B. TECH. PROJECT REPORT

On

Design & Manufacturing of Rotor Blade of Small Horizontal Axis Wind Turbine

BY

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DISCIPLINE OF MECHANICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY INDORE

November, 2018

Design & Manufacturing of Rotor Blade of Small Horizontal Axis Wind Turbine

A PROJECT REPORT

Submitted in partial fulfillment of the requirements for the award of the degrees

of
BACHELOR OF TECHNOLOGY
in

MECHANICAL ENGINEERING

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INDIAN INSTITUTE OF TECHNOLOGY INDORE
November, 2018

CANDIDATE’S DECLARATION

We hereby declare that the project entitled **Design & Manufacturing of Rotor Blade of Small Horizontal Axis Wind Turbine,** submitted in partial fulfillment for the award of the degree of Bachelor of Technology in Mechanical Engineering completed under the supervision of **Dr. Subbareddy Daggumati,** IIT Indore is an authentic work.

Further, we declare that we have not submitted this work for the award of any other degree elsewhere.

Signature and name of the student(s) with date

CERTIFICATE by BTP Guide(s)

It is certified that the above statement made by the students is correct to the best of my knowledge.

Signature of BTP Guide(s) with dates and their designation

PREFACE

This report on **Design & Manufacturing of Rotor Blade of Small Horizontal Axis Wind Turbine** is prepared under the guidance of Dr.Subbareddy Daggumati.

Through this report we have tried to give a detailed design and manufacturing process of a Small Horizontal Axis Wind Turbine rotor blade. The design is aimed at developing a blade, capable for generating 10kW of power in low wind condition, which can be used as source of electricity in decentralized grid system. Firstly, a detailed analysis on aerodynamics of wind turbine blade is portrayed. .Secondly, a description is given on blade structure, material, its placement along the blade length. Different kind of wind conditions and loads associated with wind turbine blade, are discussed briefly. Further, aero elastic calculations along with the FEA of blade are done to investigate the blade response to different-different wind and loading condition. Lastly a 2m long is fabricated with the aim of identifying an automized manufacturing technique, which is presented in the 5th chapter.

We have tried to the best of our abilities and knowledge to explain the content in a lucid manner. We have also added descriptive images and figures to support the sentences and our work.

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ACKNOWLEDGEMENTS

We wish thanks to Dr. Subbareddy Daggumati for providing us the opportunity to work on such a valuable project. We also express our sincere gratitude for his kind support and valuable guidance not only on the technical stuffs but also on presentation and other skills that are essential for an all round development of an individual.

We appreciate Mr. Akash Sharma for helping us in carrying out the FEA simulations.

Finally, thanks to everyone else that we did not mention but helped us, even just several inspirited words.

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ABSTRACT

Design & Manufacturing of small Horizontal Axis Wind Turbine Blade

This work is about development of a rotor blade for 10kW wind turbine, operating under low wind conditions, with the aim of encouraging decentralized power generation system in India. The blade plays a crucial role in harnessing wind energy, while subjected to various alternating wind loads and harsh weather conditions. Hence its design should not only be aero-dynamically efficient but also sufficiently stiff & strong. The aerodynamic efficiency of the blade is governed by its shell shape (airfoils). This shell shape is internally supported by some internal geometries- shear webs & spar cap. These internal geometries provide structural stiffness to the blade. Different mathematical tools and software are employed to get an optimized design from both the perspectives. After selecting appropriate airfoils, ***Qblade*** is used to generate the optimum aerodynamic shell shape. Material placement (composite layup) and internal structures are modeled with the aid of ***NuMAD***. Blade's structural response is simulated in ***Ashes***. It's output contains time varying loads and tip deflections, based upon which blade structure is modified to optimize it. Further detailed analysis of blade is done in ***ANSYS APDL*** to examine material's response such as stress, strain & buckling load factor. Lastly a small prototype is manufactured with a VARTM manufacturing process.

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Chapter 1: **Introduction**

Electrical energy production has played a major role in the development of a nation. Industrialization and urbanization has led to rapid growth in electricity demand. This has further proved to be the source of drastic increase in pollution level due to the emissions caused by conventional method of electricity production. In principle, electricity production by conventional method has been a prime reason for climate change which is a serious threat to the mankind. Apart from this, conventional method of power production also put a large pressure on the non renewable natural resources like coals, natural gases and fossil fuels. This in turn raised the question for finding the alternate ways of power production. As a result, renewable sources of energy have become an interesting field of research.

Solar energy, wind energy and bio fuels have shown to be a feasible and alternate way of generating electrical power. However, wind energy has been most popular in large scale power production. Consequence of this, wind energy has drawn more attention in the last few decades. A lot of research has been done to improve the efficiency of wind turbines. And today it has developed into more mature pollution free technology. Wind energy offers numerous benefits, which clarifies why it's one of the quickest developing energy sources on the planet.

Wind turbines particularly convert the wind kinetic energy into the electrical energy. Broadly there are two kinds of wind turbines had been developed to serve this purpose. They are:

- Horizontal Axis Wind turbine (HAWT)
- Vertical Axis Wind Turbine (VAWT)

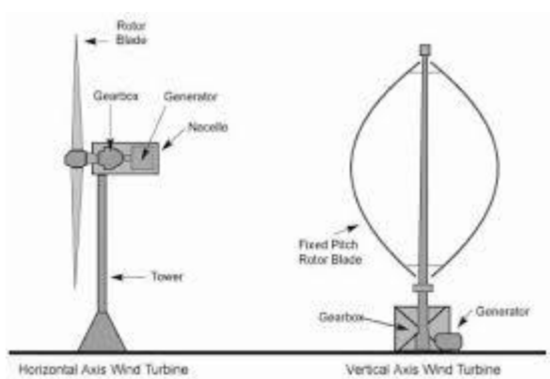


Fig 1.1 Wind turbine types

Both of these types have their own benefits and limitations. But the most important characteristic that makes VAWT unpopular is that it needs to be installed near ground level where wind speed is low, thereby lower power production.[1]

The National Renewable Energy Sources (NREL) in US defines wind turbines whose rated power is not greater than 100kW with diameter not more than 19m as Small Wind turbines.

1.1 Advantages of Small Wind Turbines

- Since large wind farms are already occupied by the large wind turbines which operate in highly wind efficient regions, small wind turbines can operate in low wind regions that too with less installation cost.
- They can be used as power source for decentralized grid system which actually reduces the investment by avoiding the use of long power transmission cables.
- Combination of Solar PV cells along and small wind turbine can generate sufficient power for the domestic needs.

1.2 Goals and outcomes

The purpose of this work is to deliver a preliminary design for a 10kW HAWT blade along with the details of design process. With this as the final goal, following tasks have been accomplished:

- Necessary tools and softwares for designing wind turbine blade are identified.
- A streamlined process for designing HAWT blade has been figured out.
- GFRP blade fabrication with an automized manufacturing technique- Vacuum assisted resin transfer mold (VARTM).

Above being the final goals, this work turns up with the following outcome:

Development of **Small Horizontal Axis wind Turbine** for decentralized power production.

1.3 Contribution of this work

1) Aerodynamic design for the blade is done which can extract 10 $\pm$ 3kW power in low wind condition of 5m/s. All aerodynamic calculations and associated calculations are done on ***Qblade-*** an open source tool.
2) Structural designing and optimization is accomplished with the aid of ***NuMAD***&***ANSYS APDL.***
3) ***Ashes***, an aero elastic simulation software is employed to obtain the time as well as position varying wind loads on the blade.
4) Further, detailed analysis is carried out using ***ANSYS APDL*** to investigate material and structural response of the blade.
5) Lastly, a 2m long GFRP blade is fabricated using VARTM manufacturing process.

Chapter 2: **Aerodynamic Design**

2.1 Aerodynamics of HAWT blade

The blade cross section of a HAWT rotor is of airfoil shape, because of the fact that this shape experiences a high lift force when subjected to some fluid flow field, which is then responsible for the rotation of the rotor blade. In this way, the wind kinetic energy is converted into the rotational mechanical energy of the rotor.

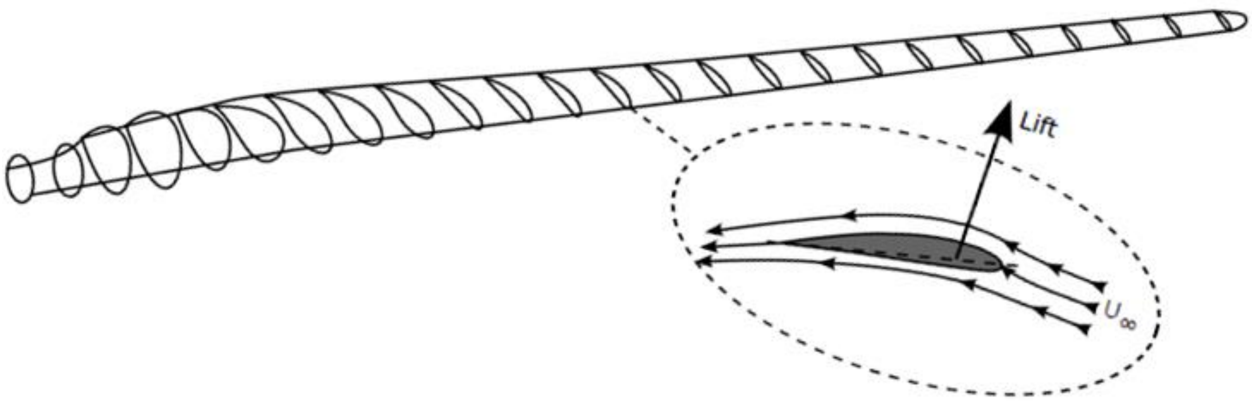


Fig 2.1 HAWT blade profile

Airfoils- Terminologies& definition:

Leading edge: Front edge of airfoil
Trailing edge: Rearmost edge
Chord (c): Line joining leading and trailing edge
Mean camber: Curve traced halfway between the upper & lower surface
t/c ratio: Ratio of maximum thickness to chord length
Angle of attack (α): Angle between flow direction and the chord line
Lift coefficient: $C_L = L/(0.5\rho AW^2)$
Drag coefficient: $C_D = D/(0.5\rho AW^2)$

