A Study of Wind Turbine Blade Shape Design

by

Suraya Hani Binti Mostar

Dissertation submitted in partial fulfillment of
the requirements for the
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(Mechanical Engineering)

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CERTIFICATION OF APPROVAL

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Approved by,

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TRONOH, PERAK
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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

SURAYA HANI BINTI MOSTAR

Abstract

Recently, the demand for the utilization of clean renewable energy sources shows an increasing interest as a result of the fluctuation in oil prices and the increased awareness of human-induced climate change. With the current technology, wind energy has shown to be one of the most promising sources of renewable energy and become competitive towards the conventional sources of energy such as coal and petroleum. Wind turbine blades play an important role in the production of wind power. This paper explores the analysis of wind turbine blade as subjected to static and dynamic loading. The main objective of this study is to recommend for improvement of wind turbine blade shape to ensure safety in the interest location which is Malaysia. Several aspects and criteria are discussed in this paper to achieve the desired objectives. Methodology starts with the background study on the subject, related problem and possible designs where they are the starting points before moving to the next important step which is finite element modeling. At the same time, mathematical modeling is also done to prove the finite element modeling. Last but not least, comparison between the modeling results with the current standards of wind turbine blade design is done to ensure the reliability of the design. The paper would be concluded with the achievement of the project.

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CHAPTER 1: INTRODUCTION

In this chapter, the introduction of the project entitled 'A study of wind turbine blade shape design' is explained. This introduction chapter is including the background study, problem statement, objectives and scope of work for the project.

1.1 Background Study

Nowadays, the concern over alternative energy resources is rising because of the vulnerability of our main energy supply which is petroleum that contributes to the fluctuating price of petrol around the world. See Figure 1 and Figure 2. Wind energy is a free and sustainable energy to be harnessed for the usage of the increasing population and industry capacity. The wind power generation is one of government strategies of achieving national energy objectives focused on targeting for renewable energy to be significant contributor and as an effort to further reduce the dependency on petroleum.[1]

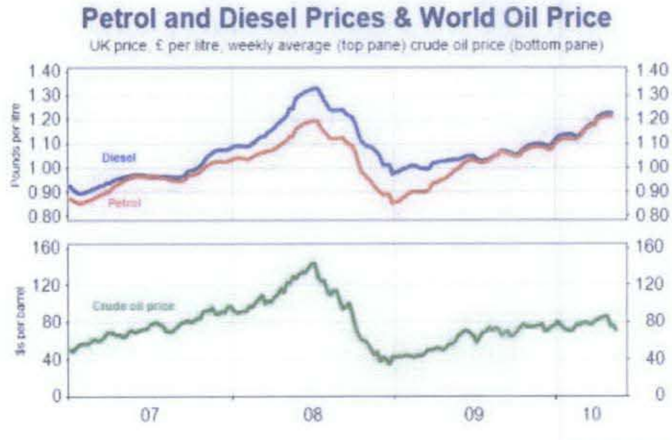


Figure 1: Petrol and Diesel Prices & World Oil Price

Figure 2: Malaysia Petrol vs Crude Oil Prices (2004-2008)

Wind power is produced using wind generators to harness the kinetic energy of wind. The moving air contains kinetic energy and the air flows through a wind turbine would cause the turbine rotor to turn. The mechanical forces such as lift force, drag force, and torque induced from the turbine rotation is then converted to electrical energy by generator attached to the turbine rotor.

An example of early uses of wind energy is the windmills that were used to grind grain. Meanwhile, the modern uses of wind energy is including the generation of electricity and pumping water. Current wind energy machines are called wind turbine generators, wind pumps, or more generally, wind turbines.[2]

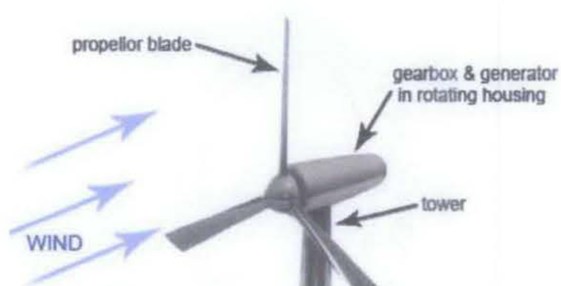


Figure 3: Components of wind turbine tower

The power harnessing ability is mainly depend on the propeller blade design of the wind turbine. The blade shape and specifications must be well-suited for the purpose of generating enough electricity to be supplied from house to house connected by grid connection. However, the structural integrity of wind blade is also important to ensure the wind rotor operating in a safe manner when subjected to wind loading statically and dynamically.

1.2 Problem Statement

The free energy of wind can be harnessed especially at the location where there is potential wind power such as at the coastal area. The usage of wind turbine system locally is rare. It is should be an advantage to Malaysia as the country has large coastal area and one potential site to be applied the wind turbine system is the East Coast of Peninsular Malaysia. The wind turbine system could help mainly the poor fishing community who lives along the coast. However, the knowledge about the wind turbine system is still lacking among Malaysian especially in the safe blade design based on slight wind power production development in Malaysia neither small-scale nor mega-scale. Thus, this study is a part of work to solve the problems facing by the communities.

1.3 Objectives of Study

Upon completing the project, a few objectives need to be achieved. The objectives are as follows:

1. To understand the structural integrity of blade design based on the static and dynamic loading on wind turbine blade
2. To address failure mode, location and load of the blade designs
3. To determine if the blade designs are safe based on their structural integrity

1.4 Scope of Study

The scopes of work in this project are:

1. To generate possible models of blade design by varying the cross section shape with different material strength for comparison
2. To do static structural and modal analysis of blade models using ANSYS software
3. To discuss the blade analysis of natural frequency, mode shape, deflection and stress

1.5 Significance of Study

Wind turbine blade designs are generated based on the possible designs available in the market mainly for small scale power production for household. Then, analysis was done based on the wind loading. The result obtained from this study will be used to recommend safety of wind turbine blade system for electrical supply of poor fishing community household. Since the East Coast of Peninsular Malaysia has potential source of wind power, this study could help improving the structural integrity of wind turbine blade in harnessing the power when subjected to wind loading. In addition, the poor communities not only can have the access to alternative energy supplies and decrease their dependency on fuel supply but also can avoid damage losses due to the wind turbine system.

1.6 Relevancy of Project

Malaysia has large coastal area with wind energy potential thus the free energy from the wind could benefit the poor communities. The knowledge about wind turbine blade design could improve the long term performance of wind turbine and also safety of surrounding location.

CHAPTER 2: LITERATURE REVIEW

2.1 Case Studies

2.1.1 Malaysia Wind Power Development

In Malaysia, the development of wind power production is slight. The first wind farm in Malaysia was set up on Pulau Terumbu Layang-Layang off Sabah. A study from University Kebangsaan Malaysia (UKM) in 2005 has shown that the use of 150 kW turbines on the island has shown a good degree of success.[3] Another project installed in 2007 at Pulau Perhentian is set to receive two of 100 kilowatt wind power systems. The project consists of installing and commissioning two wind turbines by NorthWind® with a 100kW photovoltaic energy system installed together to generate power from the solar energy in conjunction with the wind turbines to generate power.[4]

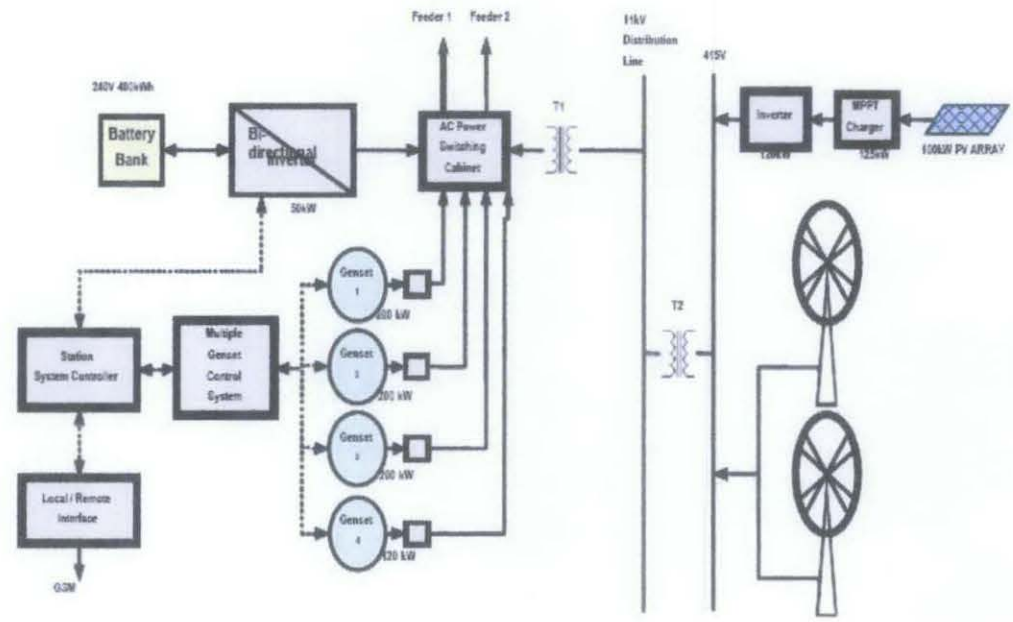


Figure 4: Block diagram of the Solar Hybrid System in Pulau Perhentian

In addition, a research about the wind turbine designs for local usage was done by Prof. Ir. Dr. Abas Abd. Wahad from Mechanical Faculty, Universiti Teknologi Malaysia (UTM). A turbine model, 'Low Wind Speed Wind Turbine' (LWSWT) has been designed to be use as a practical turbine in our country. This type of turbine has been tried at Pulau Tioman project and was a success. It has cut-in-speed 1.5m/s with rated velocity of 3.0 m/s. The turbine has 3 blades, 10 meter diameter with efficiency of 85% and the turbine can operate a minimum of 10 hours per day. Using this turbine, the communities have the potential to access the wind energy supply from their homes. However, it is not too practical to install LWSWT on the roofs since the diameter of blades is large and some space is needed for safety purpose.[5]

2.1.2 Wind Turbine Failures

In United State of America, the Department of Labor reported that 75 wind turbine accidents involving injuries had occurred since 1972 and 8 were reported in 2007. The reports do not included no-injury-accidents. The failures reported are included rotor blade throws (separation of the blade from the rotor), oil leaks, fires and tower collapses. The potential reasons might be because of excessive wind and rotor speed, material fatigue, excessive stresses or vibration from seismic ground shaking. Excessive wind speed can cause torsional strain and distort the blades where the previous cases showed that the blade could even bend and hit the tower, causing it to collapse.[6]

2.2 Wind Turbine Blade Design

Power production from the wind has been done for centuries. Steady improvement of the wind generator designs were conducted over the years including the wind turbine blade. Generally, the blade design is optimized to allow for more power generation from less wind, noise reduction during operation as well as aesthetic reasons. The terminology of blades can be seen at Figure 5, 6 and 7.

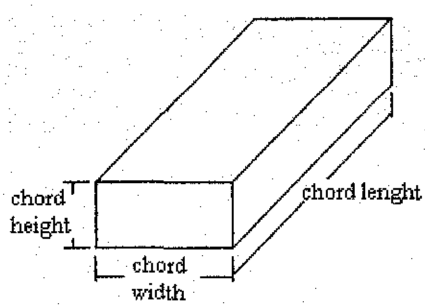


Figure 5: Height, width and length of wind turbine blade

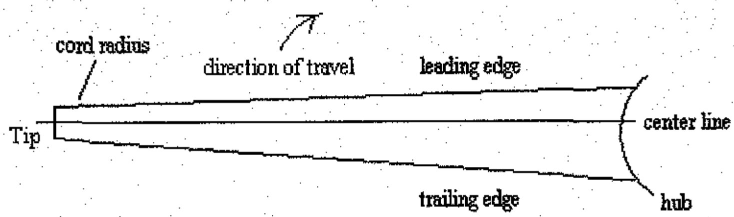


Figure 6: Tip, hub and direction of travel of wind turbine blade

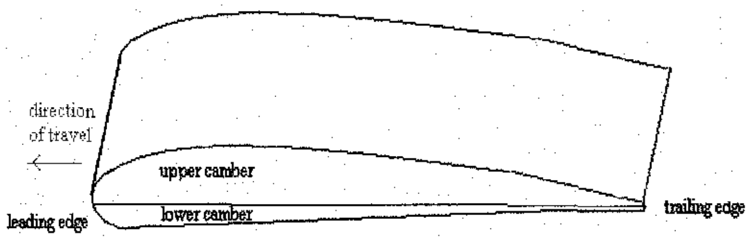


Figure 7: Cross section of wind turbine blade

Wind turbine blade design differs from each other according to blade dimensions, number of blades, weight, materials, cross section shape, planform shape and surface texture of blade etc. The performance would be different with the combinations of those parameters.

