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Design and weight minimization of a small windturbine blade for operation at low wind areas

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Abstract

The power produced by wind turbine is determined by two main factors, wind velocity and rotor swept area. Due touncertainty in nature, wind velocity cannot be predicted. For low wind areas to extract more power, blades of turbine shouldstart rotating at low wind speed which is known as cut in wind speed. In order to reduce cut in speed and increase poweroutput it is necessary to design the blade as light as possible without failing under given loading conditions. This studyaims to design wind turbine blade of 1.5 m length which is suitable especially for low wind areas. Research work is mainlyfocuses on minimization of blade weight so as to reduce cut in wind speed keeping the strength of blade to develop morepower. This work includes determining and overcoming issues which are related to design and optimization, methodologyfor design of wind turbine blade, so as to meet required load and comparison of optimized blade with conventional blade.

Keywords:*Wind turbine, Blade length, Weight of blade, Cut in wind speed, Minimization.*

1. Introduction

Small Wind Turbine(SWT) can beused for residential applications, agricultural purpose, ruralelectrification and commercial applications such as in telecomtowers.The technology of large wind turbines has been developedwidely, however SWT needs more attention as following issues are concerned with design of SWT:

High cut in wind speed- It is a speed of wind at whichturbine starts generating useful power. Generally this speedranged from 3 m/s to 5 m/s. For low wind areas, cut in speedneed to be reduce for getting better performance from turbinemachine.

Material selection- Wind turbine blade should meet given structural requirementsuch as- High material strength to withstand extremeloads, high fatigue strength to resist varying load, goodmaterial stiffness to prevent collision and maintain aerodynamicshape as well as it should be light weighted in order toreduce cost of generated energy.
Depending on applicationand properties one must select the material which can resistthe given load at the same time it must be cost effective.

Structural constraint- In order to get the power at verylow cut in wind speed, small wind turbines are designed withincreased blade length which results in striking of blades totower of the turbine.

Noise - When rotor diameter is increase, tip speed ratio becomes high which causes noise and vibrations associated with the same. Allowable noise level in daytime is 55dBa and in night time is 42dBa

In order to overcome from above issues, we need to improve performance of SWT.To do the same, factors such as power coefficient, swept area, number of blades as well asmaterial used for turbine blade should be taken into consideration.

The blades of wind turbine rotor are exposed to cyclicloads from wind and gravity. Hence material selection forwind turbine blade plays an important role in performanceanalysis. Most widely used materials in wind turbine technologyare metals, compositessuch as Glass fibre, carbon fibre, aramid fibre etc., woodand bamboo.Wood is being used widelyfor manufacturing turbine blades from a long time because of its good strength. According to (Peterson and Clausen, 2004), wood may be suitable for SWT blades having capacityup to 5 kW and with 2.5 m length. However, the manufacturingand selection of wood is the main concern. Othermaterial option is bamboo which is having good mechanical performance such as greater fracture toughness, greaterspecific strength and modulus. Also the processing cost isnot high and bamboo grows quickly (Holmes *et al*, 2009). However, singlebamboo stalks are not big enough for a blade; it has to be combined with composites. Glass fibre is a low-cost materialhaving high tensile strength. It is also easily knitted and wovento meet load requirements. Carbon fibre is also becomingpopular because of its higher modulus, higher tensilestrength as well as lower density than fibreglass and lessersensitivity to fatigue (Veers *et al*, 2003).Only concern is,Cost of carbon fibre is high for industry sectors- 530 Rs/Kg as compared to glass fibre whose cost is approx.110Rs/Kg.Recently, the use of hybrid fibreswhich combines glass and carbon together is gaining attentionto achieve goodmechanical performance with moderate cost (Bronsted, 2005).