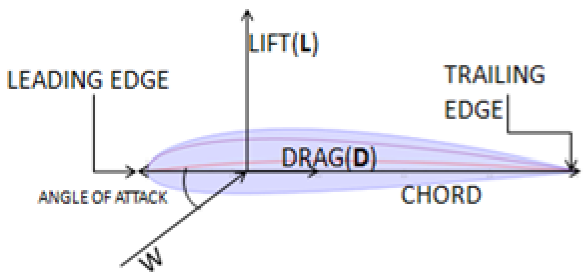


Fig 2.2 Airfoil terminologies

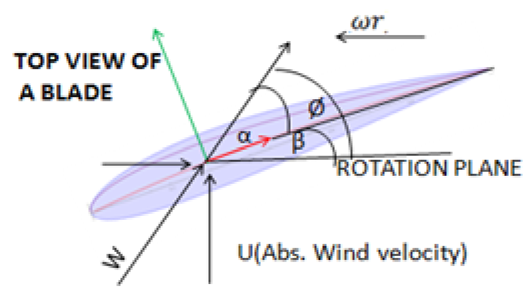


Fig 2.3 HAWT blade terminologies

HAWT blade- Terminologies:

Swept area: $A=\pi R^2$, R: blade length
Flow angle (ø): Angle between the wind flow direction& rotation plane
Twist angle (β): Angle between the wind flow direction & rotation plane
Power coefficient: $C_P = P/(0.5\rho AU^3)$, U: absolute wind velocity
Tip speed ratio (TSR, λ): $\lambda = \omega R/U$

2.2 Aerodynamic performance of HAWT – analytical methods

The aerodynamic performance of HAWT is completely dependent on the external shell shape of the blade. This shell is actually defined by the airfoils used, chord length and twist angle distribution along the length. Various analytical models have been developed to obtain the optimized shell shape. These analytical models are discussed below[3]:

1. ***Actuator Disc theory***: This theory states that the wind flow decelerates as it approaches the turbine and, portrays the importance of considering induction factors ***a****(axial induction factor)* while closely analyzing flow over the blade[2].This theory is further used to obtain the maximum value of Blade efficiency(C_P) which is called Betz Limit.
   $a = \frac{U_\infty - U}{U_\infty}$and maximum value of C_P i.e. Betz limit = 16/27.

2. ***Momentum Theory with wake rotation***: The previous theory can be extended to the case where angular momentum conservation is also considered. Based on this a term rotational induction factor ***a'*** is introduced in a way very similar to ***a*** was produced. In nutshell, this theory develops mathematical relations to analyze thrust force and rotational moment force experienced by the rotor blades.
   Thrust force: $dT = 4\pi\rho U_\infty^2 a(1-a)rdr$
   Rotational moment force: $dM = 4\pi\rho U_\infty(\omega r)a'(1-a)rdr$

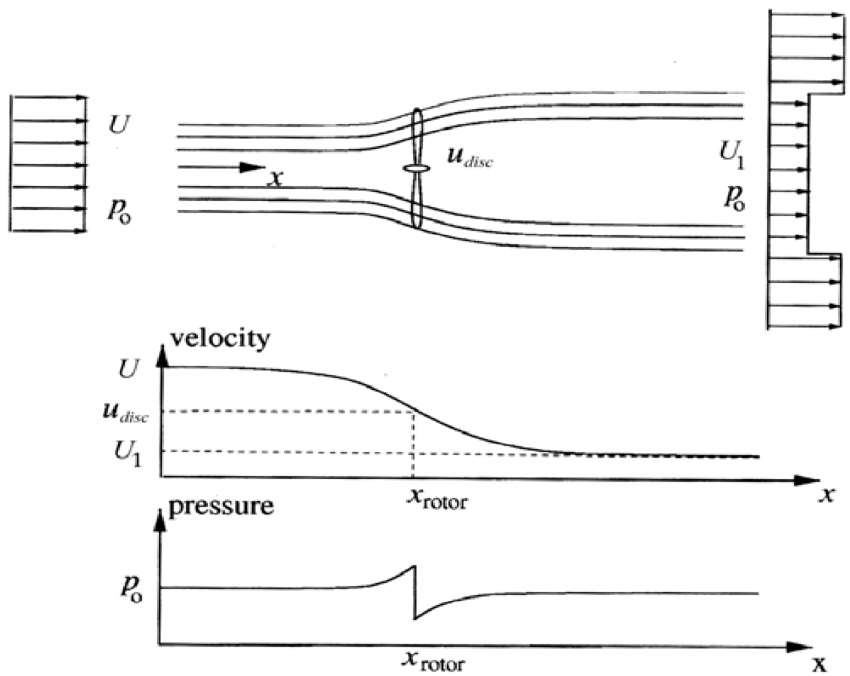


Fig 2.4 Wind flow representation: *Source*: Gundtoft (2009)

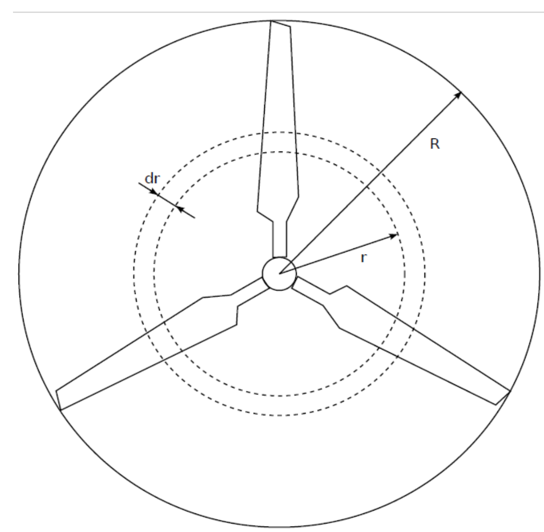


Fig 2.5 Blade differential element

3. ***Blade Element Theory***: This theory formulates thrust and tangential force in terms of C_L, C_D, flow angle **(ø)**. The blade is divided into several sections and each section is an airfoil of certain chord length **(c)** having some twist angle **(β)** with the plane of rotation. Only aerodynamic characteristics of airfoil is considered and forces on blade is solely determined by lift and drag coefficient. Following are its results:
   Thrust force: $dT = B\frac{\rho}{2}W^2cdr(C_L cos\emptyset + C_D sin\emptyset)$

Rotational moment force: $dM = B\frac{\rho}{2}W^2cdr(C_L sin\emptyset + C_D cos\emptyset)$,where B: no. of blades

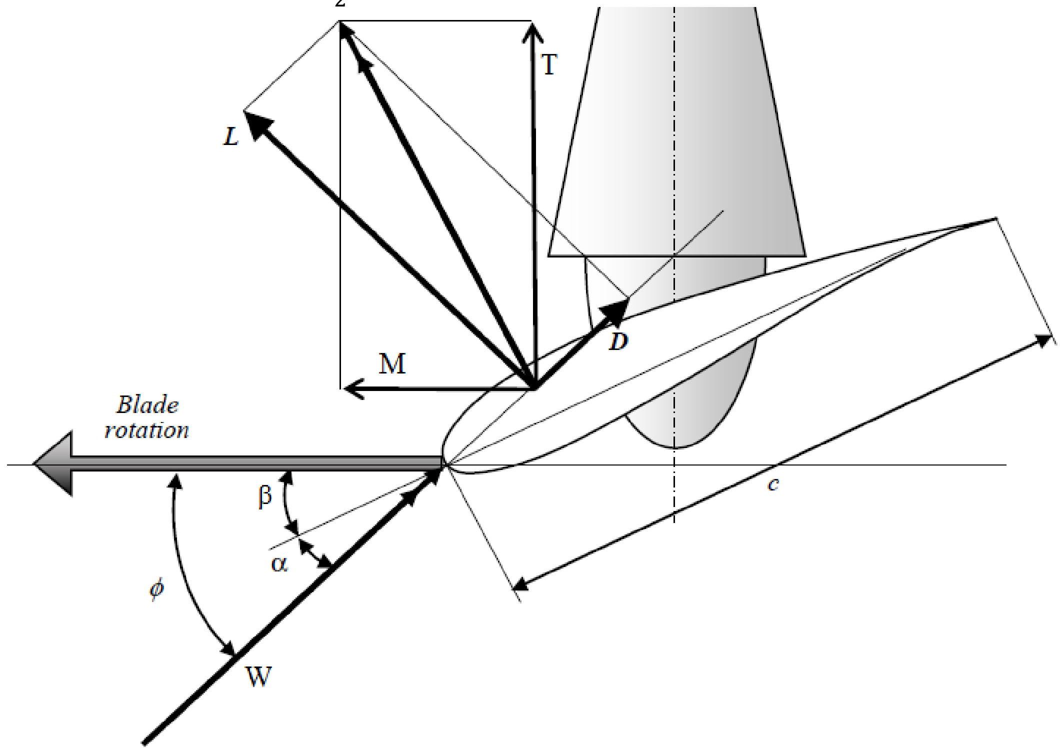


Fig 2.6 Thrust &Tangential force on HAWT blade

4. ***Blade element momentum theory (BEM)***: Blade element and momentum theory are combined together to calculate induction factors- ***a*** and***a'***, which are critical parameters for analyzing the aerodynamic performance of the blade. The above obtained equations can be solved iteratively using 2D airfoil data. However due to its assumptions BEM cannot some aerodynamic effects on wind turbines, hence various correction factors, such as ***tip loss, hub loss,***etc are developed to consider these effects.

Once the values of induction factors are known the thrust, torque and hence the power developed by turbine can be obtained for a given blade and other operating conditions like wind speed, TSR, power regulation technique (pitch regulated or stall regulated). But before all these things the blade's aerodynamic design should be known. The aerodynamic design essentially means the airfoils' placement, chord length and twist angle distribution along the blade length.

Several researchers have used different formulae to get optimum chord length distribution based on parameters viz TSR, radial location (r), no. of blades (B), wind velocity (U), etc[3].

Some popularly used are[4]:

$$\textit{Schimtz:}\quad c = \frac{16\pi r}{BC_L} sin^2\emptyset$$

$$\textit{Betz:}\; c = \frac{16\pi R}{9BC_L\lambda_o}\frac{1}{\sqrt{\left(\lambda_o\frac{r}{R}\right)^2+\frac{4}{9}}}$$

$$\textit{Manwell(without considering wake rotation):}\; c = \frac{8\pi r}{BC_L}\left(\frac{sin\emptyset}{3\lambda_r}\right)$$

2.3 Design methodology

It is the blades' external shell shape which is highly responsible for developing torque at rotor and hence the power. This external shell shape is referred to as ***aerodynamic design***. It involves obtaining the blade geometry in terms of airfoils, chord length and twist angle. It requires the selection of appropriate airfoils, determination of suitable blade length along with the choosing a reasonable value of TSR. Calculation of these variables require following information: *rated wind speed, power requirement & power regulation-pitch or stall regulated*.

According to *Manwell et al.*[2] TSR depends particularly on the number of blades that are there in the turbine . For turbines with 3 blades: **TSR = 5**.

