DESIGN AND MANUFACTURE OF A ONE METRE WIND TURBINE BLADE USING BAMBOO

By

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DECLARATION

I hereby declare that this submission is my own work towards the Master of Science degree and that, to the best of my knowledge, it contains no material previously published by another person nor material which has been accepted for the award of any other degree of the University, except where due acknowledgement has been made in the text.

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DEDICATION

This work is dedicated to the honor of JEHOVAH for He has been my provider and sustainer, to the late Prof. Abeiku Brew-Hammond who initiated the thought of this research in me, and also to my parents Mr. Jonas Boateng and Madam Cecilia Osei – whose counsel, love and support has brought me this far and to my aunt, Madam Lydia Boateng who has been my foster mother.

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ABSTRACT

Wind energy is among the cheapest means for the production of renewable energy currently existing. But wind power generation will be impossible without an effective or an efficient wind blade. Currently, wind turbine blades are high performance and hybrid material structures. But bamboo has been observed to be more sustainable than the current materials in terms of life cycle and renewability of the resource. Bamboo which is known to have notable properties of low density, good strength and high modulus across the culm wall has not been used yet to design a wind turbine blade. An attempt was made to design and manufacture 1m wind turbine blade using bamboo. During the production of the bamboo wind blades, the detailed drawing of the blade was produced using AutoCAD (2010) software and profile 2.16; fresh bamboo culms were harvested and were split into strips. The strips of the bamboo culms were planed and laminated into boards with a torque of 2MPa. The board produced had the dimension 1.0 m x 0.18 m x 0.02 m. The wind turbine blade carved out and the following properties of the blades were obtained: solidity of 0.10, blade density of

0.658 g/cm^3, moment of inertia of $1.5313 \times 10^{-4} m^4$, and natural frequency of 130Hz. In conclusion, bamboo can be used to manufacture wind turbine blades and should be employed in areas where the forest needs to be reserved and other wood and composite materials are scarce.

Keywords: Bamboo Culm, Laminated, Low Density, Renewable Energy, Wind Turbine.

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SYMBOLS AND ABBREVIATIONS

Amph Ampere hour

Amps Amperes **ft** Feet **Hz** Hertz

kg Kilogram **km** Kilometre **kW**

Kilowatt **kWh** Kilowatt hour

kWh/yr Kilowatt hour per year

lit. Litre

m Metre

m/s Metre per second **mph**

Miles per hour

MW Megawatt

R Radius

RPM Revolution per minute

V	Volts
W	Watt
W/m2	Watt per square metre
a.g.l.	Above ground level
AC	Alternating Current
CSIR	Council for Scientific and Industrial Research
DC	Direct Current
DNV	Det Norske Veritas
EC	Energy Commission
Eq.	Equation
HAWT	Horizontal Axis Wind Turbine
KNUST	Kwame Nkrumah University of Science and Technology
Ltd.	Limited
MSD	Meteorological Service Department
NREL	National Renewable Energy Laboratory
pcs.	Pieces
PM	Permanent Magnet
PV	Photovoltaic
PWF	Present Worth Factor
Re	Reynolds Number
TSR	Tip Speed Ratio

TV	Television
USA	United States of America
VAWT	Vertical Axis Wind Turbine

CHAPTER ONE

INTRODUCTION

1.1 Background of study

The issue of energy production and sustainability for national development is one that is currently threatening the frontiers of industry and technology. It is not surprising that countries all over the world are looking for alternative sources of energy, whiles others are trying hard to keep up with energy management. According to the Daily Graphic on January 10, 2013 Ghana "government is committing GH¢ 1m a year for the next three years to stimulate the purchase of new refrigerators". The expected gain is to save 216MW of electrical power in the country, which is more than half of power capacity of the Bui Dam when completed. No one need researched evidence to know that there are vast growths of industrial technology and development and as a result energy requirement and its usage are on ascendency. Currently, corporate businesses are remotely connected and hosted in the cloud, and service rendered at the click of a button; the world is now a global village. And behind the ease of business, though, is the growing demand for more and more energy.

1.2 The energy trend

Many researches are being conducted daily to find alternative sources of energy to meet the growing demand for more energy (Anonymous, 2013). These researches have become exceedingly necessary, considering the fluctuations and manipulations of energy prices. Currently, "large investment banks control 80% of oil derivatives compared to 30% a decade ago (Dean, 2011). Kuwait's Oil Minister Hani Hussein supports that "under the supply and demand theory, oil prices today are not justified"" (Reuters, 2012). The trend of events throughout history suggest that continual usage of petroleum, coal, natural gas and many other non-renewable resources pose a lot of great challenges to the whole world.

Historical trends in energy crisis:

- Energy disasters in 1970s – by the peaking of oil production in major industrialised countries and restrictions from other producers.
- The oil price shock in 1990 –by the Gulf war.
- The California electricity crisis in 2000-2001 - by market influence by "the Enron scandal" and unsuccessful deregulation.
- The Argentine energy disaster in 2004.
- The Central Asia energy disaster in 2008 – by "uncharacteristically" cold temperatures and low levels of water in areas that were dependent on hydroelectricity.
- The South African power disaster in February 2008.

To avoid the serious social and economic implications a global decline in oil production could entail, the 2005 Hirsch report emphasized the need to find alternatives, at least ten to twenty years before the peak decline, and to phase out the use of petroleum over that time (Robert L. Hirsch, 2005). This was similar to a plan proposed for Sweden that same year, (Independence, 2006). Because of this, development and use of renewable energy resources instead of the traditional resources are extremely necessary and indispensable, especially in many developing countries like Ghana.

Renewable energy commercialization is increasingly becoming a better option. According to the U.S. Energy Information Administration, the most frequently used renewable energy resources are biomass, hydro, geothermal, wind and solar. Moreover, the New York Times December 12, 2012, says that in recent years, wind power has been one of the fastest-growing sources of energy around the world. Yinyao et al (2009) confirms that till now wind energy is the most matured technology compared to the other new power generation technologies. The international wind energy market showed a record in 2003 with a growth rate of 15%. Globally, a total power of 240GW was installed in 2011 and the industry was estimated to grow by another 40GW at the end of 2012. The International Energy Agency (IEA) new policy scenario puts total wind energy capacity to reach 587GW by 2020. Following wind energy developments, it is evident that wind power is gaining grounds. But wind power will be a cliché at best or a figment of imagination without an effective or an efficient wind blade capable of capturing the power in the wind. This makes wind blades - with their design and manufacture - an imperative and indispensable parameter in wind energy exploitation and generation. Yinyao et al (2009) supports that the development of wind turbine blades is still moving on and the layout of turbine blades has almost been agreed by the countries which could generate and apply wind energy.

1.3 Modern wind turbine blade materials

Modern wind turbine blades are high performance and hybrid material structures. They are being manufactured using polymer matrix composite (PMC) materials, combined with monolithic (single skin) and sandwich composites. And this has been supported by Brice Tremeac (2009) that, present day designs are mainly based on glass fibrereinforced polymer (GFRP) composites. Current research shows that glass-fiber seems to have matured and become applicable material for the manufacture of turbine blades.

However, according to Karl Larsen's research on glass fibre application the end of life of the glass fiber cannot reach a completely sustainable level (Consoli et al, 1993). This suggests that glass fibre still has some potential space for development or it might be replaced by other more sustainable material for improvement, (Yinyao Q.et al, 2009). Presently, glass-fibre is the most common raw materials for producing turbine blades. But consideration of the environmental impact suggests that if an alternative material with low cycle cost can be obtained for the production of wind blades it will enhance wind power generation. And this is where the road is paved for the utilization of resources like bamboo, more especially in developing countries like Ghana.

1.4 The Naturally occurring Bamboo

Bamboo has been observed to be more sustainable than glass fiber in terms of life cycle and renewability of the resource. Bamboo consists in a variety of fast growing species of grass plants and is a high yield renewable resource. Bamboo growth depends on the species, but generally all bamboo mature quickly. Aminuddin et al (1991) state that bamboo might have forty to fifty stems in one clump, which adds ten to twenty culms yearly. Bamboo can reach its maximum height in four to six months with a daily increment of 15 to 18 cm (5 to 7 inches). Wong (1995) stated that, bamboo culms take two to six years to mature; and this depends on the species. According to Perry et al (1994), bamboo matures in about three (3) to five (5) years. Arguably there are inconsistencies with the real period for maturity and even cutting cycle, but this does not debunk the fact that bamboo matures relatively early. This means that bamboo's growth is more rapid than most plants on the face of the earth. Some bamboo species have been observed to surge skyward as fast as 48 inches in one-day (Farrelly, 1984). The fast growth characteristic of bamboo is an important incentive for its utilization in engineering. Due to the fact that it is abundant and cheap, research into the application of bamboo should be done to the "fullest" extent (Anonymous, 2013).

1.5 Properties and Applications of bamboo

Naturally, bamboo has hard and smooth surface with ease of working. Currently, bamboo is used for building and scaffolding, for roofs and flooring, pipes, baskets, walking sticks, fishing poles, window blinds, arrows and furniture than it used to be several years ago when few countries knew of bamboo. The diverse application of bamboo is due to its "incredible" properties. The mechanical behavior of bamboo is simply overwhelming.

Bamboo has a density of 0.6-0.8 g/cm^3; Young's modulus of 1500-2000 MPa; yield strength (elastic limit) of 35-44 MPa, tensile strength of 36-45 MPa; strain of 0.0290.055; hardness (Vickers) of 19.7-118 MPa; fatigue strength of about 25-35 MPa; and a fracture toughness of 5-7 MPa.$\sqrt{m}$. In fact, bamboo is one kind of renewable material with special properties of strength, good toughness and light weight. Considering these and many other remarkable properties of bamboo, it is really important to find how to work with this renewable material in the area of wind energy applications.

1.6 Bamboo Species in Ghana

There are currently seven species of bamboo growing in Ghana:Bambusa arundinacea; Bambusa bambos; Bambusa multiplex; Bambusa pervariabilis; Bambusa vulgaris; Bambusa vulgaris var Vitata; and Dendrocalamus strictus. Among these species only B. vulgaris is indigenous to Ghana; the others were introduced from Asia (Shyam and Follet, 2003). The taxon in focus for this research was B. vulgaris (the common man's wood in Ghana). The idea of using B. vulgaris in this research was to serve as an incentive to the local craftsmen, to support their activities with bamboo and to gradually move from timber to bamboo. Also to present to professionals how bamboo can be used to manufacture laminated boards for applications where strength and low density are of importance; like the wind turbine blade.

1.7 Justification of the study

Data compiled and analysed by some research institutions such as the Meteorological Service Department (MSD), The Energy Commission (TEC) and the Mechanical Engineering Department of Kwame Nkrumah University of Science and Technology (KNUST) suggests that, wind energy harnessing may be possible in some parts of the country, especially, along the coast (Appiah, 2005). Small wind turbine applications are mostly used for refrigerators, computers, televisions, radio/cassette players, ceiling fans and commercial battery charging among others. But as a country, we are unable to harness the energy in the wind for power production. A 600 W locally-made wind turbine was mounted on an 18 m guyed tower at Alorkplem, Dangbe East District, for battery charging. The system was installed about 30 m off the shore of the Volta Lake and produces 220V AC output from one 12V 100 Ah batteries with 1000 W inverter. But a heavy storm and downpour in April, 2005 broke the wooden blades and rendered the system inactive to date. The problem as witnessed from the locally manufactured wind turbines is with the property of the blades as regards the strength and weight. It is therefore imperative that a replacement for a local wind turbine blade material be sought that can afford the strength capacity and the low density as required by the wind blades.

1.8 Objectives

The main objective of this project is to design and manufacture a one-meter wind turbine blade using bamboo. The specific objectives of this project were:

- To manufacture a laminated bamboo board from bamboo culm (stem).
- To find the bending and compression strengths of the laminated bamboo lumber.
- To manufacture a wind turbine blade from the board.
- To test how the blades will perform on a wind turbine machine.

1.9 Methodology

- Draw the model of the wind blade.
- Make laminated bamboo boards from the bamboo culm.
- Perform the bending and compression strength test of the laminated board
- Manufacture a wind turbine blade from the bamboo boards.
- Perform the bending test on the blade
- To install the bamboo blades on a wind rotor to test the performance.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

This chapter introduces the parameters of wind energy generation, material requirement of wind turbine blades and how bamboo has the potential to meet the materials requirement of these blades. Because the scope of this research was on the outstanding properties of bamboo and how they can be used to make small wind turbine blades, the details of wind turbine components would be left out except the rotor blade.

2.1 Wind power generation

Wind energy (wind power) generation describes the process by which the wind is used to generate mechanical power or electricity. Wind turbines convert the kinetic energy in the wind into mechanical power which can then be converted into electric power. The operation of the wind turbines is opposite to electric fans – the directions of rotation of the blades in the two cases are opposite. Another disparity is that, instead of using electricity to produce wind, like the fan, wind turbines use wind to generate electricity. In wind power generation, the oncoming wind turns the blades connected to a generator to produce electricity. The power in the wind available for harvest greatly depends on the wind speed blowing against the blades, the blade aerodynamics and the area swept by the rotor blades. Wind energy, is an alternative source of energy to fossil fuels. Unlike fossils, wind energy is inexhaustible, renewable, widely distributed, clean, produces no greenhouse gas emissions in its operation and it is environmentally friendly. Wind energy generation avoids:

- The emissions of mercury and other common air pollutants.
- Emissions associated with extracting and transporting fuels. Lake and stream-bed acidification from acid rain or mining.
- Production of toxic solid wastes, ash, or slurry Greenhouse Gas Emissions

2.2 Types of wind turbines

The types of wind turbines are dependent on the orientation of the main rotor shaft. Basically, a wind turbine is either:

- A vertical-axis wind turbine (VAWT) or,
- A horizontal-axis wind turbine (HAWT)

2.2.1 Vertical Axis Wind Turbines (VAWTs)

VAWTs are wind turbines which have their main rotor shaft set vertically. VAWTs are seldom seen in operation, because they are not as efficient as the HAWTs. The main existing types of VAWT are the Darrieus turbine, Giromill, and Savonius turbine.

The major disadvantages observed with a VAWT are that it produces unsteady torque and is difficult to erect on a tower. Thus, they are installed on the base which they rest upon. Moreover, as wind speed is slower at lower altitudes, less wind energy is available to harness by VAWTs. Air movement nearer the ground can create turbulence causing VAWTs to vibrate. Its operation is also accompanied with increased noise and bearing wear which may shorten the service life of VAWTs and decrease the mean time between failures of parts.

Some advantages of using VAWTs are the following:

- Turbines do not need to be oriented to face into the wind to be effective: they can use wind from all directions. This makes it particularly useful on sites with highly variable wind direction.

- The generator and gearbox can be placed near the ground making it faster and easier for maintenance.
- No need for a giant tower to support it
- Relatively lower construction and maintenance costs.

Some disadvantages of vertical axis wind turbines are the following:

- Vertical axis wind turbine systems usually operate near the ground where there's not much wind.
- They produce wavy (sinusoidal) power pulses to drive the device
- They don't start themselves in a breeze
- Repair of the main bearing usually means having to take the whole machine apart
- Typically about 40% less efficient than the HAWTs in energy production.

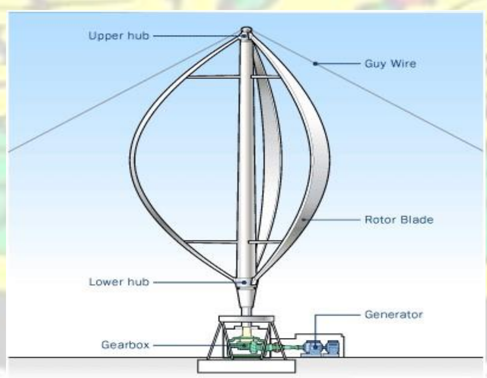


Figure 1: Darrieus VAWT *(Anonymous, 2013)*

VAWTs are omnidirectional but usually not self-starting and often require an electric motor to get them started (Koenemann, 2005). Most of the designs are drag-based and have a tip speed ratio (TSR) less than 1. Thus, these designs turn relatively slow, but yield a high torque. One might use a gearbox, but efficiency might be compromised and the machine may not start at all or at best start with much difficulty. Darrieus wind turbines have a tip speed ratio (TSR) between 5 and 7.

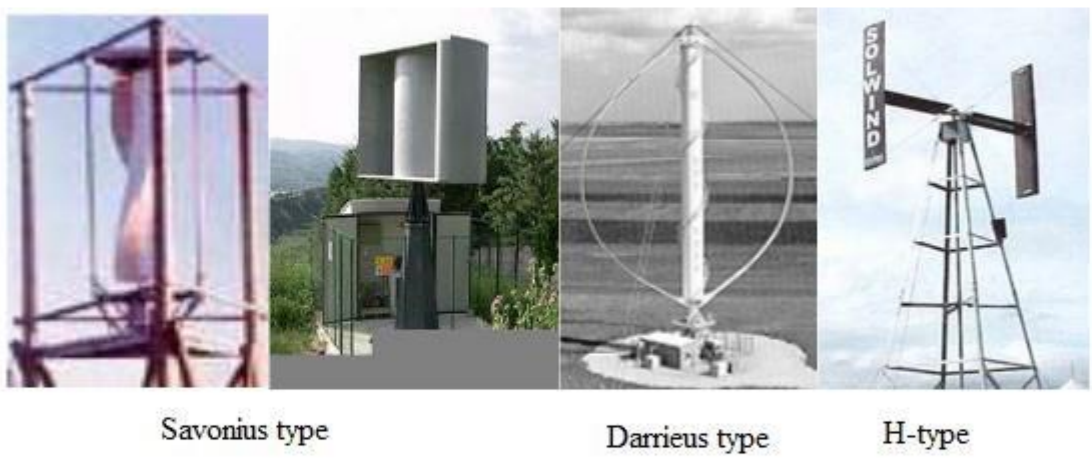


Figure 2: Vertical Axis Wind Turbines *(Anonymous, 2013)*

2.2.2 Horizontal Axis Wind Turbines

Horizontal axis wind turbine (HAWT) is a type of wind turbine where the main rotor shaft is set horizontally. HAWTs have been modernized from the traditional windmill designs that have been around over the eras.