Another method to increase the performance of SWT isto increase the wind speed passing through the rotor plane.In order to do so the wind turbine is modified with a coneshaped wind diffuser through which wind speed increase dueto pressure drop downstream.(S. Zanforlin et al, 2015) performed experiment on wind turbine having 2.436m diameter blade with diffuser. This results in increasing the power output as power in the wind is directly proportionalto the cube of the wind speed. This technique tends to increase power by 40%. The limitation of this diffuserstructured wind turbine is there is no relation developedwhich can able to describe the link between the geometry ofdiffuser and velocity profile. Moreover, the structure resultsin high cost. Hence the technique is not yet developed in theworld.

Increase in power can also be done by increasing numberof blades which increases rotor swept area.(Maalawai*et al*, 2003) conducted an experiment based on this conceptin which optimum rotor is selected to produce more output ofpower which results into good start up torque and reduced cutin wind speed but additional cost is involved due to increasednumber of blades. Also if number of blades increases, it createsblockage to wind which results in reduction in power coefficient and hence useful power. To get good starting performance, most starting torque should generate near the huband most power extracting torque should come from tip region.To analyse this,(Wright and Wood, 2004) has donetesting of a three bladed 600W wind turbine having 2 m diameterwhich gives 4.6 m/sec cut in wind speed. They statedthat as the size of wind turbine gets smaller, friction associatedwith generator increases. To overcome this issue, windturbine should have multiple blades to compensate for lowstarting torque.

Keeping all these concerns in view, one of the promisingalternatives to increase power is to raise the blade length.Increase in the length of the blade results in maximizingweight of the blade and cut in wind speed. For low wind areas cut in speed need to be minimum so as to get maximumuseful power. Hence design of wind turbine bladeshould have minimum weight though its length increases. (Stanciuet al, 2016) did finite element analysis (FEM) onrotor blade having NACA 2412 aerofoil and 1.5m length usingOptistruct solver of HyperworksHypermesh. They haveused input model which consists of nine layers of glass fibremat and epoxy matrix. The optimization process givesreduction in blade weight by 16 % without failure of turbine blade.

2. Methodology

Methodology for design of wind turbine blade for lowwind areas consist of selection of material for turbine blade, modelling of geometry in Catia V5R20 and minimizationof blade weight in Hypermesh-Optistructsolver with givenboundary conditions is shown in fig 1.

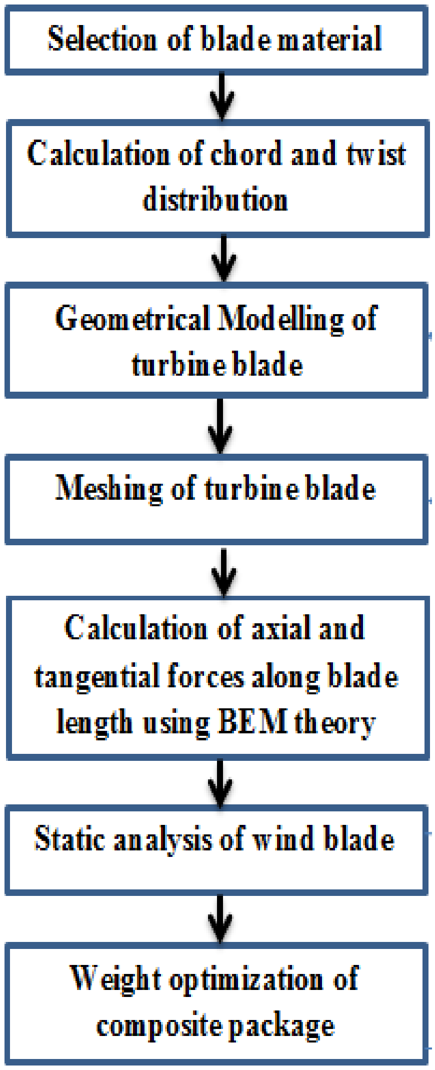

Fig.1 Procedure to carry out research work

2.1. Selection of blade material

Now days, for construction of rotor blade, compositesare widely used as a manufacturingmaterial. Compositesare materials which are combination of two or more dissimilarmaterials, most commonly fibres held in place by matrix.Current wind turbine technology prefers Glass fibre as wellas carbon fibre as blade material. As carbon fibres are expensive, glass fibres are alternativeto this because of its low cost and good tensilestrength. In present study,fibreglass composite is used foranalysis. Fibreglass fabric- RT900 is selected as reinforcementand epoxy- Mat T600 as matrix material.