Basically, wind generators are designed to extract the most possible wind energy however, based on Betz theory, the highest possible power production from the wind is 59.3% which is also referred to the Betz limit. In practice three effects lead to a decrease in the maximum achievable power coefficient are wake rotation, finite number of blades and associated tip losses and the non-zero aerodynamic drag.[7] In order to increase the performance of the wind turbine, the shape of wind turbine blades takes an important role to produce high lift force and at the same time reduce the drag force acting on them.

One of the suggested shapes is the airfoil design. Basically, the function of airfoil shape is to generate lift by the presence of pressure differences across the airfoil. This is because the airflow over an airfoil produces a distribution of forces over its surface. The convex surface at its suction side has higher airflow velocity which results to lower average pressure compared to the concave surface. This phenomenon happens because of the law of continuity where the air molecules separate from the leading edge and they should meet on the trailing edge at the same point and time. Besides, as the air flow over the surface, there is viscous friction happen on the surface of airfoil which slows the air flow next to its surface.[8]

In general, these pressure and friction forces are resolved to two forces (lift and drag) and a moment (pitching moment). Lift force is defined to be perpendicular to the direction of the airflow where it is a result of unequal pressure on the upper and lower surface of airfoil. The drag force is due to the viscous friction at the airfoil surface and also the difference of pressure between the surface facing toward and away from the airflow. Meanwhile, the pitching moment is defined to be about an axis perpendicular to airfoil cross-section.

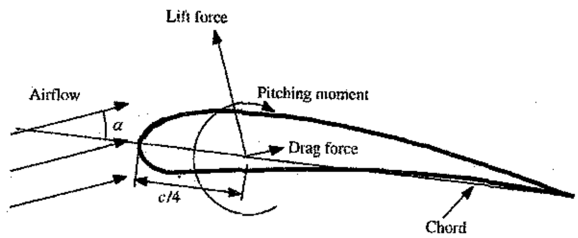


Figure 8: Drag and lift forces on stationary airfoil

2.3 Wind Turbine Blade Design Analysis

The wind turbine blades are tested before they are available for usage. There are many types of analysis done to ensure for best and safe operation. The analyses are to address their aerodynamic performance, structural integrity, and cost and many more. For a safe operation, typically the analysis of structural integrity is done mainly to understand the behavior of wind turbine blades when subjected to static and dynamic loadings.

2.3.1 Finite Element Analysis

Finite Element Analysis (FEA) was first developed by R. Courant in 1943, who prepared the approximate solutions to vibration systems by utilizing the Ritz method of numerical analysis and minimizing the variation in calculus.[9] The method is basically by a numerical technique for finding approximate solutions such as Euler's method, Runge-Kutta, etc. In case of structural failure, FEA may be used to evaluate the performance of model when react to certain loading conditions and also help determine the design modifications to meet the desired condition.

2.3.2 Cantilever Beam Theory

In wind turbine blade analysis, the characteristics of the system can be represented using a mathematical model where the blade is assumed to act like a cantilever beam. The simplest model is a lumped mass model with single degree of freedom.[10]

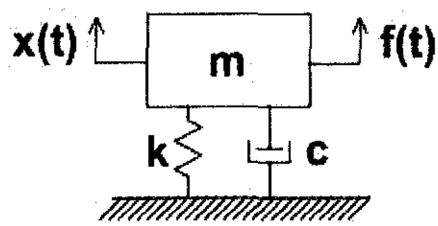


Figure 9: Single degree of freedom lumped mass model

It is defined by the second order differential equation with constant coefficients.

$$m\frac{d^2x}{dt^2} + c\frac{dx}{dt} + kx = f(t)$$

where m is the mass, c is the damping and k is the stiffness with the displacement, velocity and acceleration and the forcing function as shown in the Figure 9.

i) Mode Shape and Natural Frequency[10]

An equivalent model can be developed for analysis purposes by applying basic strength of materials approximations together with the continuous beam vibration equation.

The mode shapes for a continuous cantilever beam are given from previous as

$$f_n(x) = A_n\,[(\sin\beta_n L - \sinh\beta_n L)(\sin\beta_n x - \sinh\beta_n x) + (\cos\beta_n L - \cosh\beta_n L)$$
$$(\cos\beta_n x - \cosh\beta_n x)]$$

where $n = 1, 2, 3, \ldots\infty$ and $\beta_n L = n\pi$

The natural frequencies are given as

$$\omega_n = (\alpha_n^2/2\pi)\,\sqrt{(EI/mL^3)}$$

where α_n = constant (1.875, 4.694, 7.855, 10.966..)

L = length of the cantilever beam

E = Young's Modulus of Elasticity

I = bending moment of inertia

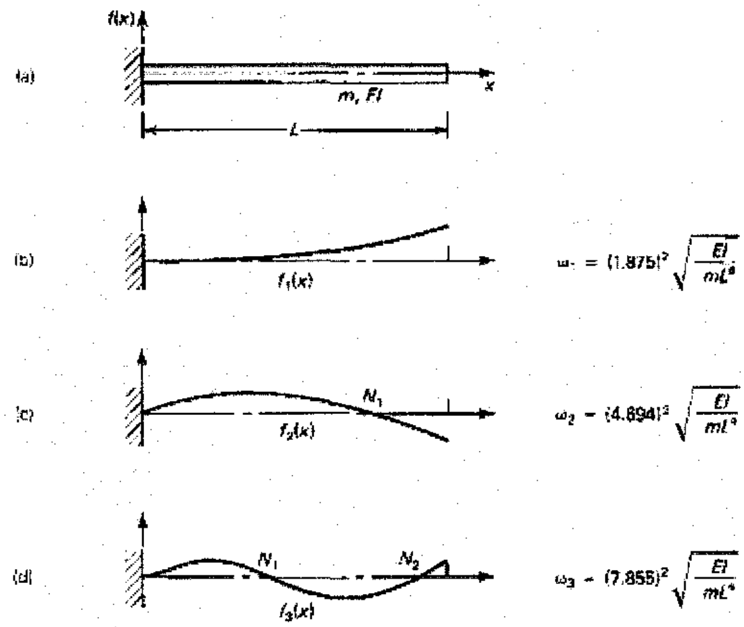


Figure 10: Frequencies and Mode shapes of Cantilever beam

ii) Stress and Deflection[10]

The deflection, x predicted by the well known strength of materials formula is $x = F L^3 / (3 E I)$

where x = tip displacement

F = applied load

L = length of the cantilever beam

E = Young's Modulus of Elasticity

I = bending moment of inertia

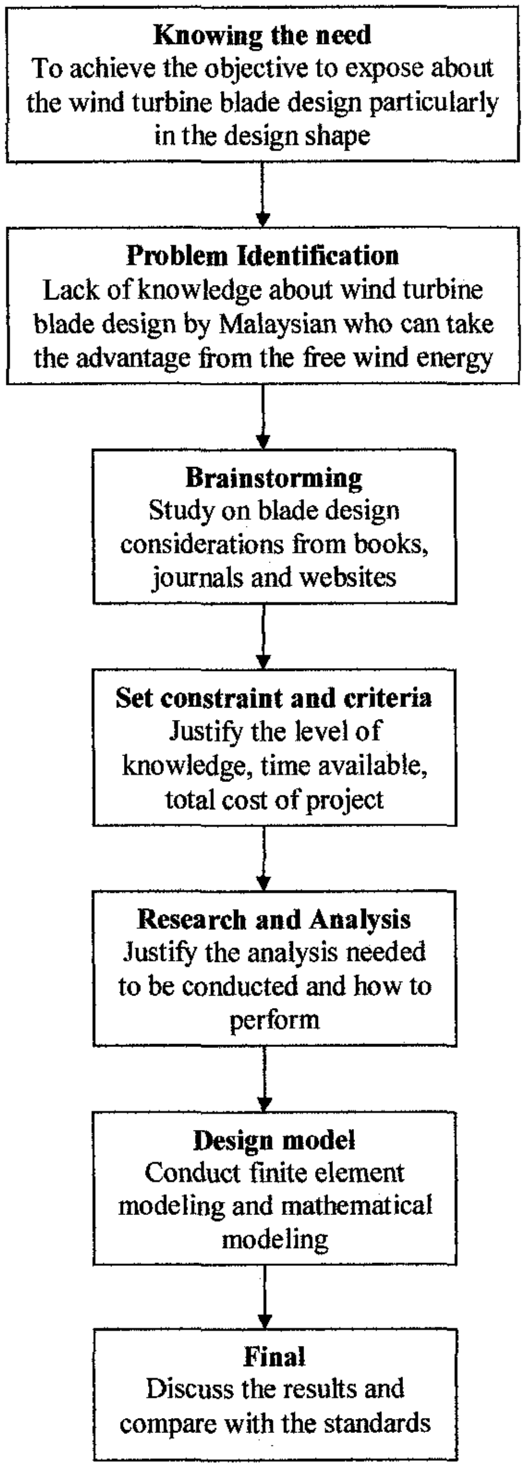
The maximum stress, σ predicted by the usual strength of materials formula for beam and the equation is

$\sigma = F L y / I$

where y = maximum distance from neutral axis

CHAPTER 3: METHODOLOGY

3.1 Process flow of the project



As reference to problem statement earlier, in the first part of project, a study is to be done on the wind turbine blade as well as the criteria that need to be looked into which then will help in designing the wind turbine blade. The main goal of designing is to evaluate the performance of possible wind turbine blade designs that might be acceptable for the wind power production in coastal area in Malaysia. There are several important considerations that should be taken into consideration in designing the blade particularly its material strength and also the cross section shape which later on contribute to mechanical forces acting along the blade. All these characteristics should fulfill the objectives of the project.

In order to achieve the objectives, several stages of design processes should be going through. First and foremost is to understand on several designs of turbine blade which is already in the market nowadays and any improvement on the designs. Next, the project is continued with the justification of parameters that affect the performance of turbine blades. Research is also conducted through books, journals and websites about the parameters to be used which satisfy the criteria of a blade. Those criteria are the static structural analysis and dynamic analysis.

Then, after evaluating the criteria, experimentation is conducted based on the criteria required using engineering software. Simulation analysis is done using ANSYS software. After that, the project proceeds to the next step of design process which is the mathematical modeling. Mathematical modeling of the design is to be done to evaluate the performance of the blade or to prove the analysis numerically. Finally, the potential models are to be compared with the standards of wind turbine blade design such as IEC etc. This is to ensure the objectives of this project are achieved.

Table 1: Gantt Chart for FYP2

No.	Details/Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14	15
1	Project Work Continues								Mid-Sem Break								
2	Submission of Progress Report																
3	Project Work Continues																
4	Pre-EDX																
5	Submission of Draft Report																
6	Submission of Dissertation (soft bound)																
7	Submission of Technical Paper																
8	Oral Presentation																
9	Submission of Project Dissertation (Hard Bound)																

3.2 Availability of Wind Power in Malaysia

In Malaysia, the wind power generation is still new and there are only several developments done in this area. From the wind data provided by several researchers from Universiti Sains Malaysia (USM), it was stated that there is a potential to use wind energy for electrical power generation especially in the East Coast of Peninsular Malaysia during Northeast monsoon.[11]

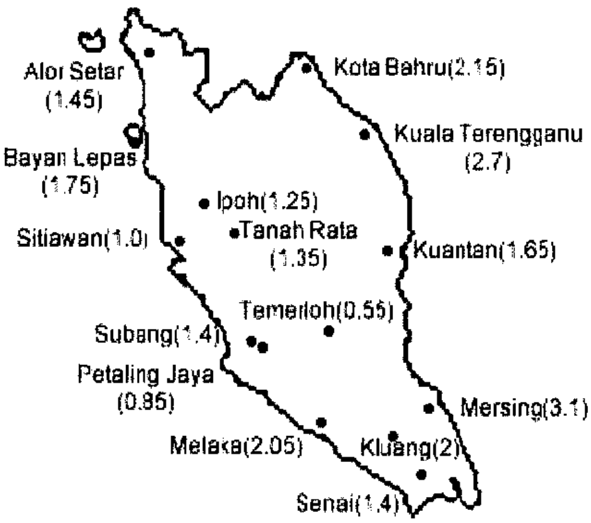


Figure 11: Annual wind speeds at 18 meteorological stations in Peninsular Malaysia

From the study, the meteorological data obtained has indicated that the average wind speed in Peninsular Malaysia is quite low and varies with season. This is based on the wind speed data from 18 meteorological stations for the year of 1984 and 1985. Mersing, Kuala Terengganu and Kota Bharu are the locations with highest wind speed in Peninsular Malaysia which are mostly located at the East coast areas. Furthermore, the data also indicates that Mersing is the most potential site for wind power production in Peninsular Malaysia.[12]

3.3 Material Selection

The material to be selected must available to reduce the effect of mechanical forces acting on the blade. In order to reduce the effect of gravitational forces and to obtain optimal aerodynamic performance, a material with a low density and high stiffness must be utilized. A long fatigue life or high fatigue strength property is also important to reduce material degradation because of the periodic load and to reduce its cost. Good formability property plus high availability of material in the market are also contributing to its cost. Besides, high strength and stiffness material is crucial to reduce the effect of vibration and torque during operation. To improve the blade performance, the material should also have high corrosion and wear resistance properties.[13]

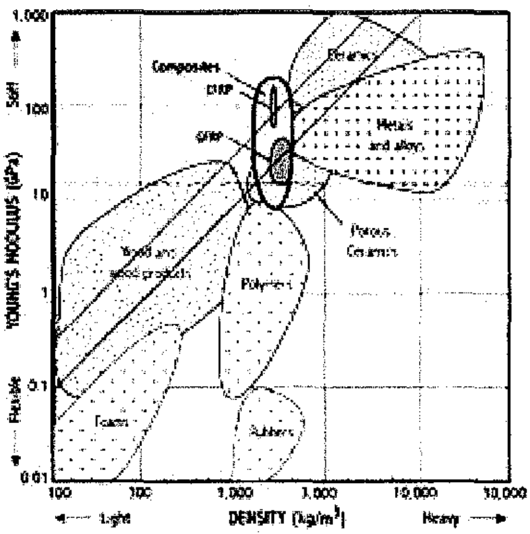


Figure 12: Graph of stiffness vs density

Based on the graph above, the candidate materials for blades are as follows: [14]

1. Metals: aluminum, stainless steel and titanium.
2. Composites: glass, aramid, and carbon (high modulus and high strength) fibres in epoxy resin matrices.