The HAWT is mainly made up of the nacelle (which houses the main rotor shaft, electrical generator and gearbox to boost the rotation speed of the blades) with the blades mounted on the tower. Another essential component of the HAWT is the wind vane. It is used to direct small turbine whilst large turbines use a wind sensor coupled with a servo motor. Most HAWTs have a comparatively slow rotating speed thus a gearbox is incorporated to increase the slow blade rotations to drive an electric generator. HAWT blades are carefully designed to be stiff to prevent them from being pushed into the tower at high gusts. The blades are also placed a fair distance from the tower and are often tilted through small angles to increase efficiency in energy by avoiding turbulence created by the tower. The advantages of HAWTs are:

i. They offer higher efficiency – their blades are perpendicular to the direction of the wind and hence receive more power for the rotation.
ii. The traditional designs allow easy installation and easy maintenance.

Disadvantage of HAWTs

i. They require high altitudes making it difficult to install. It becomes necessary in such cases to provide very tall and expensive cranes coupled with skilled operators for installation.
ii. Design requires massive tower construction consideration to support the heavy blades, gearbox, and the generator.

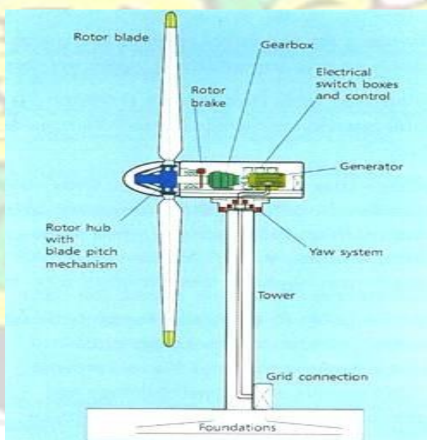


Figure 3: Horizontal Axis Wind Turbine *(Anonymous, 2013)*

The horizontal axis wind turbine comes in different types. They are one-bladed, twobladed, three-bladed and multi-bladed.

Figure 4: Horizontal Axis Wind Turbines (Anonymous, 2013)

2.3 Energy capture in small wind turbines

The suitability of a wind turbine for low wind speed zones is its capability to extract the wind power at that low speed. Therefore, the lowest wind speed at which the wind turbine starts to produce power is of particular interest.

2.3.1 Lift and Drag Principle of Wind Energy Conversion

There are two main physical forces which act on the wind blades as they rotate through the wind; these are lift and drag force. They are defined by Equations (2.1) and (2.2).

$$Lift\ force = C_L(\rho/2)AV_a{}^2; \quad 2.1$$

$$Drag\ force = C_D(\rho/2)A_aV^2; \quad 2.2$$

Where C_L and C_D are the lift and drag coefficients respectively, which depend on the cross section of the blade and on the angle of attack (α), at which the wind strikes the blades and the Reynolds number (a measure of the size and speed of the blade);

V= the apparent wind speed through the rotor;

A= the swept area of the rotor; ρ

= the air density.

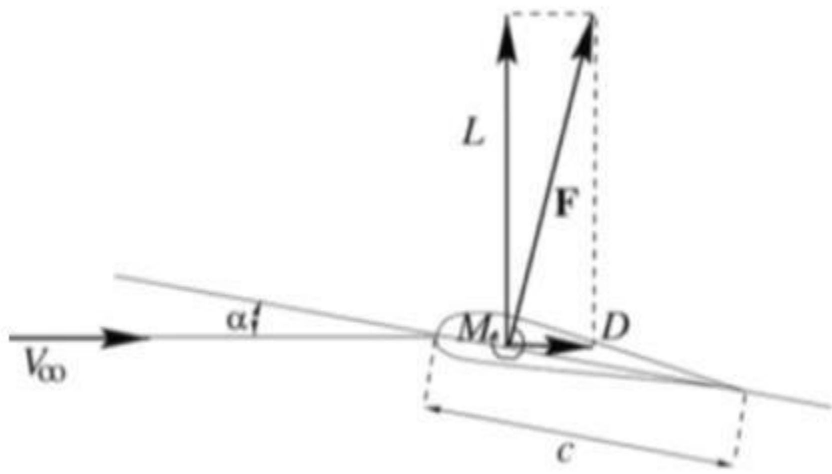


Figure 5: Lift and Drag forces acting on a Turbine Blade (Hansen, 2008)

For the wind blades to act like an airfoil as the wind passes over them, pressure gradient must be created at the leading and the trailing edges of the blades. This established pressure gradient creates a lift which produces the blades spin.

An essential condition to satisfy when extracting wind energy is the Betz criterion which propounds that the maximum possible value of the aerodynamic efficiency is attained when the turbine diminishes the wind speed to one-third of the uninterrupted upstream wind. (DNV/Risø, 2002)

2.3.2 Blade Design

Designing the rotor blade requires that the chord width C, and the blade angle β at each station along the span of the blade be specified. The performance of the blade and the strength depends on the shape of the blade. Therefore, at each station along the blade the right shape to produce the right lift to satisfy Betz criterion is created.

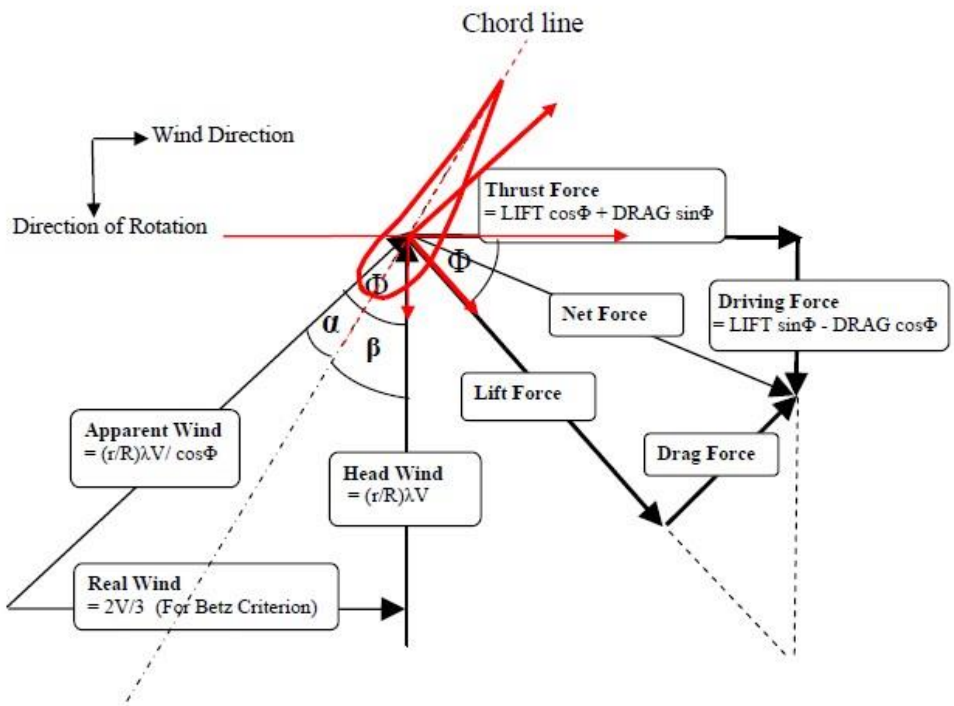


Figure 6: Forces acting on the Blade of a Wind Turbine (Hansen, 2008)

Blade Angle, β

From Figure 2.6, $\phi = \beta + \alpha$ 2.3

Where, ϕ is the angle at which the apparent wind strikes the rotor plane

β, is the blade setting angle α, is the angle of attack

To satisfy Betz criterion, the angle of attack, α, is chosen to optimize the lift. A graph of Lift versus angle of attack, α, is shown in Figure 7. It can be deduced from the graph that lift increases with α, until a point is reached where the blade stalls. At stalling, the lift starts to decrease and drag begins to increase rapidly. This principle is used to regulate the blade from rotating beyond its allowable speed limit.

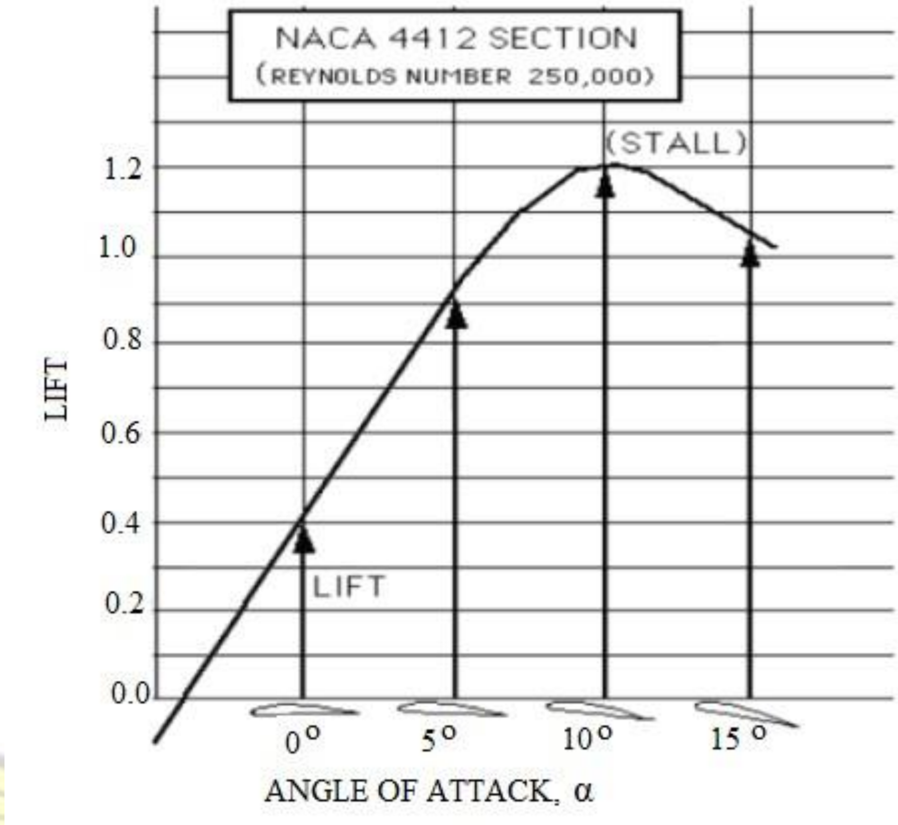


Figure 7: Lift versus Angle of Attack (Piggott, 2005)

The measure of a wind turbine performance is the ratio of the lift to drag. In practice, most sections will produce their best LIFT/DRAG at α = 5, so as a general rule, where detailed data is not available, β can be set to give this angle of attack. (Piggott, 2005)

Thus, $\beta = \phi - 5$ 2.4

But the variation of the headwind along the blade also changes ϕ along the span of the rotor. It can be deduced from Figure 2.6, that:

$$\tan \emptyset = 2R/(3r\lambda) \quad 2.5$$

Therefore, $Blade\ Angle, \beta = \tan^{-1}(\frac{2R}{3r\lambda}) - 5$ 2.6

Hence the ideal shape of the blade must be twisted at each section of the blade as shown

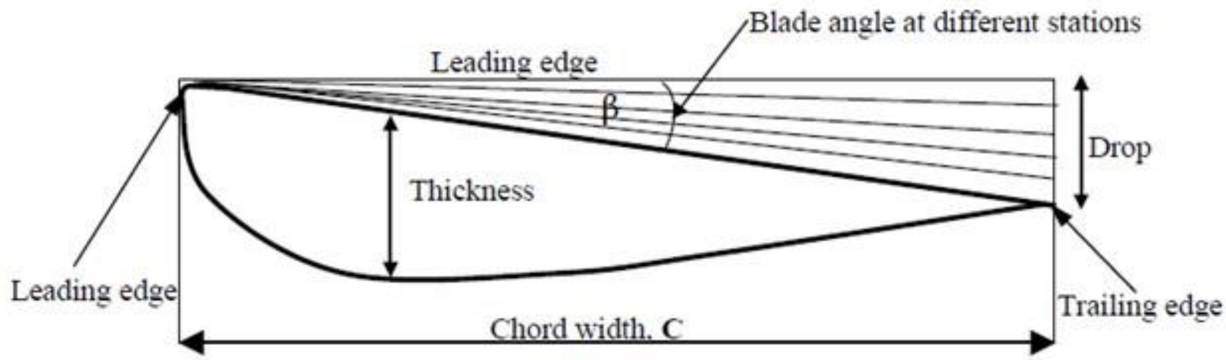


Figure 8: Blade Section showing the variation of the Blade Setting Angle at different Stations (Piggott, 2005) **Chord**

Width, C

From Figure 2.6, the basic blade element derivation is as shown below:

$$Driving\ Force = \sin\phi_L - \ \cos\phi_D \qquad 2.7$$

$$= \sin\phi_L\,(1 - \cos\phi/k)$$

$$= \sin\phi_L\,(1 - (3r/2R)\lambda k) \qquad 2.8$$

Where k is the LIFT to DRAG ratio

$$Thrust\ Force = \cos\phi_L + \ \sin\phi_D \qquad 2.9$$

Satisfying the Betz's criterion, the wind in each part of the swept area of the rotor is slowed down to 1/3 of its upstream velocity. Thrust force which is closely related to the Lift force is used to slow the upstream velocity.

Neglecting Drag in Equation (2.9) becomes,

$$Thrust\ Force = \cos\phi_L$$

Considering a blade element of thickness, Δr.

$$Thrust\ Force = (4/9)\rho AV^2 = (4/9)\rho(2\pi r\Delta r)V^2 \qquad 2.10$$

Equation 2.1 can also be expressed as

$$Lift\ Force = C_L(\rho/2)BC\Delta r(\lambda V(r/R)/cos\phi)^2 \qquad 2.11$$

Where C is the chord width

B is the number of blades

Hence an approximate expression for the chord width, C, to meet the Betz condition is:

$$Chord\ Width, C = \frac{16\pi R(R/r)}{9\lambda^2 B} \qquad 2.12$$

Both C_L and $cos\phi$ were assumed to be approximately one (1) for simplicity, and Equation (2.12) is best for the outer part of the blade. Figure 9 portrays the chord width at each station along the blade.

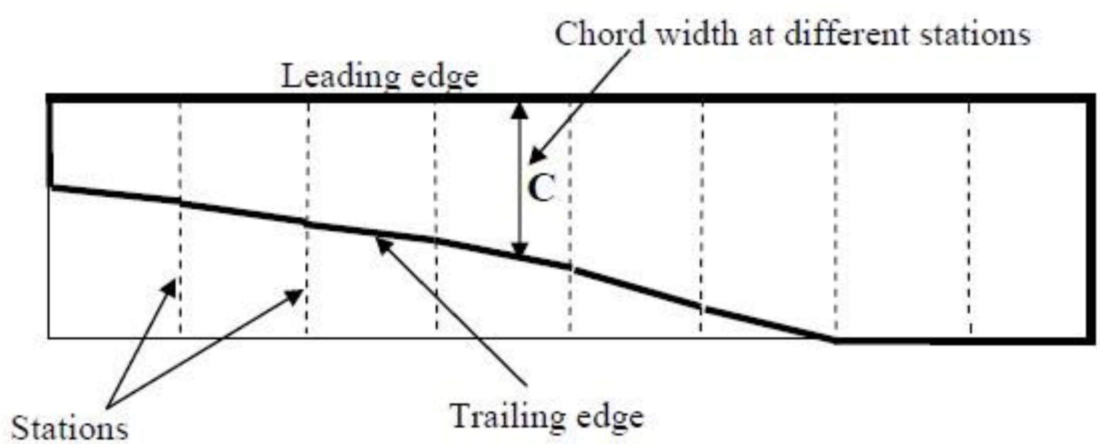


Figure 9: Variation of chord length along the span of a blade (DNV/Risø, 2002)

Cut-in Wind Speed, U_C

From Figure 2.6, the torque on each blade element:

$$Driving\ Force = \sin\phi_L - \cos\phi_D \qquad 2.13$$

Therefore,

$$Driving\ Torque = 1/2\, BC\rho V_r^{\,2}(C_L sin\phi - C_D cos\phi)R \qquad 2.14$$

Many authors have suggested that the lift and drag properties of any airfoil at a high α can be approximated by equations (Wood, 2011)

$$C_L = 2sin\alpha cos\alpha \qquad 2.15$$

$$C_D = 2sin^2\alpha \qquad 2.16$$

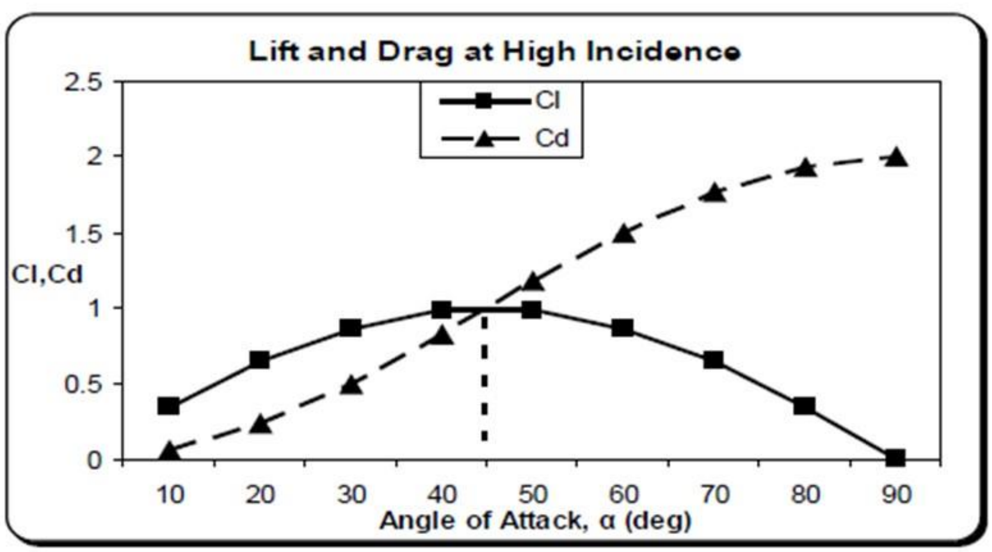


Figure 10: Variation of Lift and Drag with Angle of Attack (Bergey, 2005)

At an angle of 45° equations (2.13) and (2.14) are considered good fits to the data, which is the best range of starting blades.

