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Design of Composite Gyrocopter Main Rotor Blade Involving Rib and Spar Elements

Yonas Mitik Degu[1] and Derbew Alebel[2]
[1]Assistant Professor, Faculty of Mechanical and Industrial Engineering, Bahir Dar Institute of Technology, Bahir Dar University, Ethiopia. E-mail: yonasm@bdu.edu.et (corresponding author).
[2]Airline Pilot, Ethiopian Airlines, Addis Abeba, Ethiopia. E-mail: derbewalebel@yahoo.com

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Abstract: Gyrocopter or gyroplane is a type of rotorcraft that uses an unpowered main rotor in free autorotation to develop lift. Gyrocopter rotor blades have smaller cord length and longer span compared to helicopters blades. National Advisory Committee for Aeronautics (NACA) 8-H-12 gyrocopter rotor blade profile, unsymmetrical airfoil sections were used for this research. An attempt has been made in this work to investigate the effect of ribs and spar elements in response to applied load. Three possible modeling alternatives were studied to predict the actual induced stress and deformation of the blade: Model I is by considering the blade shell part only, Model II is blade shell with 25 numbers of ribs and without the spar element and Model III is blade shell with 25 numbers of ribs and with spar element. The rotor blade was sized based on single seat open frame and high-wind-start gyrocopter. Structural static analysis has been carried out to evaluate the strength of composite rotor blade using ANSYS Workbench 15. The results show that among these three proposed models; Model III had registered minimum Von Mises stress and deformation. Also the result reveals that by considering ribs and spar element during analysis of gyrocopter blade is crucial because, it will help to know the actual induced stress and deformation. The predicted value of induced stress and deformation is closer to the actual values will help the designer not to overdesign the parts. Consequently, the main drawbacks related to overdesign increase in weight and cost will be minimized; thereby the product operational efficiency will be improved.

Keywords: Gyrocopter, main rotor blade, ribs, spar, composite materials.

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1. Introduction

A gyroplane is a type of rotorcraft using an unpowered rotor operating by autorotation to develop lift. An engine-powered propeller to provide thrust which is necessary to balance the gyroplane drag force (Stalewski, 2016). Generally, a two-bladed teetering rotor is used in modern gyroplanes with simple design. Therefore, they are lighter, more reliable and require less maintenance than helicopters (Trchalík, 2009). In contrast to helicopters, the torque of gyrocopter rotor does not come from an engine but from aerodynamic forces generated by airflow passing through the rotor disc (Trchalík, 2009; Simhachalam et al., 2015; Stalewski, 2016).

The rotor blade of gyrocopter is to withstand centrifugal force exerted in outwards, to distribute air load and self-weight of the blade. Though the gyrocopter rotor blades appear like helicopter blades, they have a significant difference in terms of blade profile and its design. Since rotor blades in gyrocopter have an autorotation, it needs not only enough area to produce lifts but also to store enough energy for rotation. Gyroplane rotor blades are flexible, and quite stiff in torsion (Trchalík, 2009).

Gyrocopter rotor blades can be made of bamboo, fabrics, wood, metals or composites. Use of composites has resulted in remarkable achievements in many fields including aviation, marine and automobile engineering, in terms of improved fatigue and corrosion resistances, high specific strength, specific modulus and reduction in energy requirements owing to reduction in weight (Moorthy et al., 2013).

A composite material is engineered to provide combined characteristics are very challenging. It combines high strength with light weight and demonstrate a wider range of characteristics than any other materials to meet the diverse requirements of a gyrocopter rotor blade. Epoxy/Carbon composites have an exceptional mechanical properties and it is widely used in aerospace, automotive, and other industries. These strong, stiff and lightweight materials are an ideal choice for applications where lightweight and superior performances are important (Leihong, 2008; Mallick, 2008; Batra, 2012; Mohammadreza and Mohseni, 2014; Rohmani, 2014).

Composite gyrocopter rotors have sandwich structure composed of ribs used to handle transverse loads and spars to withstand longitudinal loads. The strength of composite structures depends on the nature of fibers,the orientation of fibers, the number of layers, and the manufacturing process (Rajappan and Pugazhenthi, 2013).

Traditional solution methods for optimizing complex real-life engineering problems is expensive and often results in sub-optimal solutions. The purpose of structural optimization is to minimize the mass of the overall structure by considering all the components which makes the entire product (Ramu et al., 2010). Optimization methods are very effective tools which are improves the performance of contemporarily designed and constructed aircraft. A fast development in computational methods and computer hardware is lead to expand the range of applications (Stalewski, 2016).

Analysis of composite materials is to arrive at an optimized outcome is requires complex modeling, analysis and iterations, whereas finite element software reduces this problem to a large extent. Because of computational time and facility, the designers preferred to a simplified approach so as to arrive at solution in short time. But extensive simplifying of the real problem will lead to under estimate or overestimate the results. Hence the quality and performance the final product will be adversely affected.

This research is aimed to review the previous works related to modeling and analyzing the gyrocopter rotor blade, and propose different models to show the significance the models in terms induced stress and deformation.

2. Literature Review

Trchalik (2009) investigated aeroelastic behavior of gyroplane rotors and identifies possible hazardous rotor operation modes. In order to obtain the input parameters for structural model of the blade, a series of experimental measurements were taken to determine the physical properties of a typical gyroplane blade.

A series of parametric studies were performed to examine the effect of variation of selected design parameters of rotor blade and stability of a rotor during autorotation.

The results show the parameters that affect span-wise distribution of blade and angle of attack have a strongest influence on the performance of rotors in autorotation.

Rajappan and Pugazhenthi (2013) used finite element analysis for aircraft wings made of composite material. They developed a physical model for subsonic aircraft wings made by laminated composite structure of Epoxy/Carbon fiber without any ribs and spar, to show different results of wing loading. They were also investigating the comparison between the loads applied individually and combined loads and obtained the deflection and stress.