3.4 Geometric Modeling

The first step in analyzing the blade designs is to generate the geometry of the blades using available software and for this project, the blade designs are generated using ANSYS. There are four shapes listed to be analyzed using finite element analysis and the blades' dimension is made constant. Just for comparison, two different types of material are selected in order to review the performance based on the materials' tensile strength.

Table 2: The blade's criteria for the project

Dimension/Size	Material	Shape
1. Length: 10 meter 2. Chord length/width: 2.5 meter 3. Thickness: 0.5 meter	4. Aluminum i. Stainless steel	1. Flat, unmodified blade surface 
		2. Flat surface with gradient 
		3. Wing shape, with one leading edge rounded with the other edge tapered to a thin line 
		4. Both edges tapered to a thin line 

3.5 Finite Element Analysis of Wind Turbine Blade Designs

3.5.1 Linear Static Analysis[15]

The analysis is concerned about the linear behavior of the blades with prescribed boundary conditions and statically applied loads without responding to time. The calculation of displacements such as total displacement and directional displacement, stresses and strains including the Von Misses, principal, normal, shear etc, and also energy in the objects being analyzed are included in this analysis. Generally, the boundary conditions are specified displacements values at nodes, multi point constraint equations, coupled displacements or rigid links. In addition, the applied loads include prescribed forces, moments, uniform and un-uniform pressure on the face of elements, gravitational and centrifugal forces and also the loading because of thermal expansion or contraction.

The blade is assumed to be a cantilever beam has a fixed support at the root. For this case, the applied load is from the incoming wind pressure towards the blade planform. The response of the system does not change with time and the analysis includes the calculation of total displacements and Von Misses stresses. Static structural analysis is done using ANSYS software and to be compared with the manual calculation of cantilever beam theory. The results are then evaluated to identify failure location and failure load by comparing to the standards.

i) Deflection Analysis

Deflection analysis has to be performed to prove that the ultimate tip deflection is acceptable. When comparing the resulting available clearance between the rotor blade tip and the tower, a specified minimum clearance must be met. The value of the tip-to-tower clearance has to be greater than the blade deflection multiplied with the safety factor.[16] The available standards for blade deflection are as follows:

1. Deflection: [17]

    The operation limit of blade are between two allowable deflection standards, R/300 and R/180, where R is the blade length.

2. Tip-to-tower clearance: [16]

Table 3: Partial safety factor for the blade deflection

Regulation/Standard	GL (1, 12)	IEC (3)	NVN (11)	DS (8)
Safety factor	1,428	1,485	1.5 [1)]	Sufficient clearance [2)]

[1)] Safety factor on the load, not on the deflection

[2)] No value stated in the regulations

ii) Stress Analysis

For the study of stress distribution in complex composite parts such as wind turbine blades, it is good to use finite element analysis (FEA) by ANSYS code. The program can specify for supports, loading, environment, joint etc of the parts going to be analyzed. The results from FEA should be compared with theoretical calculation and must be checked with the standards. The standards for stress analysis are as follows:

1. Maximum wind speed: [16]

   55.6 m/s (NVN IIA), 59.5 m/s (IEC IIA)

2. Stress: [16]

Table 4: Regulations and Standards at blade root applying flatwise loads

Extreme loads blade root flatwise	GL-II/DIBt III (1)	NVN IIA (11)	IEC IIA (2)	DS class 0 to 3 (8)
Mx [kNm]	4092	5173	4306	3755
γf	1,50	1,35	1,35	1,30
γn	1,00	1,00	1,00	1,00
γm	2,45	1,75	1,10 [1)]	1,70
Mx *γf*γn*γm [kNm]	15038	12221	14242 [2)]	8299
Relative	1,00	0,81	0,95	0,55

1) Not accepted by the major certification bodies for FRP

2) For this comparison γ_m as in GL (1) has been chosen

Table 5: Regulations and Standards at middle section applying flatwise loads

Extreme loads blade middle flatwise	GL-II/DIBt III (1)	NVN IIA (11)	IEC IIA (2)	DS class 0 to 3 (8)
Mx [kNm]	899	918	800	753
γf	1,50	1,35	1,35	1,30
γn	1,00	1,00	1,00	1,00
γm	2,45	1,75	1,10 [1)]	1,70
Mx *γf*γn*γm [kNm]	3304	2169	2646 [2)]	1664
Relative	1,00	0,66	0,80	0,50

1) Not accepted by the major certification bodies for FRP

2) For this comparison γ_m as in GL (1) has been chosen

3.5.2 Modal Analysis

It is also called Eigen value analysis which involves the analysis of undamped free vibration of a structure in the absence of damping and applied loads. The analysis addressed the natural frequencies (Eigen values) and corresponding mode shapes (Eigen vectors) of the structure where it does not represent the response due to any loading. For ease of calculation, the lumped mass formulation may be used. In this project, ANSYS software is run to get the natural frequencies and respective modes shapes up to 10 modes. This is to predict the failure mode of selected designs.

i) Comparison of Mode Shape

The tests are to be computed for all eight models to find the first ten mode shapes of the prebend test blade. The possible mode of shapes are flapwise, edgewise, torsional or combination bending mode.[18]

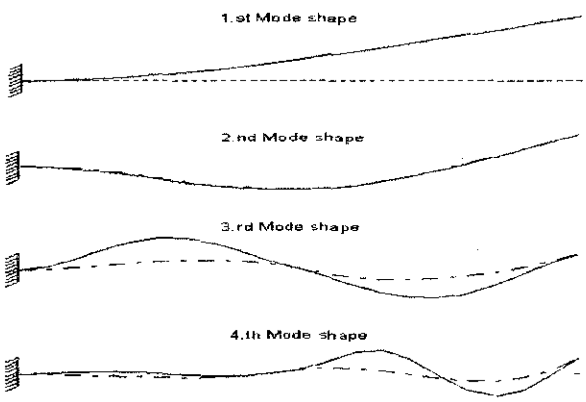


Figure 13: Mode Shapes

ii) Resonance

The modal analysis is done at least the two lowest eigenfrequencies of the rotor blade, both in flapwise and edgewise oscillation because of the low frequencies. These eigenfrequencies should be compared to the rotational frequencies of the wind turbine. A sufficient margin to these frequencies must be available to avoid resonance of the blade. It is recommended to keep the eigenfrequencies outside a range defined as the rotational frequency ±12%.[19]

CHAPTER 4: RESULTS

4.1 Analysis requirements

1. Static stress and displacement analysis of the turbine wind loading approximated by concentrated forces acted along the span
2. A resonant frequency check using normal modes of vibration analysis

4.2 Deflection and Stress Analysis

4.2.1 Important Parameters

i) Wind speed range[11]

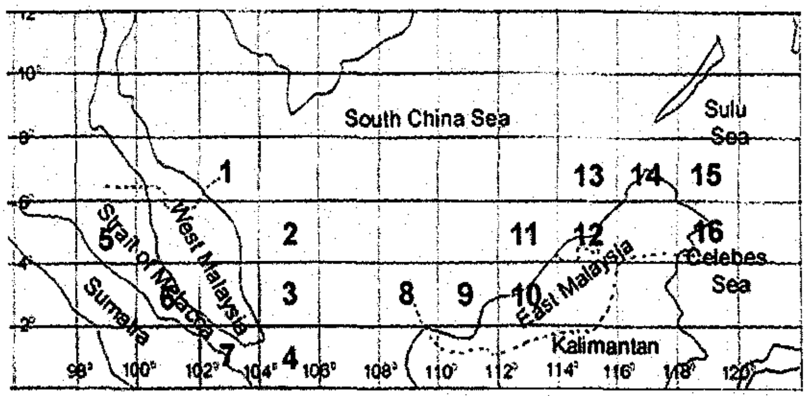


Figure 14: Map of Malaysia with study locations

Table 6: Monthly vector resultant mean wind speed in m/s

Month	East Peninsular Malaysia				West Peninsular Malaysia			Sarawak				Sabah				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Jan	5.8	6.8	6.7	5.7	2.4	0.7	2.2	5.7	3.8	2.5	3.9	4.0	6.8	4.0	3.1	2.7
Feb	4.8	5.3	5.4	4.6	1.6	0.7	2.4	4.7	3.8	2.2	3.4	3.7	6.2	4.2	5.7	1.9
Mar	3.9	4.0	3.8	3.3	1.4	1.0	1.4	3.8	2.5	1.9	2.6	2.8	5.2	4.0	3.6	2.3
Apr	2.7	2.0	1.7	1.1	1.2	0.9	1.4	1.2	1.2	0.9	0.9	1.3	2.9	2.2	0.5	1.3
May	2.2	2.5	2.1	1.6	1.0	1.0	1.6	1.4	1.2	0.8	0.7	1.2	1.6	1.5	0.0	1.4
Jun	3.1	3.4	3.1	2.6	1.4	1.5	1.9	2.2	1.0	0.6	1.2	1.6	2.7	2.5	2.6	1.7
Jul	2.4	4.9	4.3	3.7	1.3	2.1	2.2	3.2	1.5	1.2	1.7	1.7	3.5	2.8	3.5	1.6
Aug	3.9	4.8	4.5	3.7	1.6	1.4	1.9	2.9	1.2	1.5	2.0	2.4	4.4	3.5	2.1	2.8
Sep	3.3	3.5	3.3	3.0	0.9	0.8	1.3	2.9	1.6	1.1	1.2	8.7	2.9	2.7	0.0	1.9
Oct	0.0	1.1	1.7	2.7	1.6	1.2	1.5	2.7	1.5	1.0	1.9	1.7	2.8	2.7	3.1	1.2
Nov	5.1	3.6	2.7	2.3	2.1	1.7	2.2	1.6	1.4	1.3	1.2	1.9	2.4	2.1	3.1	1.8
Dec	5.1	7.6	5.9	5.0	2.4	1.5	2.9	4.6	2.5	1.4	1.7	2.1	4.3	2.8	4.3	3.1
Mean	3.5	4.1	3.8	3.3	1.6	1.2	1.9	3.1	1.9	1.4	1.9	2.8	3.8	2.9	2.6	2.0

The wind speed from the Meteorological Department of Malaysia is evaluated for the estimation of wind pressure on the blade. For this project, Mersing is selected as the potential location for the wind power production. Based on the above figure, the range of wind speed for Mersing is from 1.7 m/s to 6.7 m/s.

ii) Material

The purpose of varying the material is to address the importance of material strength in decreasing the deflection and stress of the blade during operation. For comparison, aluminum and stainless steel are used for this project because both materials always have been used as the material for wind turbine blade. Stainless steel has Modulus of Elasticity of 200 GPa which is higher compared to aluminum which is 70 GPa. The other material properties of the both materials are as follow:

Table 7: Material properties of Aluminum and Stainless steel

	Aluminum	**Stainless Steel**
Density (kg m^{-3})[20]	2770	8030
Specific strength (MPa/kg m^{-3})[20]	0.173	0.154
Specific stiffness (GPa/kg m^{-3})[20]	0.025	0.025
Young's modulus (GPa)[20]	70	200
Yield Strength (MPa)[21]	240	350
Poisson's ratio[22]	0.334	0.305
Fatigue Strength (MPa)[23]	48 – 85	193 – 650
Fatigue Limit[23]	N/A	After 10^7 number of cycles
Formability	Lower than stainless steel	Excellent
Cost (USD/kg)[24]	2.438	6.975

4.2.2 Geometric Model

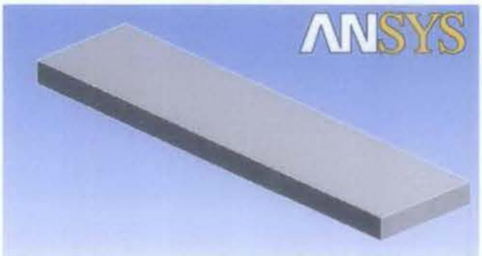


Figure 15: Shape 1 of wind turbine blade model

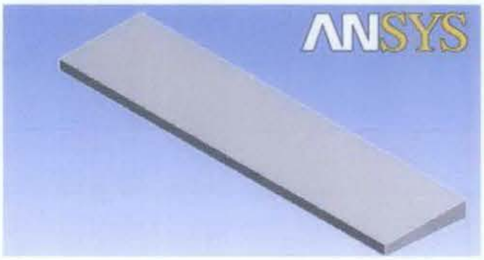


Figure 16: Shape 2 of wind turbine blade model

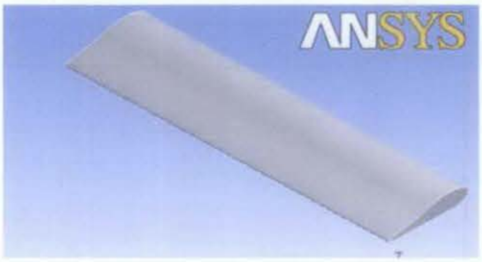


Figure 17: Shape 3 of wind turbine blade model

Figure 18: Shape 4 of wind turbine blade model

4.2.3 Static structural analysis

Below are the tables of deflection and Von Misses stress value of the eight models based on the increasing wind pressure. The results are from finite element analysis by finite element analysis using ANSYS code and also manual calculation of beam theory.

