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DETERMINING HELICOPTER BLADE LENGTH PER AIRWORTHINESS STRENGTH REQUIREMENT

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DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

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Date:

STATEMENT 1

This thesis is the result of my own investigations, except where otherwise stated. Other sources are acknowledged by giving explicit references. Bibliography/references are appended.

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NOMENCLATURE

L	:	Lift force [N]
F_c	:	Centrifugal force [N]
v	:	Linear speed [ms^{-1}]
A	:	Area [m^2]
a	:	Centripetal acceleration [ms^{-2}]
C_L	:	Lift coefficient
ρ	:	Mass air density [kgm^3]
m	:	Section mass [kg]
x	:	Radial position [m]
ω	:	Angular speed [$rads^{-1}$]
r	:	Radius of rotation [m]

MENENTUKAN PANJANG BILAH HELICOPTER BAGI MENEPATI KEPERLUAN KEKUATAN KELAYAKAN TERBANG

ABSTRAK

Kertas ini menunjukkan kaedah untuk menentukan panjang bilah pemutar logam helikopter beroperasi pada 500 RPM (putaran per minit) bagi memenuhi keperluan kekuatan kelayakan terbang. Untuk mencapai matlamat ini, analisis tegasan telah dijalankan pada panjang bilah yang berbeza menggunakan SOLIDWORKS 2016 x64 Edition. Aerofoil NACA 8-H-12 dengan panjang kord seragam 5.25 inci dipilih; sesuai sebagai bahagian bilah pemutar untuk helikopter dan pesawat putar-sayap lain berdasarkan kajian sebelum ini. Keupayaan struktur untuk menahan beban operasi maksimum dilihat dan dikaji. Projek ini hanya menganalisa terhadap bilah pemutar helikopter yang dipasang tegar (diapit diakar). Keputusan yang diperolehi daripada analisis menunjukkan bahawa 2 m (78 in) panjang bilah rotor ialah panjang yang boleh diterima dan memenuhi keperluan kekuatan kelayakan terbang.

ABSTRACT

This paper demonstrates a methodology to determine the length of a metal helicopter rotor blade operating at 500 RPM so that it fulfills the airworthiness strength requirement. To achieve this, stress analyses were performed on different blade length using *SOLIDWORKS 2016 x64 Edition*. The NACA 8-H-12 airfoil sections with a 5.25 inches uniform chord length was chosen; suitable as rotor-blade sections for helicopters and other rotary-wing aircraft due to previous investigation. The capability of the structure to withstand maximum operating load were observed and checked. Focusing only for rigidly mounted (clamped root joint) helicopter rotor blade analysis. Result obtained from the analysis showed that 2 m (78 in) length of rotor blade is acceptable length and fulfills the airworthiness strength requirement.

1.0 INTRODUCTION

Main rotor blades are slender, flexible beams. The rotating blades deform structurally and interact with unsteady air flow and control systems. To deal with this complex multidisciplinary design, many researchers have employed optimization techniques to trade off among the disciplines of aerodynamics, dynamics, structure acoustics, and control. Optimization methods were introduced to helicopter design from the early 1980s [1]. Friedmann [2] summarized the early research of vibration reduction on helicopters using structural optimization. Celi [3] and Ganguli [4] provided further reviews rotorcraft design optimization. A more recent review of multidisciplinary design of rotor blades can be found in Ref. [5].

Yuan and Friedmann [6] and Ganguli and Chopra [7] focused on forward flight vibratory load reduction at the hub subject to frequency and aeroelastic stability constraints. Kim and Sarigul-Klijn [8, 9] developed a multidisciplinary optimization method that strived for minimum weight and vibration and maximum material strength of the blade with a constraint to avoid flutter. Soykasap [10] focused on aeroelastic optimization for composite tilt rotor blades. Ozbay [11] investigated the potential of the star cross-section to tailor extension-twist coupling for tilt-rotor blades.

The optimization model includes design objectives, constraints, assumptions, and variables. Currently, in rotor blade structural design, it is quite popular to assume a specific topology of structural components inside a given airfoil shape. This sort of assumption reduces the problem to a sizing optimization in which one varies dimensions, orientations, and locations of structural components to achieve the desired sectional properties.

Some researchers did not assume any specific connectivity and designed the cross-section layout from scratch. This design concept is called "topology optimization." [12] Using this concept, Fanjoy and Crossley, [13] minimized the distance between the shear center and point of load application for a given airfoil; but, as the authors pointed out, the computational load was significant. Arora and Wang [14] reviewed alternative formulations for optimization of structural and mechanical systems, including configuration and topology design, and discussed features of various formulations. Compared to sizing optimization, topology optimization provides innovative cross-sectional layouts that can meet requirements for sectional properties. However, the resulting layouts from topology optimization need to be refined by sizing or shape optimization [12]. As computing capability increases continuously, topology optimization is attracting more attention.

Strivers and Rice [15] investigate on aerodynamic characteristics of four NACA airfoil sections designed for helicopter rotor blades. The characteristics of airfoil that are suitable for use as rotor blade sections are pitching moment is nearly zero, low drag throughout the range of low and moderate lift, and moderate drags at high lifts. However, there are some undesirable characteristic such as, lift-curve slope, sensitivity to roughness and abrupt adverse changes in drag, and pitching moment in the vicinity of the high-lift end of the range of low drags. Strivers and Rice is have conclude that NACA 8-H-12 and 9-H-12 airfoil sections seem to be more promising for use as rotor blade than any other airfoil that have been tested at the NACA laboratory.