Alice et al (2014) performed linear static analysis of carbon fiber reinforced plastic (CFRP) aircraft wings using ANSYS software. It is found that the maximum stress intensity of magnitude 2240 MPa occurring at the portion of rear spar which is more than the permissible stress in CFRP (1800 MPa) and the maximum deflection in refined model is at the tip of wing.

Ahmedand Azhar (2011) did static analysis to find the best location of boxes inside the woven glass fibers composite wing-box structure. These results were used as a base for composite wing-box to find the numbers of layers and location of the box beam and its dimensions. With respect to stress to weight ratio, composite wing-box having two boxes is better than single or triple boxes. It is achieved 40 percent mass reduction in composite wing-box instead of Aluminum wing.

Stalewski (2016, 2017) proposed two alternative main rotors aerofoil for light gyroplanes. The first designed rotor were made of Aluminum alloy show that there is an increase in maximum speed of 10 percent and reduction in drag force is 7.5 percent, compared to NACA 9H12M. The second designed rotors were made of composite material with variable-chord-blade rotor. Compared with reference rotor the second designed rotors had 13.8 percent reduction in drag force.

The structural modeling and aeroelastic optimization of auto-rotating rotors is relatively unexplored and only few publications on the topic are available in open literature. No research studies focused on considering the structural design and optimization of gyrocopter rotor main blade considering spar and ribs elements.

Hence this research work have been carried out in order to assess the effect of all the major blade forming structural elements during rotor design and optimized by selecting NACA 8H12 profile, because, it has the recommended aeroelastic for gyroplane.

Till now researchers did modeling gyrocopter main rotor blade without considering all major blade forming elements. This study is an attempt to consider different models of rotor blade and show the significance of modeling via the result obtained on stress and deformation.

3. Material and Methodology

3.1. Material

The outer shell fiber material was made of Epoxy/Carbon woven type composite material and its property is equivalent to the material Epoxy-Carbon-Woven-395GPa-Prepreg mentioned in ANSYS Workbench material library (Reference required). The ribs were made up of polyester foam equivalent to the material Foam-80kg/m^3 in ANSYS material library. Spar is made of structural steel (carbon steel).

Unidirectional composite materials have many possibilities to alter the strength of the blade by combining different fiber angles, thickness and nature of fibers. Composite materials can be tailored in such a way that to get desired properties in specific directions and areas. In this research, woven type [0, 90] degree arrangement is used, which does not allow to combining different angles. In woven type arrangement, it is increased the number of layers and fiber volume ratio.

3.2. Methodology

The method involved in this research is to develop a 3-D model using SolidWorks 2015 and exporting the model to

ANSYS 15 for finite element analysis. ANSYS workbench platform is allows to create new models, faster process and efficiently interacting with external tools such as CAD systems. Single layer thickness, orientation angle and layup sequences were defined using ANSYSAPDL from ANSYS Workbench. Assumptions have been made to simplify the model without affecting the result significantly.

- Rotor blades are considered as a cantilever beam fixed at the root
- Pre-cone angle is not considered in the modeling
- Variation of pressure load from root to tip is neglected
- Centrifugal load is applied at the annulus part of the blade tip area
- Contact between the spar and ribs is frictionless
- Contact between the ribs and outer shell is bonded type

Static structural analysis has been utilized to analyze the strength of gyrocopter composite rotor blade. Element type SOLID186/187 is used in ANSYS Workbench. SOLID186/187 is used as PLANE 183, SOLID 186/SOLID 187 or 18x element classes in ANSYSAPDL (Thomas and Erke, 2004).

4. Rotor Blade Model Description

The CAD modelling of rotor blade carried out using SolidWorks 2015 premium. The blade was sized based on single seat open frame high-wind-start gyrocopter. NACA 8H12 and NACA 9H12 airfoils are the most commonly used main rotor blades in gyroplanes. NACA 8H12 unsymmetrical rectangular cross-section airfoil were selected for this research. A uniform span wise distribution of airfoil and usually is not twisted cross sectional profile (Fig. 1).

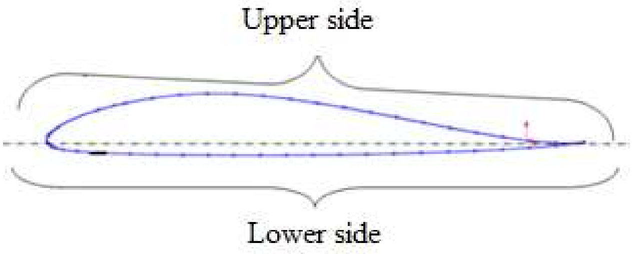

Fig. 1. NACA 8-H-12 airfoil profile

The coordinates to develop the airfoil profile is given in Table 1. provided by NACA (Stivers and Rice, 1946; Stalewski, 2016).

Structural parts of the rotor blade:

The rotor blade structural elements (shown in Fig. 2) are:

1. Shell: is the outer blade skin of the rotor blade which supports aerodynamic pressure distribution from which the lifting capability of the blade is derived. These aerodynamic forces are transmitted in turn to the ribs by the skin.
2. Ribs: are used to carry transverse load acting on the blade. The ribs provide the necessary aerodynamics shape required for generation of lift by the gyrocopter. Ribs maintain structural stiffness and transfer loads from blade skin to spar elements.
3. Spar: is made of steel rod, its primary function is to support longitudinal load and to increase stored energy at the time of rotation of free spinning blade.

The total span length of the blade and cord length of 7.5 m and 0.2 m respectively. The thickness of blade at outer shell is 0.003 m and ribs were modeled by offsetting 0.003 m from outer dimension of the airfoil. The spar having 0.006 m diameter; passing through the length of the rotor blade with 27 percent of chord length along the side of leading edge for increase in longitudinal strength of the blade and to store rotational energy.