Table 8: Maximum deflection of the test blades (Aluminum)

		Shape 1 (10^{-3} mm)		Error	Shape 2 (10^{-3} mm)		Error	Shape 3 (10^{-3} mm)		Error	Shape 4 (10^{-3} mm)		Error
Velocity (m/s)	Pressure (Nm)	ANSYS	Calc.	%	ANSYS	Calc.	%	ANSYS	Calc.	%	ANSYS	Calc.	%
1	0.6	0.986	0.984	0.124	1.832	1.832	0.007	1.474	1.475	0.037	1.834	1.835	0.049
2	2.4	3.942	3.937	0.124	7.327	7.327	0.010	5.897	5.899	0.036	7.338	7.341	0.048
3	5.4	8.870	8.859	0.125	16.487	16.485	0.012	13.268	13.273	0.036	16.510	16.518	0.047
4	9.6	15.769	15.749	0.126	29.310	29.307	0.011	23.588	23.596	0.034	29.351	29.365	0.047
5	15	24.639	24.608	0.125	45.790	45.792	0.004	36.856	36.869	0.035	45.861	45.883	0.047
6	21.6	35.480	35.436	0.125	65.947	65.940	0.011	53.072	53.091	0.036	66.039	66.071	0.048
7	29.4	48.292	48.232	0.124	89.761	89.752	0.010	72.237	72.263	0.036	89.887	89.930	0.048
8	38.4	63.075	62.997	0.124	117.240	117.227	0.011	94.350	94.384	0.036	117.400	117.459	0.051

Table 9: Maximum deflection of the test blades (Stainless steel)

		Shape 1 (10^{-3} mm)		Error	Shape 2 (10^{-3} mm)		Error	Shape 3 (10^{-3} mm)		Error	Shape 4 (10^{-3} mm)		Error
Velocity (m/s)	Pressure (Nm)	ANSYS	Calc.	%	ANSYS	Calc.	%	ANSYS	Calc.	Velocity (m/s)	Pressure (Nm)	ANSYS	Calc.
1	0.6	0.363	0.364	0.241	0.676	0.676	0.029	0.544	0.544	0.059	0.677	0.677	0.056
2	2.4	1.456	1.455	0.038	2.706	2.705	0.029	2.177	2.176	0.059	2.708	2.709	0.057
3	5.4	3.276	3.275	0.036	6.088	6.086	0.029	4.899	4.896	0.059	6.092	6.096	0.057
4	9.6	5.823	5.821	0.035	10.823	10.820	0.028	8.709	8.704	0.059	10.831	10.837	0.055
5	15	9.099	9.096	0.035	16.911	16.906	0.028	13.608	13.600	0.062	16.923	16.933	0.058
6	21.6	13.103	13.098	0.038	24.352	24.345	0.029	19.595	19.583	0.060	24.369	24.383	0.058
7	29.4	17.834	17.828	0.034	33.146	33.136	0.029	26.671	26.655	0.060	33.169	33.188	0.058
8	38.4	23.290	23.285	0.019	43.293	43.280	0.030	34.830	34.815	0.044	43.323	43.348	0.057

Table 10: Von Misses stress of the test blades (Aluminum)

		Shape 1 (kPa)		Error	Shape 2 (kPa)		Error	Shape 3 (kPa)		Error	Shape 4 (kPa)		Error
Velocity (m/s)	Pressure (Nm)	ANSYS	Calc.	%	ANSYS	Calc.	%	ANSYS	Calc.	%	ANSYS	Calc.	%
1	0.6	0.692	0.691	0.052	1.124	1.124	0.010	0.981	0.980	0.030	1.484	1.483	0.093
2	2.4	2.766	2.765	0.052	4.494	4.494	0.013	3.922	3.921	0.030	5.936	5.930	0.093
3	5.4	6.224	6.221	0.053	10.111	10.113	0.015	8.825	8.822	0.031	13.356	13.344	0.093
4	9.6	11.605	11.059	4.704	17.975	17.978	0.016	15.688	15.684	0.027	23.744	23.722	0.093
5	15	17.289	17.280	0.053	28.087	28.090	0.012	24.513	24.506	0.029	37.100	37.065	0.093
6	21.6	24.896	24.883	0.053	40.445	40.450	0.013	35.299	35.288	0.030	53.424	53.374	0.093
7	29.4	33.886	33.868	0.052	55.050	55.057	0.013	48.046	48.031	0.030	72.716	72.648	0.093
8	38.4	44.260	44.236	0.054	71.902	71.911	0.013	62.754	62.735	0.031	94.976	94.887	0.093

Table 11: Von Misses stress of the test blades (Stainless steel)

		Shape 1 (kPa)		Error	Shape 2 (kPa)		Error	Shape 3 (kPa)		Error	Shape 4 (kPa)		Error
Velocity (m/s)	Pressure (Nm)	ANSYS	Calc.	%	ANSYS	Calc.	%	ANSYS	Calc.	%	ANSYS	Calc.	%
1	0.6	0.686	0.685	0.153	1.123	1.121	0.198	0.988	0.987	0.156	1.483	1.483	0.006
2	2.4	2.746	2.742	0.152	4.492	4.483	0.200	3.953	3.947	0.156	5.931	5.930	0.004
3	5.4	6.178	6.169	0.154	10.107	10.087	0.198	8.894	8.880	0.156	13.344	13.344	0.004
4	9.6	10.984	10.967	0.156	17.969	17.932	0.203	15.811	15.786	0.157	23.723	23.722	0.005
5	15	17.162	17.136	0.153	28.076	28.019	0.201	24.704	24.666	0.155	37.067	37.065	0.004
6	21.6	24.713	24.676	0.152	40.429	40.348	0.200	35.574	35.519	0.155	53.377	53.374	0.005
7	29.4	33.638	33.586	0.154	55.029	54.918	0.201	48.420	48.345	0.155	72.652	72.648	0.005
8	38.4	43.935	43.868	0.153	71.874	71.730	0.201	63.243	63.144	0.156	94.892	94.887	0.005

4.3 Natural Frequencies and Modal Shape

Figure 20 until 25 show the mode shape of the finite element analysis blade model for the first 6 modes with the corresponding frequencies and relative deformation for the none-rotating aluminum blade. The figures for stainless steel can be seen at Appendix Chapter.