Taylor [16] considered a propeller blade as a cantilever rigid at the boss. Conolly [17] combined theory and with experimental work for wide blades. Chang Suplee [18] investigated the main sources of propeller blade failure and determined the problems that is related to blades symmetrically. Beet [19] studied the interference between the stress conditions in the propeller blade and the hub. Colcough [20] examined the advantages of a composite propeller blade with fibre reinforced plastic over that of the propeller blade made from variety of other materials. Lin [21] executes stress calculations for fibre reinforced composite thrust blade.

2.0 METHODOLGY

Federal Aviation Regulations (FARs) prescribed by the United States of America Federal Aviation Administration are used here.

Below are some statements from the **FARs**:

FAR 25.303:

> Unless otherwise specified, a factor of safety of 1.5 must be applied to the prescribed limit load which are considered external loads on the structure. When a loading condition is prescribed in terms of ultimate loads, a factor of safety need not be applied unless otherwise specified.

FAR 25.305 (a):

> The structure must be able to support limit loads without detrimental permanent deformation. At any load up to limit loads, the deformation may not interfere with safe operation.

FAR 25.305 (b):

> The structure must be able to support ultimate loads without failure for at least 3 seconds. However, when proof of strength is shown by dynamic tests simulating actual load conditions, the 3-second limit does not apply.

From the **FARs** stated above, structure can:

- use ultimate factor of safety of 1.5 in general.
- have no detrimental permanent deformation.
- support ultimate loads without failure.

As a summary, the structural maximum stress due to limit load must always be below of whichever is lower of the two strength conditions below:

1.
$$\begin{aligned} Ult.strength/\,factor\ of\ safety &= Ult.strength/1.5 \\ &= 2/3\ Ult.strength \end{aligned} \quad (1)$$

2. yield strength (cause detrimental permanent deformation).

Stress analyses were performed on 5 blade models with 6, 7, 8, 9, 10 feet length using Finite Element (FE) method with loading condition according to single fixed rotation speed. And from each analysis, the values of highest Von Mises, highest 1st principal stress were extracted and tabulated corresponding their length. Then, according to stress types and materials, plots of highest blade stress vs blade length were plotted separately. In the plots, in addition to highest blade stress curve, the limit allowable stress for each stress type was also included. Note: highest Von Mises stresses are limited by yield strength and highest 1st principal stresses are limited by at least a factor of safety of 1.5 to the ultimate strength according to airworthiness requirements.

So, the intersection of the highest blade stress curve and critical limit allowable stress line is regarded as the critical point. Hence, the corresponding blade length at this critical point is the maximum length for fulfilling the airworthiness strength requirement.

3.0 MODELING AND ANALYSIS

In performing the calculations, the Finite Element (FE) Method was employed. And the software SOLIDWORKS 2016 was utilized for the FE modeling and analysis.

3.1 Configuration and Materials

Figure 1 shows the picture of an actual NACA 8-H-12 rotor blade with a uniform chord length of 5.25 inches which was used as reference for the 3D analyses that were designed in SOLIDWORKS 2016 software. 6063-T6 aluminum is the material of the rotor blade with steel rod inside of the airfoil leading cell hole; realizing the best compromise between strength, extrudability, and cost; the thin-skinned cross section of the blade precludes the use of higher strength aluminums [22].

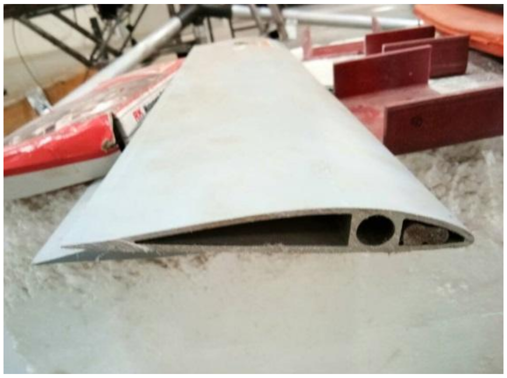

Figure 1: Model of rotor blade and its cross section

Material properties for aluminum and steel used.

Table 1: Properties of Aluminum Alloys (6063-T6)

Properties	Value
Density (kg/m^3)	2700
Yield Strength (MPa)	215
Ultimate Tensile Strength (MPa)	240
Elastic Modulus (GPa)	69
Shear Modulus (GPa)	25.8
Poisson’s Ratio	0.33

Table 2: Properties of Steel Alloy

Properties	Value
Density (kg/m^3)	7700
Yield Strength (MPa)	620.422
Ultimate Tensile Strength (MPa)	723.8256
Elastic Modulus (GPa)	210
Shear Modulus (GPa)	79
Poisson’s Ratio	0.28

3.2 Finite Element Modeling

Modeling of the blade was done using SOLIDWORKS 2016. In order to model the blade, it is necessary to sectionalize the blade at various radii as shown in figure 2.