Material properties of fibreglass model are shown in Table-1 which areused as input of static analysis.

- Material Used- Fibreglass composite,NPS-100
- Density of material- 2400 kg/m^3

(RT-900- Fibreglass fabric, Mat T600- Mat fibreglass, epoxyresin)

Table 1 Properties of composite material (Stanciu*et al*, 2016)

Layers	Elasticity Modulus		Poisson Coefficient
	E_1(MPa)	E_2(MPa)	
RT-900	48000	35000	0.30
MAT T600	10000	10000	0.25

2.2. Calculation of chord and twist distribution

For modelling of wind turbine blade, we need to findchord and twist distribution for each blade element. Chord length is the distance between leading edge and trailing edgeof an aerofoil. It varies along length of the blade.

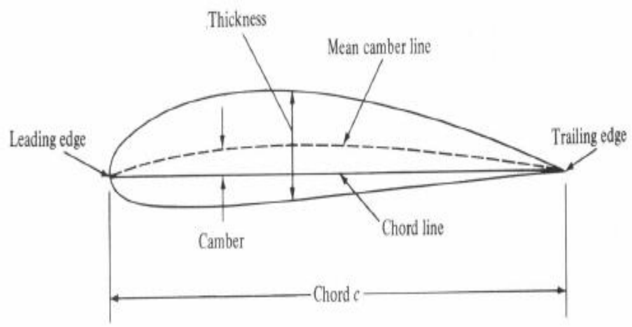

Fig.2 Nomenclature of an aerofoil

Value of chord and twist are obtained with respect tonon-dimensional radius(r/R)

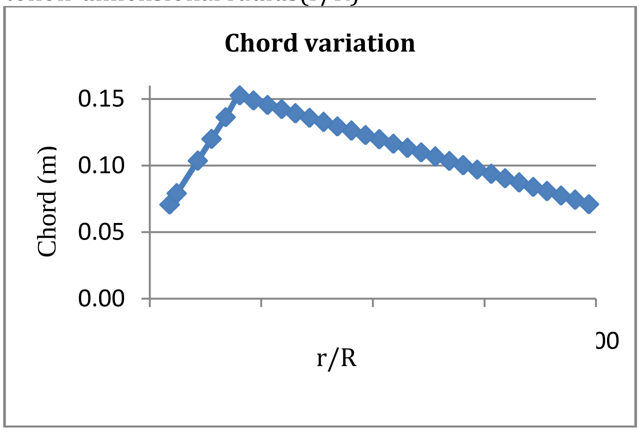

Fig.3 Chord variation as function of non- dimensional radius(r/R)(Roy *et al*, 2009)

Now days, wind turbine blades are twisted along thelength of the blade. For static analysis, twist has been considered as 14˚ from root to tip.

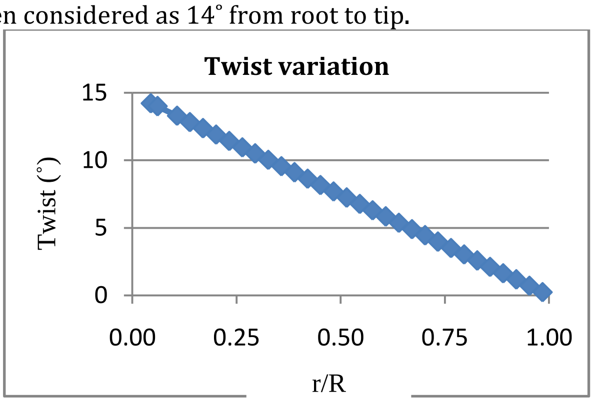

Fig.4 Chord variation as function of non- dimensional radius(r/R)

2.3. Geometrical modelling of wind turbineblade

For design of 1.5 m wind turbine blade geometry accordingto given chord and twist distribution, CATIA V5R20software is used in which blade surface is generated by joiningcoordinates of each aerofoil.Fig 5 shows surface modellingof 1.5 m turbine blade.