Table 1. NACA 8-H-12 Coordinate points for gyrocopter blade airfoil profile

	Upper Side		**Lower Side**	
S. No.	**X**	**Y**	**X**	**Y**
1	0.0000	0.0000	0.0000	0.0000
2	0.0036	0.0152	0.0114	-0.0095
3	0.0080	0.0201	0.0169	-0.0112
4	0.0198	0.0294	0.0302	-0.0141
5	0.0442	0.0431	0.0558	-0.0174
6	0.0691	0.0538	0.0809	-0.0192
7	0.0943	0.0626	0.1057	-0.0206
8	0.1450	0.0763	0.1550	-0.0224
9	0.1961	0.0860	0.2039	-0.0226
10	0.2475	0.0924	0.2525	-0.0242
11	0.2979	0.0953	0.3003	-0.0245
12	0.4029	0.0903	0.3971	-0.0249
13	0.5039	0.0767	0.4961	-0.0244
14	0.6036	0.0585	0.5964	-0.0229
15	0.7025	0.0585	0.7988	-0.0164
16	0.8011	0.0189	0.8998001	-0.0105
17	0.9001999	0.0034	0.9500	-0.0063
18	0.9499	0.0012	1.0000	-0.0000
19	1.0000	0.0000	-	-

(Source:http://airfoiltools.com/airfoil/details?airfoil=n8h12-il])

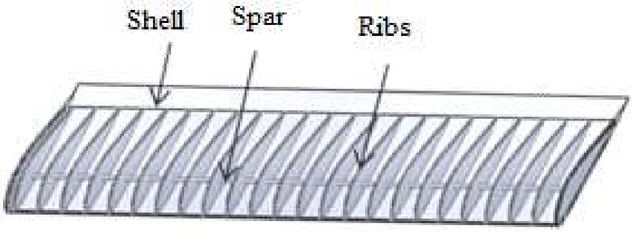

Fig. 2. Structural parts of gyrocopter main rotor blade

5. Analysis

5.1. Composite Material Failure Criteria

The choice of failure criteria is very important for different types of failure, which will lead to alter the results. Failure theories for composite lamina can be classified into three distinct groups:

1. Non-Linear or Limit Theories: failure modes are predicted by comparing individual stresses or

strains with respect to ultimate stresses and strains. However, such theory does not account for interplay between different stresses components. Examples of such theories are maximum stress criteria and maximum strain criteria.

2. Interactive Theories: this theory goes a further step ahead than limits theories, and accountability of interaction between various stress/strain components were considered. Examples of such theories are those of Tsai-Hill.

Failure Mode Based Theories: these theories provide separate criteria for failure of matrix, fiber and interface. Examples of such theories are those of Puck and Hashim-Rotem (Nachiketa, 2013).

Tsai-Wu is investigated the stresses along the material direction using layer-by-layer basis. This theory is an interactive theory and popularly used. The most important of this is Tsai-Hill Criterion, which is an adaptation of the Von Mises Criterion (Nachiketa, 2013). Due to the abovementioned advantage, Von Mises stress failure criterion is selected for this investigation.

5.2. Boundary Condition and Blade Loading

ANSYS finite element software package is used to investigate the proposed three models as listed in Table 2 to arrive an optimum model by looking into the results of stress and deflection.

Table 2. Proposed alternative models for the gyrocopter main blade

Model	Description	Remark
I	Rotor blade shell part only	Ribs and spar is not considered
II	Rotor blade and ribs	Spar element is not considered
III	Rotor blade shell, ribs and spar element	All elements are considered

At the root of the rotor blade, the connection to the hub was considered as rigid (all DOF zero) and free at the opposite end as illustrated in Fig. 3 (shown in Appendix). Mesh is very dense at the location where the loading is applied. Refined mesh size at the far boundaries is not so important referring to Fig. 4 (shown in Appendix). By default, ANSYS tool is refine the meshes at a point of applied load and the areas of stress concentration.

Blade loads which affect severely are considered in this analysis. Major loads are acting on the blade during operating at normal conditions are as follows:-

1. *Centrifugal Force*: Rotating objects exert high amount of centrifugal force to keep an object in a circular path.

$$\mathrm{Fc} = \mathrm{m_b}(\omega^2)\mathrm{r_{CG}} \qquad (1)$$

where,

Fc - Centrifugal force

ω- Angular speed of rotor blade $\mathrm{r_{CG}}$-Blade center of gravity from the axis of rotation.

For single seat gyrocopter the amount of centrifugal force is estimated 188.1 kN at maximum speed 380 rpm/ 40 rad/s (Derbew et al., 2015).

2. *Air Load (Pressure Load)*: To produce sufficient lift high pressure exists over the bottom surface while a low pressure exists on the top surface of the blade.

Assuming steady air loads condition and the air load force is calculated using equ.2:

$$\mathrm{F_a} = \frac{1}{2}\rho a c\omega^2 R^2 \Delta r \left(\theta x^2 + \lambda x + \frac{\mu\theta^2}{2} + \frac{\mu^2 b}{4}\right) \qquad (2)$$

where,

$\mathrm{F_a}$= air load distribution force, [N]

x = Blade station = $\frac{r}{R}$

R = Radius of rotor disk, [m]

θ= Blade pitch, [rad]

λ= In flow ratio

μ = Tip speed ratio

Δr = Length of blade element, [m]

ρ= Mass density of air, [kg/m3]

a=Blade element lift slope, [per rad]

b = Profile cord-wise, [m]

c = Mean chord of blade element, [m]

The variation of air load generated by pressure variation from the root to the tip of the rotor blade is 3kN. However, there is variation to simplify the finite element analysis; the maximum constant pressure load value is taken 25 kN at blade tip.

3. *Self-Weight*: Due to the self-weight of the blade considerable amount of load acts on the blade in downward direction.