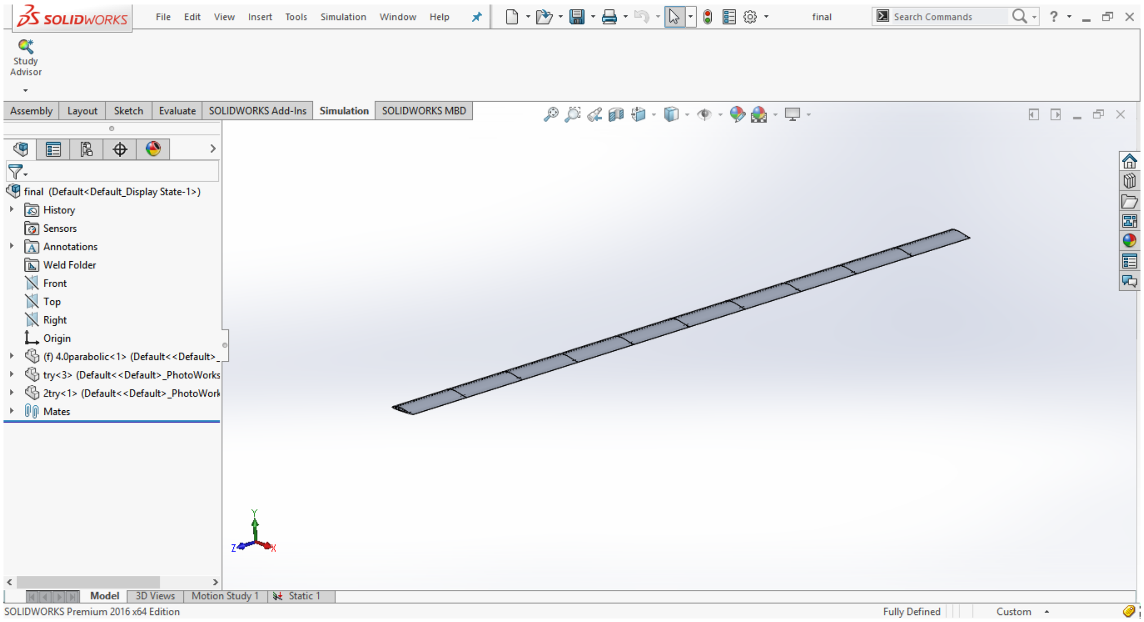

Figure 2: Shown sections on rotor blade

Maximum fine meshing option was applied and can be viewed as in the figure 3.

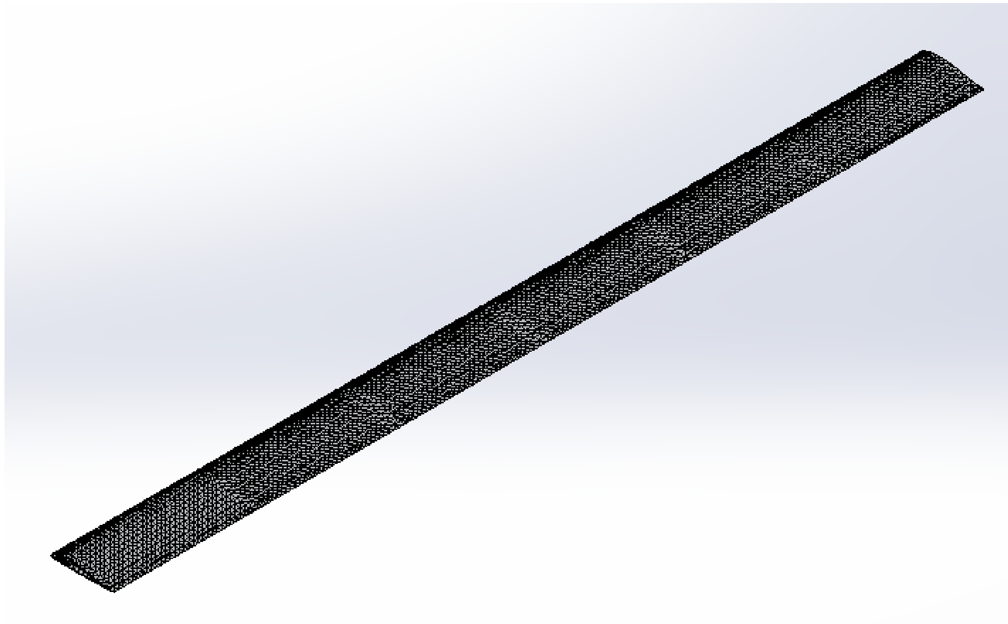

Figure 3: Picture of the fine mesh on the whole blade

The calculation of the stresses in a blade is extremely complicated, due to the fluctuating load, its distribution over the blade surface is difficult to calculate, and the geometry of the blade is rather complex. Therefore, simplified method was used to calculate the stresses in the blade and applied parameter for maximum case scenario.

The simple method is based on following assumptions:

i. The blade is assumed to be a cantilever fixed (clamped joint) at the root.
ii. The maximum rotational speed applied which would be 500 rpm.
iii. The lift force, L and centrifugal force, F_c on the blade is assumed to act through the surface of each section (as stated below).
iv. The value of lift coefficient, C_L mass air density, ρ and blade sectional mass, m would be applied are 0.85, 1.122e^{-7} lb sec^2/in^2, 0.003998016 lb sec^2/in.
v. Sectional length and chord length would be 12 in and 5.25 in, respectively.

Let x be the radial position of each sections, and the blade rotates at a ω (500 rpm) when developing lift forces, L.

The related formulas used are shown as follow.

$$L = C_L \frac{\rho}{2} v^2 A \quad (2)$$

$$F_c = ma \quad (3)$$

$$v = x\,\omega \quad (4)$$

$$A = sectional\ length \times chord\ length \quad (5)$$

$$a = x\,\omega^2 \quad (6)$$

Figure 4 shows plot of the lift forces acting at corresponding radial positions from the blade root to the tip while figure 5 shows the plot of section centrifugal force also acting from the blade root to the tip. These force values were input into the FE model for the analyses.