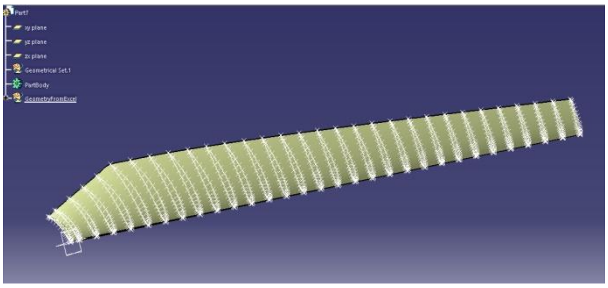

Fig.5 Geometrical modeling of 1.5m wind turbine blade using Catia V5R20

2.4. Meshing of wind turbine blade

After modelling of blade geometry, next step is meshingof the given structure. Meshing has been done in HypermeshV12.For analysis, 2-D elements have been used as two of thedimensions i.e. length and width are very large in comparisonto the third dimension which is thickness of the blade.

Quality check parameters for 2-D meshing are warpage andaspect ratio.

1. Warpage- This is the amount by which an element deviates from being planar. Warpage of up to ten degrees is generally acceptable.
   Ideal value= 0˚ (acceptable ≤10˚)
   Maximum warpage from given 2-D meshing is 9.15

2. Aspect ratio (AR) - It is the ratio of the longest edge of an element to either its shortest edge or the shortest distance from a corner node to the opposing edge. AR should be up to 5:1
   Ideal value = 1 (acceptable ≤ 5)
   Maximum aspect ratio obtained from the meshing is 2.27

Hence from meshing quality checking, it can be observed that quality parameters are within the given limit.

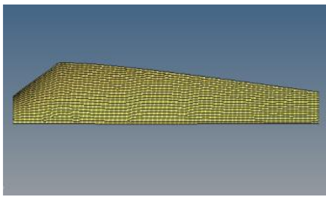
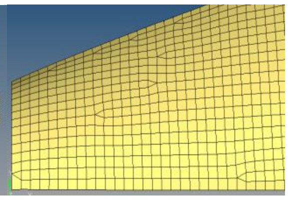

Fig.6 Meshing of blade **Fig.7** Detailed meshing

Meshing gives rise to 9289 number of elements which include9233 quad elements and 56 tria elements.

2.5. Calculation of forces along blade length

Forces which effects on performance of wind turbineareaxial force and tangential force.To calculate theseforces,Blade Element Momentum (BEM) theory has been used inwhich blade is divided into 30 numbers of sections, then bycalculating axial (a) and

rotational (a’) induction factors foreach element, we can calculate given forces.
These factors are determined by taking forces due tochange in axial and angular momentum of air. The angle between relative wind velocity and plane of rotation is knownas relative flow angle (ψ) which is given as

$$\psi = \tan^{-1}\{\frac{(1-a)}{(1+a')\lambda}\} \qquad 1$$

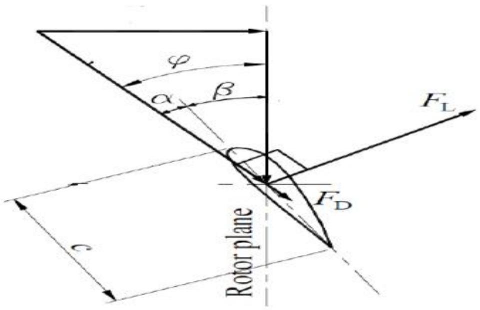

Fig.8 Angles associated with blade element

Angle of attack (α) is the angle between chord line ofblade and relative wind velocity.