The mass of the blade calculated by the formula given by Eq. (3). (Sairajan, et. al 2005).

$$\mathrm{m_b} = \frac{\frac{1}{20}\mathrm{GWT}(0.15\mathrm{B_n}+0.7)}{\mathrm{R}\,\omega^2} \qquad (3)$$

where,

m_b = Mass of single blade = 10 kg

GWT = Gross weight of gyrocopter = 325 kg

B_n = Number of blades = 2

6. Results and Discussion

The boundary condition, mesh size, blade loading and initial setups are the same for all three proposed models refer Fig.3. However, Von Mises stress results (Fig.5, Fig.8, and Fig.11 - shown in Appendix), total deformations (Fig.6, Fig.9, and Fig.12 - shown in Appendix), and directional deformation along y direction (Fig.7, Fig.10, and Fig.13 - shown in Appendix), were obtained for each design alternatives. Irrespective of the alternative models the maximum Von Mises stress result showed at the root (hub) of the blade. In addition the maximum deflection occurs at the tip of the blade during operation as indicated on the contour plot. The deflection and stress levels are shown from minimum to maximum in the colour contours. Their values are given in Table 3.

Table 3. Summary of finite element result

Model Type	Von Mises stress [MPa]		Total deformation [m]	Directional deformation along y- axis [m]	Location of Max. stress
	[Min.]	[Max.]			
I	4.0780	856.79	2.73230	2.73050	Shell
II	0.0134	373.18	0.85390	0.85347	Ribs
III	0.0005	225.11	0.26011	0.25989	Spar

In all three models, finite element analysis was carried out. The study result showed that Von Mises stress, total deformation and directional deformations. The maximum directional deformation resulted along 'y' direction.

Model I is represented by composite outer shell element without ribs and spar, refer Table 2 has found maximum Von Mises stress of 857 MPa (Table 3.) occurring at shell part and the blade deformation is 2.7323 m which is very large comparing to the allowable values.

Model II having blade with ribs and without spar refer Table 2 the maximum Von Mises stress is found within the permissible limit, whereas the maximum directional deformations are still larger.

According to Sairajan et al. (2005) the permissible stress and deflection were 1800 MPa and 0.3 m respectively. Both the minimum and maximum Von Mises stresses acting on the spar. Since spar material has yield strength of 420 MPa. Hence it can handle the maximum induced Von Mises stress of 225.11 MPa.

Even though all the three models represent the same blade made of same material and loading condition, the finite element analysis result is far among the models as it shown in Table 3. The total deformation in model I is higher by 10.5 percent and in Model II by 3.3% comparing to Model III. Similarly the induced stress is 3.8 percent and 1.7 percent higher. Both the total deformation and induced stress in Model I and Model II is higher than Model III. This is due to the fact that the ignored structural part has a significant role in load carrying. Modeling by neglecting parts will over estimate the total deformation and induced stress. Consequently this leads to over design and large volume of material consumption. It can be understood that properly modeling of gyrocopter blade is the most critical step, every designer should give greater attention to design with competent price without compromising the intended product quality.

Developing a gyrocopter main rotor blade made of light weight will reduce the overall mass of the system. This is usually neglected during the design stage and considering this ignored part is enhancing the accuracy of design. Hence Model III is considered all structural blade elements, shell, ribs and spar which improve the design quality. So that, the over design will no more be a factor to decrease in efficiency.

Because of the gyrocopter blade rotates by auto, the less weight is required less fuel and get started at early speed of the engine rotor. The pay load capacity of such design gyrocopter will increase with the same engine capacity. This is due to the reduction in self weight. The performance will be improved and provide relatively simple maneuverability of a gyroplane.

7. Conclusion

This work is an attempt to optimize the design of composite gyrocopter rotor blades with minimum material cost and optimum blade mass. It is obvious that the rotor blade with 25 numbers of ribs and a spar (Model III) can handle the actual loads with adequate safety margin recommended for ultra-light gyrocopter by Federal Aviation Association (FAA).

The result shows that neglecting structural elements like ribs and spar at the time of modelling will lead to the occurrence of over-design. Hence, the mass and cost of the blade will increase, and the blade performance gets affected. The model proposed in this research improves the quality of the product and increase the performance. Moreover the operating efficiency will be improved. The significance by considering all the parts of rotor blade are provides in the stress and deflection analysis gives a realistic result during the analysis. The results show that the induced stress and deformation is less by considering the ignored parts. Hence this is an optimized safety; cost and quality of the product.

Over design were increases the self weight and strength of the structure beyond the design capacity and thereby increase the cost, volume of material consumption, and operational efficiency.

The presented methodology seems to be a much wider potential for future applications. The researchers recommend to investigate the blade static strength, dynamic strength and delimitation through experimental study in future.

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Yonas Mitiku Degu is Assistant Professor of Mechanical Engineering, Institute of Technology, Bahir Dar University, Bahir Dar, Ethiopia. He received his B.Sc. in Mechanical Engineering from Bahir Dar University, Bahir Dar, Ethiopia in 2005; pursued M.Sc. in Applied Mechanics (Mechanical Design) in Addis Ababa University, Addis Abeba, Ethiopia in 2008. Author of several articles, books chapter and participated in several international conferences. He supervises many MSc. Students projects (thesis). His research interests are composite materials and product design and development.

Derbew Alebel Sisay is a pilot in Ethiopian airlines, Addis Abeba, Ethiopia. He received his B.Sc. in Mechanical Engineering from Bahir Dar University, Bahir Dar, Ethiopia in 2013. He has one year teaching experience as Assistant Lecturer.

