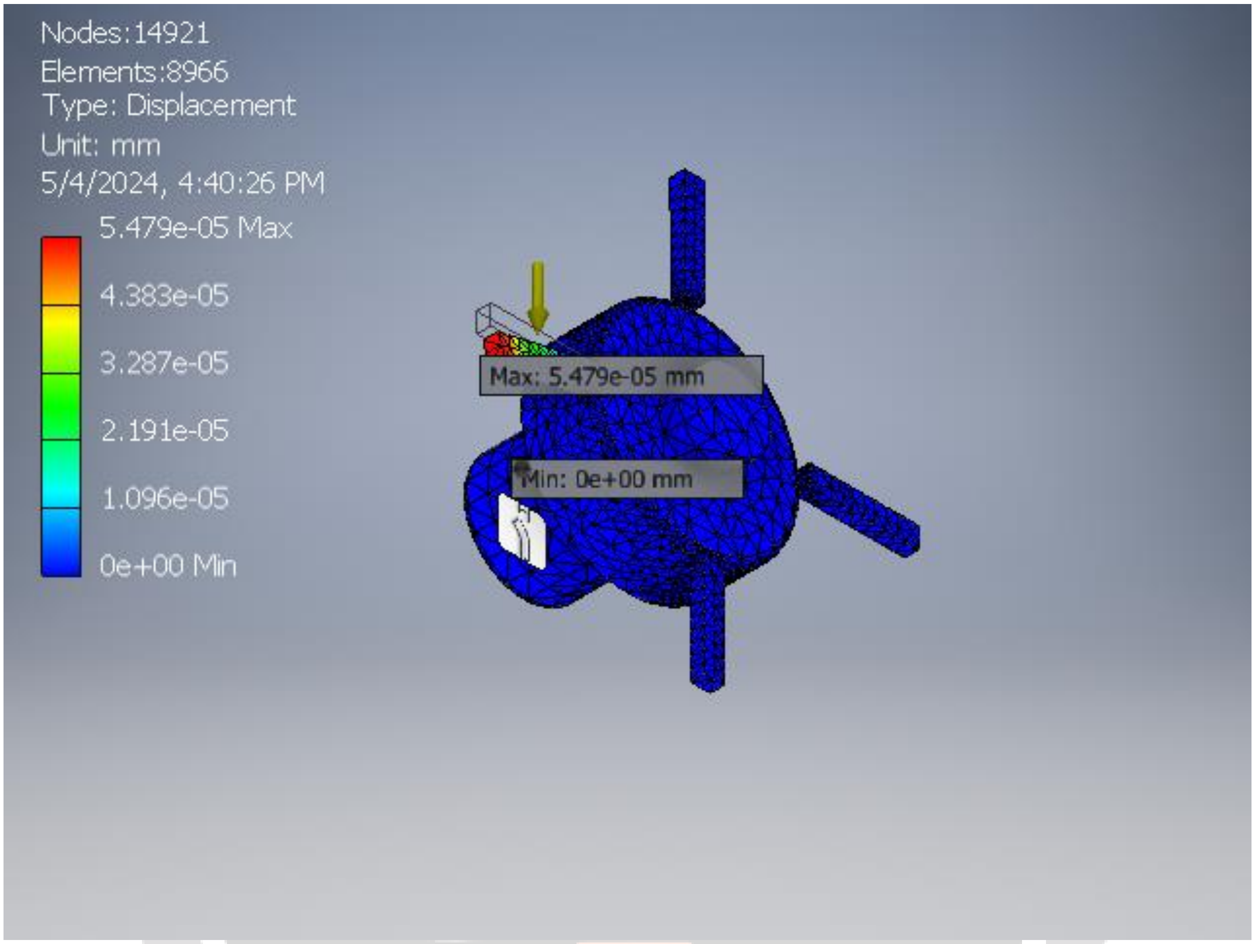

Fig 8.0: Deformation on Blades

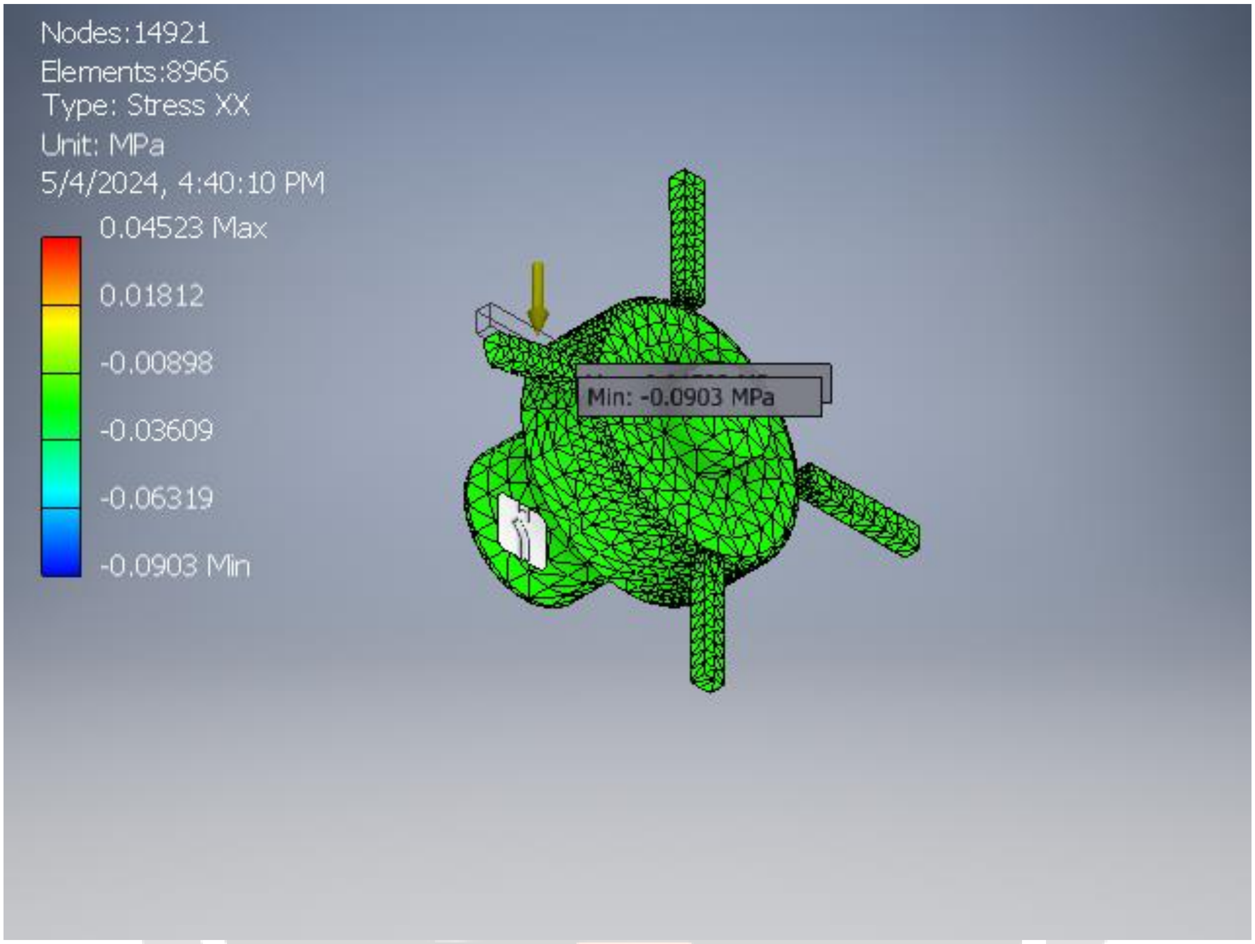

Fig 9.0: Maximum Stress on Blades

According to **Fig 4.0**, result showed that the Von Mises stress was found to be 0.211202 MPa. Since, yield strength of the assigned material is 250 MPa; it suggested that failure of rectangular blade due to wind yielding load is not possible under the given conditions.
According to **Fig 5.0** and **Fig 6.0**, the 1st and 3rd principal stresses were found to be 0.153905 MPa and 0.029736 MPa respectively. These results indicated that the rectangular blade would fail due to tensile stress on wind impact rather than compressive stress; these results, suggested that to improve reliability and stability of operation, excessive attack of wind/impact on rectangular blades along horizontal axis must be avoided. Stress concentration was found to be much at the, bonded heads and tails of blades, as well as rotor circumference.