- Rated wind speed (U): 5m/s
- Power requirement (P): 10 $\pm$ 3kW
- Power regulation: stall regulated

2.3.1 Determination of blade length

Blade length can calculated using the following relation:

$$P = \frac{1}{2} C_P \rho A U^3 \text{where} A = swept\ area = \pi R^2 \&\ R = rotor\ length$$

C_P is the power coefficient of wind turbine, which itself depends on the blade shape which is unknown. ***C_P = 0.3*** is its anticipated value which is based on the data of some existing HAWTs tabulated in Table 2.1:

Rated Power kW	Diameter m	Swept area m^2	Rated Wind Speed m/s	Cp
3	4	12.6	12	0.224957708
5	5	19.6	12	0.241026116
10	8	50.24	12	0.188061778
20	10	78.5	12	0.240719076
30	12	113	12	0.250837798
Source : http://www.huayaturbine.com				
5	6.4	32.17	10	0.253753973
10	8	50.26	10	0.324841437
Source : http://www.windturbinestar.com/				
10	7	38.465	11	0.318896766
Source : http://bergey.com/documents/2013/10/excel-10-brochure_2013.pdf				
10	7.8	47.78	11	0.25670644
Source : https://chinawindenergy.en.made-in-china.com/product/keAmrzLMYdph/China-10kw-Wind-Turbine-for-on-Grid-Power-Supply-System-Plan.html				

Table 2.1

Finally, blade length calculated is **R = 10m**.
However power corresponding to 10m is **7.216kW** which is within the range of 10 $\pm$3kW .

2.3.2 Airfoil Selection

Airfoil selection is one of the most crucial step while conducting aerodynamic design of wind turbine blade. The wind loads experienced by the blade is all dependent on the geometry of airfoils used and their placement. Literature survey is done to down select the appropriate airfoils for stall regulated purpose.

Properties of airfoils used in stall regulated HAWTs:

- The sharp stall should be avoided otherwise it would lead to load problems (fatigue issues and additional noise) with the blade and other components [5].
- The capability to control machine, slowing down the rotor and avoiding over power issues depend on the airfoil stall and post stall behavior, if the lift curve is excessively flat, it could not control the over power issue, while a sharp stall would make it difficult to restart the machine and would cause sudden changes in loads faced by the blades[5].
- The sharp stall also causes lower damping force and so to large vibrations, while a gentle stall (relatively flat lift curve) avoids the occurrence of stall induced vibrations[5].
- The airfoils on stall regulated should be C_{Lmax} insensitive to roughness in order to minimize the loss in peak power owing to roughness effect[5][6].

Airfoils that are insensitive to roughness: *S7012(thin), S822(moderate), S823(thick), SD 7037(thin)*[6].

Airfoils suggested by NREL for 10-20 m blade & stall regulation: *[S807, S805A, S806A], [S808, S805A, S806A], [S821, S819, S820]*[7].

Out of all the airfoils, that are reported in literatures, the down selected are:

S820- *tip*, **S819**- *mid portion*&**S821- root**.

These airfoils are developed by NREL, among which S820 is the thinnest and S821 is the thickest. Their polars i.e. shape coordinates are readily available on NREL website.

2.3.3 Qblade-Results

Fig 2.7 gives the overall picture of Qblade working.

Once the inputs are determined they are put into Qblade in required format. With the selected airfoils, a preliminary design of blade is modeled. Chord optimization is done based on Schmitz relation.

$$c = \frac{16\pi r}{BC_L} sin^2ø$$

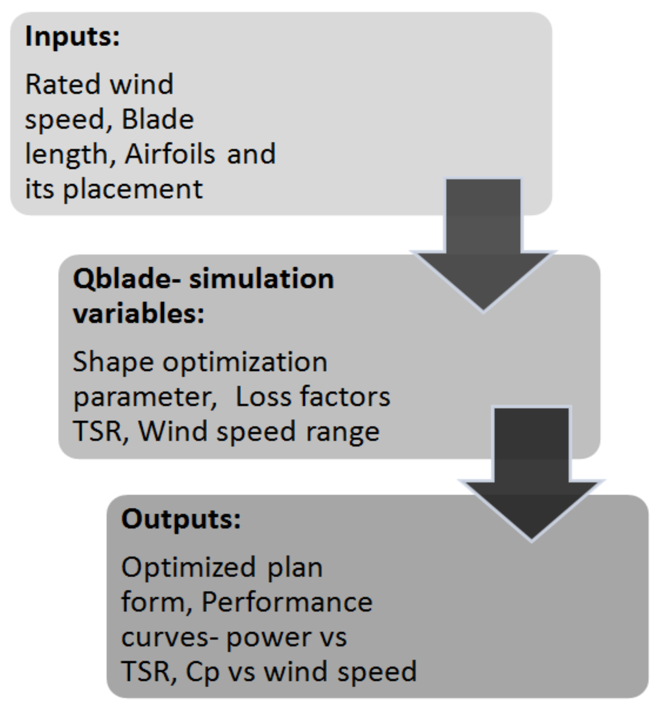


Fig 2.7Qblade Work representation

Chapter 3: **Structural Design**

The purpose of structural designing is to provide enough stiffness and rigidity to the blade, so for its proper functioning. The main reasons, which make structural design an important part of the design process are:

- The blade material should be able to sustain both the extreme and fatigue load conditions.
- Blade should not deform so much that it hits the tower of wind turbine.
- Excessive blade deformation could cause significant loss in power generation.

Structural designing consist of: *design of internal structures- webs & spars and material placement along the blade*. It is the internal structures which are responsible for taking the loads.

3.1 HAWT Blade structure

Important elements of a HAWT blade structures include: ***root, webs and spar***. 30% of the blade length from root end is considered as the ***root portion***[8]. Its ending is marked by the maximum chord location. This region carries the maximum amount of bending moment due to the wind loads. ***Spars*** and ***webs*** together forms the I- section beam inside the blade shell. Spars are the horizontal members located on both the surfaces- top & bottom, while web is the vertical member that joins both the spars. Spars takes the bending moment normal stresses and webs take the shear forces. Number of webs can be 2 or 3 depending on the blade width. For small 10m blades, 1 web is sufficient to provide stiffness.

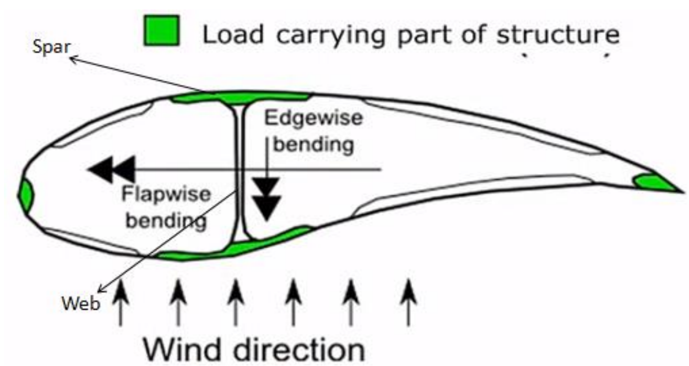


Fig 3.1 HAWT blade section and internal structures

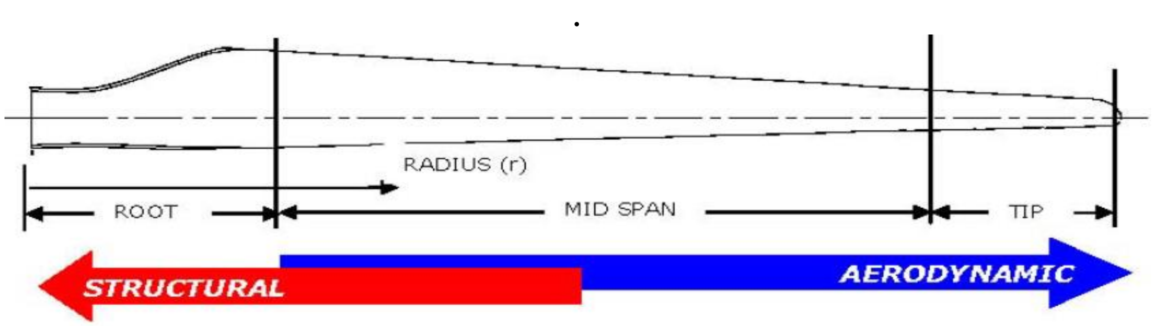


Fig 3.2 Different regions on HAWT blade

3.2 Overview of blade material

Due to its high- strength to weight ratio, compositematerials have become very popular in making large structures like wind turbine blade. Very commonly used material for HAWT blade is composite of *Glass Fiber- Epoxy* called **GFRP** *(Glass fiber reinforced polymer).* Different regions of blade are composed of different-different plies with different thickness in order to get an optimal structure with the aim of producing light weight blade.

Triax plies are used at the root. It is also used as shell material all along the blade with decreasing thickness from root to tip. ***Unidirectional*** plies are put to form the spar on both the upper and lower surface. It generally begins at the maximum chord position and ends at around 90% of the blade length. ***Biax*** plies or balsa can be used as core material for webs. The leading edge and trailing edge portion are not critical from blade's stiffness point of view but the trailing edge is more susceptible to buckling instability. So care needs to be taken while assigning material to trailing edge. However foam can be used as core material in these regions[9][10].

LEP :*leading edge panel*, TEP: *Trailing Edge panel*

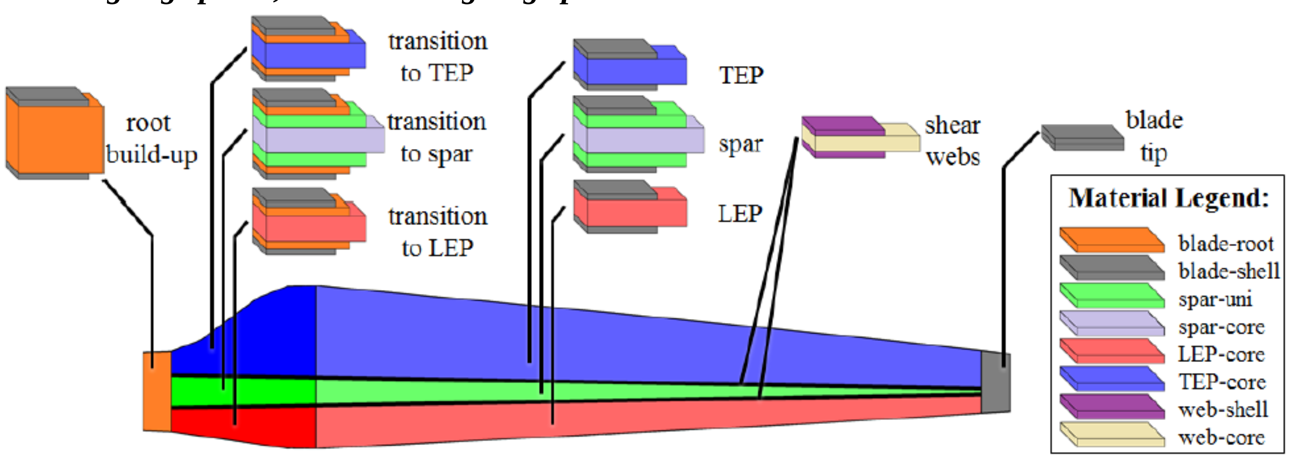


Fig 3.3*Source: CoBlade guide*

3.3 Structural modeling in NuMAD

NuMAD stands for Numerical Manufacturing and Design, is a tool that allows to model material placement-composite layup of a HAWT blade. It is an open source code written in MATLAB, developed by Sandia National Laboratory [11]. It requires the blade shell shape, material properties and ply orientations as input. Shear webs and spars can be designed as per requirement. Once the modeling is done, NuMAD generates the structural file using PreComp. This structural file contains the structural properties of the blade. Few of them are given in table 3.1.