The rotor blade rotation begins only when the aerodynamic torque of blades exceeds the resistive torque of the generator.

$$Cut - in\ wind\ speed, U_C = (\frac{2T_R}{B\rho R^3 I_{CP}})^{0.5} \quad 2.17$$

I_{CP}, is the chord-pitch integral.

Equation (2.17) becomes the main result of the analysis. The chord-pitch integral performed for two wind turbine blades is as displayed in Figure 11. $I_{CP} = 2.36 \times 10^{-3}$, for the 2.5m blades and 6.22×10^{-3} for the 1m blades.

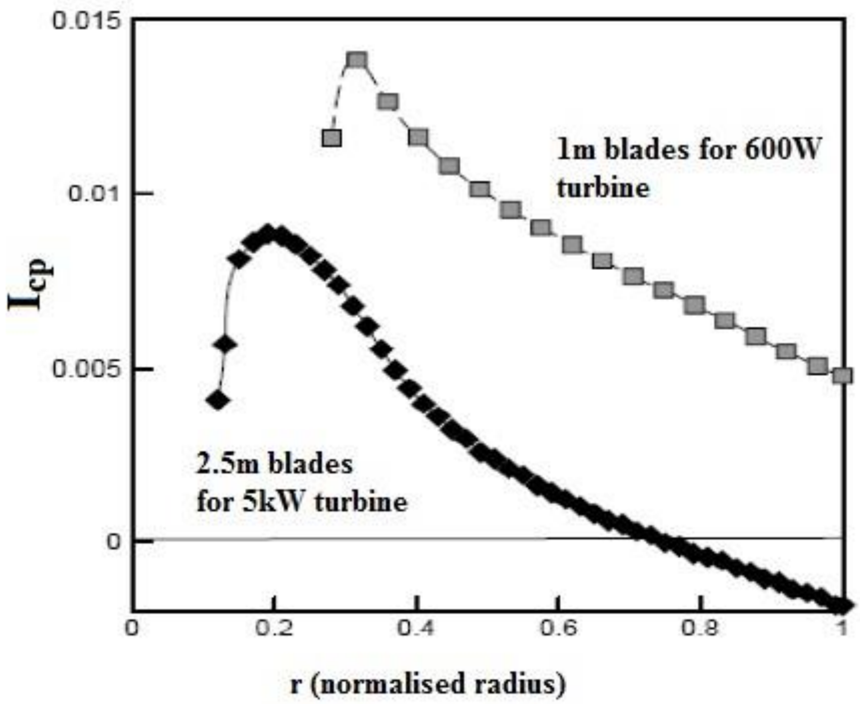


Figure 11: Chord-pitch integral for two blades (Appiah, 2005)

2.3.3 Power in the Wind

The amount of kinetic energy which the wind transfers to the rotor is dependent on the swept area of the blade, the wind speed and the density of the air. The relationship is represented by equation 2.18:

$$P = \frac{\rho . A . V^3}{2} \qquad 2.18$$

Where P is the Power (W), ρ is the air density (kg/m^3), A is the swept rotor area (m^2), and V is the wind speed (m/s). The proportionality of the power to the wind speed is very noteworthy because it shows to what extent wind speed relates to power in wind energy production.

2.3.4 Available Power

Even though Equation (2.18) expresses the theoretical power in the wind, the actual power that can be extracted in the wind is less. The actual power depends on several parameters such as, the type of machine and rotor used, the blade design, friction losses, and the losses in the pump or other equipment connected to the wind machine.

Betz places the theoretically maximum amount of power that could be extracted from the wind to be 59.3% (16/27) and this is known as the Betz limit. Practically, this value is usually around 45% (maximum) for large electricity producing turbines and around 2540% for small wind generators (Clancy and Hulscher, 1994). Well-designed blades will typically extract 70% of the theoretical maximum (Rai, 2001).

Thus,

$$Power\ Available, P_a = \frac{C_P.\rho.A.V^3}{2} \qquad 2.19$$

Where C_P is the Capacity factor of the wind turbine machine.

2.4 WIND TURBINE CLASSIFICATION

Wind turbines are generally classified according to:

- The rated power of the turbine
- The swept area of the rotor blades
- The application

2.4.1 Rated Power Classification

Wind turbine ratings classified according to their power is as shown in Table below.

Table 1: Classification of Wind Turbines and typical parameters

Type	Rated Power	Weight	Rotor Diameter	Height
Large Wind Turbine	>500kW	> 40,000kg	>45m	>50m
Small Wind Turbine	<500kW	<40,000kg	<45m	<50m
-Midi	<100kW	<9,000kg	<20m	<35m
-Mini	<10kW	<450kg	<10m	<20m
-Micro	<1kW	<50kg	<3m	<10m

Source: (Koenemann, 2005)

2.4.2 Swept Area Classification

According to the International Electrotechnical Commission (IEC) Standard 61400-2, small turbines are defined as having a swept area of less than 200 m^2, corresponding to a power output of about 120 kW. Smaller wind turbines considered Mini and Micro, are wind turbines with a rated power output below 10 kW (Wood, 2011).

2.5 CHARACTERISTICS OF SMALL WIND TURBINES

There are several technical factors that characterise wind turbine machines. Below are the characteristics of wind turbine machines:

2.5.1 Power and Energy Curves

The existing power curve between the power output of the turbine and its operational wind speeds is as shown in Figure 12. It illustrates some features of a turbine such as the cut-in and cut-out and the rated wind speeds, and the suitable wind regime power generation starts. Rated power output of the wind turbine occurs at particular wind speeds. The energy curve shows the total amount of energy produced by a wind turbine over a range of annual average wind speeds.

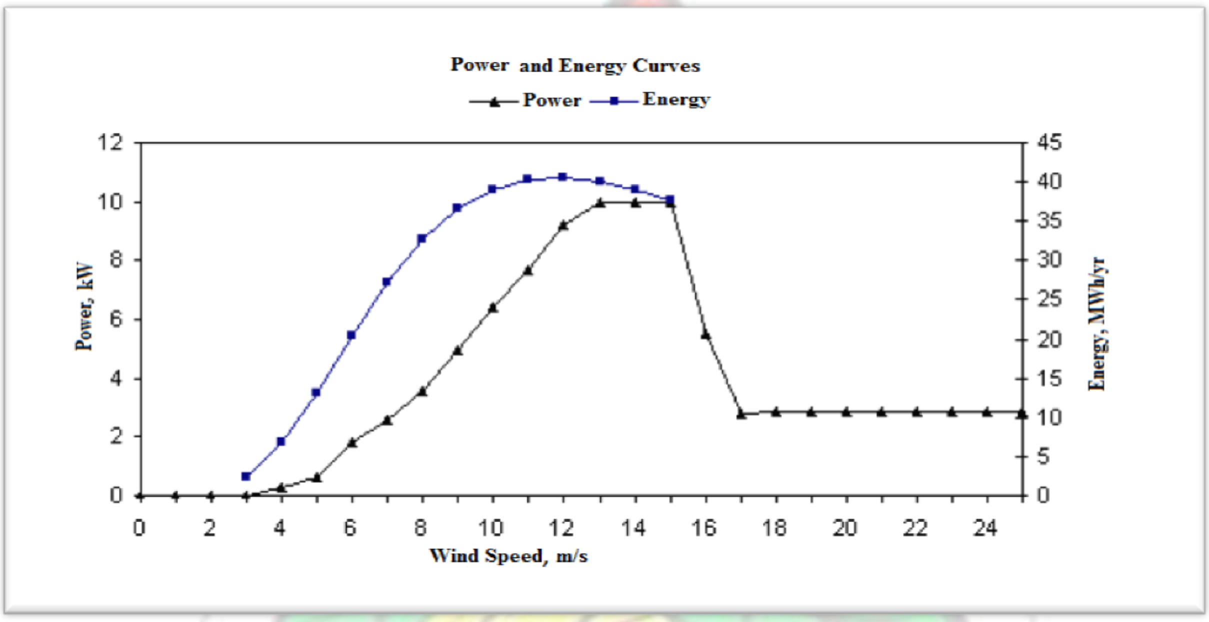


Figure 12: The Power and Energy curve of a 10kW Wind Turbine (Brice, 2009)

2.5.2 Power rating

Generally, small wind turbines are determined by their power-generating capacity, and Muir-Harmony considers small turbines to be less than 100 kW in size.

The rated power is at the speed of 13m/s for smaller turbines and 15m/s for larger turbines (Wood, 2011).

2.5.3 Starting Torque

Most small turbines do not have pitch adjustment (Wood, 2011). Because of this, the significant resistive torque created by the generator must be overcome before the blades will start rotating, and this occurs at high angles of attack. Due to the fact that small turbines rely on aerodynamic torque for rotation and Reynolds numbers (Re) are relatively small, their operational efficiency is dependent on performance at low wind speeds (Clausen and Wood., 2000).

2.5.4 Blade Radius/ Length

Does wind turbine blade length really matter? Simply put: longer wind turbine blade length means greater power production. Blades capture the wind which forces the rotation of the rotor; longer blades means more area for the wind to push against, which means greater force and rotational power (Sally, 2013).

2.5.5 Capacity Factor/Efficiency

The capacity factor, C_p, determines the efficiency of a wind turbine and relates the output of a turbine to the kinetic energy of the wind. Capacity factor, C_p, depends on the design and the tip-speed ratio. Capacity factor, or coefficient of performance, is the ratio of the wind turbines actual annual energy output and the maximum theoretical output: if the wind machine were to run at its rated (maximum) power throughout the year.

$$C_P = \frac{Actual\ Annual\ Energy\ Output}{Maximum\ Theoritical\ Energy\ Output} \qquad 2.20$$

And according to Betz, the maximum theoretical capacity factor is 0.593. Well-designed wind turbines extract approximately 70% of this value (Weisman and Eckart, 1988). Although capacity factor is not strictly efficiency, it is sometimes treated as such.

However, capacity factor can be interpreted as efficiency when comparing turbines of the same type (Wood, 2011). The capacity factor is sometimes called the load factor.

2.5.7 Tip Speed Ratio, TSR

The tip speed ratio is the proportion of the velocity at the tip of the blade to the actual velocity of the wind. Tip speed ratio becomes unity when the velocity of the tip is the same as the wind speed. The TSR relates to the efficiency with the optimum variation of the blade design. Noise levels increase with higher tip speeds and such instances require strong blades to support the load.

$$TSR, \lambda = \frac{\textbf{\textit{Tip Speed of blade}}}{\textbf{\textit{Wind Speed}}} \quad 2.21$$

$$\boldsymbol{\lambda}_{\mathbf{max}\,\boldsymbol{power}} = \frac{\boldsymbol{4\pi}}{\boldsymbol{B}} \quad 2.22$$

Where B is the number of blades.

To compensate for the slenderness of blades, modern turbines operate at high tip speeds. But high tip speeds indicate rise of flutter, which may be destructive to the rotor blade. It is often recommended to choose a tip speed of around seven (7) to enable the blade to have a longer service time. In ideal situations, varying speed-wind-turbines operate at constant tip speed ratios, which make the airfoils, operate at particular angles of attack over a wide range of wind speeds. As a result, for optimum aerodynamic performance during varying-speed operations, the low drag to lift range, “drag bucket”, can be decreased in favor of having a larger lift-to-drag ratios. Nevertheless, in order to account for possible variations in the tip speed ratios caused by atmospheric turbulence and operational considerations, the best lift to drag ratio conditions should happen over a range of lift coefficients centered about the design lift coefficient. (Selig, 2003).

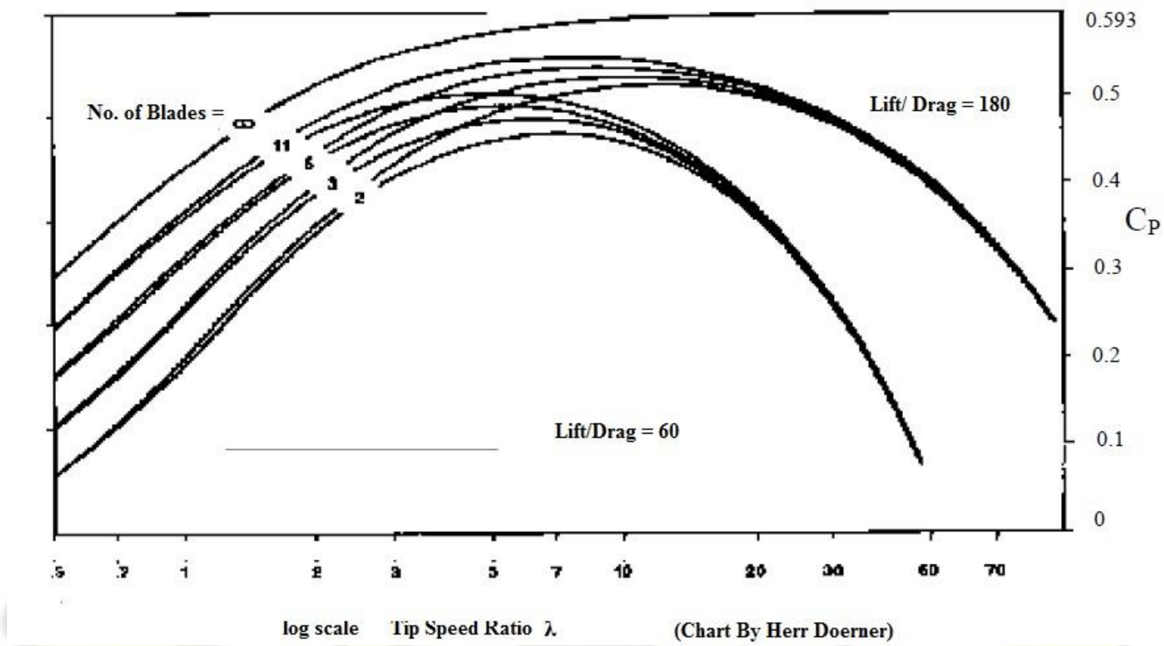


Figure 13: Effect of Tip Ratio and Lift/Drag on the Performance of the Blade (Piggot, 2004b)

2.5.8 Operational Speeds

The following are the important operational wind speeds of wind turbine:

- Start-up wind speed -- the wind speed that will turn an unloaded rotor
- Cut-in wind speed – the minimum wind speed at which energy is generated
- Rated wind speed – the wind speed at which the machine is designed to run (This is at optimum tip-speed ratio)
- Cut-out wind speed – the wind speed at which the machine will be turned out of the wind to prevent damage. (Also known as the furling speed)
- Maximum design wind speed – the wind speed above which damage could occur to the machine

For small wind turbine applications the wind has to blow at a speed of 3 m/s. For a large industrial operation the wind speed must be 6 m/s (Schultz, 2004). Most small wind energy generators begin producing power at 3 - 4.5 m/s and reach full output at 11 - 13 m/s (Bergey, 2005). The cut-out speed for small machines is 15 m/s and 25 m/s for larger machines.

2.5.9 Solidity

Solidity is commonly defined as the ratio of total rotor planform area to total swept area.