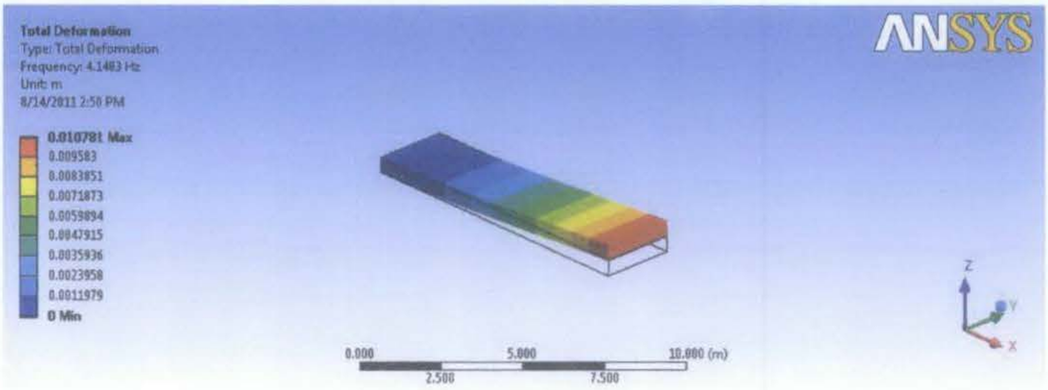


Figure 19: Flapwise mode shape

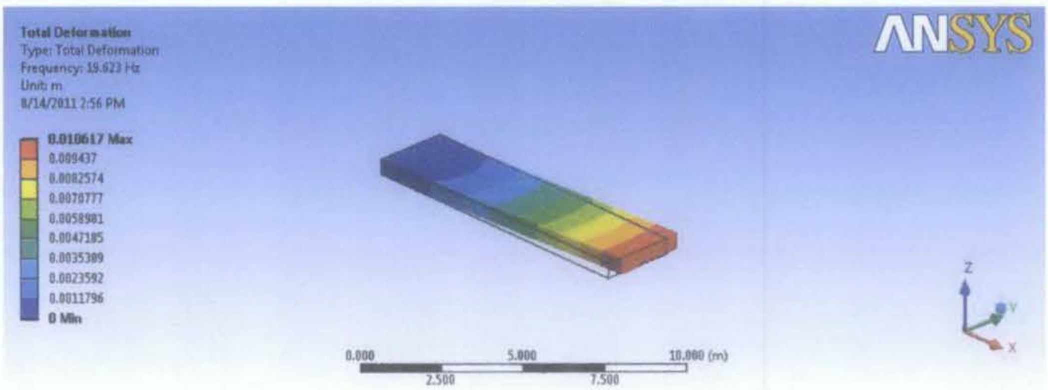


Figure 20: Edgewise mode shape

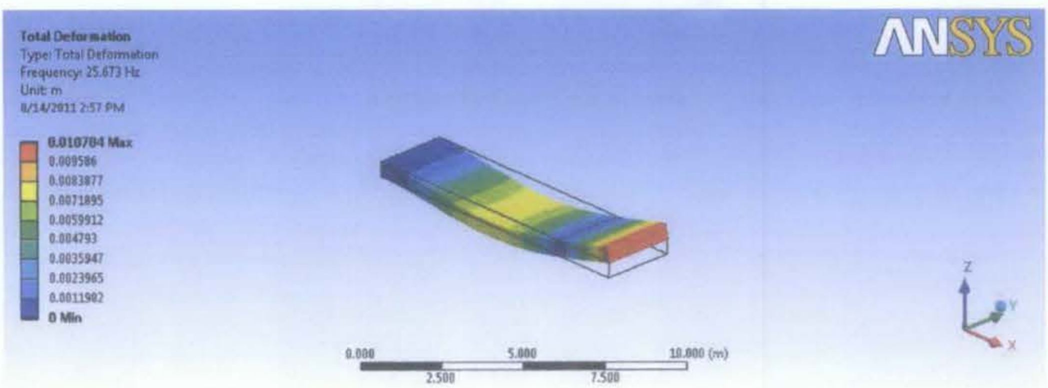


Figure 21: Stretching and compression mode shape

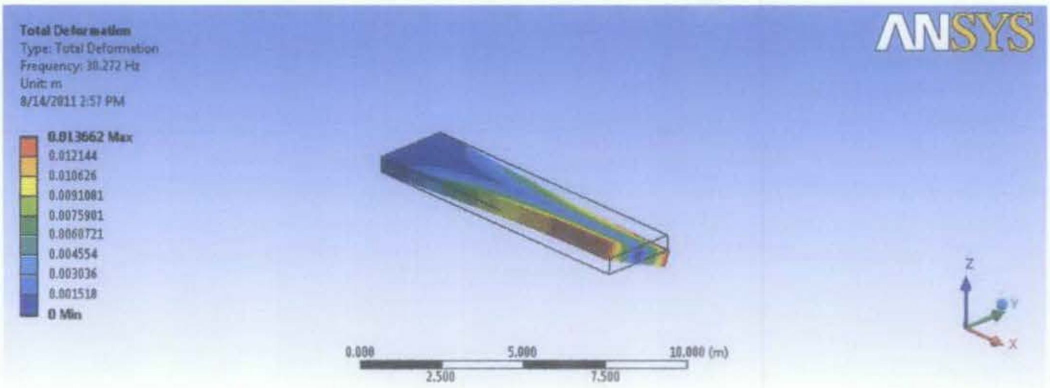


Figure 22: Twisting mode shape

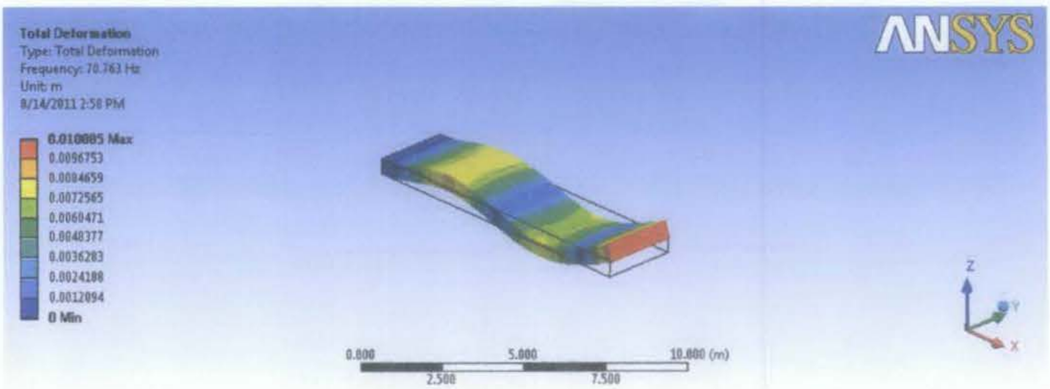


Figure 23: Sine-shape mode shape

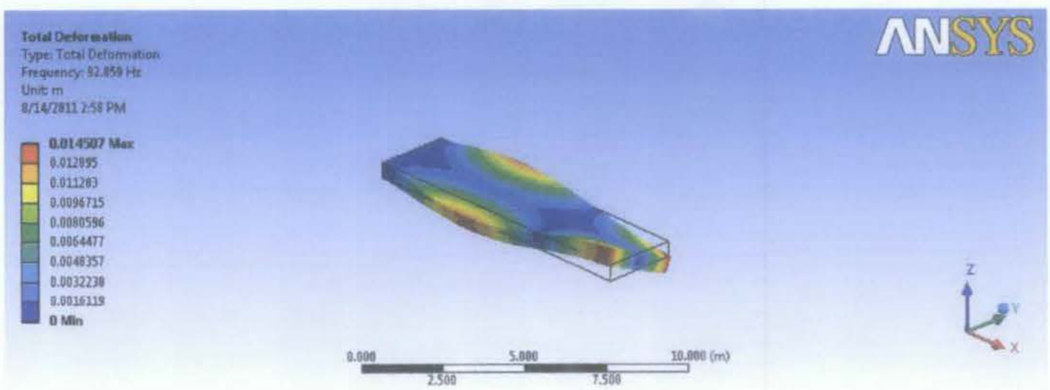


Figure 24: Combination mode shapes

Table 12: Natural Frequencies of blade models (10 modes)

Shape	Material	Frequency (Hz)									
		1	2	3	4	5	6	7	8	9	10
1	Alu	4.148	19.623	25.673	30.272	70.763	92.859	99.320	127.160	135.690	161.120
	SS	4.081	19.337	25.262	30.038	69.629	92.096	98.062	125.270	133.510	159.680
2	Alu	3.419	19.443	21.072	25.467	58.096	77.897	98.689	111.210	127.150	135.220
	SS	3.363	19.160	20.741	25.261	57.185	77.232	97.440	109.480	125.250	133.920
3	Alu	3.388	16.561	20.789	29.434	56.529	86.965	89.157	105.530	127.170	144.540
	SS	3.333	16.317	20.466	29.205	55.697	86.113	88.109	104.110	125.250	143.160
4	Alu	3.734	15.437	22.996	32.159	62.735	83.056	98.557	118.710	127.110	160.340
	SS	3.675	15.210	22.641	31.921	61.792	82.008	97.749	116.980	125.220	159.090

Table 13: Relative deflection of blade models (10 modes)

Shape	Material	Relative Deformation (m)									
		1	2	3	4	5	6	7	8	9	10
1	Alu	0.01078	0.01062	0.01078	0.01366	0.01089	0.01451	0.01048	0.00763	0.01110	0.01569
	SS	0.00644	0.00635	0.00644	0.00816	0.00650	0.00866	0.00627	0.00456	0.00662	0.00936
2	Alu	0.01213	0.01190	0.01364	0.01837	0.01250	0.01910	0.01199	0.01452	0.00853	0.02141
	SS	0.00725	0.00712	0.00810	0.01093	0.00746	0.01138	0.00717	0.00855	0.00510	0.01274
3	Alu	0.01350	0.01337	0.01445	0.02521	0.01576	0.02477	0.01871	0.02181	0.00948	0.03253
	SS	0.00807	0.00800	0.00860	0.01504	0.00930	0.01422	0.01192	0.01282	0.00567	0.01944
4	Alu	0.01324	0.01333	0.01324	0.02084	0.01326	0.01582	0.02015	0.01325	0.00945	0.02292
	SS	0.00791	0.00797	0.00791	0.01246	0.00792	0.00941	0.01208	0.00792	0.00565	0.01369

CHAPTER 5: DISCUSSION

The results from Chapter 4 are discussed in this chapter.

5.1 Deflection and Stress Analysis

5.1.1 Deflection

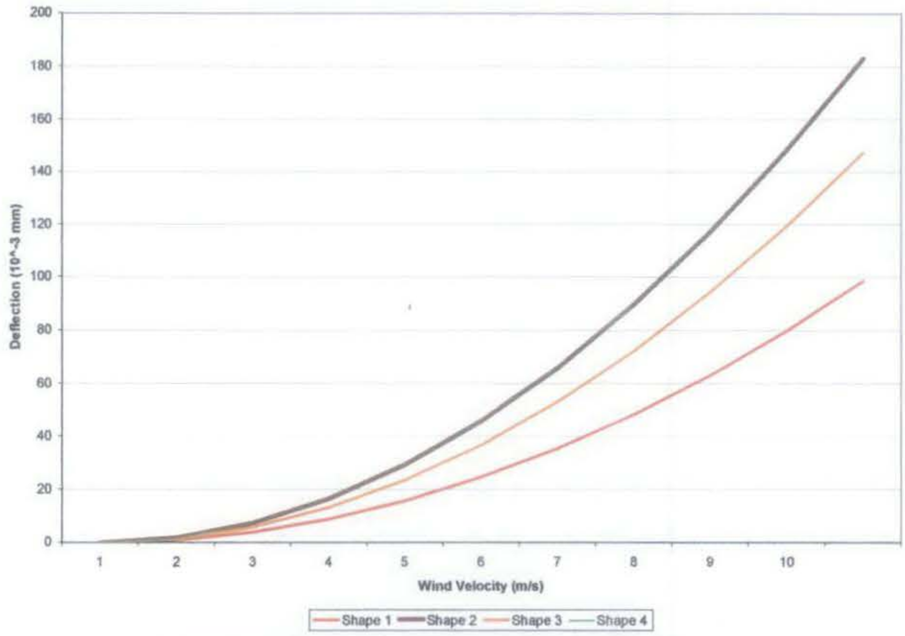


Figure 25: Deflection versus wind velocity (Aluminum)

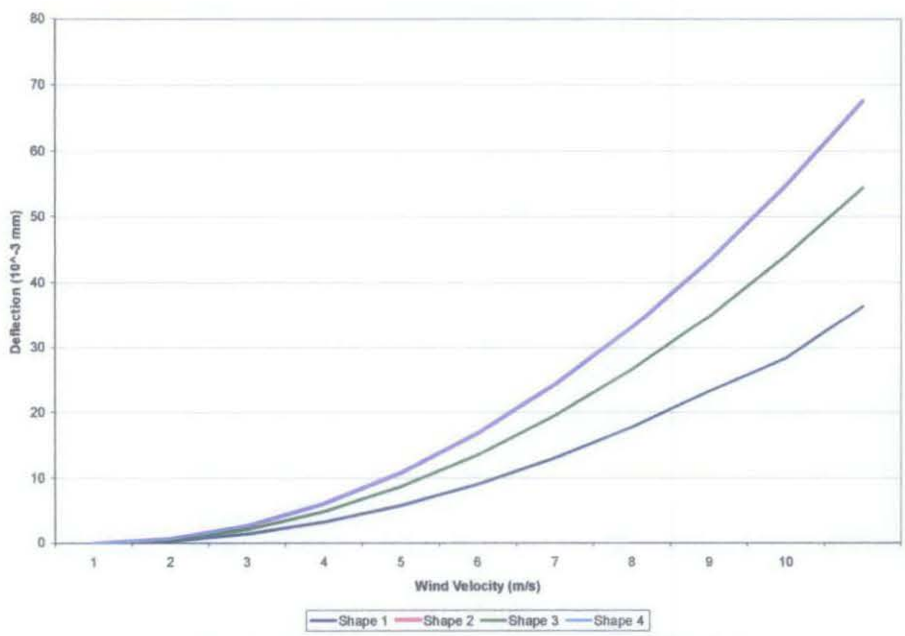


Figure 26: Deflection versus wind velocity (Stainless Steel)

From Figure 26 and 27, both graphs show the deflection of the models from finite element analysis according to shape. Shape 1 has the smallest deformation due to increasing wind velocity while Shape 2 and Shape 4 are the highest. This is because of the different stress distribution along the blade planeform. Shape 1 can withstand higher stress compared to other shapes even though the shape might not good in aerodynamic performance. The aerodynamic profile contributes to these results. Airfoil cross-section would cause different pressure on both sides of the wind turbine blade (front and back).

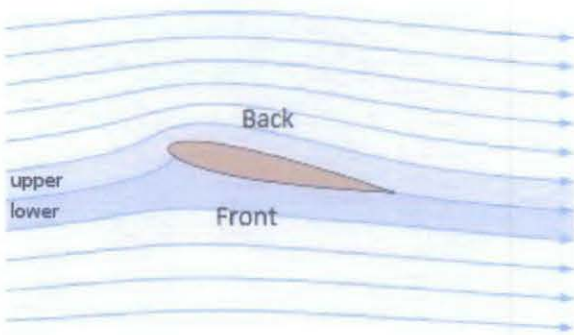


Figure 27: Airfoil cross-section

Because of the similar cross section for front and back of the blade, Shape 1 does not have any different or only slight different of pressure acting on front and back of its body. Thus, it undergoes the smallest deformation compared to other shapes. Shape 3 is an aerodynamic profile where supposedly there would be difference between pressures on both sides of the blade. The different in pressure had caused the blade to lift where this contributes to blade deflection. For Shape 2 and Shape 4, their lift forces are greater than Shape 3 hence they undergo high deflection.

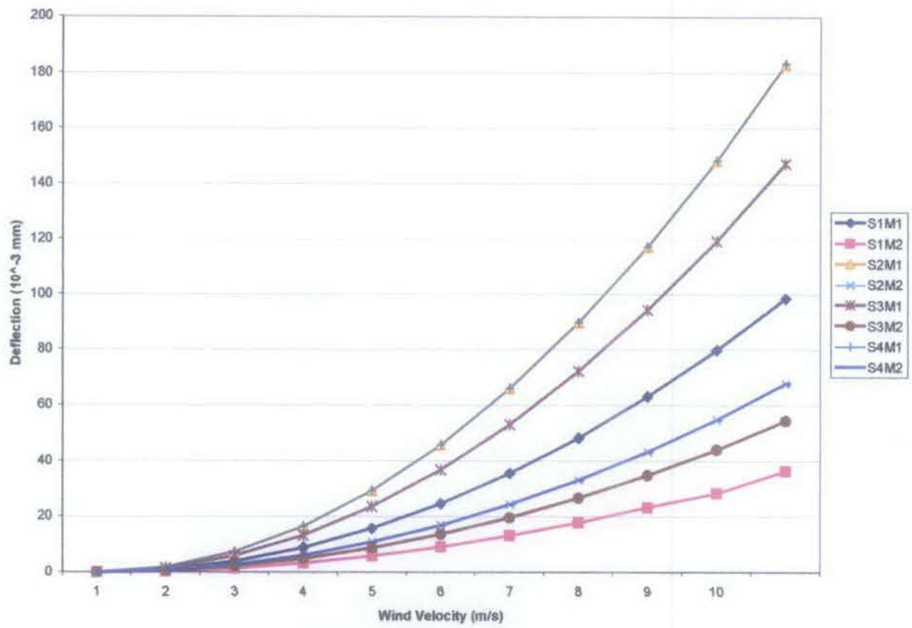


Figure 28: Deflection versus Wind velocity (All Models: S – Shape, M - Material)

As for comparison, the blade's material strength also contributes to deflection rate. The deflection rates for aluminum (M1) blades are higher compared to stainless steel (M2). Refer to Figure 28. This is because aluminum has lower yield strength than stainless steel where it starts to yield at lower stress acting on it than the stainless steel can withstand.