Span_loc	Span location of the section measured from the blade root and normalized with respect to the blade length.	-
Chord	Chord length of the section.	m
Tw_aero	Section aerodynamic twist, θ_{aero}	deg
EI_flap	Section flap bending stiffness about the Y_E axis.	Nm^2
EI_lag	Section lag (edgewise) bending stiffness about the X_E axis.	Nm^2
GJ	Section torsion stiffness.	Nm^2
EA	Section axial stiffness.	N
Mass	Section mass per unit length.	Kg/m
X_cm	X-coordinate of the center-of-mass offset with respect to the X_R-Y_R axes.	m
Y_cm	Chordwise offset of the section center of mass with respect to the X_R-Y_R axes.	m

Table 3.1 *Source PreComp guide*

Chapter 4: **Aero-elasticity and FEA**

4.1Aero elasticity

It is the study of interaction of inertial, structural and aerodynamic forces on structures. As forces(Lift &Drag) are developed in a wind turbine blade during operation thus we need to design the blade accordingly.

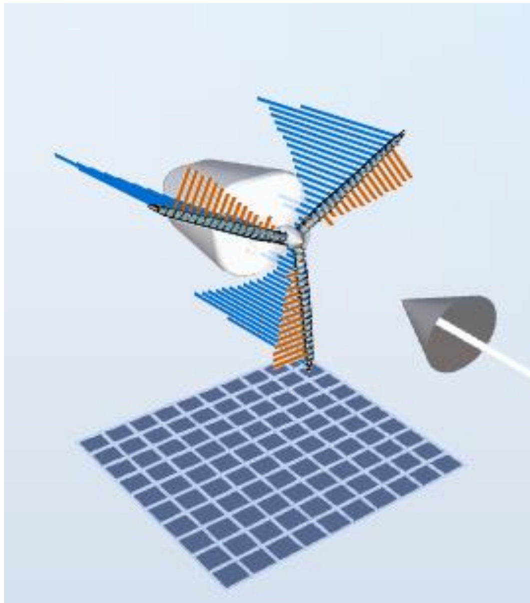


Fig: 4.1Aero elastic forces

4.2 Determination of wind conditions

Aero elasticity is a phenomenon which solely depends on the wind conditions and therefore different wind profiles are evaluated for retrieving aerodynamic forces during different phases of wind turbine operation.

4.2.1 IEC Guidelines

According to wind conditions wind turbine blades are categorized into classes as follow:

SWT Class		I	II	III	IV
V_{ref}	(m/s)	50	42,5	37,5	30
V_{ave}	(m/s)	10	8,5	7,5	6

Table 4.1 IEC wind conditions

V**ref**reference wind speed averaged over 10 min, ***V*****ave** annual average wind speed at hub height

Our blade falls in category IV, average wind velocity 5-6 m/s.But these wind conditions are normal operating wind velocity values,which does not remains same throughoutblade life. Extreme wind conditions like tornadoes, hurricanes, storms,and sudden gust conditions arise. For blade design we have taken into consideration one most important wind conditions namely EOG (extreme operating gust) which fall under IEC extreme.

EOG:***V*ref 25m/s, Turbulence percentage-12%**

4.2.2 IEC coordinate system

To define the directions of the loads, the system of axes shown in Figure 4.2 is used.

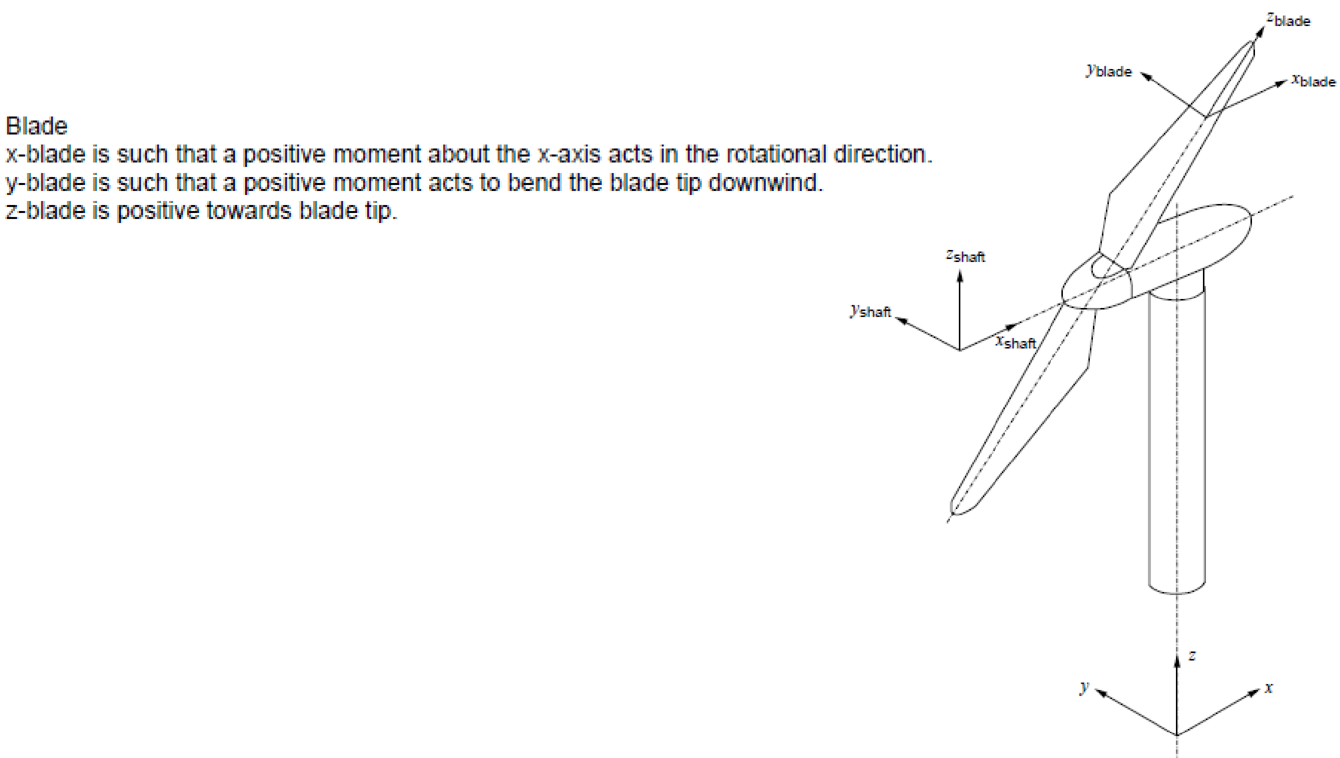


Fig 4.2 Coordinate system

Forces in x direction are generally termed as Flapwise forces and y direction forces are called edgewise.

4.3 Aeroelastic Modeling in ASHES

Modeling in ASHES require various input such as airfoil data from Qblade fig 6.1, structural file from Numad, wind profile from IEC, generator configuration .Above chapters give an insight into detailed designing of aerodynamics, structural so as the results can be used directly in aeroelastic modeling.

4.4 FEM

Finite element analysis is performed to design the blade for different failurecriterias. Input parameters are the data's collected from aerodynamic, structural and aeroelastic module from Qblade, Numad and ASHES respectively.Shell structure of blade is available in Numad with adequate boundary condition applied ,only flapwise and edgewise loads have to be applied along blade length.

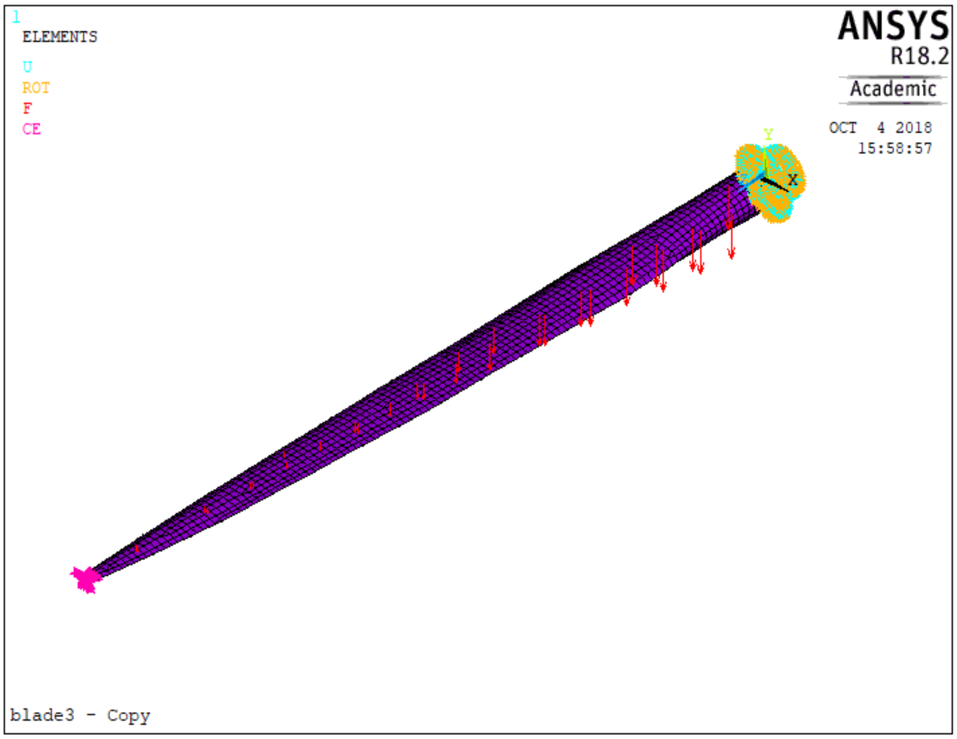


Fig 4.3 Blade loading and boundary condition

4.4.1 Partial Reduction Factors

For designing the blade, materials properties are required and values can be extracted from coupon level testing data from table **3.2**. But to use these properties for blade level analysis some factor of safety is included .

$$S_d(\gamma_f \cdot F_k) \leq \frac{R_d}{\gamma_m}$$

Where
Sd**:**Structural response (induced stress or strain) to the design load
γf: load factor
Fk: Characteristic load
Rd: Characteristic material design value
γm: Reduction factor
$\gamma m = \gamma m0.\ \gamma m1.\ \gamma m2.\ \gamma m3.\ \gamma m4.\ \gamma m5$
Finite element analysis was performed for three types of failure criteria.