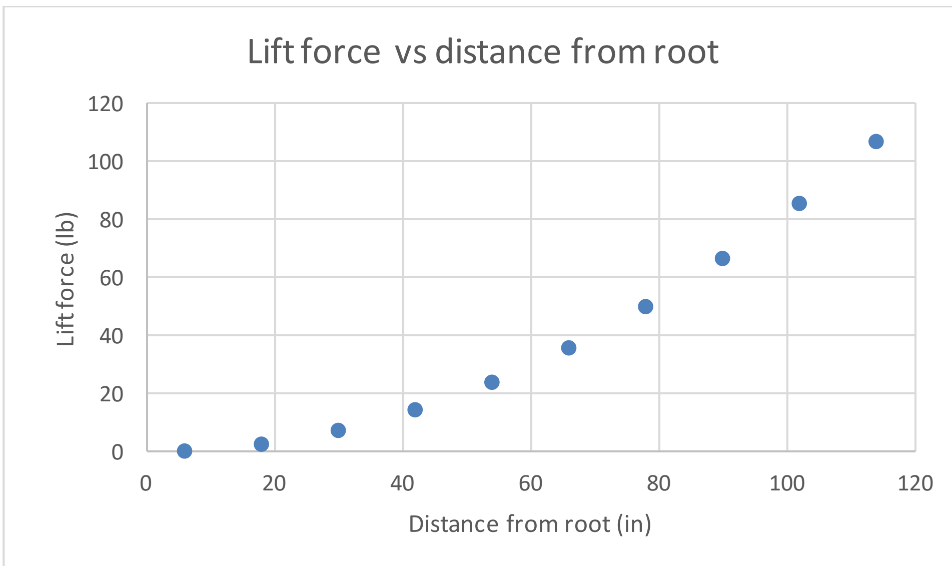

Figure 4: Graph of lift against distance from root

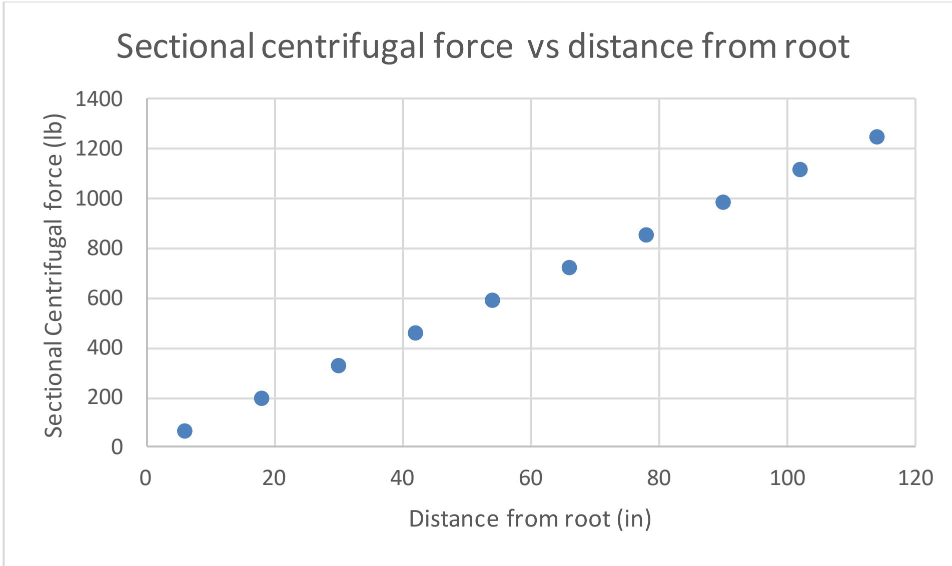

Figure 5: Graph of sectional centrifugal force against distance from root

3.3 Finite Element Analysis

As previously mentioned, the Finite Element (FE) Method utilizing software *SOLIDWORKS 2016 x64 Edition* was used for the analysis. Anticipating large displacement results in the analysis, two types of solution methods were done. The first type is implementing linear small displacement theory while the second type is applying geometrically non-linear displacement theory. The linear theory assumes small displacements. Hence, it applies the full load in one step. This approach may lead to inaccurate results or convergence difficulties in cases where these assumptions are not valid [24]. The result of analysis using small displacement theory was found to be invalid because of extremely large displacement. A large displacement solution gives more accurate results at the expense of taking more time than the small displacement solution. Note: The result of analysis using small displacement theory solution method was found to be invalid because of extreme displacement which does not representing reality. The results using large displacement theory solution method showed good outcomes and was validated by a simple analysis of a blade under gravitational force.

4.0 RESULTS AND DISCUSSION

The results of FE stress analyses are presented in the form of figures and tables. As samples, Figure 6 and 7 shows stress plots of Von Mises stress and 1st principal stress (maximum principal stress) for blade length of 7 ft, respectively.