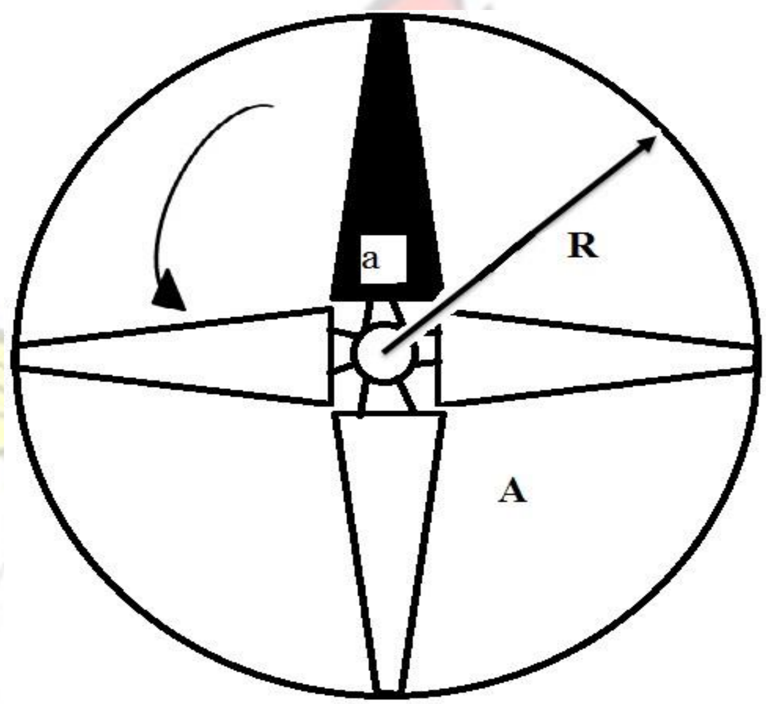


Figure 14: Rotor Solidity

$$\textbf{Solidity} = \frac{\textbf{Blade area}}{\textbf{Blade swept area}} = \frac{4a}{A}$$

Low-solidity machines, such as wind turbines, run at higher speed and tend to be used for electricity generation.

Figure 15: Low Solidity (0.10) = High speed, low torque

High-solidity machines, such as wind pumps, carry a lot of material and have coarse blade angles. High solidity machines generate much higher starting torque than lowsolidity machines but are inherently less efficient than low-solidity machines. Higher power coefficients also correspond to higher blade number.

Figure 16: High Solidity (>0.80) = Low speed, high torque (Visser, 2004)

A higher solidity and/or blade number could extract more energy at lower wind speeds and offer extra advantages of lower noise, lower cut-in wind speed, and less blade erosion over low solider (Visser, 2004).

2.5.10 The Betz's Limit

The Betz Limit (or the Betz Law) describes the theoretical limit of the percentage of power which can be extracted from fluid moving through a turbine.

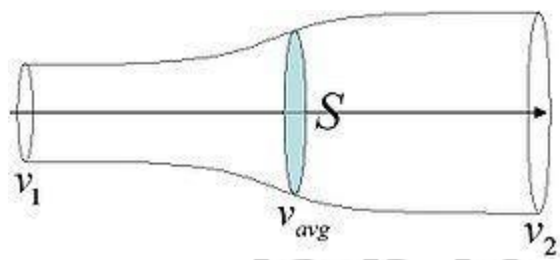


Figure 17: Conventional fluid flow through a disk-shaped actuator.

For a constant density, fluid cross sectional area varies inversely with speed. The law is derived from the principles of conservation of mass and momentum of the air stream flowing through an idealized "actuator disk" that extracts energy from the wind stream. By extracting power from the wind, the turbine distorts the velocity of the wind: downwind of the turbine moves more slowly than the upwind. According to Betz's law, no turbine can capture beyond 0.593 (59.3%) of the kinetic energy in wind. The wind speed starts to reduce even before it reaches the blades, reducing the wind speed through the swept area and hence, reducing the available power. Some of the wind that was heading for the swept area diverts around the slower moving air and misses the blades entirely. Suggesting that, there is an optimum amount of power to be expected from any given diameter: a very high or slow gust reduces the available power. The best option for an engineer is to reduce the wind speed by two-third downwind of the turbine, although the wind just before the turbine would have lost about a third of its wind speed. This allows a theoretical maximum of fifty nine percent (59%) of the wind power to be captured. Practically, utility-scale wind turbines achieve a peak at 75% to 80% of the

Betz limit. The factor of 0.593 is the Betz's coefficient.

2.5.11 The Number of Blades

The limitation on the available power means that the more the number of blades, the less power each can extract. The consequence is that each blade must be narrower to maintain aerodynamic efficiency. Aerodynamically, there is an optimum solidity for a given tip speed; the higher the number of blades, the narrower each must be. In practice, the optimum solidity is low which means that with only three blades, each one must be narrow. To slip through the air easily, the blade must be thin relative to their width, so the limited solidity also limits the thickness of the blades. It becomes difficult to build the blades strong enough if they are too thin. One other factor influencing the number of blades is the aesthetics: it is generally accepted that three-bladed turbines are less visually disturbing. The three-bladed rotor offers the following advantages over the two-bladed configuration. Although the upwind choice is based largely on noise considerations, it also results in lower blade fatigue. Tower-shadow noise and impulsive blade loading for an upwind rotor are less than for a downwind rotor that passes through the tower wake. For an upwind rotor, the blade-number choice is then a balance among blade stiffness for tower clearance, aerodynamic efficiency, and tower-shadow impulsive noise. The threebladed rotor configuration appears to provide the best (Tangler, 2000).

Generally, the rule for the optimum number of rotor blades depends on its function, as can be outlined by Twindell. For instance:

- Electricity generation requires high speed at low torque, so the rotor has few blades
- Water pumping (and historic) requires large torque at low speed and thus rotor has many blades.

2.5.12 Twist

Wind turbine blades are designed with a twist. They have higher angles at the root of the blades than at the tip. This is to equalize the lift distribution along the blade to the extent possible. During the rotation, the tips of the blades move at a faster pace than the root of the blade. If the blade did not have twist all along from root of the blade to the tip, there would be dissymmetrical rotation speed with its negative effect on the lift. Hence, the necessity for blade twists.

Typically, the twist is around 10 – 20^{o} from root to tip. The requirement to twist the blade has implications for the ease of manufacture. The twist is between the true wind and the apparent wind**.**

2.5.13 Blade Section Shape

Apart from the twist, wind turbine blades have similar requirements to airplane wings, so their cross-sections are usually based on a similar family of shapes. In general, the best lift/drag characteristics are obtained by an airfoil that is fairly thin: its thickness might be only 10 – 15% of its chord (the length across the blade, in the direction of the wind flow).

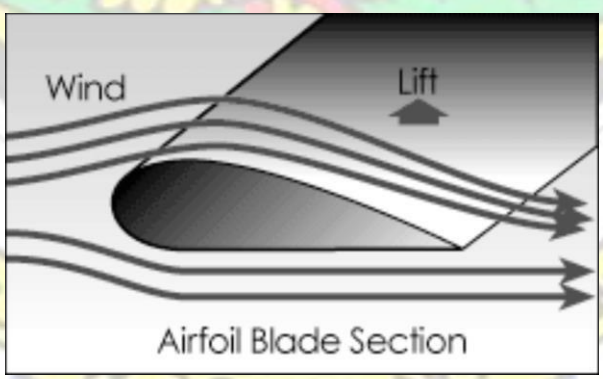


Figure 18: Blade Section Shape (Bergey, 2005)

Structural requirements generally mean that the airfoil needs to be thicker than the aerodynamic optimum, especially locations towards the root (where the blade attaches to the hub) where the bending forces are greatest. Fortunately, this is where the apparent wind is moving slowly and the blade has the least leverage over the hub, so some aerodynamic inefficiency is less serious than it would be closer to the tip. The section cannot get too thick for its chord length or the airflow will separate from the back of the blade. To increase the thickness near the root without creating a very short, fat airfoil section, some designs use a flat back section. There is a trade-off to be made between aerodynamic efficiency and structural efficiency. Even if a thin blade can be made strong enough by using a lot of reinforcement, it might still be better to make the blade a bit thicker.

2.5.14 Blade Plan Form Shape

The plan forms shape is chosen to give the blade an approximately constant slowing effect on the wind over the whole rotor area (i.e. the tip slows the wind to the same degree as the centre or root of the blade). This ensures that none of the air leaves the turbine too slowly (causing turbulence), yet preventing the wind from passing too fast (which would represent wasted energy). Recalling Betz's limit, this result is the maximum power extraction. Because the tip of the blade is moving much faster than the root, it passes more volume of air as such it must generate greater lift force to slow the air down enough Fortunately, lift increases with the square of speed so its greater speed allows for that. In reality, the blade can be narrower closer to the tip than near the root and still generate enough lift. The optimum tapering of the blade plan form as it goes outboard can be calculated. In reality, a fairly linear taper is sufficiently close to the optimum for most designs, structurally superior and easier to build than the optimum shape. The speed at which the turbine rotates is a fundamental choice in the design, and is defined in terms of the speed of the blade tip relative to the free wind speed (i.e. before the wind is slowed down by the turbine). The taper adds strength to the root where stress is highest, gives an added boost in the start-up from the wider root, and is slightly more efficient. The blades get narrower near the tip to reduce noise and wind resistance. The wide chord at the root is responsible for producing enough torque to start turbine running.

2.6 WIND TURBINE BLADE MATERIAL

The complexity of external loads on rotor blades lies in the fact that these loads cannot be adequately modelled. Building a wind turbine blade is not simple a task, however, it requires accomplishing certain benchmarks. Wind turbine blade materials need to have a strict property requirement of high stiffness, low weight, and long fatigue life (Yinyao Q.et al, 2009).

- High modulus of rigidity – to maintain optimal aerodynamic performance,
- Low density – to reduce gravitational forces,
- Long-fatigue life – to reduce material failure.

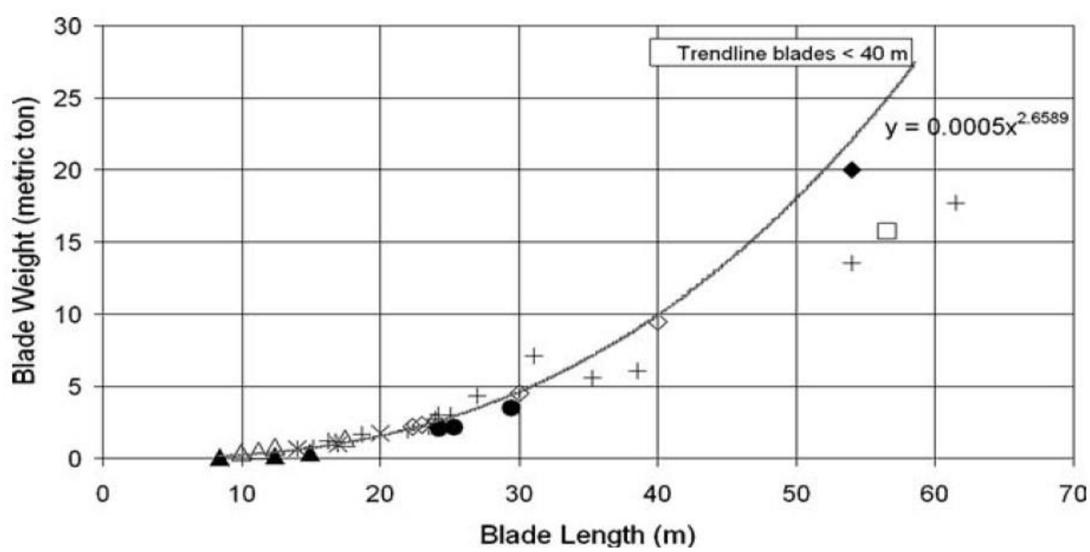


Figure 19: Blade Weight versus Blade Length (Povl Brøndsted, 2005)

As stated, high stiffness, low weight, and long fatigue life are the most essential properties for selecting a wind turbine blade material therefore, the formula in equation 2.23 provides a rule for those properties:

$$M_b = E^{1/2}/\rho \qquad 2.23$$

Where M_b = Merit index; E = the material stiffness; ρ = the material density.

M_b is the constant which has an upper line and lower line, so that it could form a range to select materials within. And now we can show the figure of wind turbine materials analysis

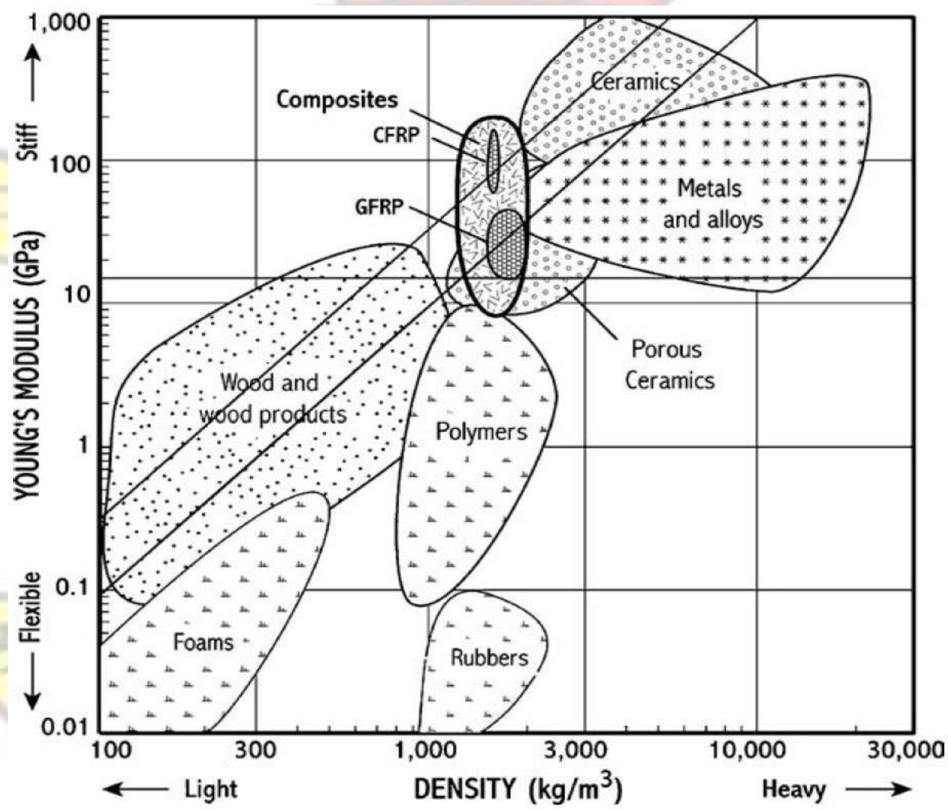


Figure 20: Stiffness versus Density for different materials. (Povl Brøndsted, 2005)

The merit index for a beam $M_b = E^{1/2}/\rho$ is represented by sloping lines with M_b= 0.003 (lower line) and 0.006 (upper line). The criterion for absolute stiffness E = 15GPa is indicated by the horizontal line. The most suitable materials based on the lower (0.003) and upper (0.006) lines are woods, composites and ceramics (Yinyao Q.et al, 2009). So the next section discussed how bamboo can help solve the issue at hand. Thus, some properties of bamboo will be discussed to know how bamboo meets the material property requirements of a wind turbine blade.

2.7 Bamboo

2.7.1 Introduction

Bamboo is a naturally occurring composite material which grows abundantly in most of the tropical countries, (Xiaobo Li, 2004). It is considered a composite material because it consists of cellulose fibres imbedded in a lignin matrix. Cellulose fibres are aligned along the length of the bamboo providing maximum tensile flexural strength and rigidity in that direction (Lakkad and Patel, 1980). As resource availability declines and resource demand increases in today's modern industrialized world, it is becoming increasingly necessary to explore opportunities for new, sustainable building materials (Meadows et al, 1992). Wood, for example, has recently gained popularity in the green building community because of its environmentally beneficial characteristics: wood is promoted as renewable, biodegradable, sequestering carbon from the atmosphere, low in embodied energy, and creating less pollution in production than steel or concrete (Falk, 2009).

Bamboo has similar environmental characteristics (van der Lugt et al. 2006; Lee et al. 1994; Rittironk and Elnieiri 2007; Nath et al. 2009). Most notably, it is highly renewable; bamboo stalks reach maturity in eight years. Its strength is comparable to that of wood. As a result, it makes an appealing candidate as a structural material. It has been used widely in household products and extended to industrial applications due to advances in processing technology and increased market demand. The Asia continents record the highest in terms of bamboo usage. The use ranges from household utilities such as containers, chopsticks, woven mats, fishing poles, cricket boxes, handicrafts, chairs, etc.; to building applications, such as flooring, ceiling, walls, windows, doors, fences, housing roofs, trusses, rafters and purlins; and also in construction as structural materials for bridges, water transportation facilities and skyscraper scaffoldings.

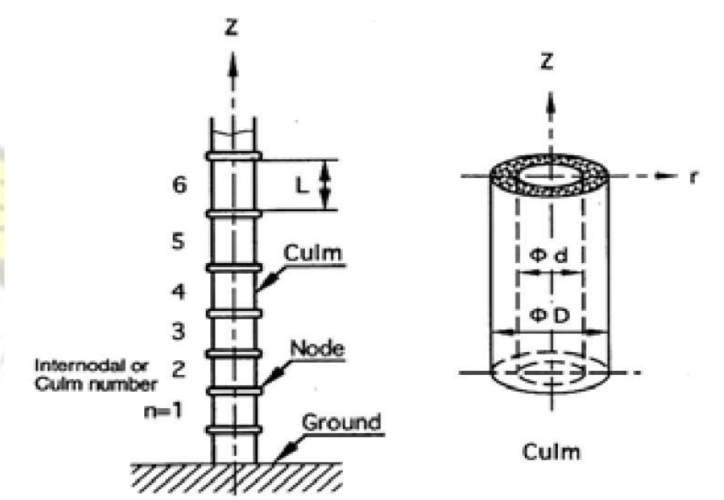


Figure 21: pseudo-structure of bamboo (Povl Brøndsted, 2009)

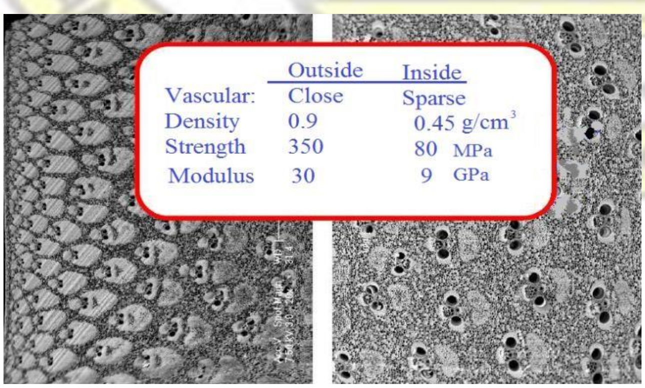


Figure 22: The outside and the inside walls of bamboo (Povl Brøndsted, 2009).