1. **Static Analysis**

   Static analysis can be used to find isolated locations in the blade that may experience high strain values and can be used to understand ply failure predicted by any defined material failure criteria. Strain values are determined and taken care that they are within the design limits. Strain limit -7500 to 8050 microns is considered after reduction values. Loads are applied in both edge and flapwise direction with root as fixed [9].

2. **Tip Deflection**

   Tip deflection analysis is done for determining the maximum deformation in blade , this analysis is important so as to keep the tip at a certain clearance so that tip does not collide with the tower.Maximum tip deflection is observed in flapwise direction due to less area moment of inertia. In general for 10m blade allowable tip deflection is 2 m in flapwisedirection[12].

3. **Buckling**

   Longer structures in compression fail due to buckling and so is the case with wind turbine blade where buckling predominantly occurs near trailing edge of blade. 10 different modes are analysed for buckling load factor.Buckling load factor is like factor of safety and generally its value is greater than 1[9][13].

Chapter 5:**Manufacturing**

Introduction

After the designing of wind turbine blade aerodynamically, structurally and its analysis, the only thing left was manufacturing. As manufacturing is most important and critical part of product cycle, steps were taken to improve the time as well as manufacturing skills.Different manufacturing techniques were studied to find suitable method for wind turbine blade. After selection it was decided to manufacture a small 2 m long prototype of 10m blade.

5.1 VARTM(Vacuum assisted resin transfer molding)

VARTM is a process were vacuum is used to facilitate resin flow in composite layup. The pressure for resin injection is about 0.69 to 1.38 MPa, and sometimes as low as 0.3 MPa. Pressure pushes the resin through the reinforced material and fills the mould cavity with resin .This method was chosen because of it's low production time , scalability to large structures , defect free manufacturing process .Below is the process schematic[14].

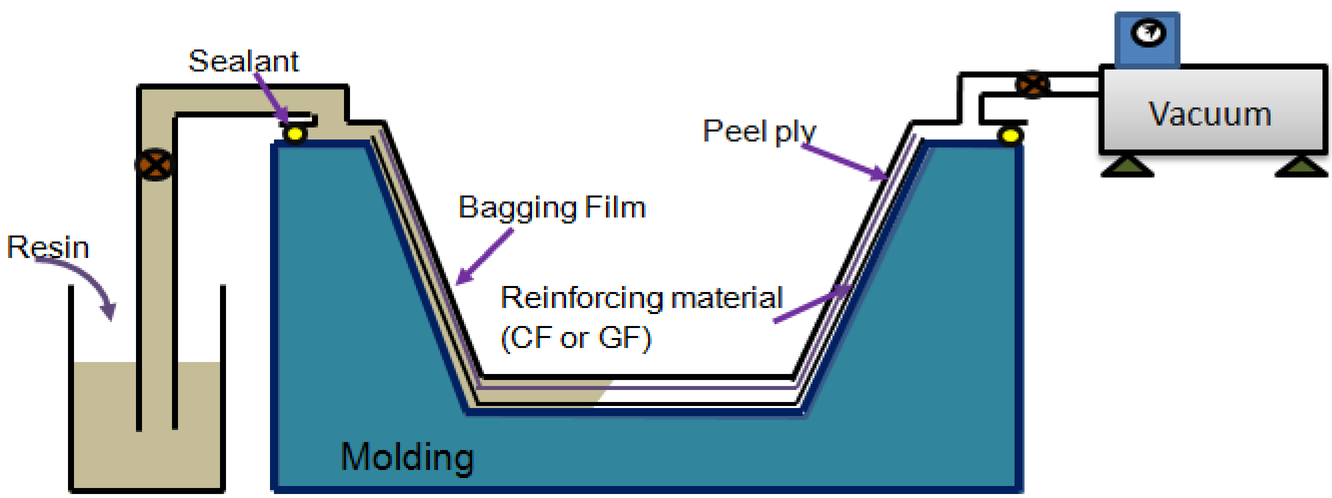


Fig 5.1 VARTM schematic

5.2 Blade Mold fabrication

Mold material was chosen according to the strength, machinability, surface properties and cost. The material that exactly fit the requirements was wood, machining was done in CNC with the help of CAD model prepared of 2m long prototype.

Fig 5.2 Molds

5.3 Blade Fabrication

After several trials final blade was manufactured in 2 halves and with the help of resin the halves were glued together.Final trimming was done to give the blade perfect airfoil shape. Detailed steps and consumables required is given below.

Fig 5.3 Manufacturing setup

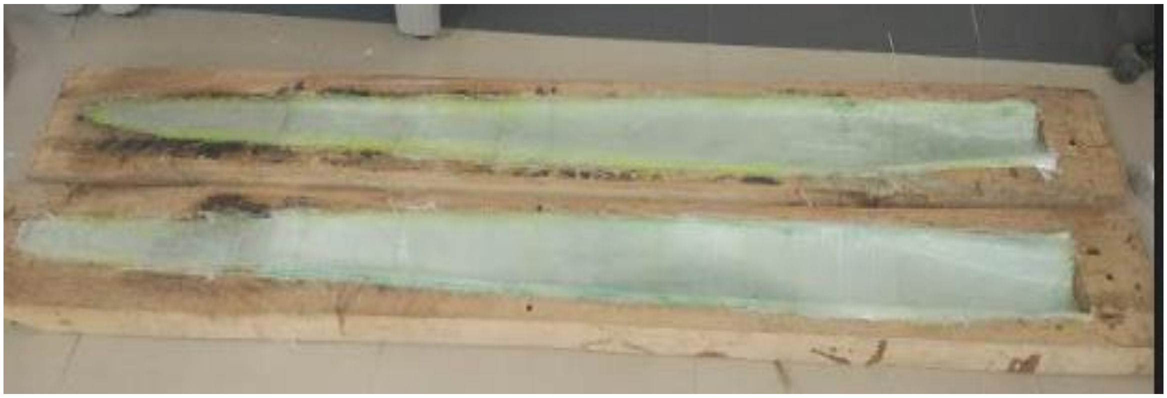


Fig 5.4 Cured 2 halves

Fig 5.5 Final 2m Blade

5.3.1 Volume Fraction

The ratio of volume of resin in total volume of composite is termed as volume fraction.Generally 60 percent volume fraction is recommended for blade manufacturing[12].Calculation for total weight of resin used for infusion is calculated accordingly.

5.3.2 Apparatus and Consumables

Two main consumables are fibres and resin and along with them mesh, packing bag, sealant, pipes are required to complete the manufacturing process, each have their function as described:

Mesh: Helps to guide the resin flow.

Sealant: Helps in creating vacuum by sticking 2 plastic layer together.

Pipes: Used as a medium for resin to flow from resin bucket to mold.

Plastic bag: Create a blanket around fiber and acts as boundary between surrounding and fiber.

Chapter 6: **Results & Discussion**

6.1 Aerodynamic design and Qblade results

Inputs:

a) Air density = 1.225kg/m^3
b) Air viscosity @ 15 ^oC = 1.81 X 10^{-5} kg/m.s
c) Airfoils:

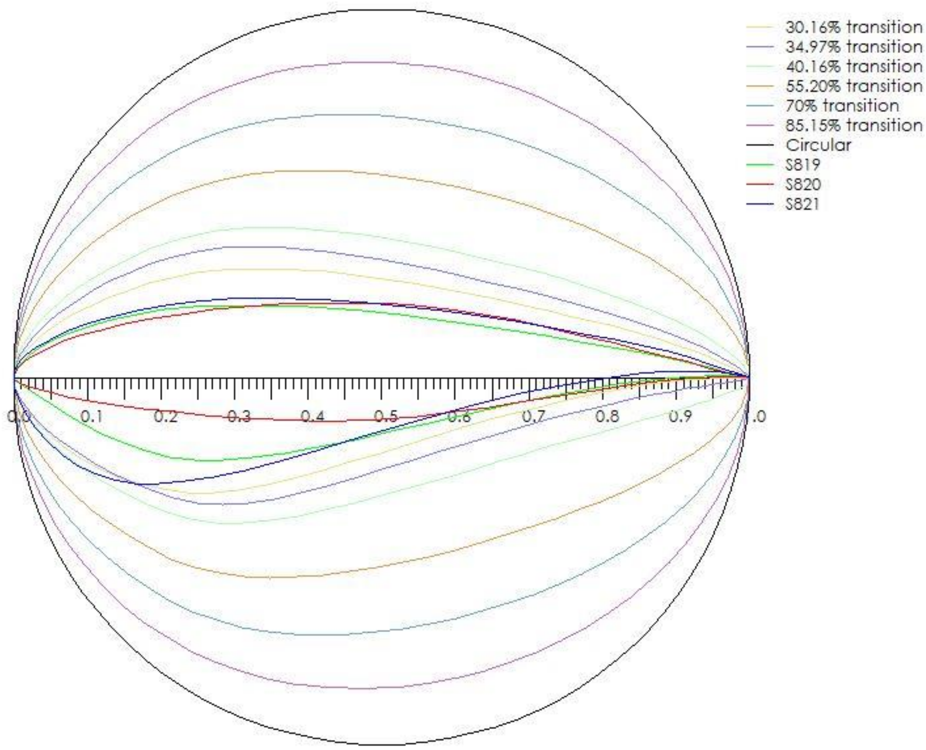


Fig 6.1 Airfoils- blade profile

Twist angle is optimized to attain stall at 8m/s of wind speed.

The blade root portion can be manipulated mainly because of the 2 reasons :

- Most of the power is extracted from the mid and tip portion with insignificant contribution comes from root region.
- The blade shape should not only be aerodynamically efficient but should also be strong structurally and feasible from manufacturing point of view.

The root end is supposed to be circular which is important for structural stiffness. Hence some elliptical profiles are placed as transition between circular root and S821 airfoil.

Results:

Below is the design and results.