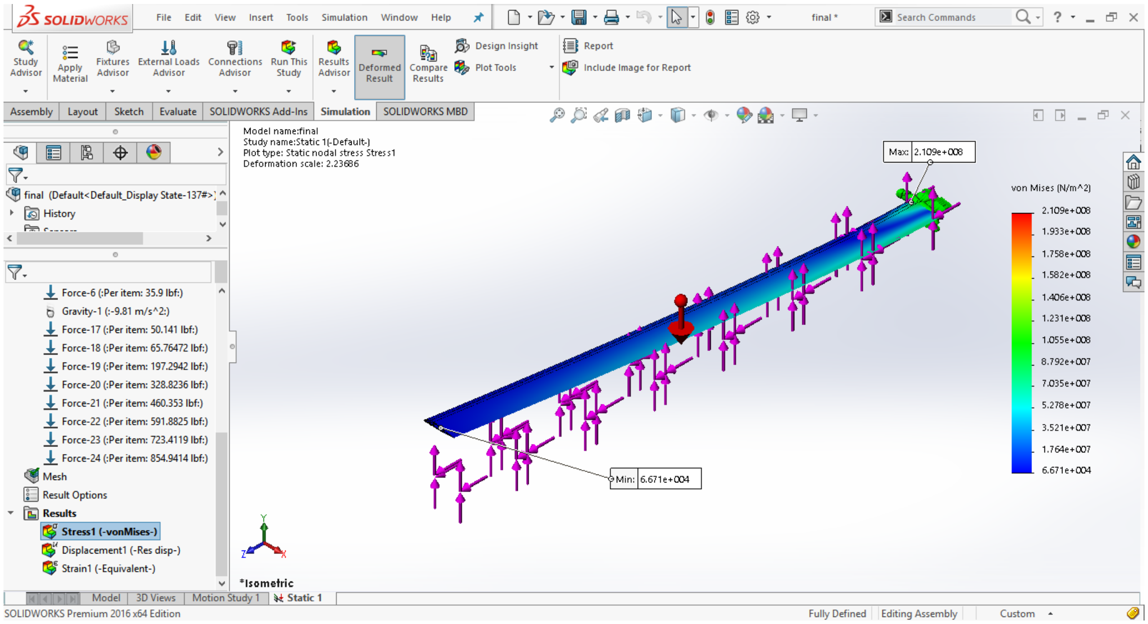

Figure 6: Von Mises Stress of rotor blade (7 ft length)

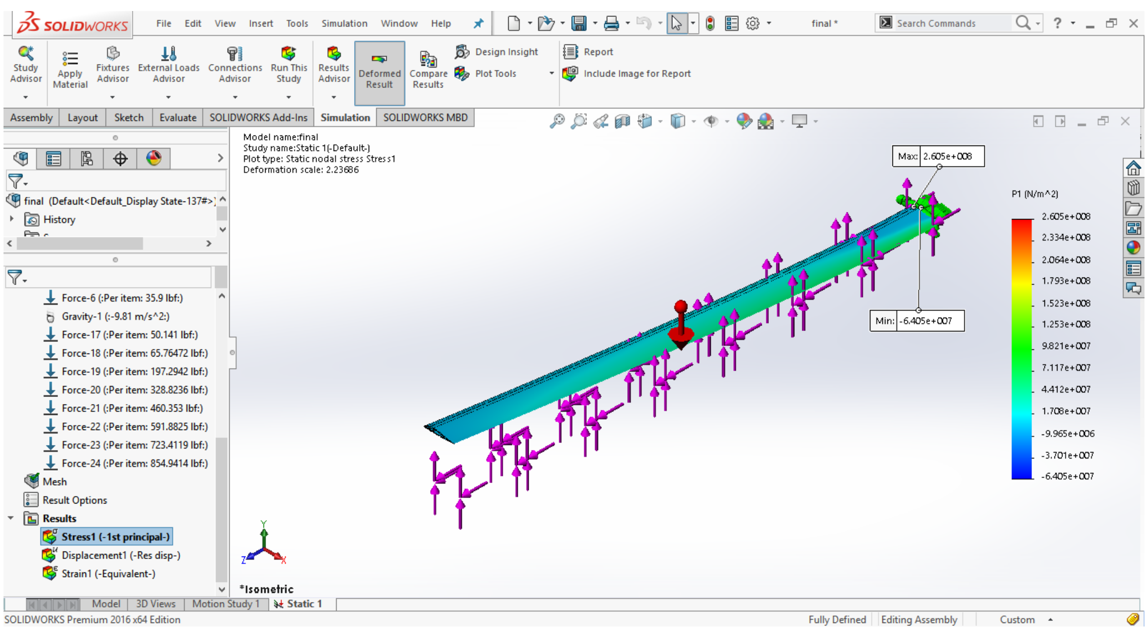

Figure 7: 1st Principal stress of rotor blade (7 ft length)

Highest stresses acting on steel material

The stresses are shown in table 3 and safety factors were checked; value of safety factors are shown in table 4. Figure 8 and 9 shows the plots of highest blade stresses against blade length for Von Mises stress and 1st principal stress respectively.