Bamboo does not contain the same chemical extracts as wood, and can therefore be glued very well (Janssen, 1995). Bamboo's diameter, thickness, and inter-nodal length have a macroscopically graded structure while the fibre distribution exhibits a microscopically graded architecture, which lead to favourable properties of bamboo (Amada et al, 1997).

Mechanical Properties of bamboo

In 2008 Yu et al. researched into Moso bamboo. After the research it was indicated that longitudinal elastic modulus and tensile strength of Moso bamboo have clear dependency on radial position. It was established that elastic modulus and tensile strength of the outer layer i.e. average, over height, of 26.9 GPa and 295.6 MPa, respectively were almost triple those of the inner layer (average, over height, of 9.7 GPa and 113.4 MPa, respectively). Tensile modulus of elasticity was found to have a mean increase across all layers by 12.8% from 1.3 to 4 m. Lee et al. (1994) investigated the effect of moisture content, height, and the presence of nodes on mean strength and stiffness properties of giant timber bamboo. Contrary to Yu et al. (2008), it was found that strength properties increased with height—the dissimilarity likely being a result of the use of different bamboo species (M. Mahdavi; P. L. Clouston, A.M.ASCE; and S. R. Arwade, A.M.ASCE, 2011). Lee et al. found that bamboo shows similar properties as structural wood species in the presence of water (moisture), i.e. strength increased with decreasing moisture content. The recorded data showed an increase in compressive strength, tensile strength, elastic modulus, and modulus of rupture (MOR) by 37.6, 19.4, 48.2, and 47.7%, respectively, when tried in air-dry conditions versus green conditions. But loblolly pine increased by 102.9, 75.3, 27.9, and

75.3%, respectively. This suggests that the effect of moisture content on the mechanical properties of giant timber bamboo is less than the effects of moisture content on the mechanical properties of wood. Therefore Mahdavi et al (2011) suggest that, in considering bamboo for structural applications, the usual (as in current wood construction) precautions must be taken for dimensional stability in wet service conditions.

Table 2: Comparison of Bending Properties of Bamboo to Other Common Building materials

Building Materials	Specific gravity	Modulus of Elasticity (GPa)	Modulus of Rupture (MPa)	MOR to specific gravity ratio
Giant timber bamboo [a]	0.52	10.7	102.7	**197.5**
Other bamboo [a]	-	9.0-20.7	97.9-137.9	-
Loblolly pine [b]	0.51	12.3	88	**172.5**
Douglas-fir [b]	0.45	13.6	88	**195.6**
Cast iron [c]	6.97	190	200	**28.7**
Aluminium alloy [c]	2.72	69	200	**73.4**
Structural steel [c]	7.85	200	400	**50.9**
Carbon fibre [c]	1.76	150.3	5,650.00	**3,205.10**

[a]Lee et al., 1998.

[b]Forest Product Laboratory, 1999. [c]Rittironk and Elnieiri, 2007.

Although giant timber bamboo is one of the weaker bamboo species listed in table 2, its properties are compared to structural wood species such as Douglas-fir or loblolly pine. The data indicate that bamboo is stronger in bending than timber, and its strength-toweight ratio (expressed as MOR/specific gravity) is greater than that of all materials listed in table 2.4 except carbon fiber. Not only is bamboo fast-growing, but it is also highly efficient compared to other raw structural materials.

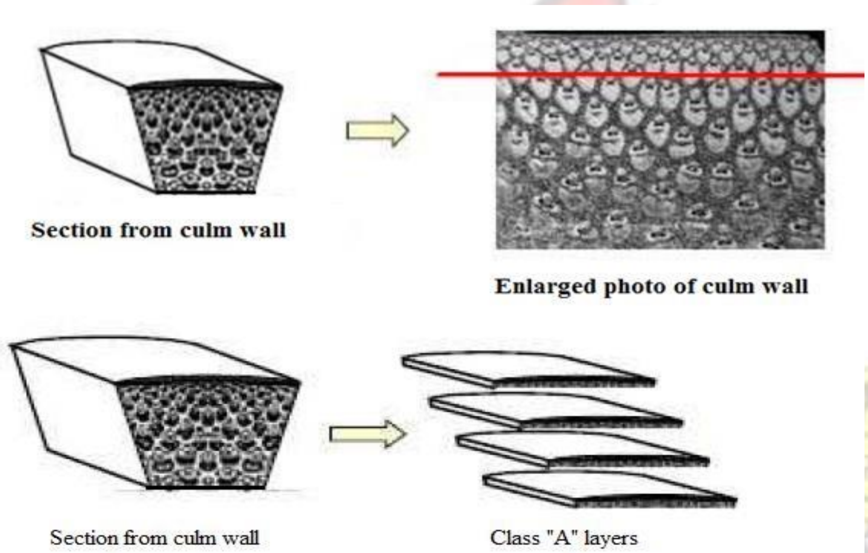


Figure 23: Section through the bamboo wall (John W. Holmes, 2008)

Table 3: Selected Mechanical properties of Bamboo compared to Glass/Epoxy (John W. Holmes, 2008)

Material	**Tensile strength (MPa)**	**Density (g/cm^3)**	**Compressive strength (MPa)**	**Tensile/Compressive Modulus (GPa)**
Bamboo–Poplar (Pilot study 2008)	175 – 191	1.0	105 – 119	22 (Average)

UD Glass/ Epoxy	800	1.9	760	40

Bending strength is in the range of 86 – 229 MPa. Bending elasticity modulus is in the range of 6,882 – 20,890 MPa. According to Abd.Latif et al (1990), bending elasticity modulus for a typical bamboo species varies in the range of 8,945 – 11,691 MPa. The lower values represent green bamboos and higher values are for air-dry bamboos.

Hardness modulus of bamboo is in the range of 902 – 1,833 N/mm.

2.5.15 Laminated Bamboo Lumber

Bamboo, as a hollow tube, is efficient in resisting bending forces. It also has large ratio of the moment of inertia to cross-sectional area. But the physical appearance of bamboo culm makes it difficult to create connections for making intricate shapes. At the same time the tubes cannot be used in applications where flat surfaces might be required. Laminated bamboo lumber (LBL) resolves these deficiencies in the natural shape of bamboo. LBL has been created in research studies by using adhesive to join strips of bamboo taken from the culm (i.e., bamboo stem). The result is a composite, solid, rectangular structural member having highly renewable characteristics that make it competitive, in this regard, with commonly used building materials.

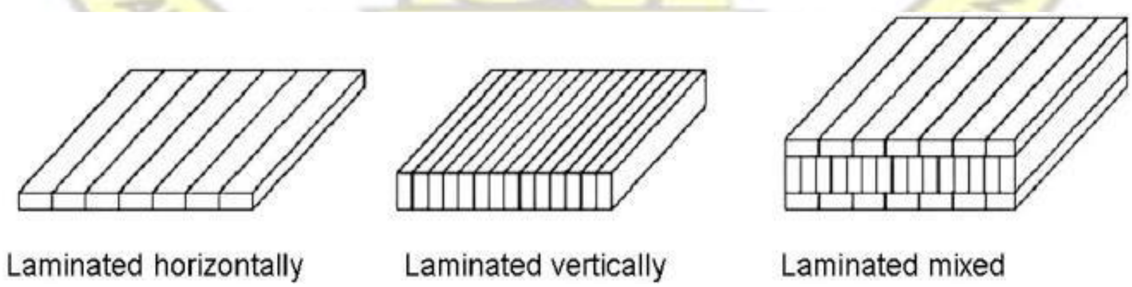


Figure 24: Laminated lumber arrangements (Rittironk and Elneiri, 2007)

After the review vertical lamination is what will be considered for this research because horizontal lamination will have less shear strength compared to vertical and mixed lamination. Also mixed lamination will pose a difficulty when carving the blade from it because of the different directions of grains. Vertical lamination possesses both good shear strength and uni-granular direction

CHAPTER THREE

METHODOLOGY

3.1 Production of the blade drawing

The production of the blade drawing was begun by searching for an existing airfoil for wind blades within the Profili 2.16 software. The airfoil selected was ARAD-D 13% with parameters: Maximum thickness 13% at 25% of the chord; Maximum camber 3.61% at 30% of the chord. After the airfoil was obtained, AutoCAD software was used to draw the wind turbine blade with its dimension to produce the graphical geometry. Afterwards fresh bamboo culms were harvested possessing the culm wall thickness of 15mm and above. Each selected bamboo had a straight culm and almost cylindrical shape.

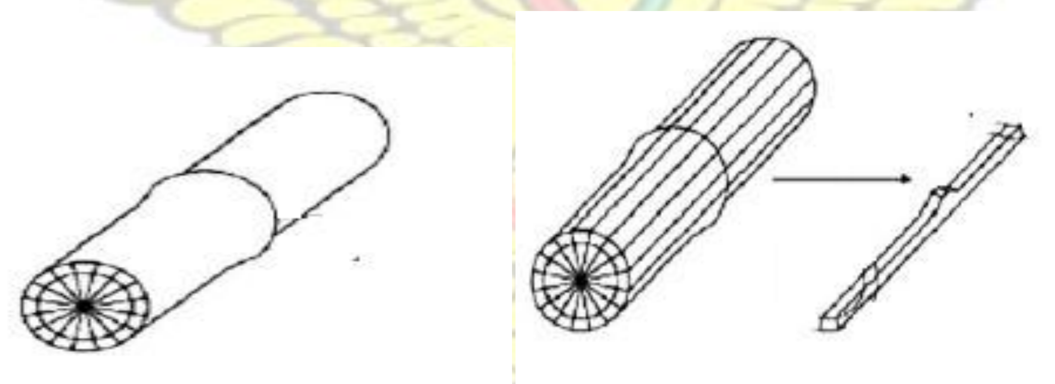


Figure 25: how a strip was obtained from the culm

The bamboo culms were cross-cut into desired length using the cross-cutting machine to required lengths. Each cross-cut piece was divided into equal sections. The projections on each strip were trimmed. The splits were planed to remove the hard silica saturated epidermis; and the internal soft and cushion-like lumen. The hardback cover contains silica. The hardness of the back cover prevents proper osmotic and diffusion motions of the preservative in and out of the bamboo strips. The internal soft lumen which was removed also absorbs water readily and is relatively weak in strength; it also has a high content of sugar that allows insects, termites and fungi to feed on the bamboo (interview with Dr. Rudolf Steiner, 2012). These two portions of the bamboo strip were planed to a desired thickness.

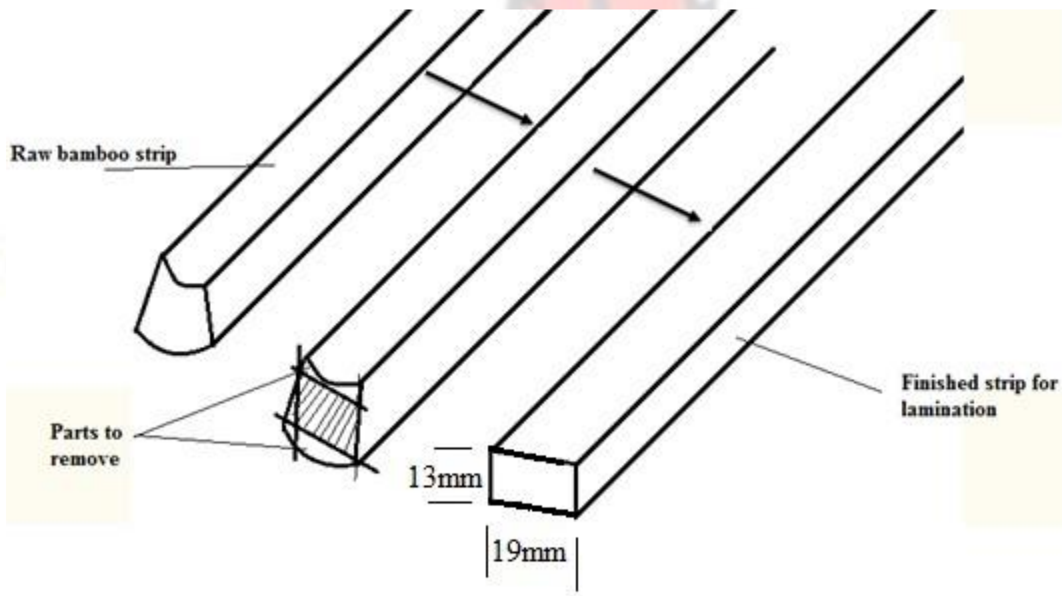


Figure 26: Stages to achieve a smooth plane bamboo strip from the split

3.2 Chemical Treatment

The prepared strips were packed into a trough. Water was added to the strips to just cover the strips. A corresponding quantity of wood preservative (Dursban 4E) was added. The planed bamboo strips were soaked in the preservative for twenty eight (28) hours before removal. This was to ensure proper penetration of the preservative into the bamboo strips and a possible leaching out of free sugar from the strips. After 28 hours the splits were carefully taken out and air-dried for three days. The drying strips were turned from time to time to ensure proper aeration throughout the drying process. The dried bamboo splits were glued. The strips were vertically oriented with their narrow edges and gluing done face wise. The vertical orientation has better structural strength compared to horizontal orientation (Joel, 2010). Polyvinyl acetate adhesive was used to join the chemically treated bamboo strips. The adhesive (Fevicol Sh: a synthetic resin adhesive) was mixed with preservative in ratio of 5:1 to prevent insects from feeding on the cured gum of the adhesive material (Steiner, 2012). During the application of the adhesive to the strips each strip was placed horizontally to allow for proper penetration of the adhesive. This is because according to Sernek et al., the tangential direction of liquid penetration is higher than the radial direction. Sernek et al. continue to say that the rate of penetration is fastest at the beginning (first 4 minutes), then gradually decreases until it shows no difference after 16 minutes (Sernek, Resnik, and Kamke, 1999). After the adhesive mixture was spread on the bamboo strips, each of the strips was allowed to absorb it for 20 minutes to allow the adhesive to seep into the pores of the bamboo strips before clamping. Clamping pressure of about 2 MPa was applied to the clamped strips to ensure that the laminates are properly adhered to each other. Each clamp lasted for 24 hours to ensure adequate curing of the laminated boards.

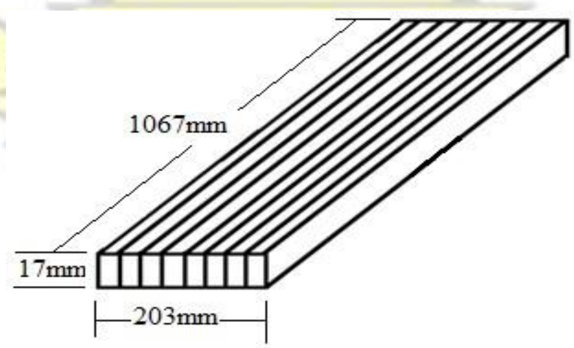


Figure 27: Laminated bamboo board

The laminated boards were removed after twenty four (24) hours of clamping. The laminated boards were then planed again to remove any irregularities on the surface to obtain the desired thickness of 17mm. Bending and compressive tests were performed on laminated samples of bamboo to obtain the compressive and bending strengths of the laminated samples. Samples for bending and compressive testing were cut to 51mm x 190mm x 19mm dimension. The bending test was performed using three point bend load and the compressive test was done parallel to the grains of bamboo.

3.3 Blade production

3.3.1 Shaping of the blade

Templates were made card board and traced onto all the three blades. The desired shape of the blade was carved out of the laminated bamboo board and details of the drawing were transferred using external calipers, adjustable protractor, rule and pencils. The blades shape was cut out using a band saw. The band saw was adjusted when necessary to give the needed angle. As the blade gets narrower towards the tip it became thinner. Figure 28 and Figure A.10 show the various measurements that were transferred to the bamboo board. Outside calipers was used to transfer measurements from the drawings to the blade. In situations where a band saw could not be used, a plane or draw knife was used. A hand plane, draw knife, file and sand paper were used, at required stages in the shaping of the blades, to remove any irregularities on the blades. Each blade was divided into sections and thickness of each section measured using calipers. The area, volume, mass and density of the blades as well as the solidity of the rotor were determined.

Natural frequency and cantilever tests were performed on the blade. The three blades were sanded and sprayed with an enamel hardener (a water resistant coat) to inhibit the hygroscopic property of bamboo.