Appendix

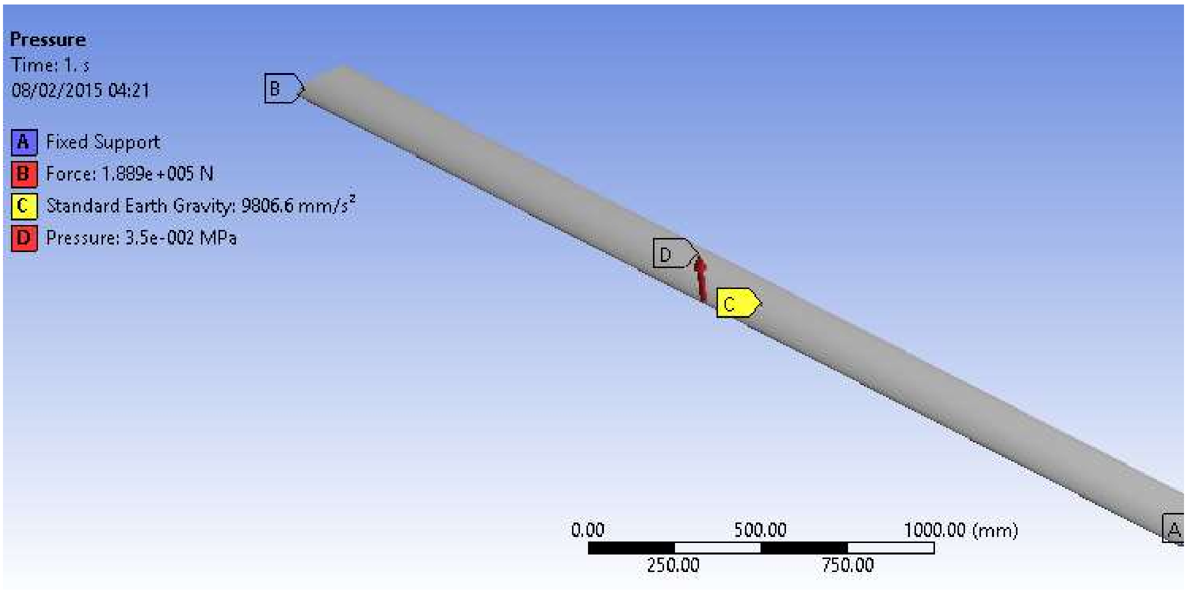


Fig. 3. Gyrocopter main rotor blade boundary condition and loading

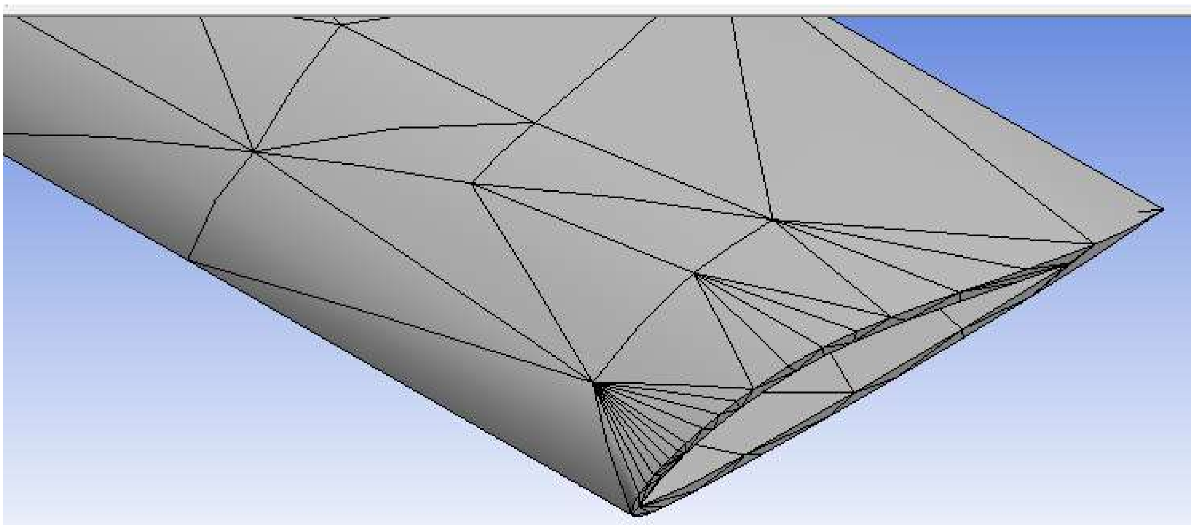


Fig. 4. Meshed rotor blade model (magnified image)