Table 3: Result of stresses of rotor blade

Length of blade (m)	**Von Mises Stress (MPa)**	**1^{st} Principal Stress (MPa)**
1.8288 (6 ft)	153.8	188.1
2.1336 (7 ft)	210.9	260.5
2.4384 (8 ft)	291.4	347.4
2.7432 (9 ft)	421.0	473.9
3.0480 (10 ft)	469.3	577.0

Table 4: Safety factor for each stresses

Length of blade (m)	**Safety Factor**	
	Von Mises Stress	**1^{st} Principal Stress**
1.8288 (6 ft)	3.92	3.85
2.1336 (7 ft)	2.86	2.78
2.4384 (8 ft)	2.06	2.08
2.7432 (9 ft)	1.43	1.53
3.0480 (10 ft)	1.28	1.25

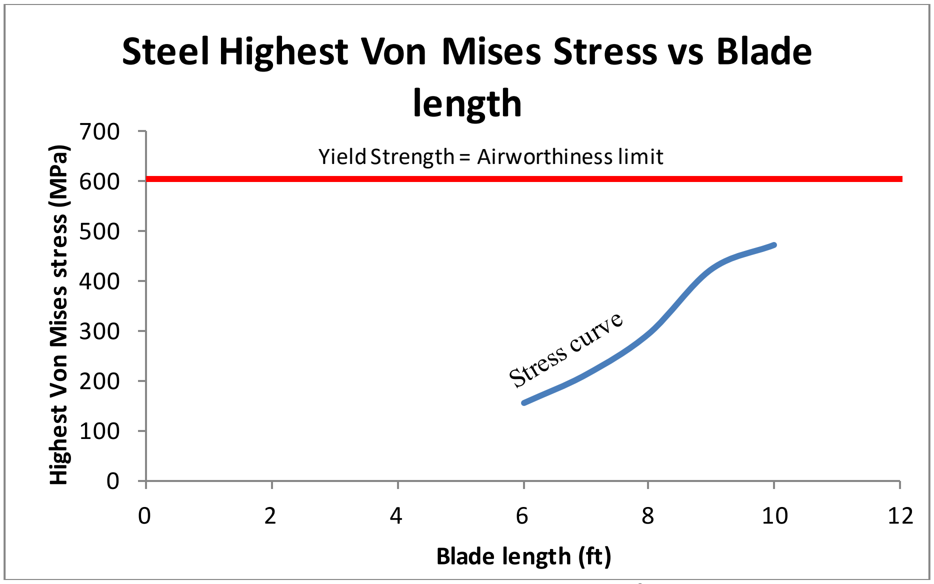

Figure 8: Highest Von Mises stress against length of the blade (steel)

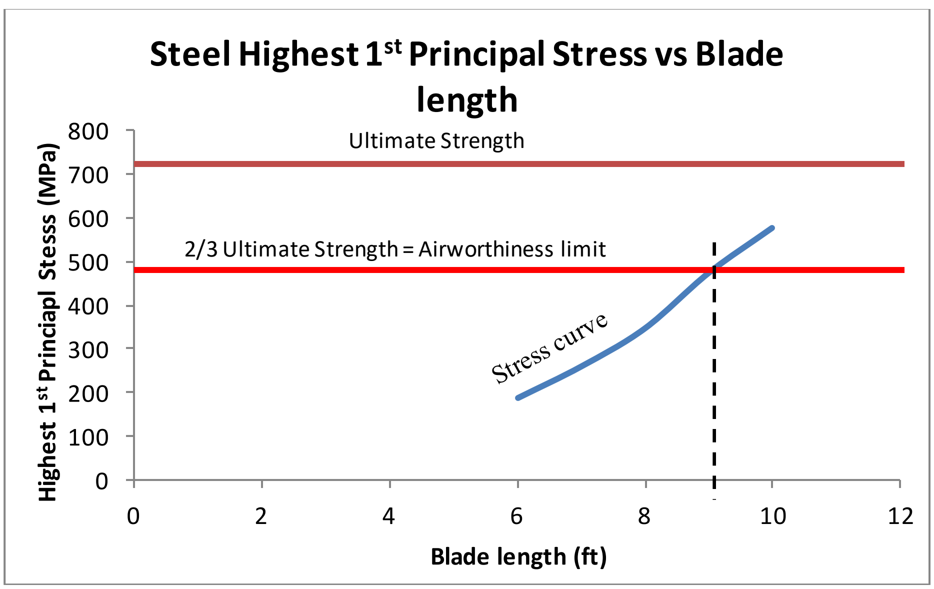

Figure 9: Highest 1st Principal stress against length of the blade (steel)

Highest stress acting on Aluminum material

The stresses are shown in table 5 and safety factors were checked; value of safety factors are shown in table 6. Figure 10 and 11 shows the plots of highest blade stresses against blade length for Von Mises stress and 1st principal stress respectively.

Table 5: Results of stresses of rotor blade

Length of blade (m)	Von Mises Stress (MPa)	1st Principal Stress (MPa)
1.8288 (6 ft)	941.5	121.9
2.1336 (7 ft)	124.4	187.4
2.4384 (8 ft)	167.6	227.8
2.7432 (9 ft)	305.5	315.4
3.0480 (10 ft)	251.3	365.4

Table 6: Safety factor for each stresses

Length of blade (m)	Safety Factor	
	Von Mises Stress	1st Principal Stress
1.8288 (6 ft)	2.28	1.97
2.1336 (7 ft)	1.73	1.28
2.4384 (8 ft)	1.28	1.05
2.7432 (9 ft)	0.70	0.76
3.0480 (10 ft)	0.86	0.66