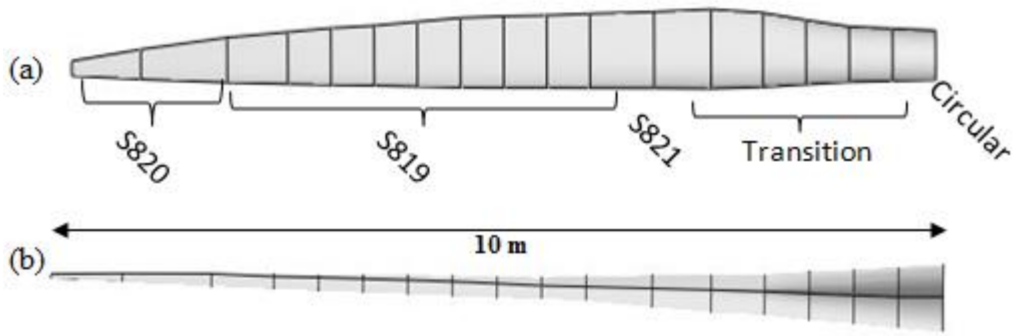


Fig 6.2 (a) Blade optimized plan form (b) blade side view

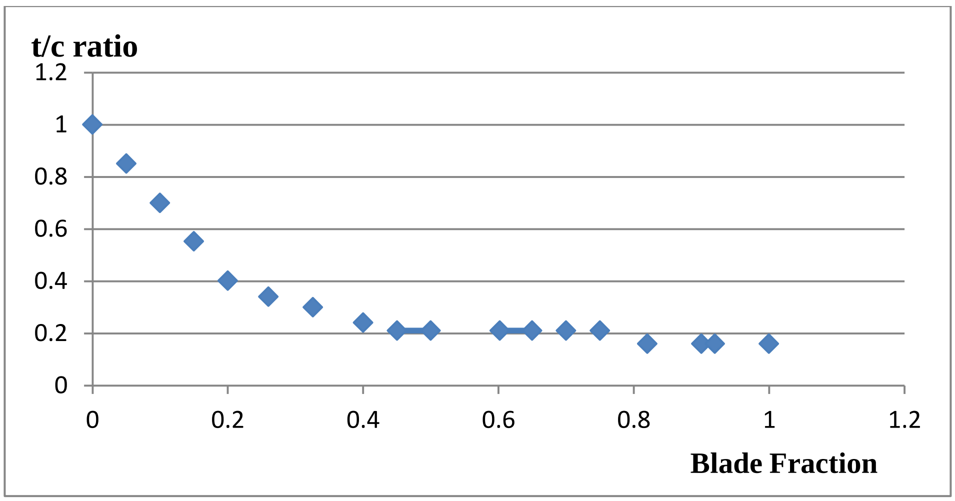


Fig 6.3 Thickness/Chord vs Blade fraction

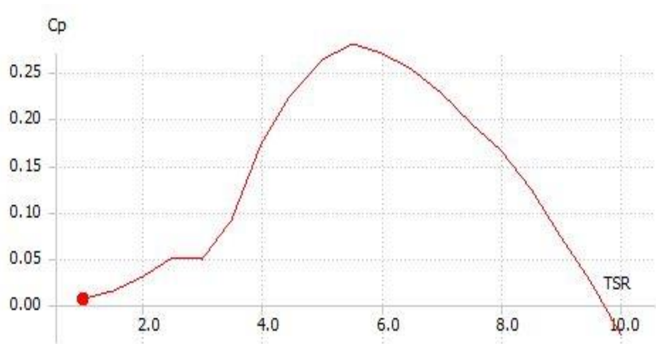


Fig 6.4 C_P Vs TSR

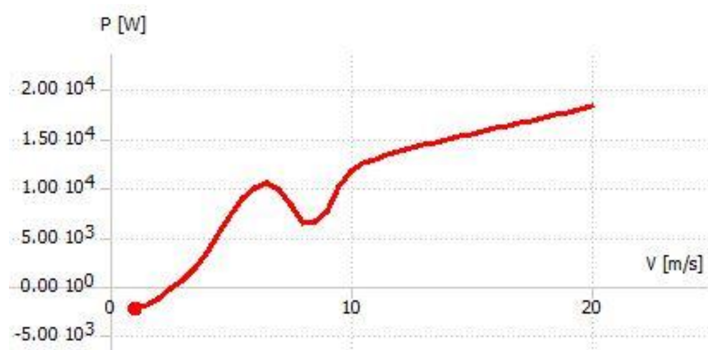


Fig 6.5 P Vs V(wind speed)

6.2 Structural Design

Inputs:

a) Blade profile:

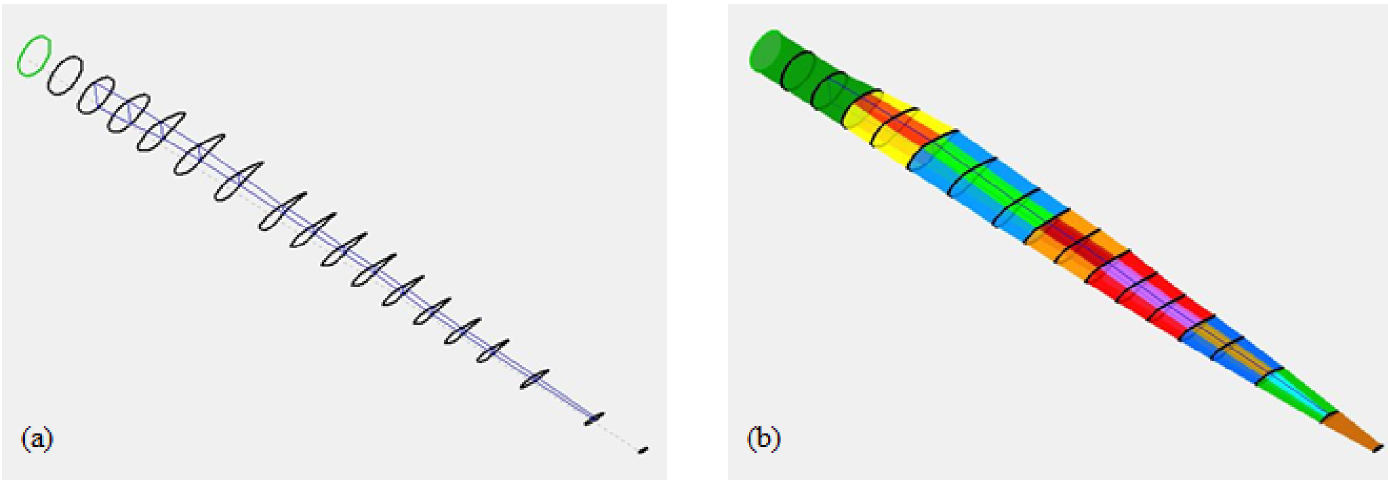


Fig 6.6 (a) Internal structure modeling (b) Material placement in NuMAD

b) Material and material properties
- Root build up : Triax laminate
- Spar : Unidirectional plies
- Shear webs : Biax plies

Laminate Definition			Longitudinal Direction								Shear
			Elastic Constants				Tension		Compression		
VARTM Fabric/resin	lay-up	V_F %	E_L GPa	E_T GPa	υ_{LT}	G_{LT} GPa	UTS_L MPa	ε_{max} %	UCS_L MPa	ε_{min} %	τ_{TU} MPa
E-LT-5500/EP-3	$[0]_2$	54	41.8	14.0	0.28	2.63	972	2.44	-702	-1.53	30
Saertex/EP-3	$[\pm 45]_4$	44	13.6	13.3	0.51	11.8	144	2.16	-213	-1.80	----
SNL Triax	$[\pm 45]_2[0]_2$	---	27.7	13.65	0.39	7.2	----	----	----	----	----

E_L and E_T - Longitudinal & transverse modulii, υ_{LT} - Poisson's ratio, G_{LT} & τ_{TU} - Shear modulus and ultimate shear stress. UTS_L - Ultimate longitudinal tensile strength, ε_{MAX} - Ultimate tensile strain, UCS_L - Ultimate longitudinal compressive strength. ε_{MIN} - Ultimate compressive strain.

Table 6.1 Material properties-DOE/MSU Database [9]

Results:

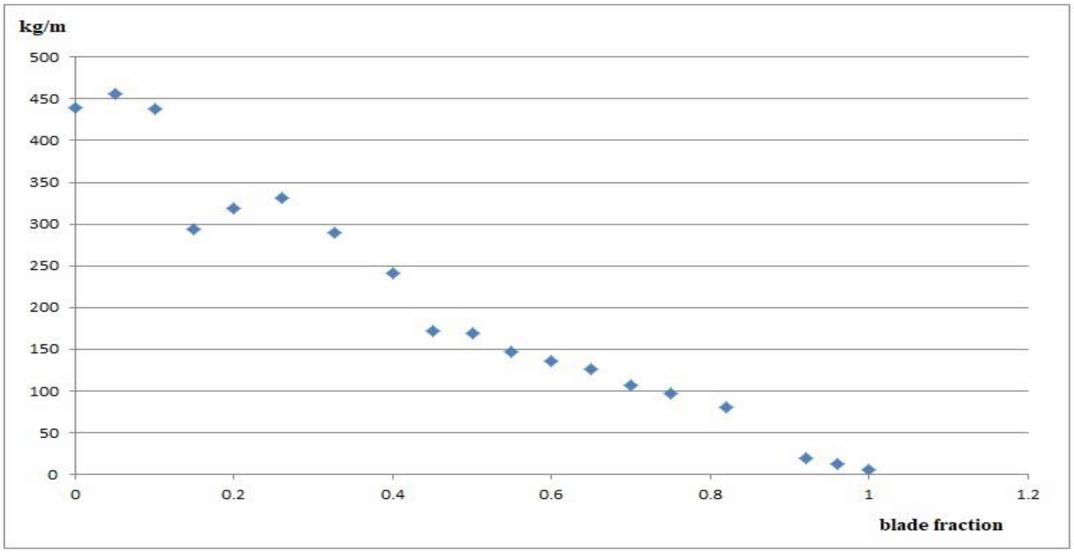
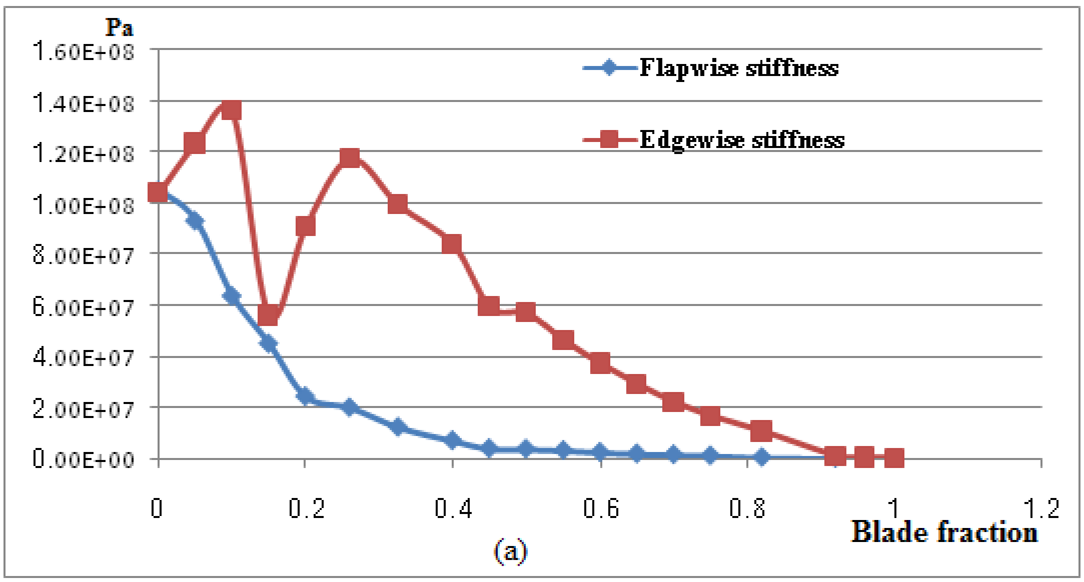