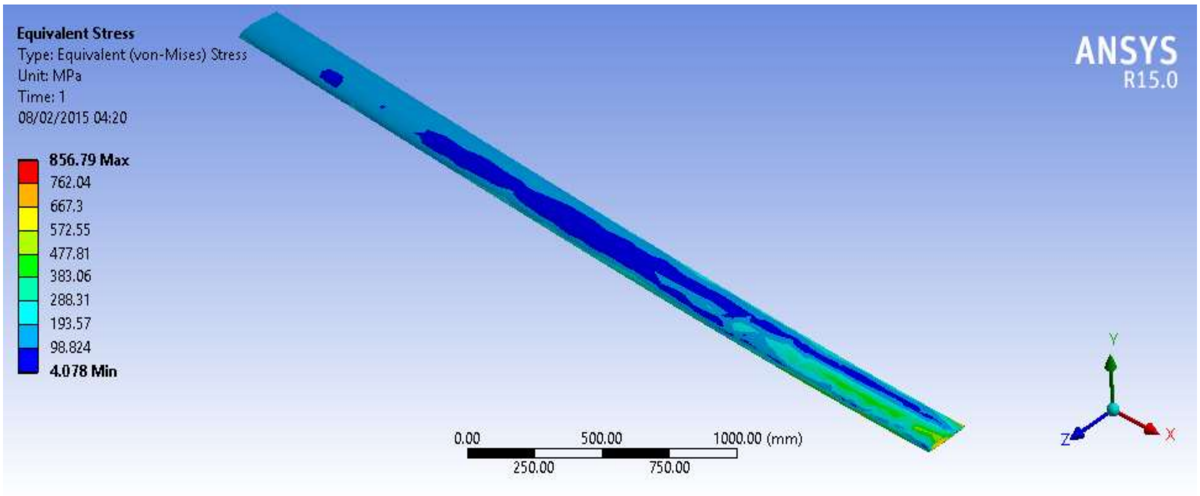


Fig. 5. Von Mises stress result counter plot of Model I

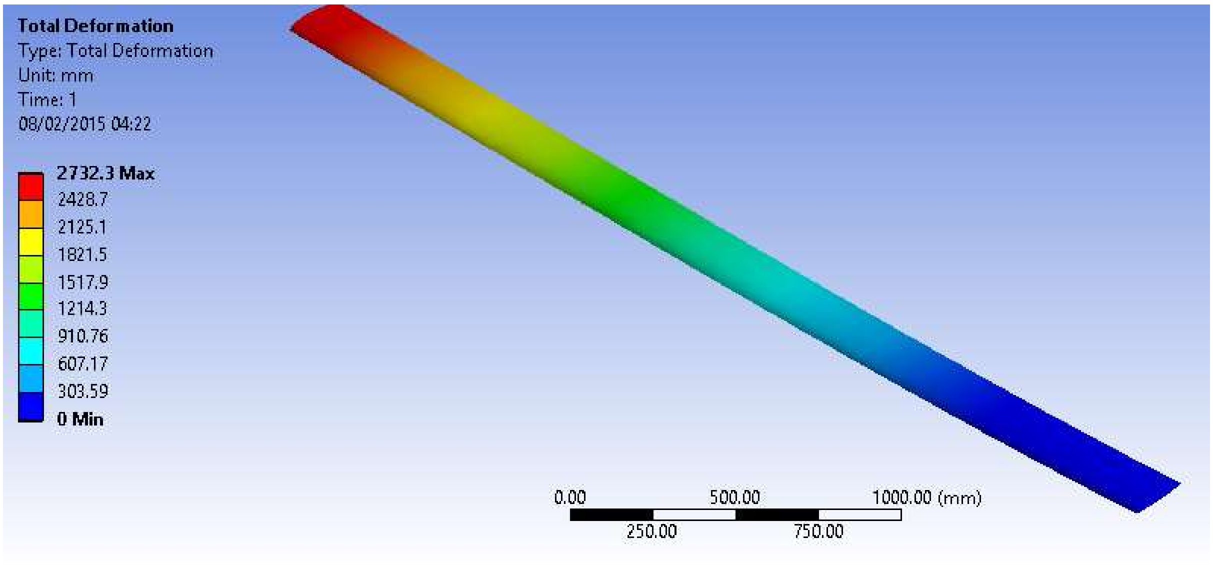


Fig. 6. Total deformation result counter plot of Model I

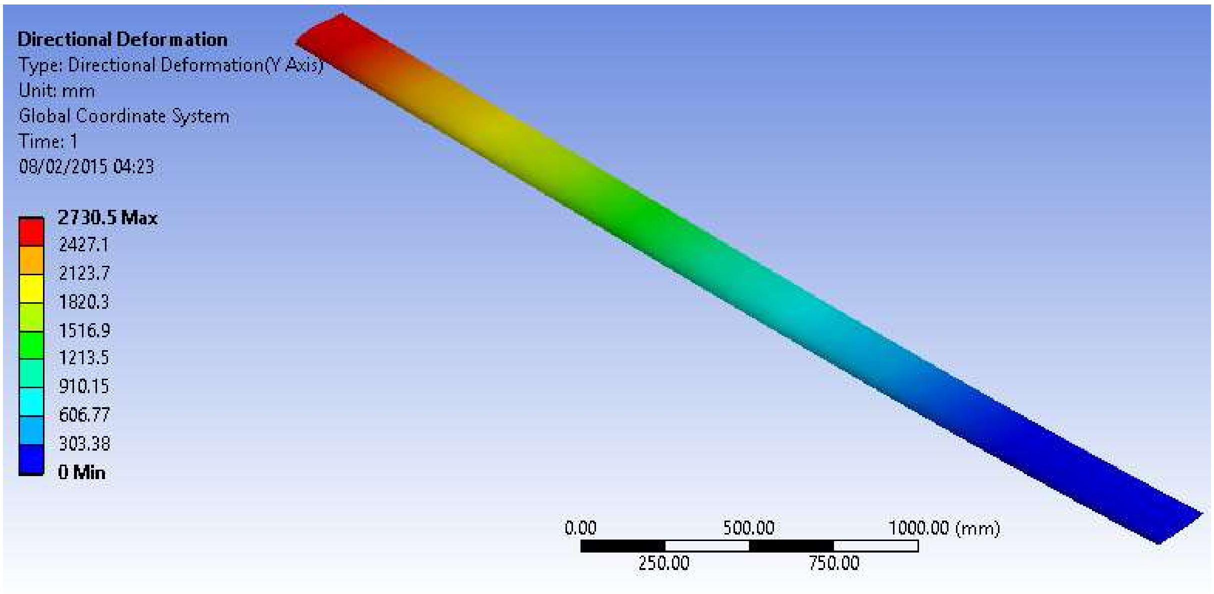


Fig. 7. Directional deformation along y-axis result counter plotof Model I

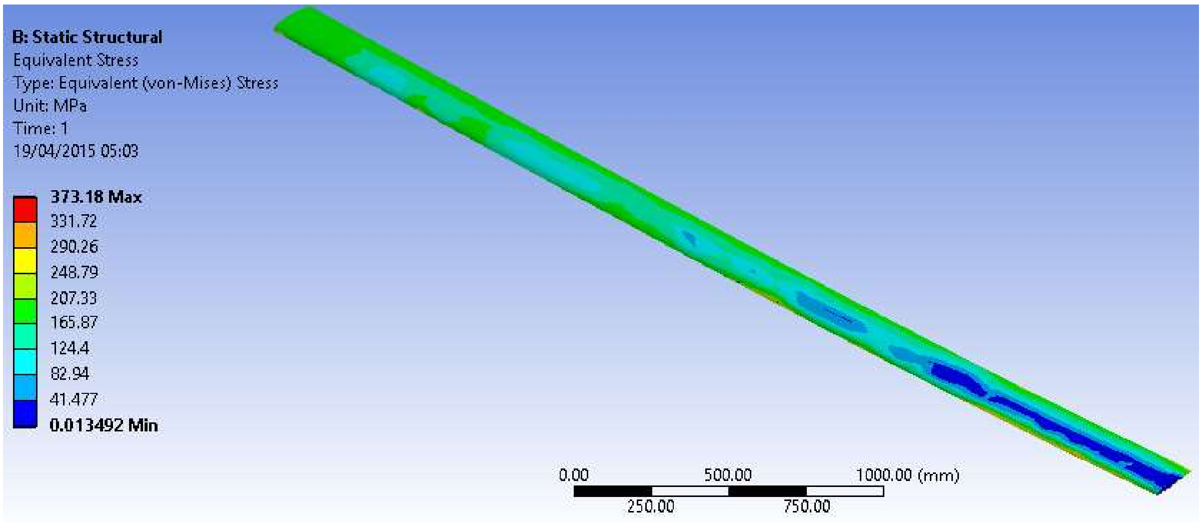