5.1.2 Von Misses Stress

Below is the graph of Von Misses stress (VM stress) versus wind velocity for all models. From the graph, it shows that VM stress of Shape 1 is the lowest while Shape 4 is the highest. Different from the previous deflection graph, VM stress of Shape 2 is not in line with Shape 4. Line for Shape 2 is lower than line for Shape 4 even though their deflection lines are the same.

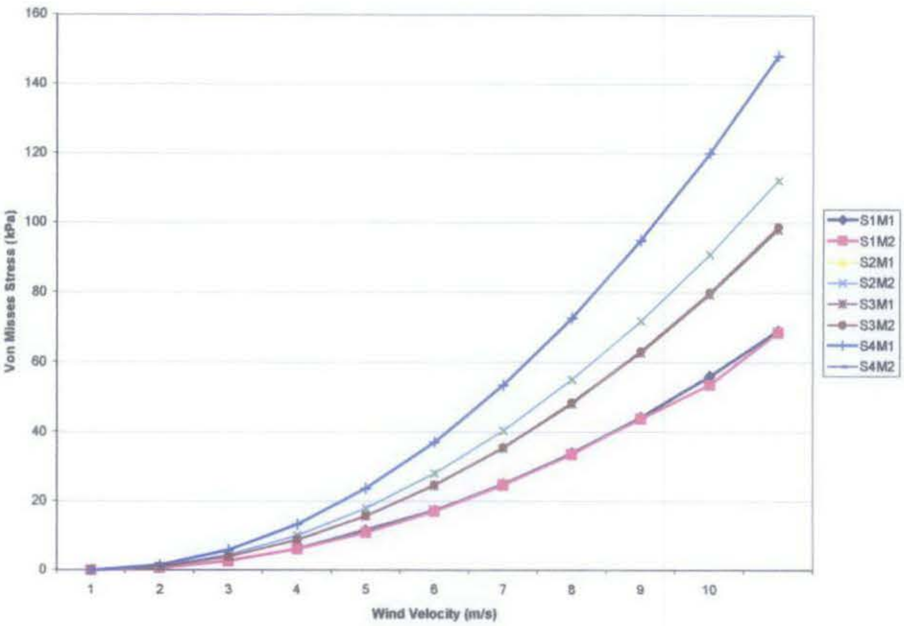


Figure 29: Von Misses Stress versus Wind velocity (All models: S -Shape, M - Material)

5.1.3 Comparison with standards

The Mersing's wind speed is not exceeding the maximum wind speed given by the standards. The maximum wind speed given by standards is 55.6 m/s (NVN IIA) and 59.5 m/s (IEC IIA) while the highest recorded Mersing's wind speed is 6.7 m/s. Refer Table 14 and 15 for the maximum stress given by standards. The maximum acceptable stress given by IEC is 14,242 kPa at root and 2,646 kPa at middle section. It is safe for any blade models in this project because the highest stress recorded for the highest wind speed of Mersing (assume 8 m/s) is only 95 kPa.

Table 14: Regulations and Standards at blade root applying flatwise loads

Extreme loads blade root flatwise	GL-II/DIBt III (1)	NVN IIA (11)	IEC IIA (2)	DS class 0 to 3 (8)
Mx [kNm]	4092	5173	4306	3755
γf	1,50	1,35	1,35	1,30
γn	1,00	1,00	1,00	1,00
γm	2,45	1,75	1,10 [1)]	1,70
Mx $*\gamma f*\gamma n*\gamma m$ [kNm]	15038	12221	14242 [2)]	8299
Relative	1,00	0,81	0,95	0,55

1) Not accepted by the major certification bodies for FRP

2) For this comparison γ_m as in GL (1) has been chosen

Table 15: Regulations and Standards at middle section applying flatwise loads

Extreme loads blade middle flatwise	GL-II/DIBt III (1)	NVN IIA (11)	IEC IIA (2)	DS class 0 to 3 (8)
Mx [kNm]	899	918	800	753
γf	1,50	1,35	1,35	1,30
γn	1,00	1,00	1,00	1,00
γm	2,45	1,75	1,10 [1)]	1,70
Mx *γf*γn*γm [kNm]	3304	2169	2646 [2)]	1664
Relative	1,00	0,66	0,80	0,50

1) Not accepted by the major certification bodies for FRP

2) For this comparison γ_m as in GL (1) has been chosen

However, the blade stress would exceed the standard limitation when the wind speed becomes so high. Refer Table 16.

Table 16: The corresponding wind speed and pressure as stress reach above IEC standard

Model	Wind speed (m/s)	Pressure (kN/m)	Deflection (m)	Von Misses stress (kPa)
S1M1	61	2232.6	0.003663	2572
	62	2306.4	0.003784	2657
S2M1	48	1382.4	0.004220	2589
	49	1440.6	0.004398	2698
S3M1	51	1560.6	0.003836	2550
	52	1622.4	0.003988	2651
S4M1	42	1058.4	0.003237	2615
	43	1109.4	0.003393	2741
S1M2	62	2306.4	0.001399	2635
	63	2381.4	0.001444	2720
S2M2	48	1382.4	0.001558	2582
	49	1440.6	0.001624	2691
S3M2	51	1560.6	0.001415	2566
	52	1622.4	0.001471	2668
S4m2	42	1058.4	0.001195	2615
	43	1109.4	0.001252	2741

All models satisfy the deflection limit. The operation limit of blade are between two allowable deflection standards, R/300 and R/180, where R is the blade length. Supposedly for this project, the limit is between 0.0333 meter and 0.0556 meter.

5.2 Modal Analysis

5.2.1 Mode Shape and Natural Frequency

A free vibration analysis of the models is performed. The corresponding mode shapes' total deformation due to increasing frequency can be seen from Fig. 30 and 31.

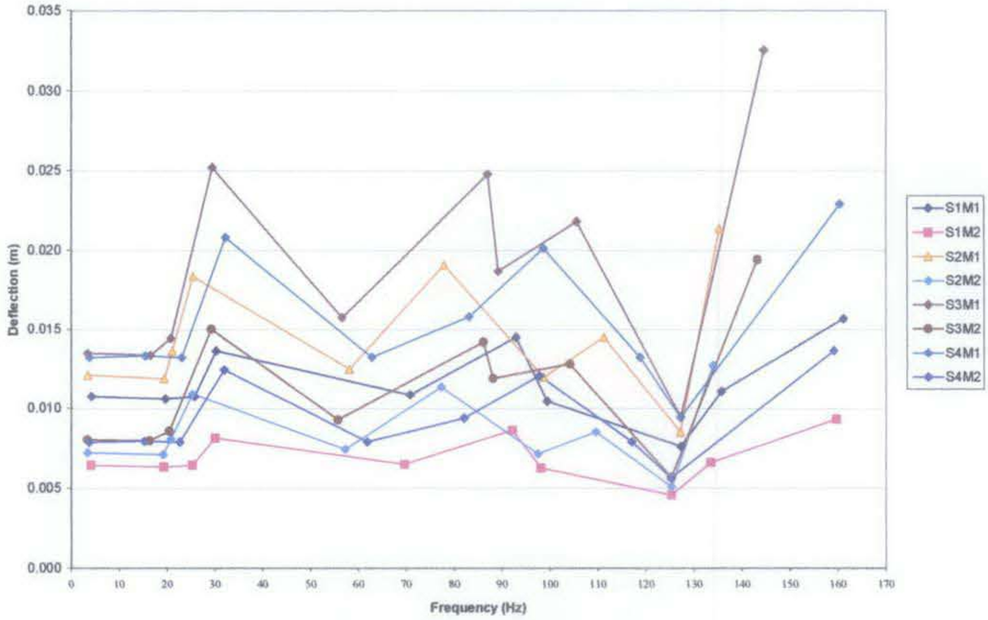


Figure 30: Relative deflection versus Frequency (All models: S - Shape, M - Material)

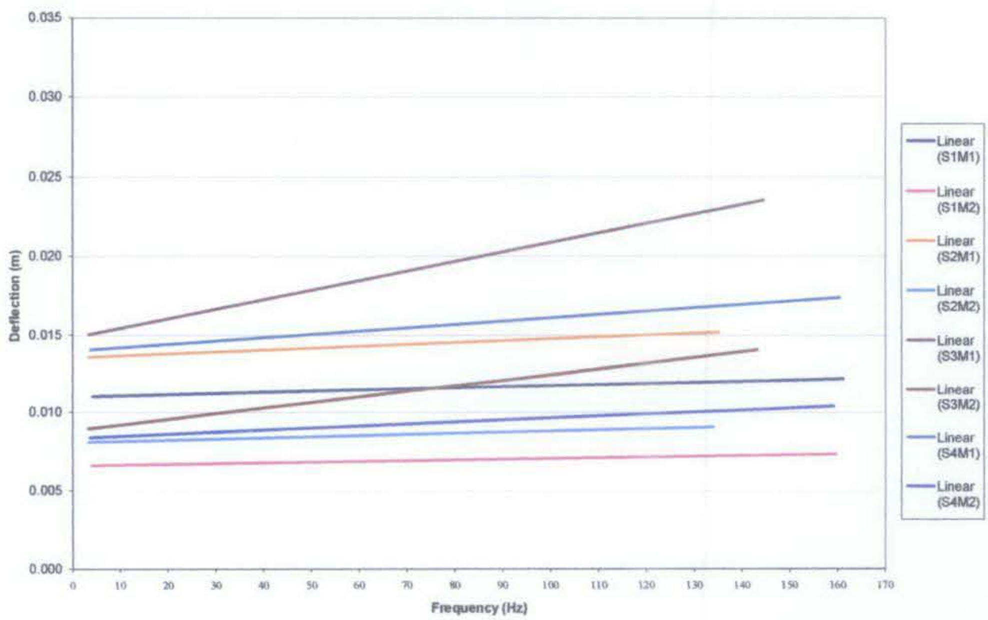


Figure 31: Relative deflection versus Frequency (All models trendline)

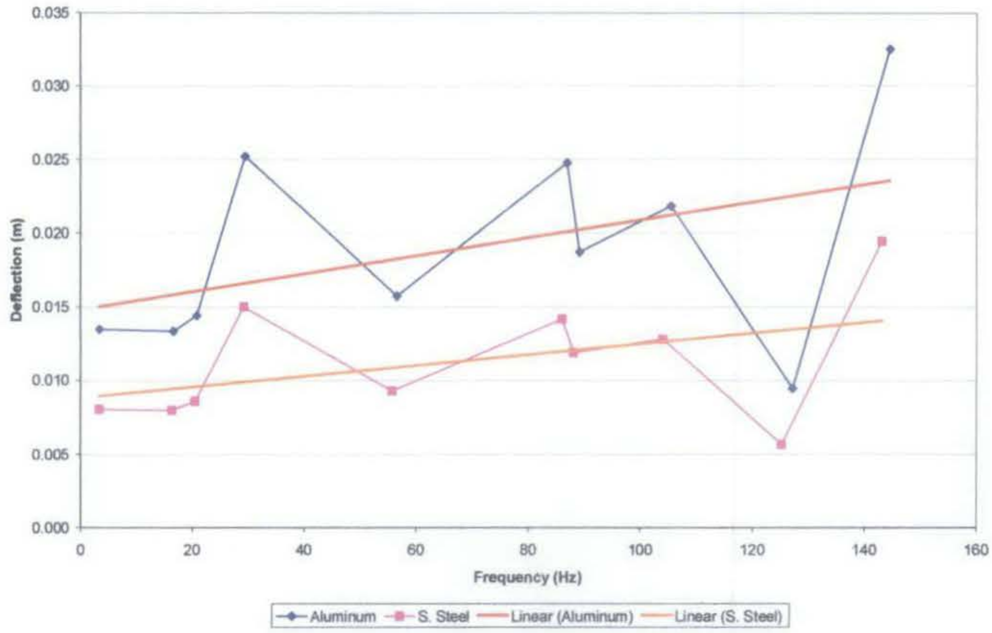


Figure 32: Relative deflection versus Frequency (Shape 3)

In addition, Figure 32 also indicated that the aluminum blades are more excited during resonance because aluminum is softer with Modulus of Elasticity (ratio of stress to strain or the measure of resistance to elastic deformation) of 70 GPa compared to 200 GPa by stainless steel.