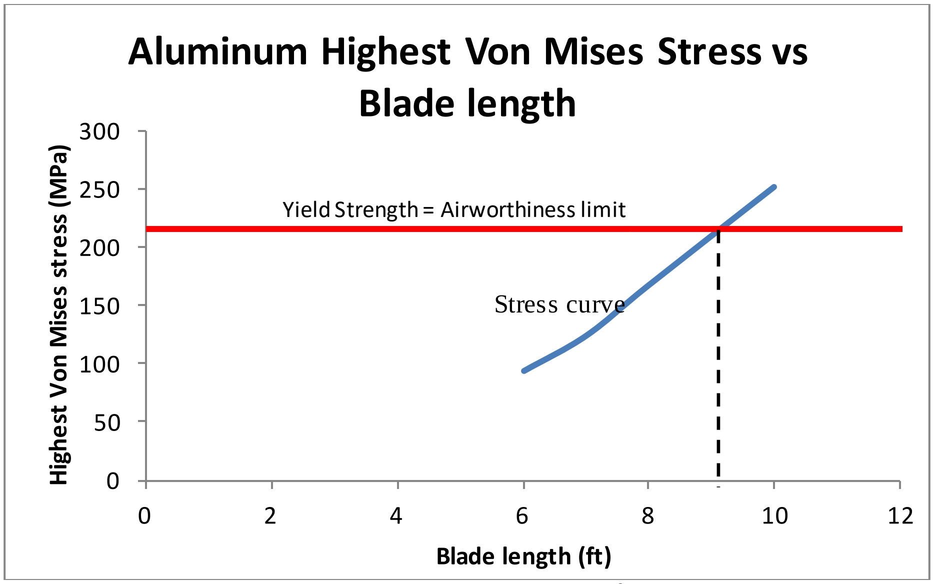

Figure 10: Highest Von Mises stress against length of the blade (aluminum)

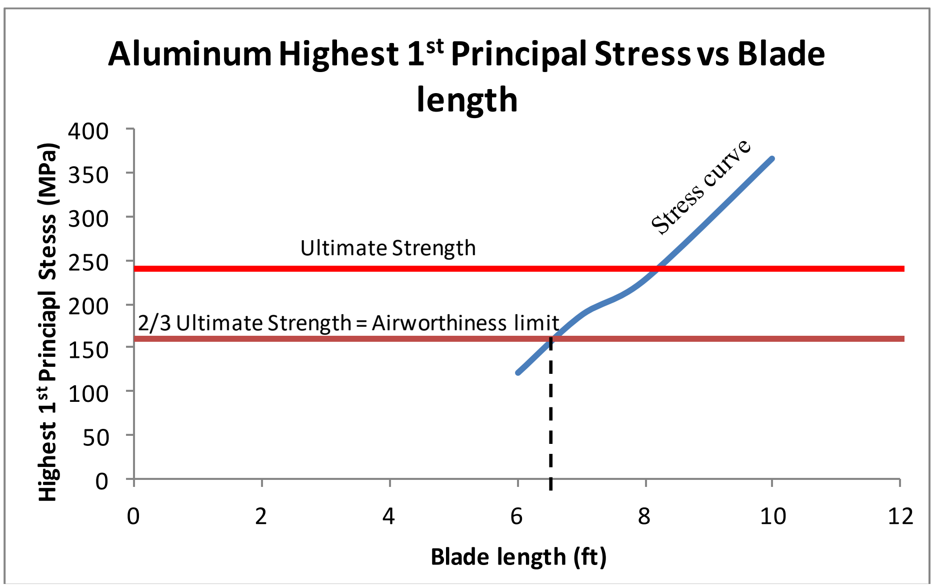

Figure 11: Highest 1st Principal stress against length of the blade (aluminum)

In general, as expected, the area near to the root of the blade has the highest stress for all the blade lengths. This is because of the cantilever beam support system that the blades are mounted. Here, the effective load and bending moment are highest as the summation or load reaction of centrifugal forces are highest and the moment arms are longest for the lift forces, noting that the longer the moment arm of a load on the structure, the more stress will experience at furthest area from the load.

Von Mises Stress

Based on observing figure 8 of the plot of the highest Von Mises stress for steel, the stress curve does not even reached the airworthiness limit line. As a result, steel rods which are part of the blade of the longest length (10 ft) analyzed fulfills the airworthiness strength requirement. However observing figure 10 of the plot of the highest Von Mises stress for aluminum, the stress curve intersects the airworthiness limit line at blade length of approximately 9 ft. So, in relation to Von Mises stress, the blade cannot be longer that approximate 9 ft to fulfill the airworthiness strength requirement.

1st Principal Stress

Looking at figure 9 of the plot of the highest 1st principal stress for steel, the stress curve intersects the airworthiness limit line at blade length of approximately 9 ft. So, in relation to 1st principal stress, the blade cannot be longer that approximate 9 ft to fulfill the airworthiness strength requirement. But, observing at figure 11 of the plot of the highest 1st principal stress for aluminum, the stress curve intersects the airworthiness limit line at blade length of approximately 6.5 ft. So, in relation to 1st principal stress, the blade cannot be longer that approximately 6.5 ft to fulfill the airworthiness strength requirement.

From, aforementioned observation and discussion, the longest blade length that can fulfill the airworthiness strength requirement.of is about 6.5 ft.

4.1 Validation Analysis

Comparison of the result is conducted in order to verify both the experimental and *SOLIDWORKS 2016 x64 Edition* FE analysis large displacement theory solution method. An experiment was conducted where the tip deflection was measured of an actual blade mounted in cantilever support free of external load except for gravitational force. Similarly, FE analysis was done and the results are as illustrated in Figure 13. Comparison of the results is shown in Figure 13. Since the difference is only slightly greater than 5% the *SOLIDWORKS 2016 x64 Edition* FE analysis large displacement theory solution method is considered as valid.