Fig. 8. Von Mises stress result counter plot of Model II

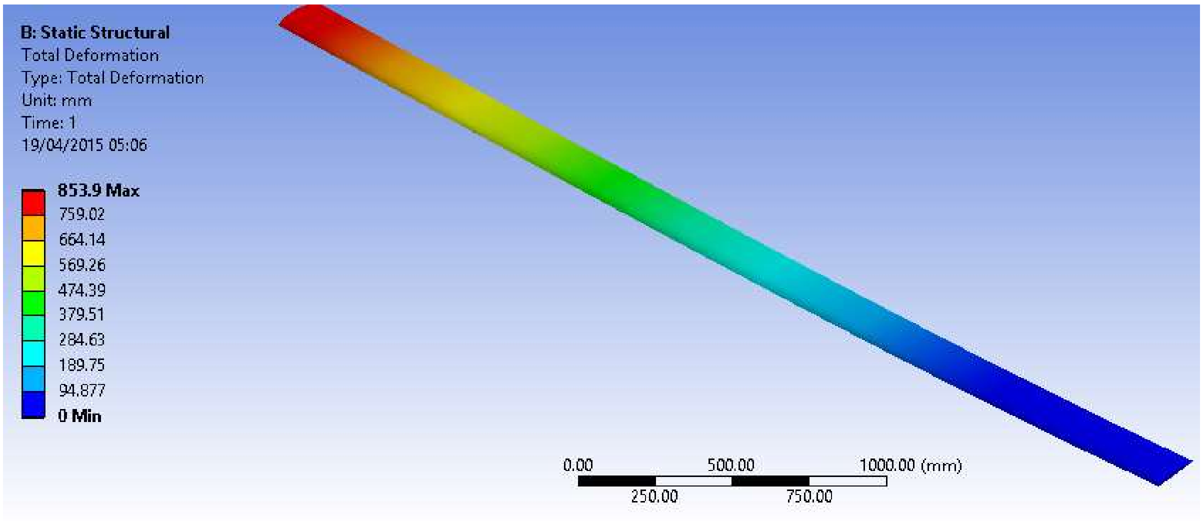


Fig. 9. Total deformation result counter plot of Model II

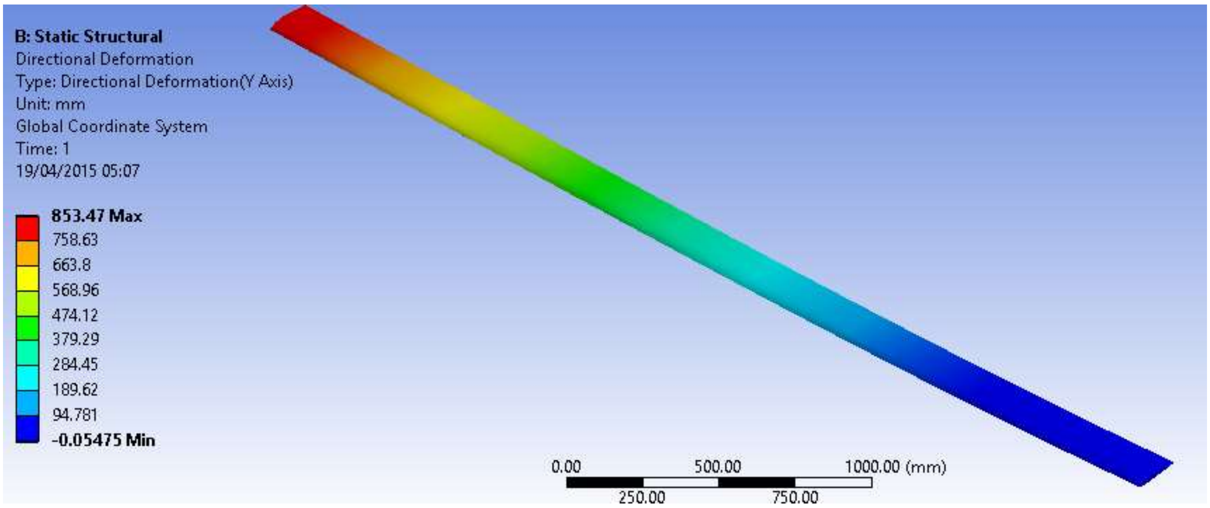


Fig. 10. Directional deformation along y-axis result counter plot of Model II

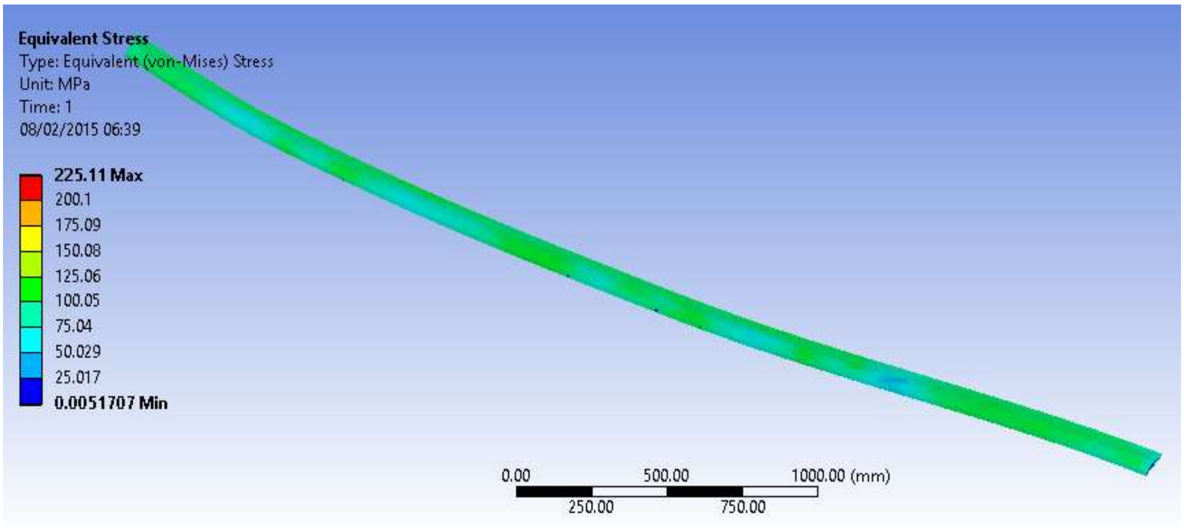
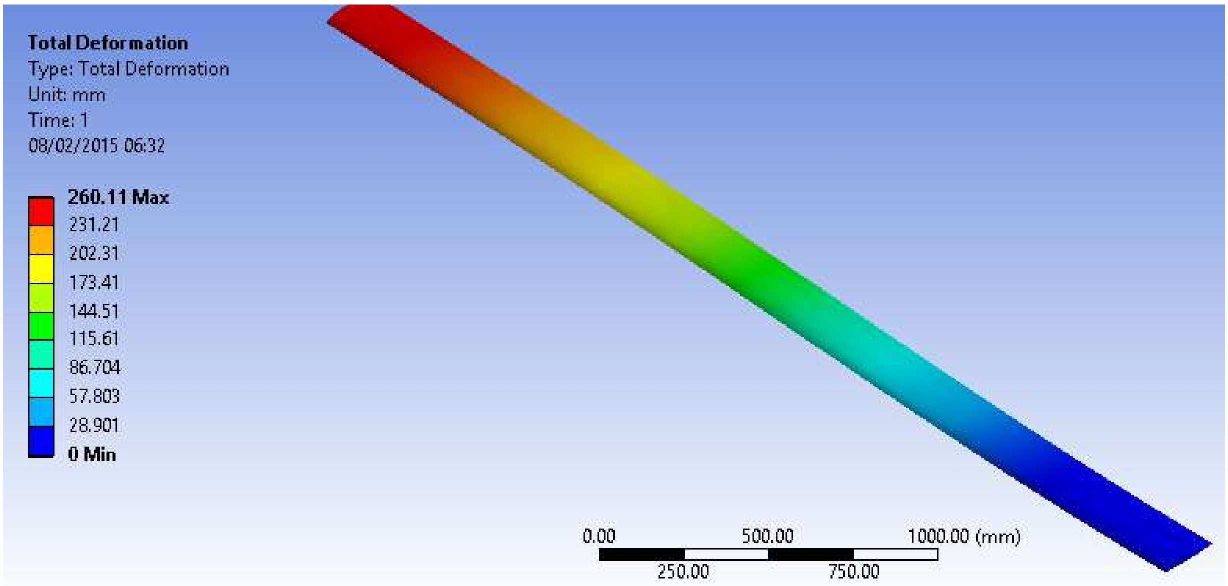
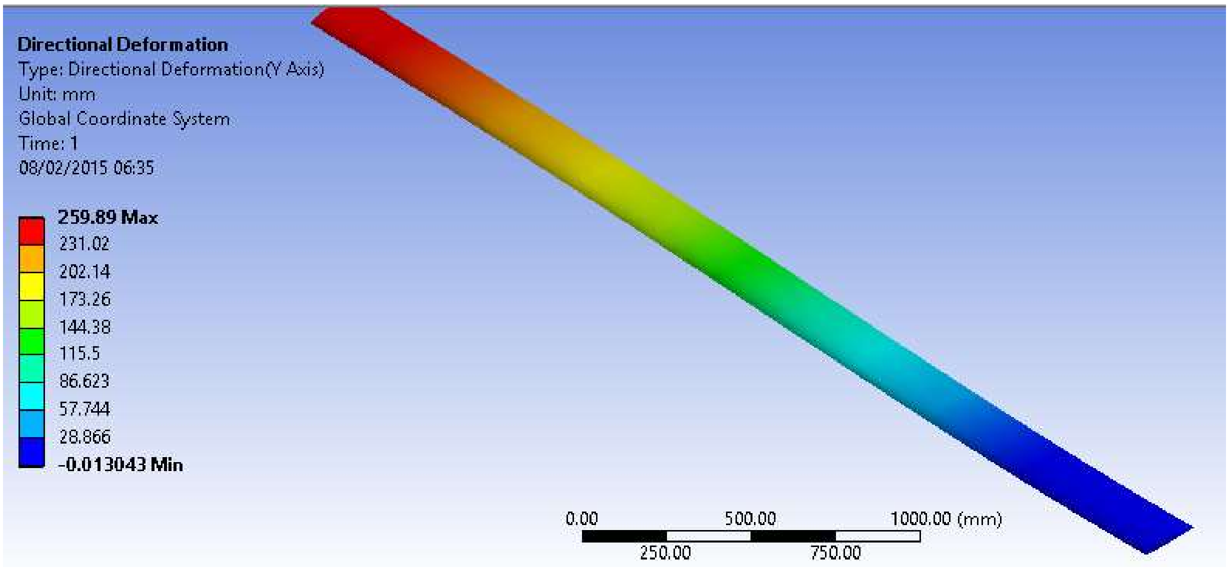


Fig. 11. Von Mises stress result counter plot of Model III



Total Deformation
Type: Total Deformation
Unit: mm
Time: 1
08/02/2015 06:32

Fig. 12. Total deformation result counter plot of Model III



Directional Deformation
Type: Directional Deformation(Y Axis)
Unit: mm
Global Coordinate System
Time: 1
08/02/2015 06:35

Fig. 13. Directional deformation along y-axis result counter plot of Model III