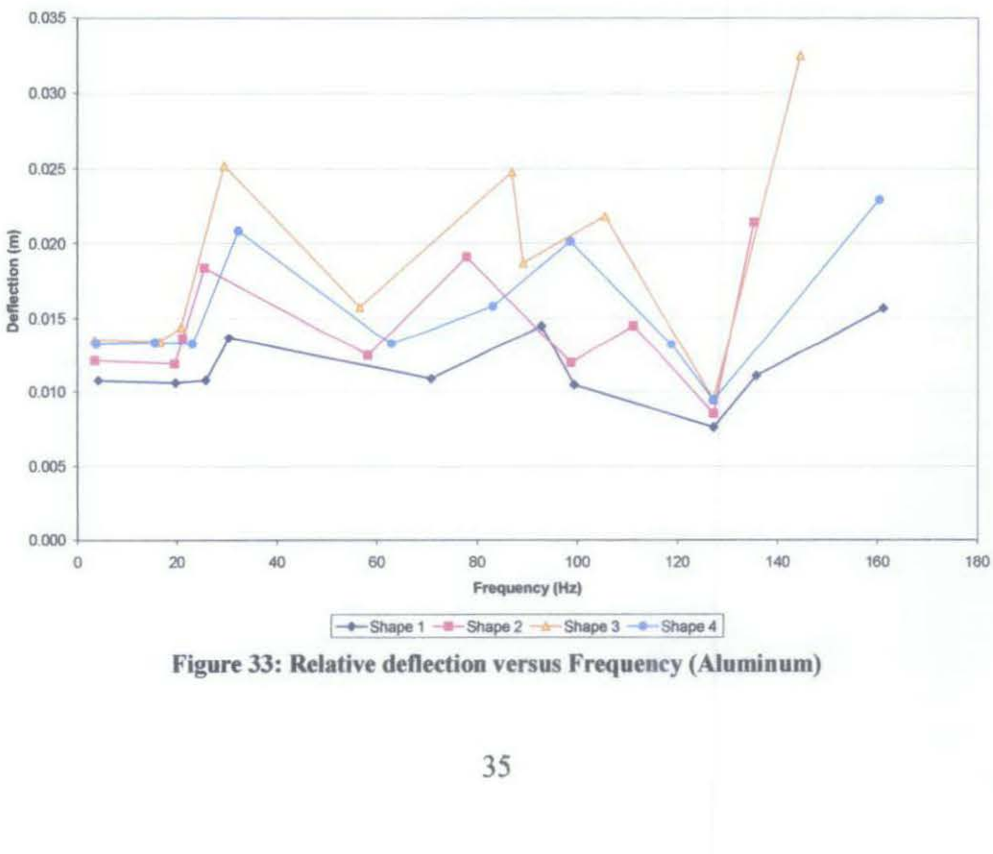


Figure 33: Relative deflection versus Frequency (Aluminum)

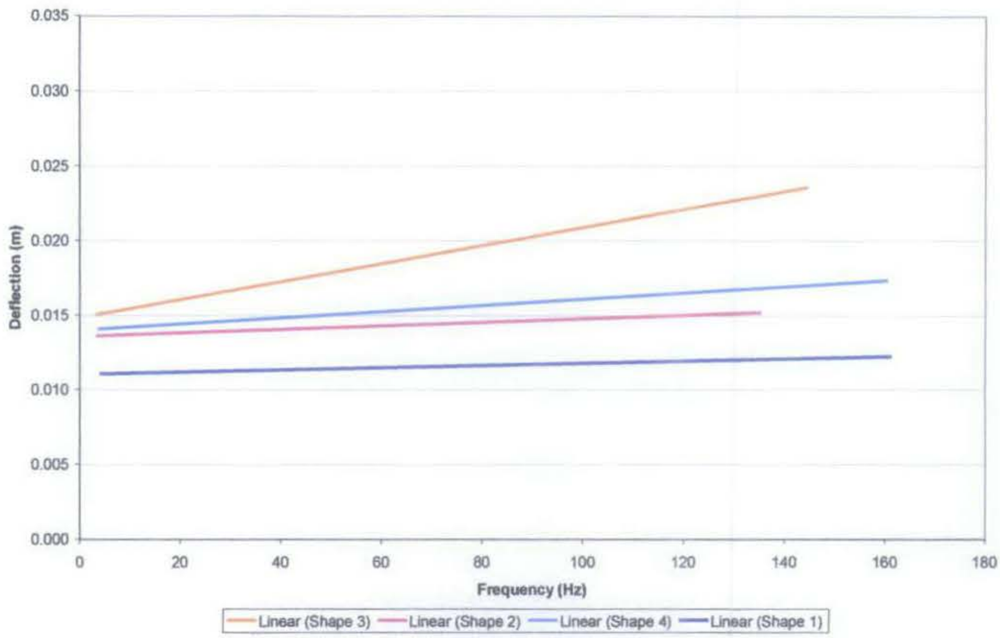


Figure 34: Relative deflection versus Frequency (Aluminum trendline)

From Figure 33, the relative deflection line Shape 3 shows the most exaggerate behavior where it represents at certain frequencies the blade is excited. This is because of the effect of resonance between two frequencies, one from the blade's rotational speed and another one is the blade's natural frequency. Blade model of Shape 3 also becomes more exaggerate as the frequency increases based on the increasing linear line of Shape 3 in Figure 34.

5.2.2 Comparison with standards

As it is recommended to keep the eigenfrequencies outside a range defined as the rotational frequency of wind turbine blade about ±12%, below are the range of rotational frequencies according to potential wind speed in Malaysia. The rotational speed is calculated based on an assumption of 5 for the tip speed ratio.

Table 17: Rotational frequency of wind turbine blade in the project for Mersing's wind speed range

Wind speed (m/s)	ω (rad/s)	*f* (Hz)	12%	-12%
1	0.5	0.07958	0.08913	0.07003
2	1.0	0.15915	0.17825	0.14006
3	1.5	0.23873	0.26738	0.21008
4	2.0	0.31831	0.35651	0.28011
5	2.5	0.39789	0.44563	0.35014
6	3.0	0.47746	0.53476	0.42017
7	3.5	0.55704	0.62389	0.49020
8	4.0	0.63662	0.71301	0.56023
9	4.5	0.71620	0.80214	0.63025
10	5.0	0.79577	0.89127	0.70028

The fundamental frequency and the second frequency obtained from the finite element analysis are collected for comparison.

Table 18: Blade models fundamental and second frequencies

Shape	Material	Frequency (Hz)	
		1	2
1	Alu	4.148	19.623
	SS	4.081	19.337
2	Alu	3.419	19.443
	SS	3.363	19.160
3	Alu	3.388	16.561
	SS	3.333	16.317
4	Alu	3.734	15.437
	SS	3.675	15.210

Referring to Table 18 and 19, the lowest frequencies of all the blade models are safe from frequency resonance at 0 rpm speed. However, the blade model of Shape 3 would start having frequency resonance as the wind speed becomes 34 m/s.

Table 19: Rotational frequency of wind turbine blade for the project

Wind speed (m/s)	ω (rad/s)	*f* (Hz)	12%	-12%
34	17.0	2.7056	3.0303	2.3810
35	17.5	2.7852	3.1194	2.4510
36	18.0	2.8648	3.2086	2.5210
37	18.5	2.9444	3.2977	2.5910
38	19.0	3.0239	3.3868	2.6611
39	19.5	3.1035	3.4759	2.7311
40	20.0	3.1831	3.5651	2.8011
41	20.5	3.2627	3.6542	2.8712
42	21.0	3.3423	3.7433	2.9412
43	21.5	3.4218	3.8325	3.0112
44	22.0	3.5014	3.9216	3.0812
45	22.5	3.5810	4.0107	3.1513

CHAPTER 6: CONCLUSION

The discussion concluded that the blade shape is made to produce lift force due to the pressure difference between front and back side of blade. Thus, the blade deflection should be controlled to avoid excessive bending and tower hitting at the same time the aerodynamic performance is satisfied. One of the ways is that the blade design should be made with high Modulus of Elasticity material in order to withstand high static (wind pressure) and dynamic (rotational) loading. However, certain materials with high Modulus of Elasticity is heavier thus, good material selection process must be done together with design improvements such as hollow type blade.

As the conclusion, the project is planned well to achieve its objectives. In order to ensure this project complete successfully, discussions and supervision from supervisor are important. Besides, the study also needs the references from journals and websites. Questionnaires during designing the project also need to be done so that problems are stated and solved very well. The author hopes this project will convey good meaning to development of wind power production in Malaysia.