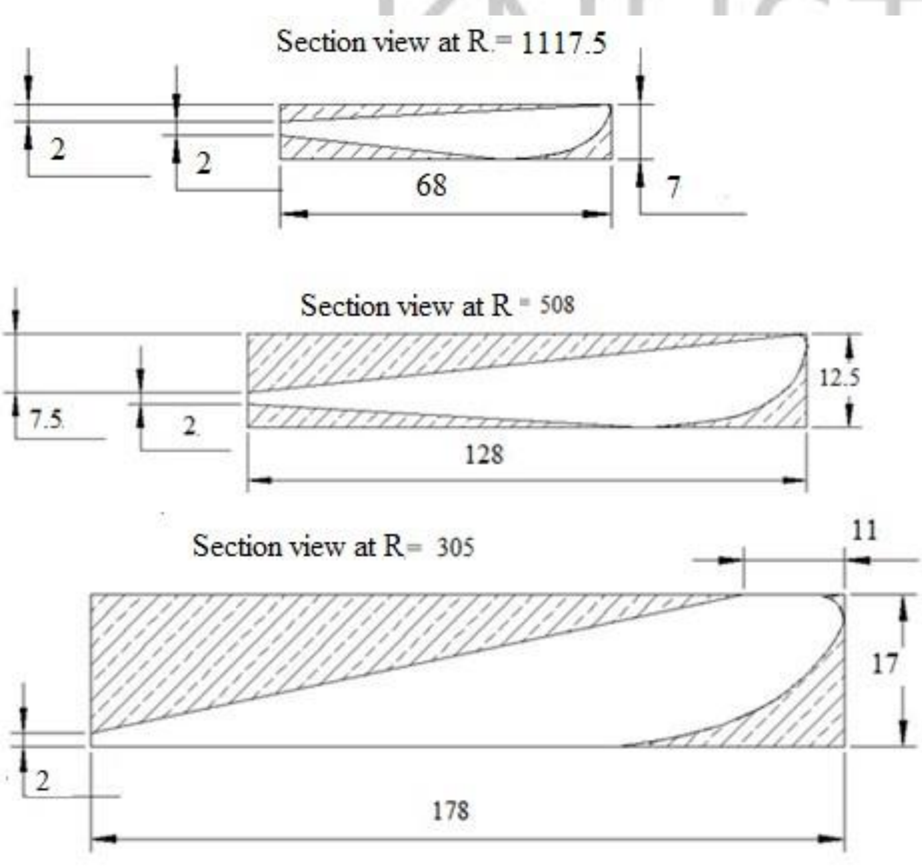


Figure 28: The Sectional Views of the Blades (dimensions in millimeters)

3.4 Reading from the wind turbine

The wind turbine was mounted on a building in KNUST, at the College of engineering on a building where the Vodafone café is located, at a height of about 7m more than the height of the building of 18m. Readings were taken from the wind turbine from the 4^{th} – 11^{th} June, 2013 except Saturday and Sunday i.e. 8^{th} and 9^{th} June, 2013. The generator used in this research was a 12V A.C generator. Wind data logger was used to log continuously throughout the reading. For the voltage output and rotor turns readings, a multi-meter was connected to the terminals of the generator while a tachometer was connected to the rotor. The tachometer had a magnet, a sensor and a wire connected the sensor a monitor to display the output. Two stop watches were used by two different people to take readings and to reconcile the timings within every ten (10) seconds. One timer was a control to the main timer. The stop watch, the tachometer monitor, and multimeter were given to three different people with three different set of people to help them in the readings. At an interval of every ten (10) seconds the timer signals to the multimeter and tachometer readers to record. This continued for every one (1) hour and they rest for fifteen minutes to take another reading for another one (1) hour and likewise wait for fifteen minutes for the final reading. In all three (3) hours was spent daily for the taking of the data. Wind velocity, blade rotation and voltage output were recorded respectively. In all, 4240 data were recorded and a mean value was determined for every 20 data recorded.

CHAPTER FOUR

RESULTS AND DISCUSSION

This chapter discusses the technically the objectives were achieved. It also discusses how the natural frequency and other important parameters of the blades were determined. Again this chapter brings to bear the recorded performance of the blades when they were mounted on a rotor.

4.1 Observation from making the laminated board

It was realised that some of the culm thickness of the bamboo selected were up to about 2.5 cm (1 inch) and an average thickness of 1.9 cm (0.75 inch). Splitting was done manually using machete initially but was later switch to mechanised means and it was observed that splitting of the cut pieces was more difficult at the nodes when it was done manually. More so, it was realised that the difficulty of splitting the culm increases with the age of the bamboo and decreased with increasing height of the bamboo culm and this made mechanised splitting a better option especially in an effort to obtain straight bamboo strips. Planing of the strips was very difficult especially as it got to the nodes. In most cases the strips had to be pulled out of the planing machine with a lot of strength. The most difficult part was with the planing of the hard-smooth-silica back cover of the culm. Planing was nearly impossible until band saw was used to remove the silica saturated back cover. Part of the difficulty associated with the planing was due to the fact that some of the cut pieces were manually split. The laminated lumber portrayed delamination along the strips. This became obvious during the planing of the laminated boards, some needed to be re-glued and clamped for several hours before lamination could be satisfactory.

4.2 Determination of the compressive and bending strength

Figure 29: Compressive test

Dimension of specimen = 190mm x 51mm x 19mm

Maximum compressive force = 4.9 tonnes (*obtained from the universal testing machine*)

Using the linear conversion equation to obtain maximum compressive load:

$$y = 11.15x + 10.365$$

Where y is the converted reading in kN and x is the direct test reading in tonnes Thus,

for the test value of 4.9 tonnes

$$y = 11.15 * 4.9 + 10.365 = 65$$

Hence the maximum compressive load i.e. the load at which the material failed was 65 kN

Cross-Sectional area of sample = 51mm x19 mm = 969 mm^2

= 9.6900E-4 m_2

Maximum compressive stress = $\frac{maximum\ compressive\ load}{surface\ area\ of\ sample}$

= $\frac{65000}{9.69 \times 10^{-4}}$ Pa = 67.079 MPa

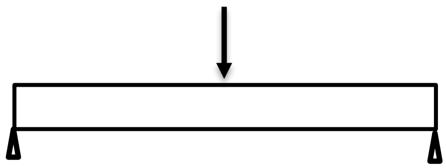


Figure 30: Bending test of specimen

The maximum bending stress in the specimen can be calculated using:

$$\sigma = \frac{\boldsymbol{F \times L / 4 \times y}}{\boldsymbol{I}}$$

Where

σ = maximum stress (N/mm^2)

y = Perpendicular distance from to neutral axis (mm)

F= load (N), L = length of beam (mm), I = Moment of Inertia (mm^4)

Dimension of specimen = 190mm x 51mm x 19mm

Maximum bending load (load at which the specimen failed) = 12kN

Perpendicular distance from neutral axis = 9.5mm = 0.0095m

The moment of inertia of a beam can also be calculated using

$$I = {hb^3}/{12}$$

Where I = Area Moment of inertia, h = thickness of the specimen, b = width of the specimen

$$I = \frac{0.019 \times (0.051)^3}{12}$$

$$I = 2.1003 \times 10^{-7} m^4$$

Thus,

$$\sigma = \frac{12000 \times {}^{0.19}/_{4} \times 0.0095}{2.1003 \times 10^{-7}}$$

$$\sigma = 25.782\ MPa$$

It was observed after the tests that laminated lumber can performed better in compression than under bending. Therefore, in applications such as wind turbine blades manufacturing where the compressive strength of the material is important, laminated bamboo board can be used.

4.3 Blades carving

One observation during the carving of the blade was the ease with which the carving was done. The parallel grains of bamboo served a good purpose during the carving of the blades. However, the change in grain structure at the nodes posed a challenge. One other observation was the difficulty encountered during the shaping of blade camber. This was as a result of the thickness of the plank used in the designing of the blades. The existing methods of lamination are horizontal, vertical, and mixed laminations. The considered lamination method was vertical – which provides a thicker board than the horizontal lamination, but not as thick as it would help in the shaping of a good camber and twist in the blades. Already the bamboo culms were split into pieces before lamination and then planed to remove the irregularities on the board. After the removal of the roughness the board became relatively thin but the strength could not be so reduced.

The board produced was of the dimension 1.067 m x 0.203 m x 0.017 m.

Blade length = 1.067 m

Average Young's modulus of bamboo = 1.75 GPa

$$\text{Solidity} = \frac{\text{Blade area}}{\text{Blade swept area}}$$

The length of the blade is taking to be the radius of the rotor since the roots of the blades meet at the middle section of the rotor. The length of the blade = 1067 mm and $\text{Solidty} = \frac{\mathbf{3a}}{\mathbf{A}} = \frac{\mathbf{3(119837)}}{\boldsymbol{\pi}\,\mathbf{(1045)^2}} = 0.104792 \approx 0.10$

- Masses of the three blades were 1.07kg, 1.079kg, 1.08kg respectively. ***Table 4: Blade properties***

	Average Mass of blade, (kg)	Blade Surface Area (m^2)	Solidity	Total volume, (m^3)	Density of blade, (g/cm^3)
Blade	1.076	0.12	0.10	1.635×10^{-3}	0.66

4.4 Determination of the natural frequency of the blade.

To determine the natural frequency of the wind blade the following parameters has to be known: the *E* = Modulus of rigidity – which is obtained from the material property; *m* = Mass of the blade – obtained by weighing the masses of the blades and finding the average; *L*= Length of the blade; *I* = Area moment of inertia; *k* = Stiffness. These five parameters have to be known before, theoretically, the natural frequency of the blade can be determined. And out of these five parameters only the stiffness and moment of inertia are of prime importance since the other parameters are known already by direct measurement and from literature.

Area and Bending Inertia of Airfoil Sections

Calculation of the vertical deflection of a wing requires knowing the spanwise bending stiffness distribution *EI*(*y*) along the primary axis of loading. For a wing made of a uniform solid material, the modulus *E* is a simple scaling factor. The moment of inertia of the airfoil cross-sections about the bending axis *x* (called the bending inertia), is then related only to the airfoil shape given by the upper and lower surfaces $Z_u(x)$ and $Z_\ell(x)$. As shown in Figure 4.29, both the area *A* and the total bending inertia *I* are the integrated contributions of all the infinitesimal rectangular sections, each *dx* wide and $Z_u - Z_\ell$ tall.

The inertia of each such section is appropriately taken about the neutral surface position $\bar{z}$ defined for the entire cross section.

$$A = \int_0^c [Z_u - Z_l]dx \tag{4.6}$$

$$\bar{z} = \frac{1}{A}\int_0^c \frac{1}{2}[Z^2{}_u - Z^2{}_l]dx \tag{4.7}$$

$$I = \int_0^c \frac{1}{3}[(Z_u - \bar{z})^3 - (Z_l - \bar{z})^3]dx \tag{4.8}$$

These relations assume that the bending deflection will occur in the *z* direction, which is a good assumption if the *x* axis is parallel to the airfoil's chord line.

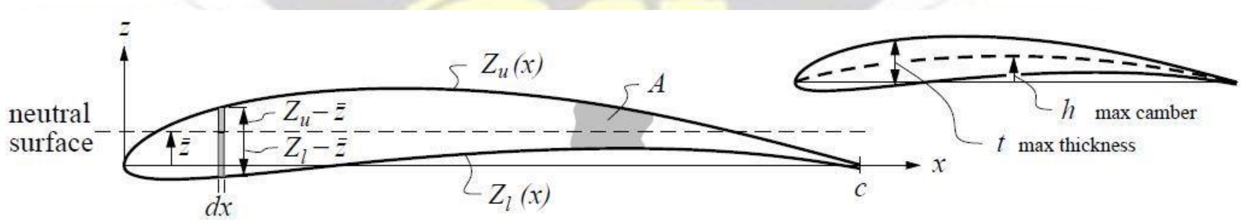


***Figure 31*: Quantities for determining and estimating the bending inertia of an airfoil section**

Although equations (1) – (3) can be numerically evaluated for any given airfoil, this is unnecessarily cumbersome for preliminary design work, where both *A* and *I* are needed for possibly a very large number of candidate airfoils or wings. For the purpose of approximating *A* and *I*, we first define the maximum thickness *t*, and maximum camber *h*, in terms of the upper and lower surface shapes. We also define the corresponding thickness and camber ratios τ and ε.

$t = \max\{Z_u(x) - Z_l(x)\}$ …4.9; $h = \max\{[Z_u(x) + Z_l(x)]/2\}$ …4.10

$\tau \equiv {}^{t}/_{c}$ ……….…4.11; $\varepsilon \equiv {}^{h}/_{c}$ ……4.12

Examination of equation (4.9) indicates that *A* is proportional to *tc*, and examination of (4.11) indicates that *I* is proportional to $ct\ (t^2 + h^2)$. This suggests estimating *A* and *I* with the following approximations.

$$A \approx K_A ct \quad = K_A c^2 \tau \qquad 4.13$$

$$I \approx K_I ct(t^2 + h^2) \quad = K_I c^4 \tau(\tau^2 + \varepsilon^2) \qquad 4.14$$

The proportionality coefficient can be evaluated by equating the exact and approximate *A* and *I* expressions above, e.g.

$$K_A \leftarrow \frac{1}{c^2\tau} \int_0^c [Z_u - Z_l] dx; \qquad 4.15$$

$$K_I \leftarrow \frac{1}{c^4\tau(\tau^2 + \varepsilon^2)} \int_0^c \frac{1}{3}[(Z_u - \bar{z})^3 - (Z_l - \bar{z})^3] dx \qquad 4.16$$

Evaluating these expressions produces nearly the same K_A and K_I values for most common airfoils:

$K_A \approx 0.60$ ………4.17; $K_I \approx 0.036$ …….4.18

Therefore, the very simple approximate equations (4.13) and (4.14), with K_A and K_I assumed fixed, are surprisingly accurate. Hence, they are clearly preferred for preliminary design work over the exact but cumbersome equations (4.6), (4.7), (4.8). As a result, inserting the known parameters into equations (4.13) and (4.14) the approximated value for *A* and *I* can be calculated as shown below:

From 4.11 and 4.12

$\tau \equiv t/c$, $\varepsilon \equiv h/c$

Now to determine which maximum thickness, though the same airfoil shape but different sizes at different locations on the blades, the average values will be used to compensate the variation. From table 4.1, the values of thickness and chord length at different stations on the blade can be determined while assuming the camber to be one-half the measurement of the maximum thickness.

Table 5: The thickness, camber and chord length at different stations on the blade

Thickness ratio, t	**Camber, *h***	**Chord length, c**
9	4.5	89
10.5	5.25	100
12	6	113
12	6	124
12.5	6.25	135
13	6.5	148
14	7	160
16.5	8.25	173
$\sum =$99.5	$\sum =$ 49.75	$\sum = 1042$
$\boldsymbol{t_{av} = 12.44}$	$\boldsymbol{h_{av} = 6.22}$	$\boldsymbol{c_{av} = 130.25}$

$$\tau_{av} \equiv {t_{av}}/{c_{av}} = {12.44}/{130.25} = 0.0955$$

$$\varepsilon_{av} \equiv {h_{av}}/{c_{av}} = {6.22}/{130.25} = 0.0478$$

Therefore from approximate equations (4.13) and (4.14),

$$A = K_A {c_{av}}^2 \tau_{av} = 0.60 \times (130.25)^2 \times 0.096$$

$$A = 972.0981\, mm^2 = 0.9721 \times 10^{-3}\, m^2$$

$$I = K_l {c_{av}}^4 \tau_{av} (\tau^2 + \varepsilon^2)$$

$$I = 0.036 \times (130.25)^4 \times 0.096(12.44^2 + 0.048^2)$$

$$I = 1.5313 \times 10^8\, mm^4 = 1.5313 \times 10^{-4} m^4$$

$$\textbf{Natural frequency}, \boldsymbol{f = \frac{1}{2\pi} \times \sqrt{k/m}}$$

Where f = Natural frequency; E = Modulus of rigidity; m = Mass; L= Length; I=Area moment of inertia; k = Stiffness

But, $k = {3EI}/{L^3}$ 4.15

Therefore inserting the known values of E, I and L into equation **4.15**

$$k = \frac{3(1.75\times10^9)\times1.5313\times10^{-4}m^4}{1.045^3} = 7.2059 \times 10^5 \text{ Pa/m}$$

Also putting the value of k and m into equation **4.14**

$$f = \frac{1}{2\pi} \times \sqrt{\frac{7.2059 \times10^5}{1.076}} = 130.2438$$

Hence, the natural frequency of the blade is 130 Hz

Set-Up for Blade's Bending Test

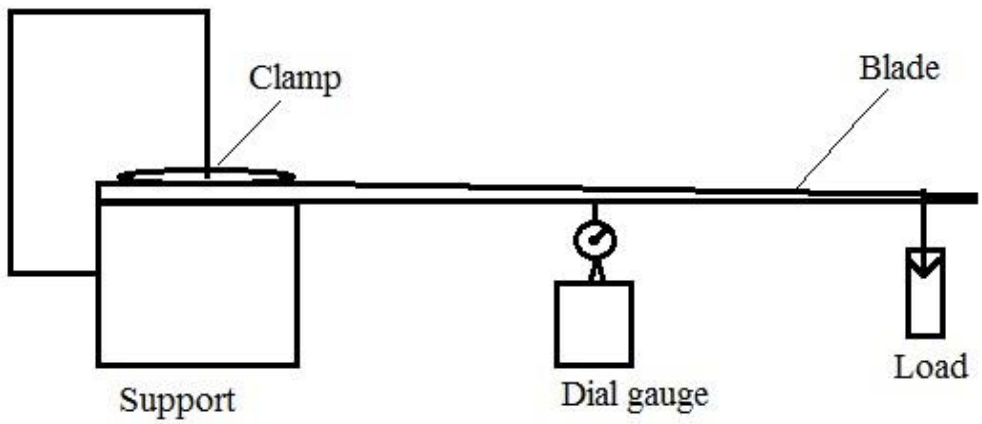


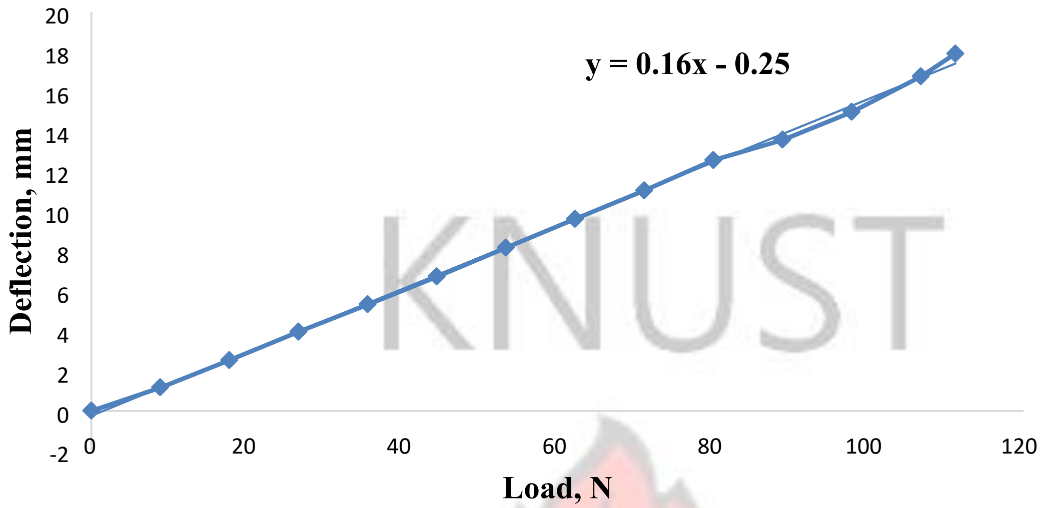
Figure 32: **Bamboo Blade test**

Table 6a: Cantilever Test Result of the Bamboo Blade

Load, (N)	0	8.9	17.8	26.7	35.6	44.5	53.4	62.3
Deflection, (mm)	0	1.2	2.5	4.0	5.3	6.7	8.2	9.6

Table 6b: Cantilever Test Result of the Bamboo Blade

Load, (N)	71.2	80.1	89	97.89	106.8	111.2
Deflection, (mm)	11.1	12.6	13.6	15.0	16.8	17.9



The rate of change with respect to deflection for any given added weight from Figure 33 is less than 0.16, indicative of the fact that for any 2N load applied at the tip of the blade produces minimal deflection in bending. This suggests that bamboo is strong and can be used in structural applications where strength is desired, especially in wind energy application.