Fig 7.0 and Fig 8.0 showed that the maximum displacement/deformation of rectangular blades due to wind impact load of 0.03N was found to be 0.0000547862 mm. This suggested that the rectangular blade geometry used showed lower deformation response and could improve service life of wind turbines. Also, **Fig 9.0** indicated that the maximum induced stress was found to be 0.0452271 MPa where as the ultimate tensile strength of material used for the rectangular blade was 540 MPa. This suggested that the rotor and blade designs were safe and not over stressed.

Table10.0: Result Summary

Name	**Minimum**	**Maximum**
Volume	91594.2 mm^3	
Mass	0.732753 kg	

Von Mises Stress	0.00000000142243 MPa	0.211202 MPa
1st Principal Stress	-0.00466748 MPa	0.153905 MPa
3rd Principal Stress	-0.2211 MPa	0.029736 MPa
Displacement	0 mm	0.0000547862 mm
Safety Factor	15 ul	15 ul
Stress XX	-0.0902965 MPa	0.0452271 MPa
Stress XY	-0.0820391 MPa	0.0420843 MPa
Stress XZ	-0.0320043 MPa	0.0135775 MPa
Stress YY	-0.144473 MPa	0.143273 MPa
Stress YZ	-0.0678283 MPa	0.0513054 MPa
Stress ZZ	-0.0605311 MPa	0.0314822 MPa
X Displacement	-0.0000521033 mm	0.000000731181 mm
Y Displacement	-0.00000359963 mm	0.00000830858 mm
Z Displacement	-0.0000156754 mm	0.000000444462 mm
Equivalent Strain	0.0000000000000661577 ul	0.000000981997 ul
1st Principal Strain	0.0000000000000101263 ul	0.000000694726 ul
3rd Principal Strain	-0.00000108412 ul	0.0000000000000990017 ul
Strain XX	-0.000000207683 ul	0.000000240484 ul
Strain XY	-0.000000552595 ul	0.00000028347 ul
Strain XZ	-0.000000215573 ul	0.0000000914548 ul
Strain YY	-0.000000756233 ul	0.000000623108 ul
Strain YZ	-0.000000456875 ul	0.000000345581 ul
Strain ZZ	-0.000000311315 ul	0.000000251606 ul
Contact Pressure	0 MPa	0.612853 MPa
Contact Pressure X	-0.288977 MPa	0.0242916 MPa
Contact Pressure Y	-0.504862 MPa	0.338131 MPa
Contact Pressure Z	-0.19286 MPa	0.0485497 MPa

4.0 CONCLUSION

According to the findings, it could be deduced that the wind turbine rectangular blade would fail due to tensile stress on wind impact rather than compressive stress; to improve reliability and stability of operation, excessive wind impact on rectangular blades along horizontal axis must be avoided. Also, the use of rectangular blade geometry would lower blade deformation and could improve service life of wind turbines.

5.0 RECOMMENDATIONS

The following recommendations are suggested based on the study:

1) To reduce the failure of rectangular geometric blades in wind turbines, excessive wind impact along horizontal axis must be avoided.
2) Rectangular blade material must have higher tensile strength rather than compressive strength, since failure due to tensile stress is predominant.
3) This research could also be done in future using different blade geometries, designs and other advanced software for generalization.
4) Rectangular blades must have stronger reinforcement/bonding at the rotor attachment points, to improve rigidity.

6.0 DISCLOSURE OF CONFLICT OF INTEREST

We hereby declare that this research article is original and the corresponding author confirms that co-authors participated actively in the development of the paper and have read and approved the manuscript with no ethical issues and with declaration of no conflict of interest.

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