Fig 6.7 Blade mass distribution



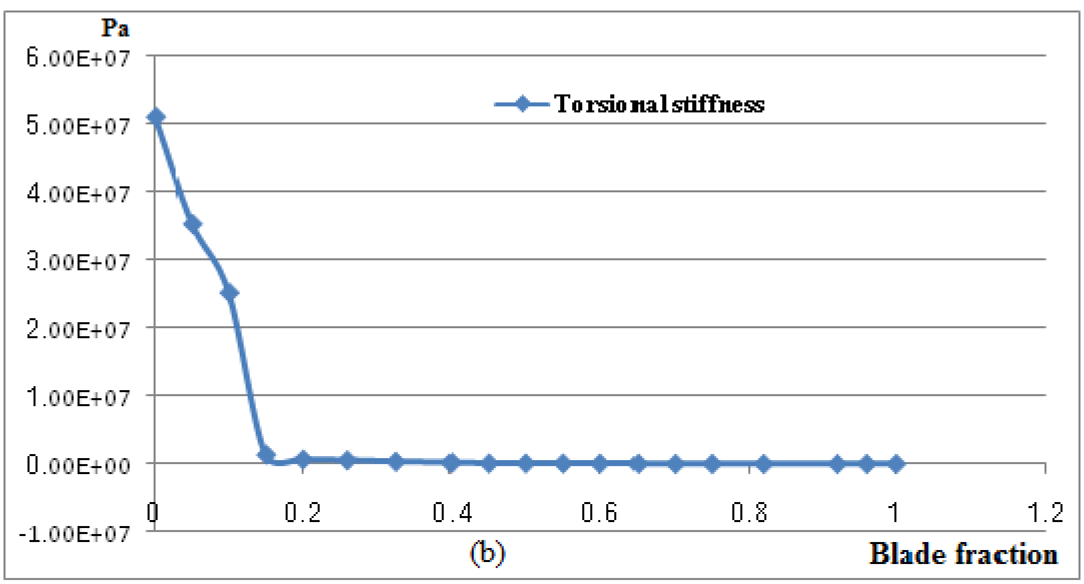
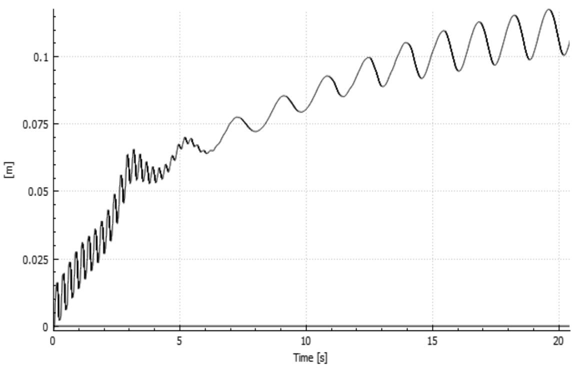


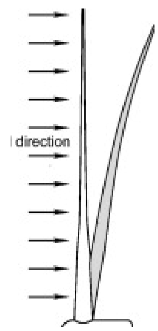
Fig 6.8 (a) & (b) :Blade stiffness distribution