Table 7a: Readings from the wind turbine from 4^{th} to 11^{th} June, 2013 on KNUST campus at the college of engineering

Wind Speed, m/s	Blade RPM	Voltage V	Wind Speed, m/s	Blade RPM	Voltage V	Wind Speed, m/s	Blade RPM	Voltage V	Wind Speed, m/s	Blade RPM	Voltage V
0.70	1.85	1.34	1.14	3.03	2.20	1.45	3.87	3.84	1.70	4.54	3.03
0.79	2.11	1.44	1.15	3.06	2.20	1.46	3.89	3.12	1.71	4.56	3.11
0.83	2.22	1.73	1.22	3.24	4.77	1.46	3.89	2.67	1.71	4.56	3.16
0.85	2.27	1.66	1.25	3.33	2.80	1.51	4.03	2.95	1.72	4.58	3.19
0.87	2.31	3.35	1.27	3.38	1.51	1.55	4.12	2.46	1.73	4.61	3.32
0.89	2.36	4.26	1.28	3.40	3.27	1.57	4.19	3.05	1.76	4.70	3.30
0.93	2.48	4.16	1.30	3.47	3.82	1.62	4.33	4.05	1.76	4.70	4.45
0.93	2.48	2.41	1.34	3.56	2.77	1.63	4.35	3.51	1.76	4.70	2.92
0.95	2.52	1.77	1.36	3.61	4.07	1.64	4.38	3.38	1.78	4.75	1.84
0.98	2.62	1.91	1.36	3.63	2.55	1.65	4.40	3.22	1.78	4.75	3.47
1.06	2.82	3.31	1.38	3.68	2.61	1.65	4.40	3.00	1.81	4.81	3.27
1.11	2.96	1.40	1.41	3.75	2.62	1.68	4.47	3.88	1.81	4.81	3.42

1.12	2.99	2.15	1.42	3.80	3.57	1.69	4.49	3.19	1.81	4.81	4.21

Table 7b: Readings from the wind turbine from 4th to 11th June, 2013 on KNUST campus at the college of engineering

Wind Speed, m/s	Blade RPM	Voltage V	Wind Speed, m/s	Blade RPM	Voltage V	Wind Speed, m/s	Blade RPM	Voltage V	Wind Speed, m/s	Blade RPM	Voltage V
1.82	4.84	3.33	1.89	5.05	3.49	1.96	5.23	3.64	2.09	5.56	3.88
1.82	4.84	4.62	1.89	5.05	4.55	1.97	5.25	4.55	2.09	5.58	3.79
1.82	4.84	2.46	1.90	5.07	3.41	1.98	5.28	3.57	2.09	5.58	3.86
1.84	4.91	3.37	1.90	5.07	2.71	1.99	5.30	4.11	2.09	5.58	3.20
1.84	4.91	3.31	1.90	5.07	4.81	2.00	5.32	3.56	2.10	5.60	4.25
1.84	4.91	3.12	1.91	5.09	3.57	2.00	5.32	4.36	2.11	5.63	3.98
1.86	4.95	3.41	1.91	5.09	3.62	2.01	5.35	6.52	2.11	5.63	3.45
1.86	4.95	3.48	1.93	5.14	3.60	2.03	5.42	4.85	2.12	5.65	3.99
1.87	4.98	3.32	1.94	5.16	3.44	2.05	5.46	3.83	2.12	5.65	3.49
1.88	5.00	3.52	1.95	5.19	3.62	2.06	5.49	2.24	2.12	5.65	4.21
1.88	5.00	3.87	1.95	5.21	3.60	2.06	5.49	4.48	2.14	5.69	4.81

1.89	5.02	3.48	1.96	5.23	3.67	2.07	5.51	2.47	2.15	5.72	4.06
1.89	5.02	3.50	1.96	5.23	3.64	2.08	5.53	3.88	2.15	5.72	3.97

Table 7c: Reading from Wind from 4th to 11th June, 2013 on KNUST campus at the college of engineering

Wind Speed, m/s	Blade RPM	Voltage V	Wind Speed, m/s	Blade RPM	Voltage V	Wind Speed, m/s	Blade RPM	Voltage V	Wind Speed, m/s	Blade RPM	Voltage V
2.15	5.72	4.67	2.24	5.97	4.95	2.35	6.25	4.24	2.46	6.55	5.80
2.15	5.74	3.70	2.25	6.00	3.57	2.35	6.25	4.26	2.48	6.60	3.81
2.15	5.74	4.04	2.25	6.00	4.30	2.35	6.25	6.00	2.50	6.67	4.59
2.16	5.76	4.40	2.28	6.06	5.32	2.35	6.27	4.33	2.53	6.74	5.34
2.17	5.79	3.86	2.29	6.09	4.34	2.35	6.27	4.17	2.54	6.76	4.70
2.19	5.83	4.53	2.29	6.11	4.13	2.42	6.44	5.95	2.55	6.78	5.24
2.19	5.83	3.96	2.30	6.13	2.66	2.42	6.46	2.49	2.55	6.81	4.23
2.19	5.83	3.01	2.31	6.16	4.19	2.43	6.48	4.65	2.58	6.88	3.73
2.20	5.86	4.08	2.31	6.16	4.36	2.43	6.48	4.96	2.59	6.90	5.64
2.21	5.88	3.99	2.33	6.20	4.32	2.43	6.48	4.45	2.59	6.90	3.33

2.22	5.93	4.06
2.22	5.93	4.07
2.22	5.93	2.32

2.33	6.20	4.17
2.34	6.23	4.43
2.34	6.23	4.01

2.44	6.50	3.96
2.45	6.53	3.92
2.46	6.55	4.76

2.62	6.99	5.03
2.63	7.01	4.90
2.64	7.04	4.65

Table 7d: Readings from the wind turbine ***from 4^{th} to 11^{th} June, 2013 on KNUST campus at the college of engineering***

Wind Speed, m/s	Blade RPM	Voltage V
2.65	7.06	4.91
2.65	7.06	4.00
2.65	7.06	4.94
2.68	7.13	3.32
2.68	7.15	5.01
2.70	7.20	4.95
2.70	7.20	5.08
2.70	7.20	6.81
2.72	7.25	4.83
2.77	7.38	4.96
2.82	7.50	5.20
2.82	7.50	5.64
2.82	7.52	3.64
2.82	7.52	5.10
2.83	7.55	5.15
2.83	7.55	5.22
2.85	7.59	4.91
2.86	7.62	4.94
2.87	7.64	2.55
2.88	7.66	4.52
2.88	7.69	5.05
2.89	7.71	5.25
2.90	7.73	5.39
2.92	7.78	5.35
2.95	7.87	5.00
2.97	7.92	5.47
3.02	8.06	5.29
3.02	8.06	3.37
3.04	8.10	5.57
3.05	8.13	5.80
3.10	8.26	3.25
3.14	8.36	5.71
3.19	8.50	5.78
3.21	8.56	4.91
3.22	8.59	5.96
3.23	8.61	5.89
3.30	8.80	4.58
3.30	8.80	5.59
3.31	8.82	6.11
3.31	8.82	7.34
3.32	8.84	6.03
3.33	8.87	3.45
3.38	9.00	6.21
3.40	9.05	6.22
3.41	9.10	4.98
3.47	9.24	5.23
3.63	9.68	6.15
3.63	9.68	6.91
3.69	9.84	6.09
3.74	9.95	5.93

2.82	7.52	5.20

2.95	7.87	5.36

3.29	8.77	5.13

3.74	9.98	2.87

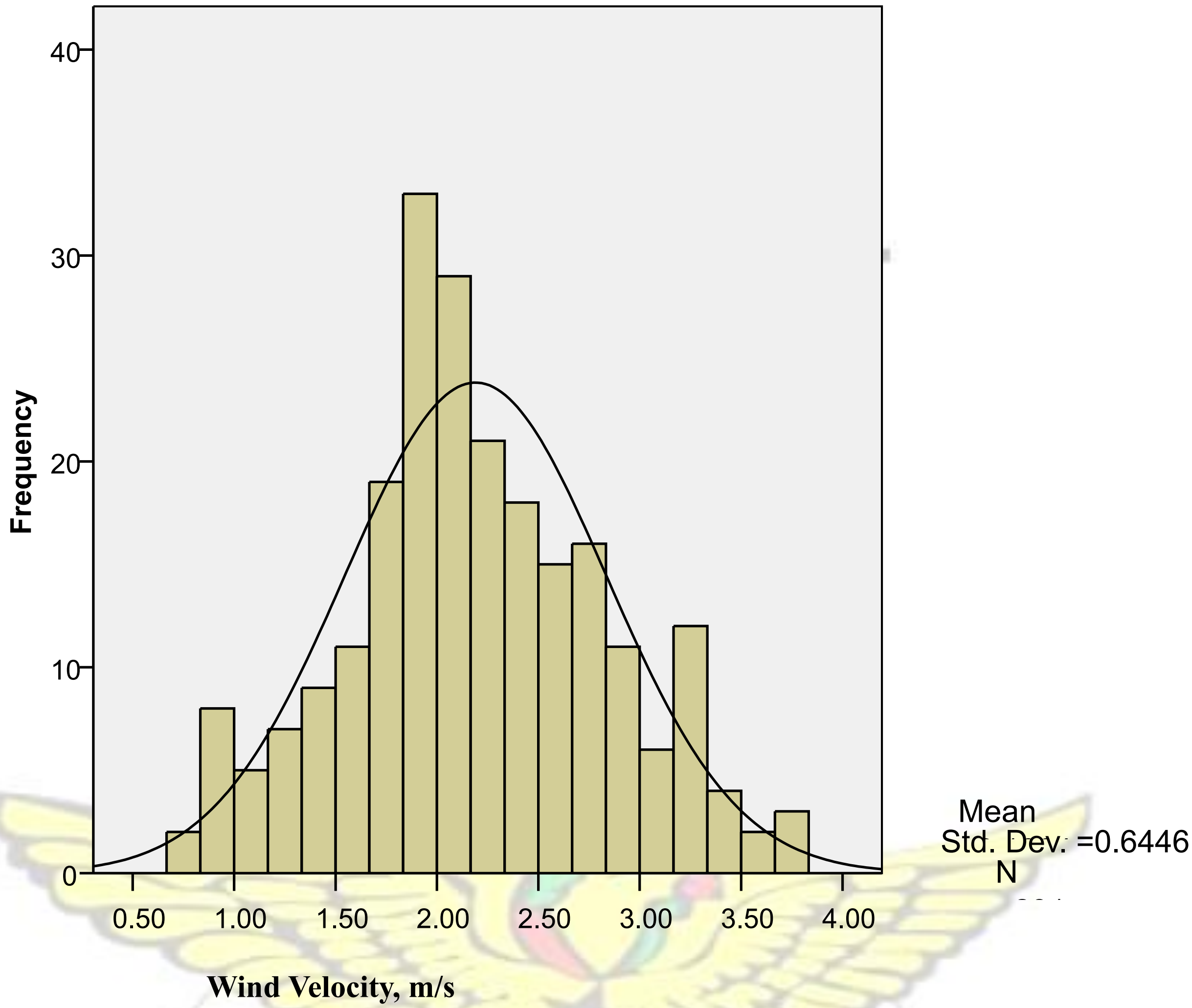


Figure 34: Graph of Wind velocity against Frequency

Figure 34 is the graph of wind velocity against the frequency. The mean wind velocity was 2.19m/s and the standard deviation was 0.6446.

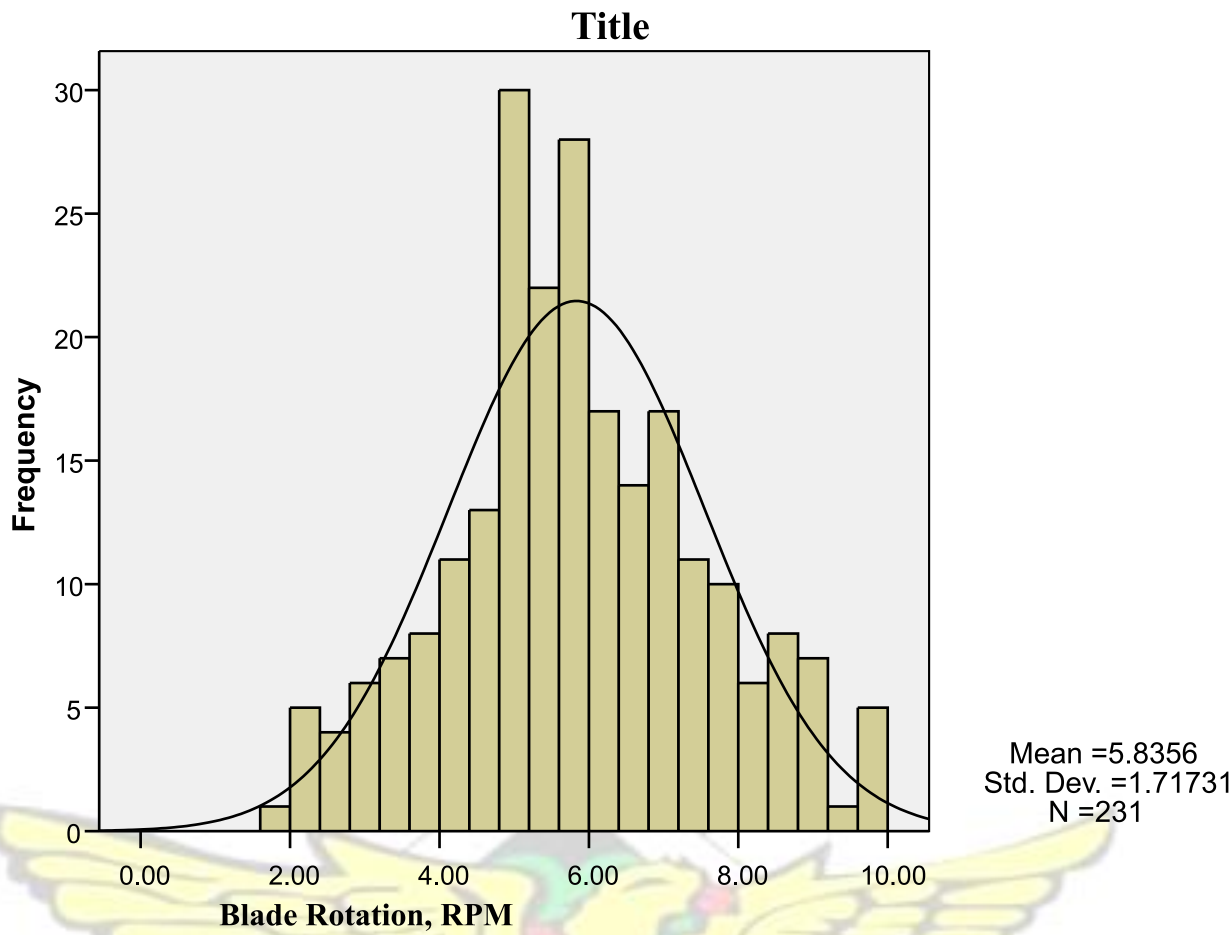


Figure 35: Blade rotation against Frequency

Figure 35 is the graph of blade rotation against frequency. The mean blade rotation was 5.8356m/s and the standard deviation was 1.7173. The mean blade rotation is indicative of how the blade responded to an increase in wind velocity.