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APPENDIX

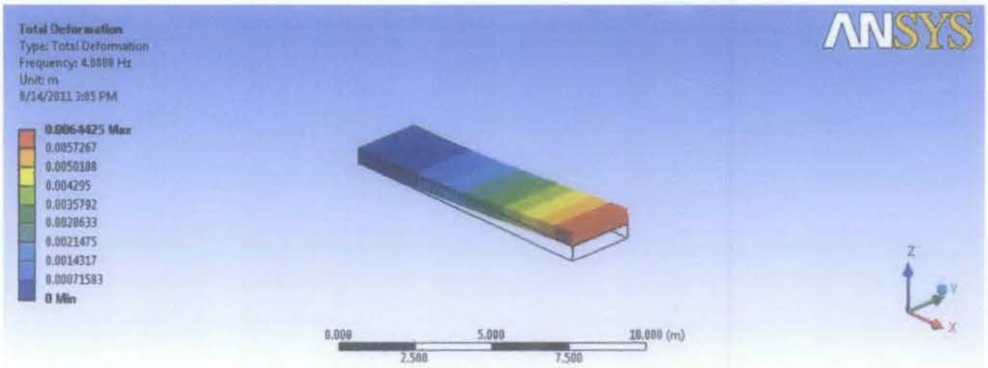

Figure A1: Shape 1, Stainless steel flapwise mode

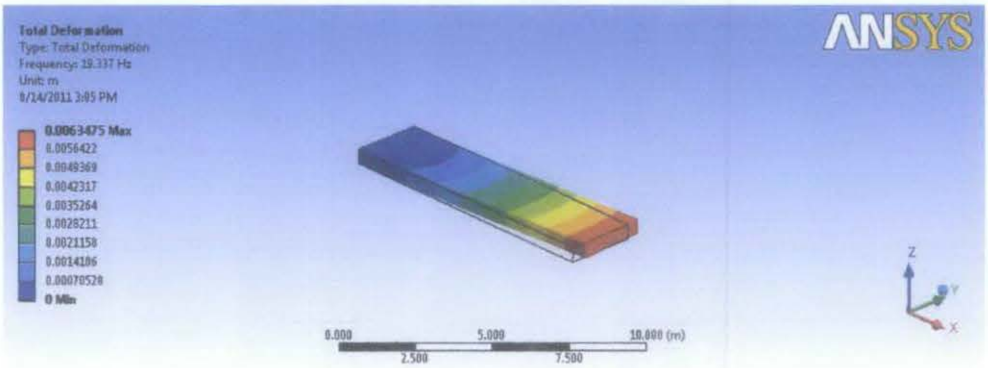

Figure A2: Shape 1, Stainless steel edgewise mode

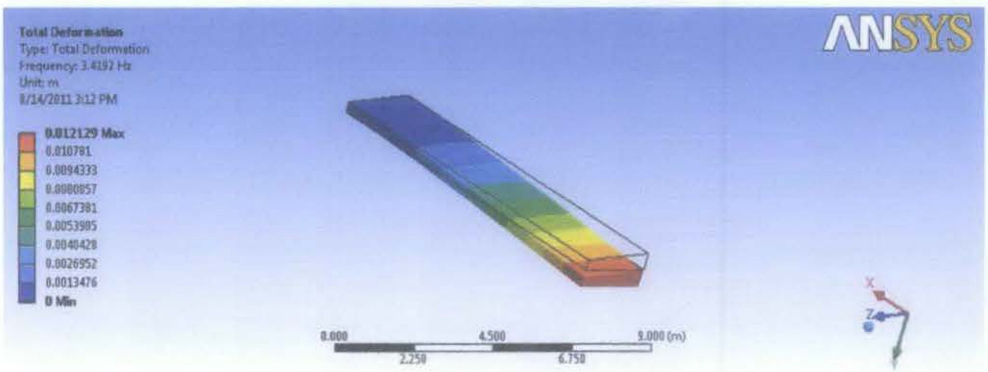

Figure A3: Shape 2, Aluminum flapwise mode

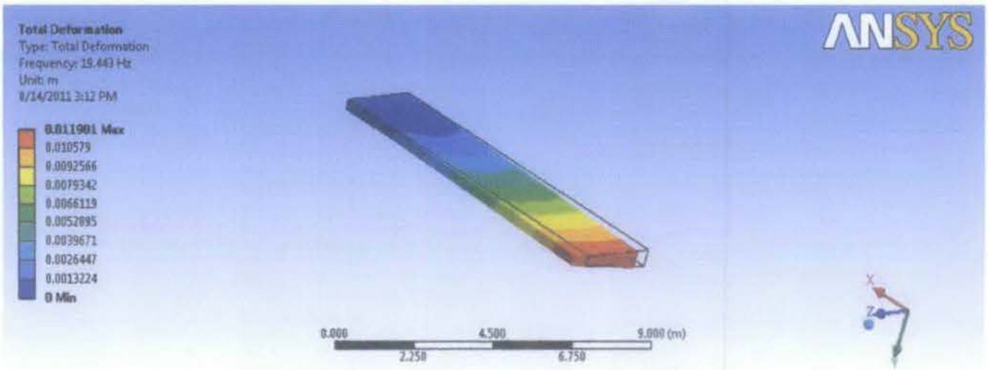

Figure A4: Shape 2, Aluminum edgewise mode

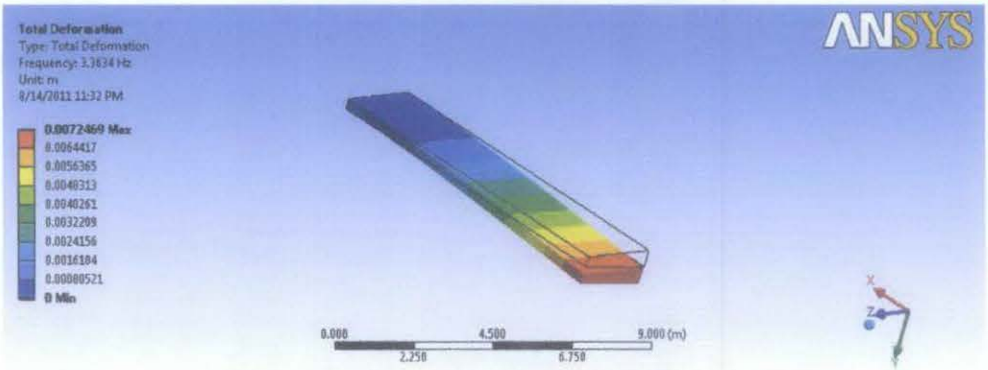

Figure A5: Shape 2, Stainless steel flapwise mode

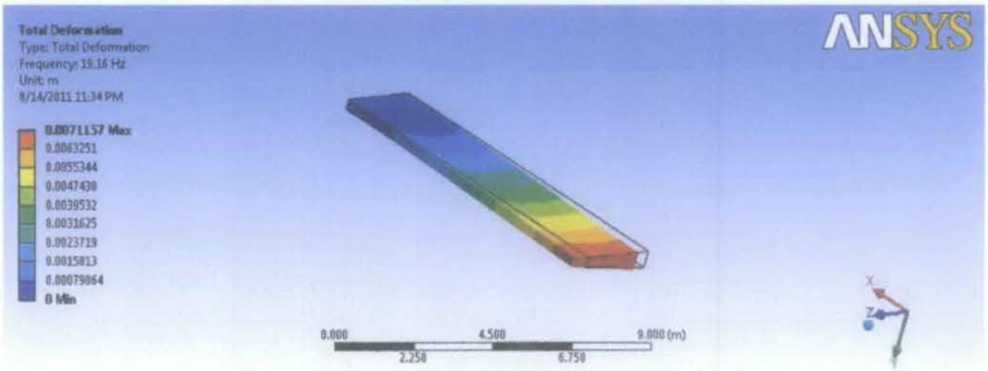

Figure A6: Shape 2, Stainless steel edgewise mode

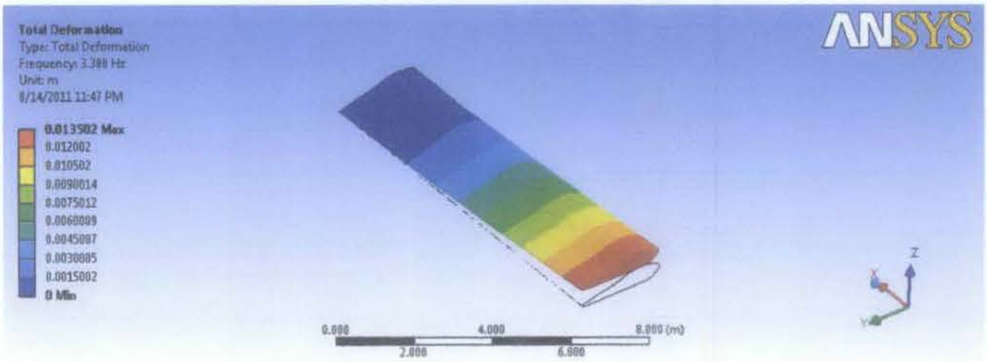

Figure A7: Shape 3, Aluminum flapwise mode

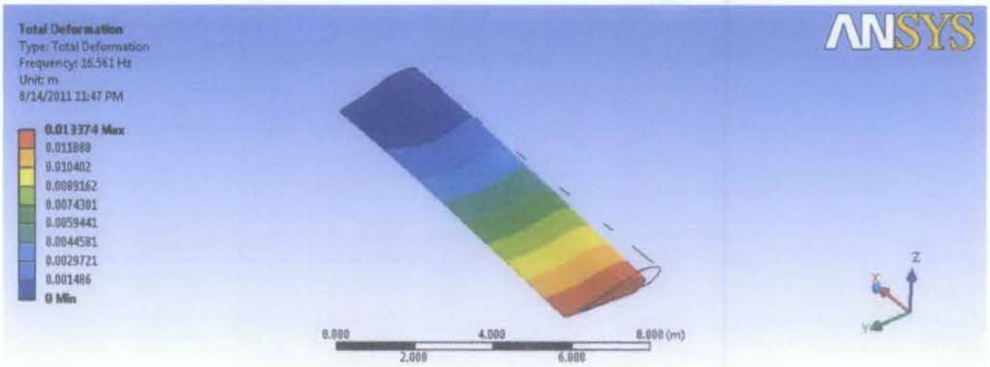

Figure A8: Shape 3, Aluminum edgewise mode

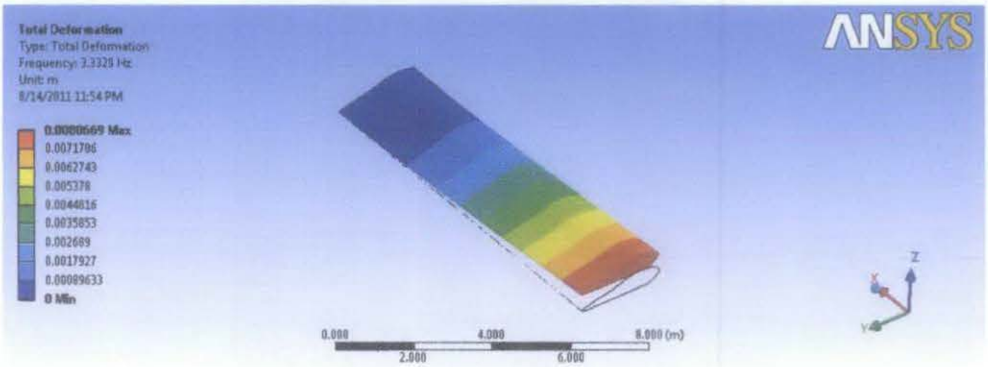

Figure A9: Shape 3, Stainless steel flapwise mode

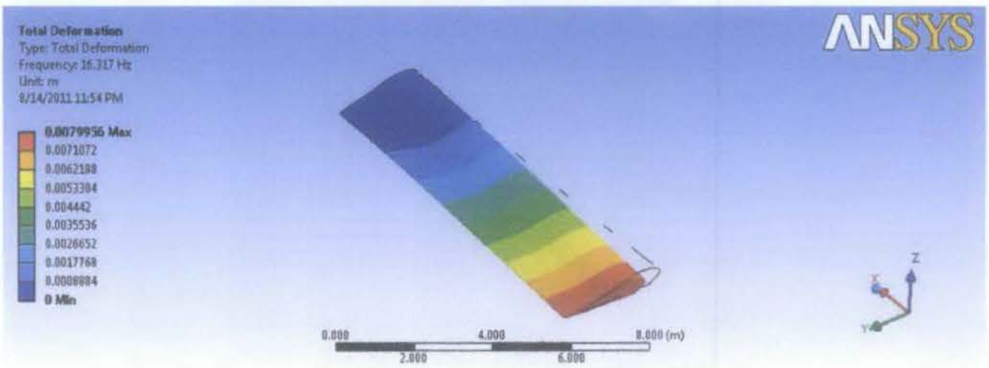

Figure A10: Shape 3, Stainless steel edgewise mode

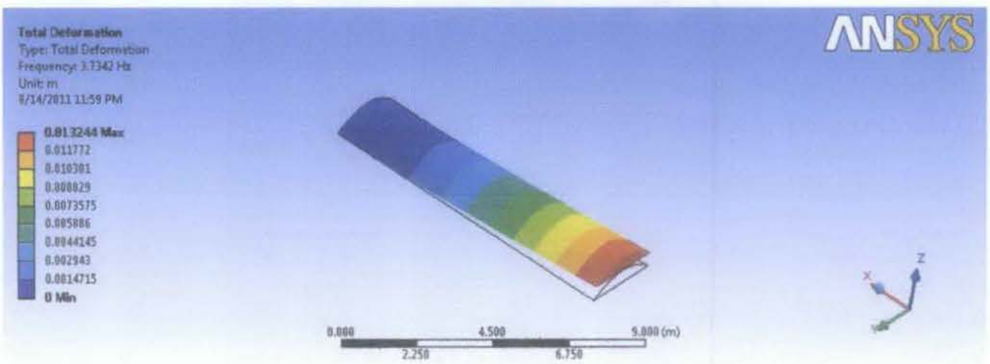

Figure A11: Shape 4, Aluminum flapwise mode

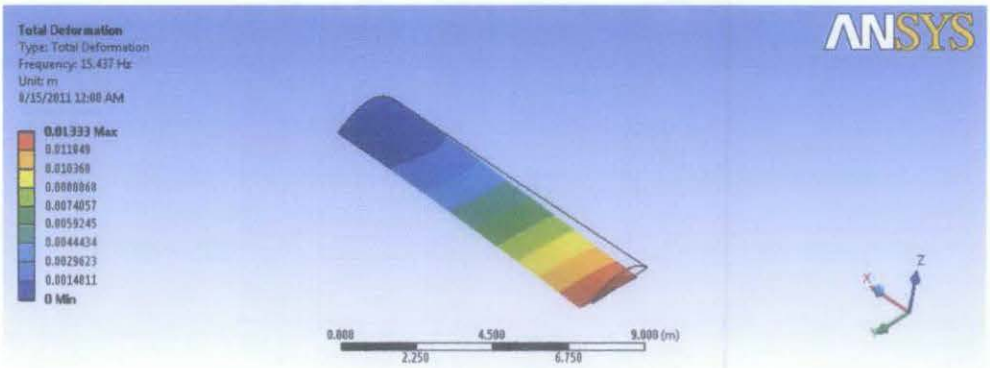

Figure A12: Shape 4, Aluminum edgewise mode

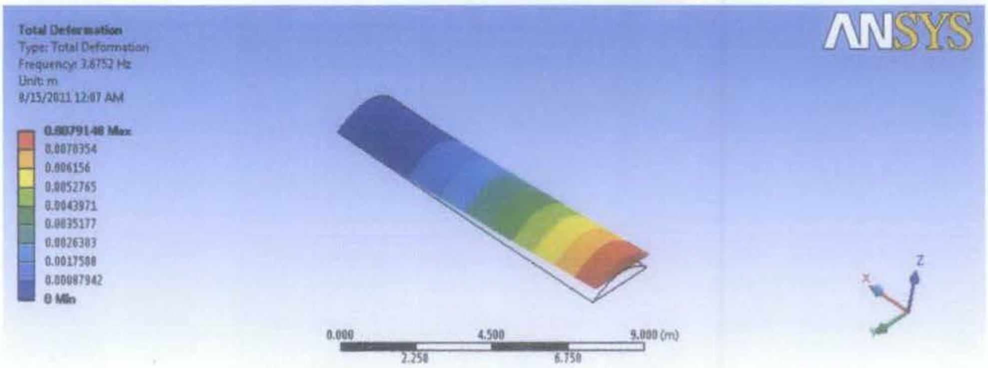

Figure A13: Shape 4, Stainless steel flapwise mode

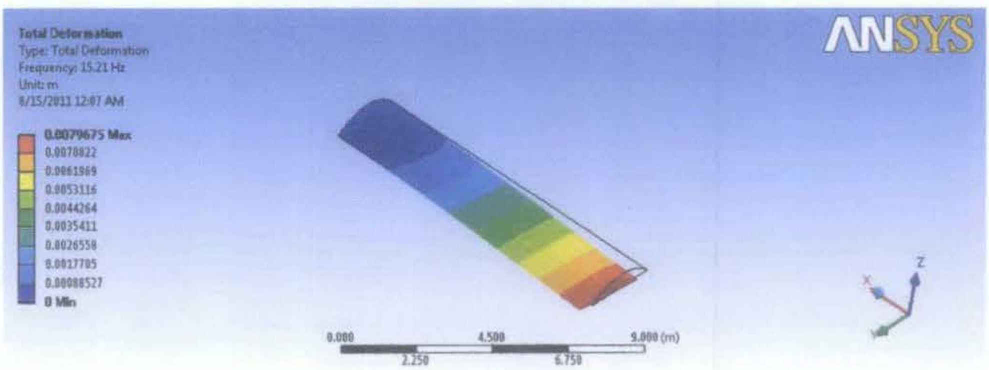

Figure A14: Shape 4, Stainless steel edgewise mode