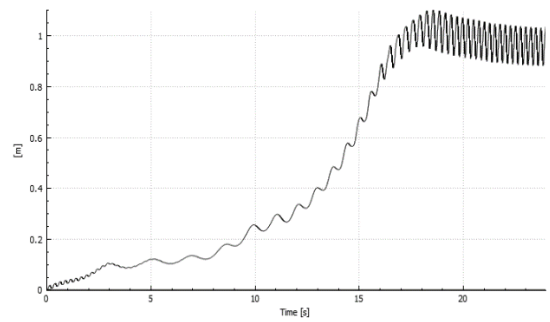
6.3 Aero elastic Simulation

Normal operating condition at velocity 5m/s

Gust condition at mean wind velocity 25m/s



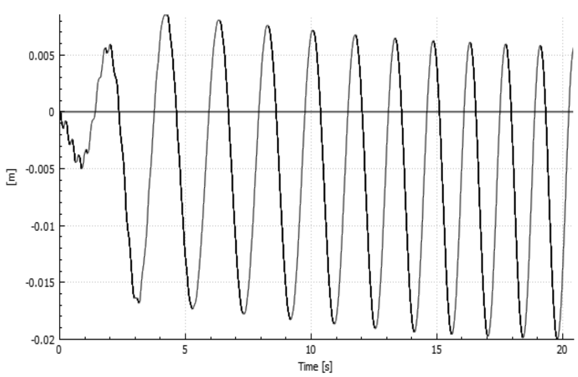


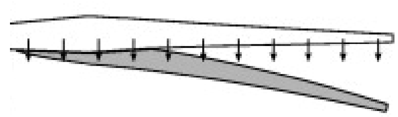


Flap wise deflection

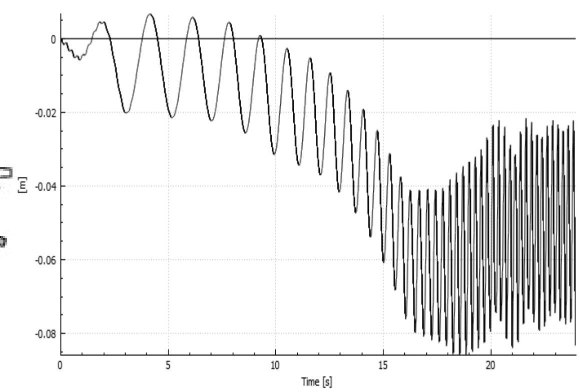
(a) Maximum tip deflection: 0.1m

(b) Maximum tip deflection: 1m





Edge wise deflection



(c) Maximum tip deflection: 0.050m

(d) Maximum tip deflection: 0.080m

Figure 6.9 (a),(b),(c),(d) Ashes deflection graphs

6.4 FEM

6.4.1 Strain Analysis

Maximum strain:5499 microns

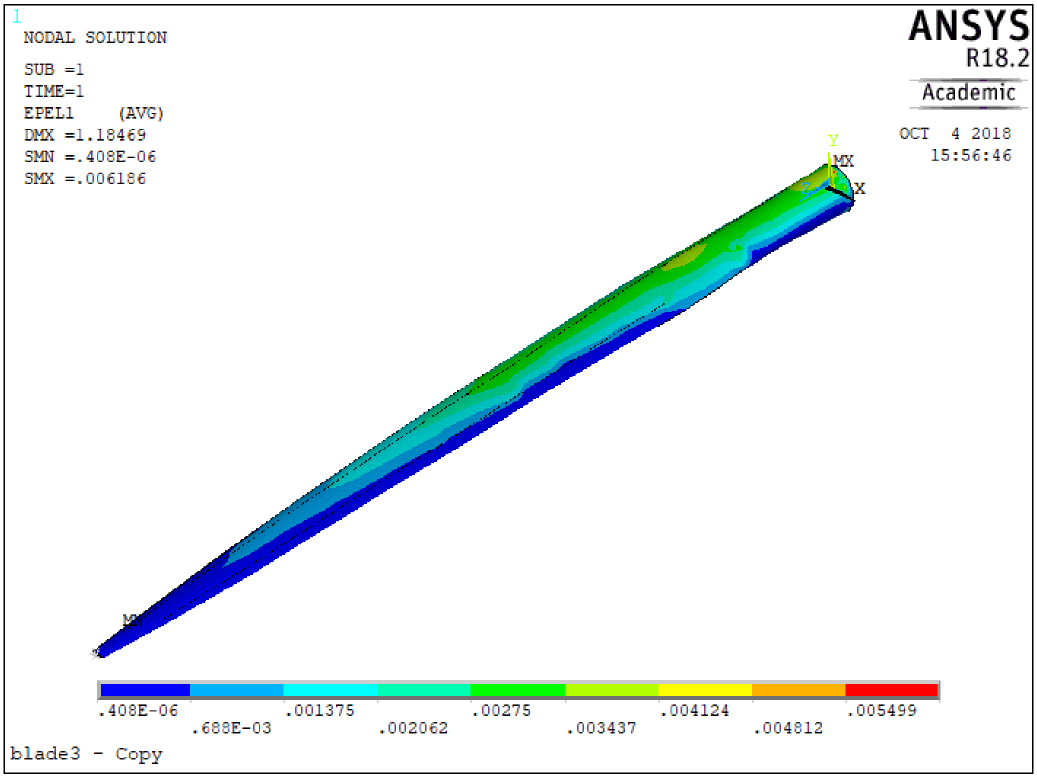


Figure 6.10 Starincountor

6.4.2 Tip Deflection Analysis

Flapwise Tip deflection:1.17m

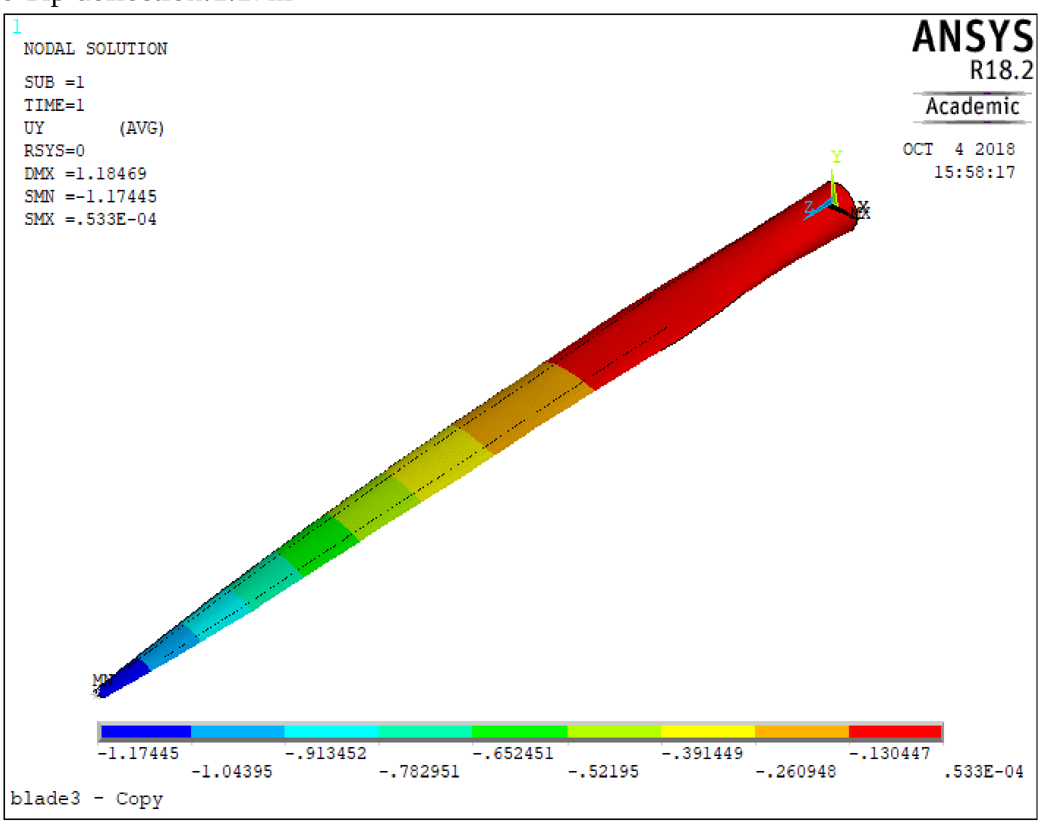
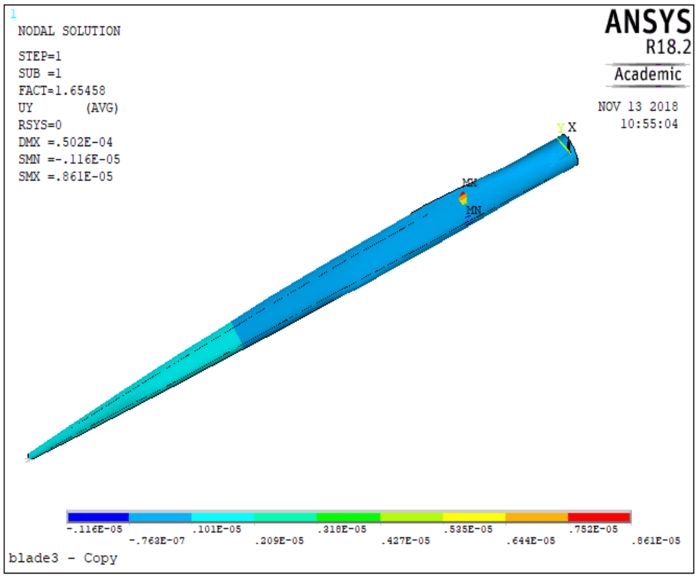
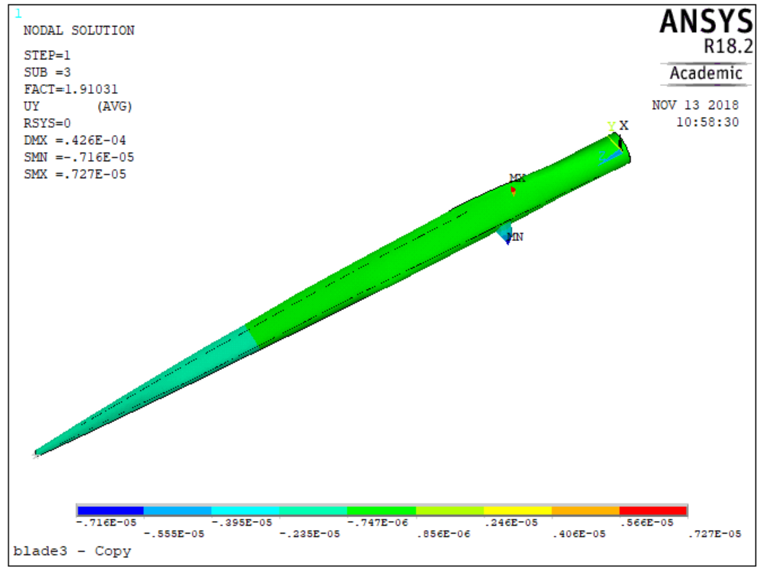


Figure 6.11

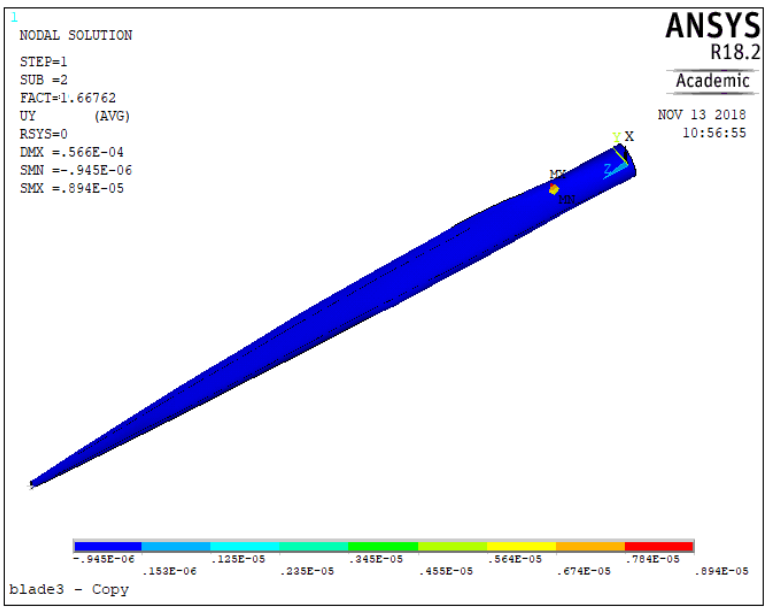
6.4.3 Buckling Analysis



(a) Mode 1



(b) Mode2



(c) Mode 3

Fig 6.12 (a), (b), (c)

Chapter 7: **Conclusion & Future work**

7.1 Conclusion

In this work, an attempt has been made to design a 10m long Horizontal Axis Wind Turbine blade that can generate 10kW of power in low wind condition of 5m/s. A detailed design process is as shown in Fig 7.1.

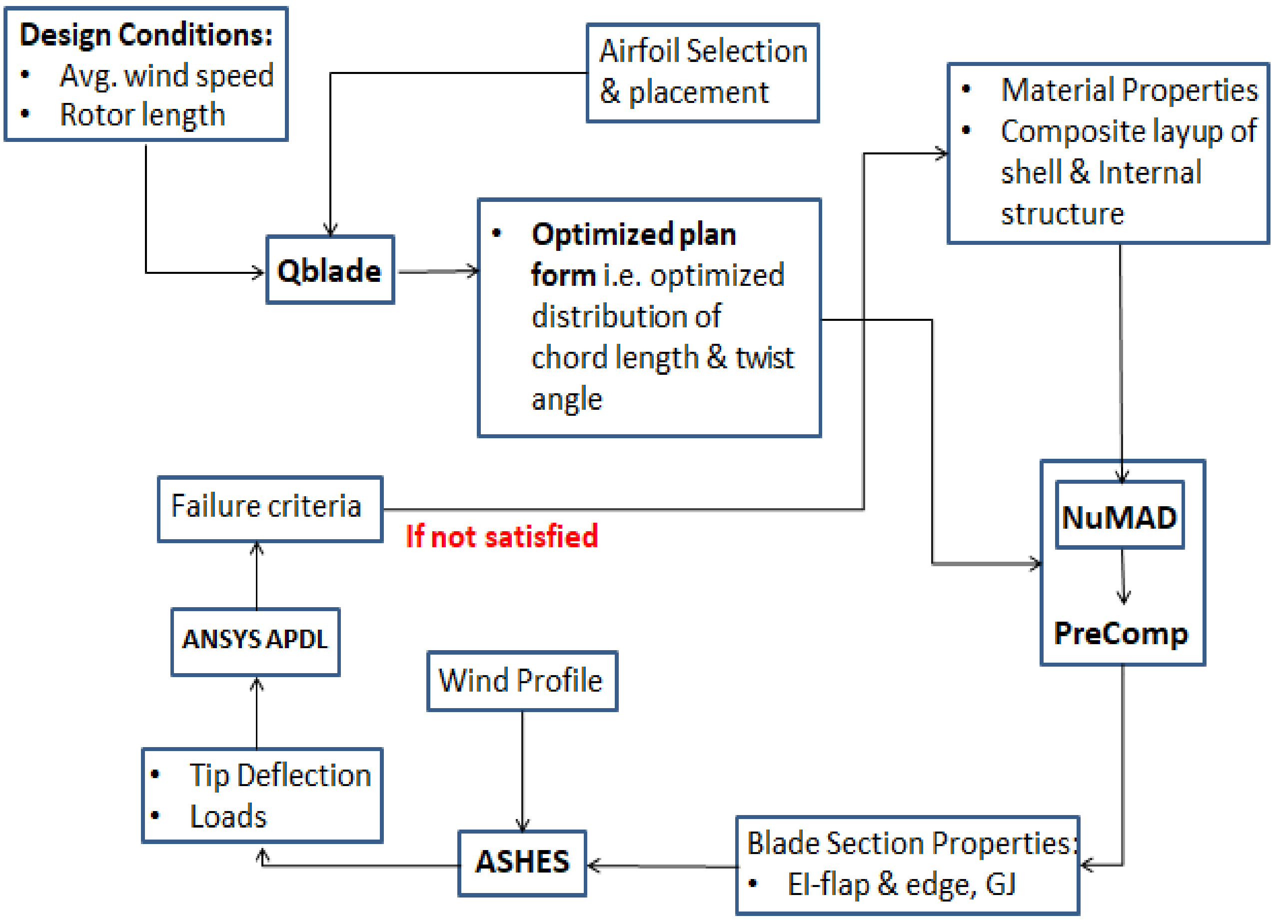


Fig 7.1 Design process flow chart

Further a 2m long *Glass fiber reinforced Polymer composite* blade is fabricated. The aim was to manufacture it in some automizedway. For this purpose VARTM technique is employed.

7.2 Future Work

This being a first attempt, the current design process needs certain more refinement and improvements. The following points direct to the future scope of this work:

- Airfoils placement along the blade length can be optimized to obtain stall phenomena at high wind speed.
- Flutter analysis should be done to investigate vibrational response of blade.
- Detailed design of root portion with mounting bolts is an important future task.

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