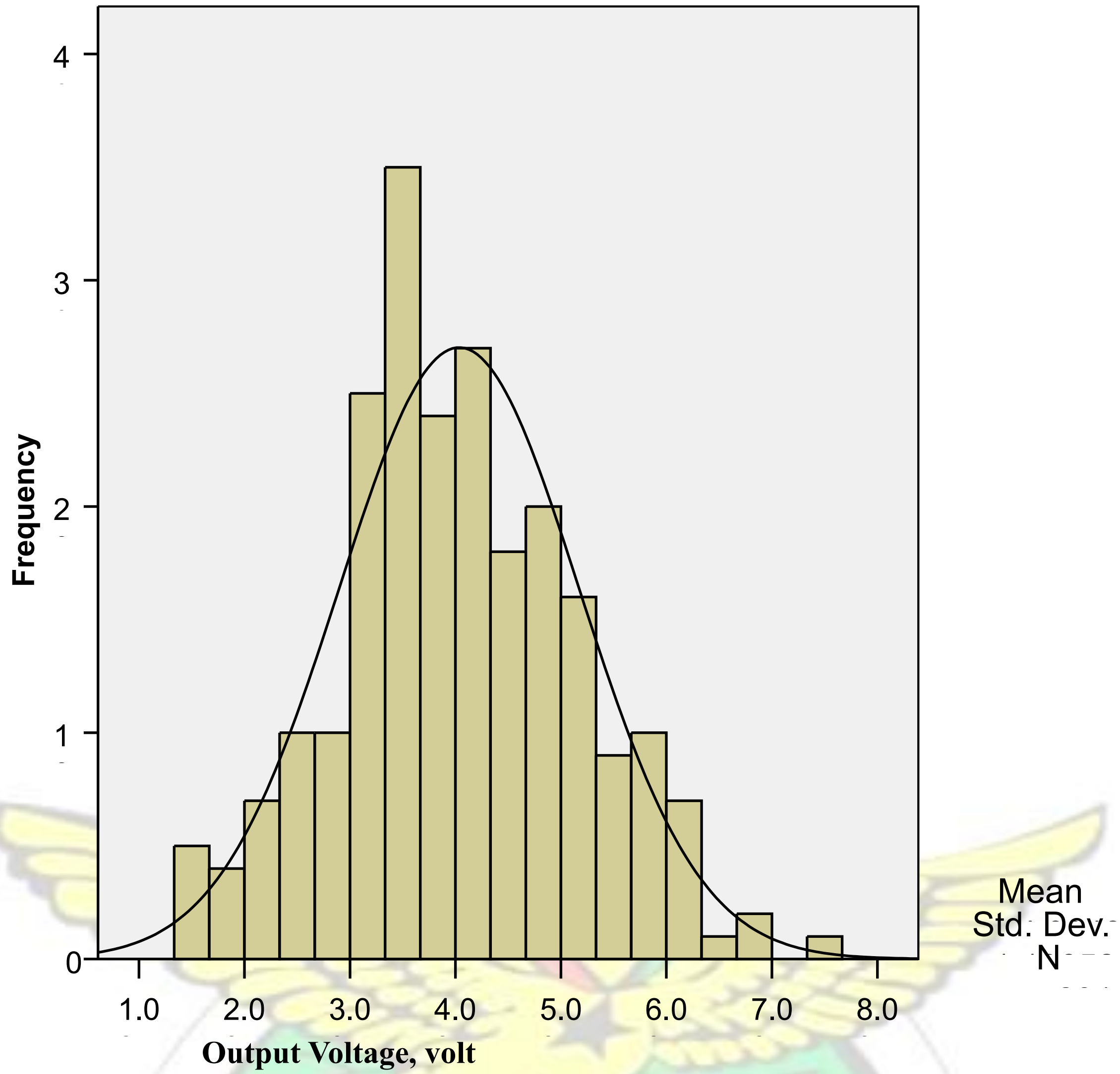


Figure 36: Output Voltage against Frequency

Figure 36 is the graph blade rotation against frequency. The mean blade rotation was 4.0348m/s and the standard deviation was 1.13652. The mean voltage is indicative of how much voltage is produced for each wind speed and blade rotation.

Table 9: Regression analysis of data

Coefficients (a)

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95% Confidence Interval for B	
	B	Std. Error	Beta			Lower Bound	Upper Bound
1 (Constant)	1.173	.179		6.567	.000	.821	1.525
Wind Speed	1.307	.078	.741	16.70	.000	1.152	1.461

a. Dependent Variable: Voltage

Excluded Variables (b)

Model		Beta In	t	Sig.	Partial Correlation	Collinearity Statistics Tolerance
1	Blade Rotation	-675.194 (a)	-.713	.476	-.047	2.20E-009

a. Predictors in the Model: (Constant), Wind Speed

b. Dependent Variable: Voltage

It can be established from Table 9 (a) that, the equation relating the dependent variable (Voltage) and the independent variable (Wind Speed) is $y = 1.307x + 1.173$; where x is Wind Speed and y is the Voltage. Similarly, Table 9 (b) shows that, the insignificant variable is the Blade Rotation (with 0.476 significance). This shows that the voltage expected from a wind turbine machine largely depends on the Wind Speed. Thus, the higher the wind speeds the greater the expected output voltage.

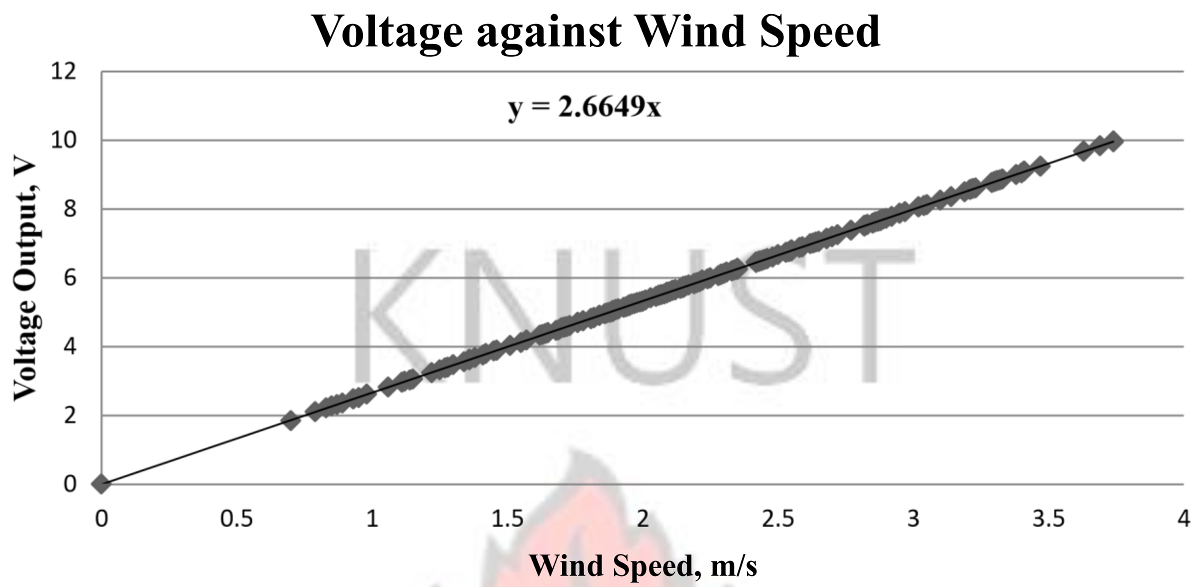


Figure 37: Wind Velocity against Blade Rotation

Figure 37 shows that wind velocity has a significant influence on the rotation of blade. It shows that for any increment in wind velocity, the output blade rotation increases by 2.6649 units.

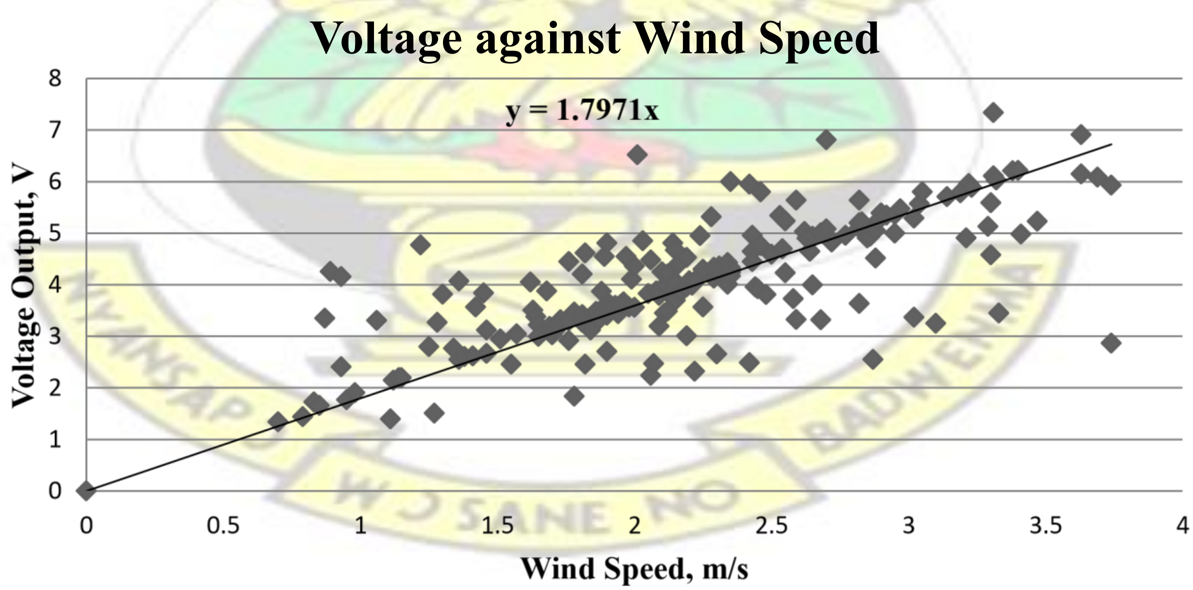


Figure 38: Wind speed against Voltage O utput

Figure 38 shows a plot of voltage output against wind speed. The rate of change of wind speed on voltage output is 1.7971 units, indicative of the fact that any increase or decrease in wind speed has a significant effect on the voltage output.

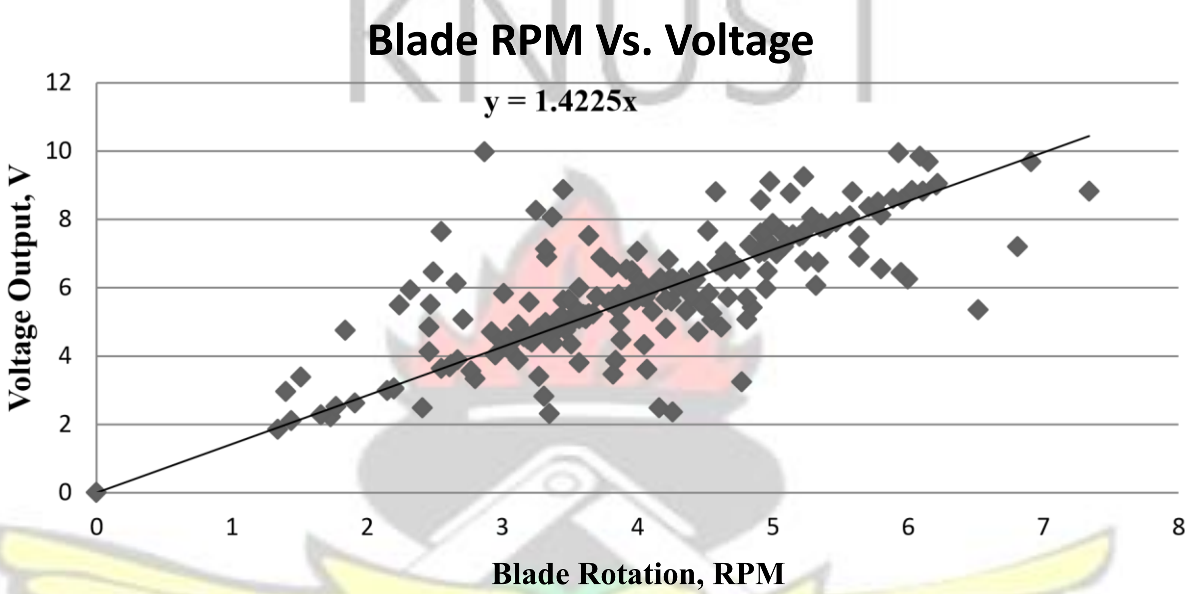


Figure 39: The graph of Blade rotation against Voltage output

Figure 39 also brings out how much the voltage output is affected by the blade rotation. The established equation makes it evident that the rate of change of the voltage output is significantly affected by the rotation of the wind turbine blade. The relation between the blade rotation and the voltage output indicates that for any rotation of the blade there is a voltage output of about one and half of the blade rotation. And this rate of change in the voltage output makes bamboo wind turbine blades a good option considering the fact that bamboo wind turbine blade, apart from their low density and high strength, if well designed can aid in the production of wind energy.

CHAPTER FIVE

RECOMMENDATIONS AND CONCLUSION

It is expected that wind turbine blade materials do not compromise on efficiency, strength, ease of construction, cost and availability of materials. Of all these parameters of a wind turbine blade material, it was with the ease of construction that was very difficult to achieve.

5.1 Conclusion

In conclusion, bamboo can be used to manufacture wind turbine blades. But the bamboo will have to be laminated before forming the desired shaped. The laminated bamboo board manufactured had a dimension of 1067mm x 203mm x 17mm.

The bending and compressions strengths of the laminate were also determined. It was realised that laminated bamboo had more bending strength (25.782 MPa) than compression strength (67.079 MPa). It shows that laminated bamboos can be used for load bearing and aerial applications where strength and light weight are much of importance.

Also, the laminated bamboo board was used to manufacture three wind turbine blades that were tested on a wind turbine machine. The performance of the bamboo wind turbine blade demonstrated that bamboo can also be used to substitute certain types of engineering materials already used in the making of wind turbine blades.

It can therefore be concluded that wind turbine and many other aerial engineering applications, where low density, low cycle cost, renewability, and affordability are required, laminated bamboo could be employed in such applications.

5.2 Recommendation

It is recommended that mechanised splitting be used to split the bamboo culm through the grains to ensure straight strips are obtained with less difficulty.

It is also recommended that the hard silica back cover be removed before using planing to reduce the difficulty associated planing whiles the back is still there.

It is again recommended that dryers be used to dry the bamboo strips to enhance effective and efficient drying of the strips thereby inhibiting the hygroscopic property of the bamboo board when drying is done in the sun or in a shade during wet seasons.

It is also recommended that other glues and gluing methods be employed to glue the strips and compared to the indigenous polyvinyl acetate glue to know which method will provide the best shearing force in the laminated lumber under similar conditions.

Due to constraints attached to the processing of the strips, the researcher was not able to evaluate a significant number of alternative airfoil families and their corresponding blade strengths. This is because most of the machine operators did not have time for me because they had been occupied with their business. It is therefore recommended that the blade design be re-examined with different airfoils.

It is again recommended that blades of other species of bamboos in Ghana be used to manufacture wind turbines blades and their properties tested to know which of the species can perform better in wind energy applications.

It can therefore be concluded that wind turbine and many other aerial engineering applications, where low density, low cycle cost, renewability, and affordability is required, laminated bamboo should be tried and tested if not to be wholly relied on.

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Appendix A

Figure A.1: Green Bamboo culms

Figure A.2: Trimming before cross cutting

Figure A.3: The Measurement of the bamboo culm before cutting into pieces

Figure A.4: Cross cutting of Bamboo culm into 3.5ft (1067mm) lengths

Figure A.5: The Cut pieces

Figure A.6: The manual splitting of bamboo culms

Figure A.7: Locally Manufactured Laminating press

(a)

(b)

Figure A.8: (a) and (b) show the planed laminated lumber

a).

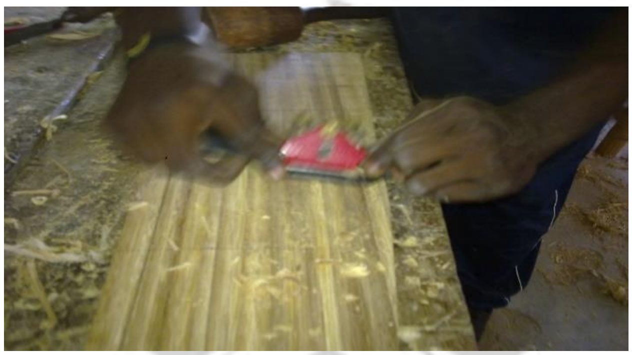
b.

Figure A.9: (a) and (b) show compression and bending tests


178
107
66
38
13
13
23°
153°
R95
127
76
62
42
59
36
22°
15
68
4 Holes Diameter 10
1045
127
17
6
Leading Edge
106
4
R40
Trailing Edge

Figure A.10: Blade model (Dimensions in millimeters)

a.



b.

c.

d.

Figure A.11 (a), (b), (c), and (d) show process of carving the blades

Figure A.12: Photo of the finished Bamboo Wind Turbine Blade