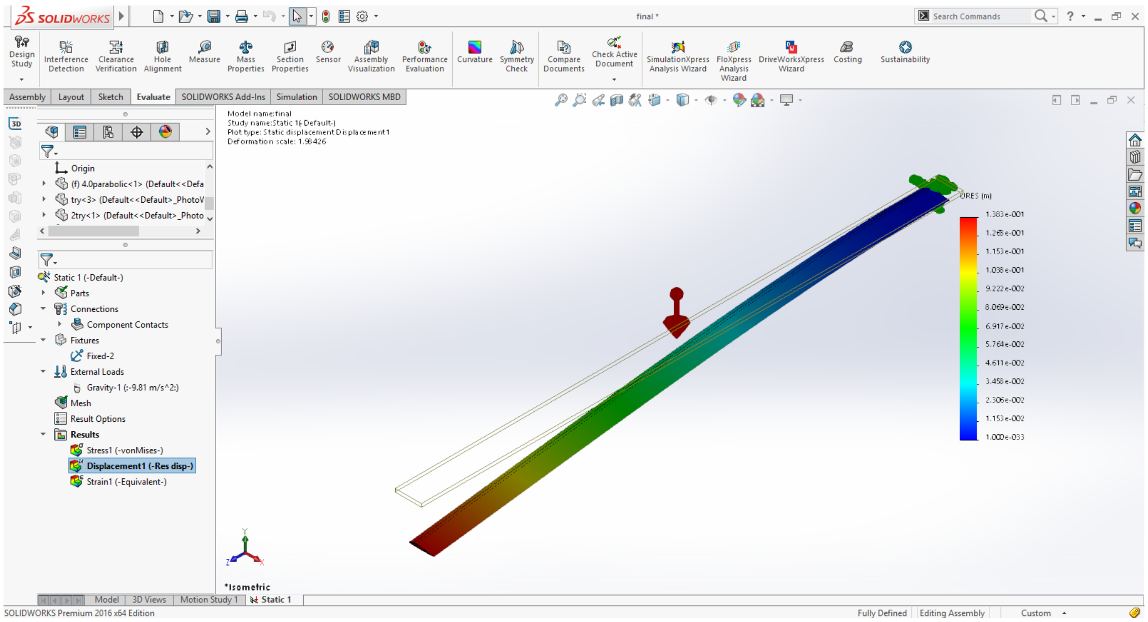

Figure 12: Analysis for verification

Table 7: Comparison of maximum deflection

Experiment	**Analysis**	**Difference %**
15 cm	14 cm	6.67

As justification, the result value was slightly different might be due to the different in mass. Where the mass of the actual blade is 7 kg, yet from the FE model/analysis the mass value is 6.75 kg (for 10 ft length of blade). Other possibility, the analysis is run for clamped joint which the root of the blade is totally fixed. For the experiment, the fixed area at the root of the blade may not be properly clamped to the support which may also be the cause of the value is slightly different.

5.0 CONCLUSION

According to airworthiness strength requirement, an aircraft structure experiencing limit load must not be permanently deformed and to have a least a safety factor above 1.5 to the ultimate strength. To fulfill this requirement, the highest Von Mises stress of the structure must be at or below the yield strength and the highest 1^{st} principal stress must be at or below the 2/3 of ultimate tensile strength value. Therefore, the following conclusion can be stated:

Comparison between five different lengths of the rotor blade, the rotor blades with 3.05 m (10 ft), 2.74 m (9 ft), 2.44 (8 ft) and 2.13 (7 ft) are not fulfilling the airworthiness strength requirement as mentioned in the discussion. And only rotor blade with length of 1.83 m (6 ft) or to be more accurate 2 m (6.5 ft) fulfills the airworthiness strength requirement with corresponding safety factor of 1.5 of its highest 1^{st} principal stress to the ultimate strength and about safety factor of 2 (> 1) for its highest Von Mises stress to the yield strength.

With respect to analysis study, the range of safety factor is 1.5 – 2.5 and more than that will still be acceptable and noting that the more value of safety factor means more weight of the structure. In order to optimize structural weight, highest stress due to limit load should be kept as close as possible to the strength condition. As observed, the length of the rotor blade 2 m (6.5 ft) is most acceptable and suitable for the design since its safety factor is about 1.5 relative to ultimate strength.

As a conclusion, evaluating the results obtained in the interested length, the length of the blade with 2 m (6.5 ft or 78 in) which operates at 500 rpm fulfills airworthiness requirement to use for rigid mounted (clamped joint) rotor blade NACA 8-H-12 airfoil section with a uniform 5.25 inches chord length.

To design or develop a rotor blade design process the analysis of loads and stresses alone is not adequate. Similarly, separate analysis of cost of raw materials, manufacturing processes, and market study or environment effect will not suffice. Compromise of design factors within the governing civil aviation regulations is also required. Therefore, simultaneous analysis of relevant factors and compromise within governing regulations constitute the appropriate tools to develop a rotor blade design process.

FUTURE WORKS

As suggestions, future works need to be done in order to get more accurate results and further improve application of the blade.

Few suggestions have been made as listed below:

- Perform Computational fluid dynamics (CFD) analysis. A CFD analysis will provided the loading loads acting on the rotor blade. The aerodynamics load such as lift force also can be obtain results that close to reality.
- If the prototype is built, put strain gauges on the rotor blades. Then, the result obtain can be used to compare experimental results to the FE solutions.
- For manufacturing, in order to avoid stress concentration, the design must be smooth as possible.

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