$$\alpha = \psi - \beta 2$$

whereβ is the angle between chord line and plane of rotation of the blade which is known as pitch angle.
Coefficients of normal force (C_n) and tangential force (C_t) are then calculated which are function of relative flow angle (ψ), lift coefficient (C_l) and drag coefficient (C_d).

$$C_n = C_l \cos\psi + C_d \sin\psi \qquad 3$$
$$C_t = C_l \sin\psi - C_d \cos\psi 4$$

Axial induction factor (a) is given by,

$$a = \frac{1}{2}\{2+K(1-2a_c)\sqrt{[K(1-2a_c)+2]^2 + 4(Ka_c^2-1)}\} \qquad 5$$

(When a>a_c)
Otherwise,

$$a = [K-1]^{-1}$$

$a_c$is the Glauert’s correction which is taken as 0.2
Rotational induction factor (a’) is given by,

$$a' = [\frac{8F\pi r \sin\psi \cos\psi}{BcC_t} - 1]^{-1} \qquad 6$$

Where F is Prandtl’s tip loss correction factor,

$$F = \frac{2}{\pi}\cos^{-1}[\exp\{-\frac{B}{2}\frac{1}{\sin\psi}(\frac{R}{r}-1)\}] \qquad 7$$

$$K = \frac{8\pi r F \sin^2\psi}{BcC_n} \qquad 8$$

For getting axial and rotational induction factors eqs-1 to 8 are simultaneously solved. On getting these factors, axial and tangential forces are calculated by following

$$\text{Axial Force } (F_a) = \frac{1}{2} * \rho * v^2 * c * c_n \qquad 9$$

$$\text{Tangential Force } (F_t) = \frac{1}{2} * \rho * v^2 * c * c_t \qquad 10$$

The variation of axial as well as tangential forces forgiven blade for wind speed 15m/s are shown in fig below

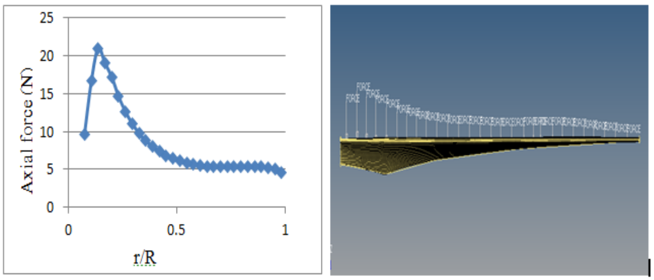

Fig.9 Distribution of axial force along wind turbine blade

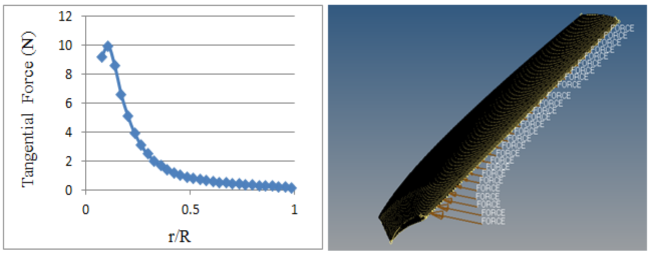

Fig.10 Distribution of tangential force along wind turbine blade

2.6. Static analysis of wind blade

Static analysis of blade with various number of compositelayer package has been taken into consideration for baselinestatic analysis. Arrangement of these layers is given inFig.11 All the fibres were arranged in unidirectional mannerwhich means angle of orientation between each layer is 0.

After performing finite element analysis, values of maximumdisplacement, Von Mises stress and mass were obtained foreach arrangement.

No Of Layers	5	7	9	11	13	15
Arrangement	RT 900	RT 900	RT 900	RT 900	RT 900	RT 900
	MAT T600	RT 900	MAT T600	RT 900	MAT T600	RT 900
	RT 900	MAT T600	RT 900	MAT T600	RT 900	MAT T600
	MAT T600	RT 900	MAT T600	RT 900	MAT T600	RT 900
	RT 900	MAT T600	RT 900	MAT T600	RT 900	MAT T600
		RT 900	MAT T600	RT 900	MAT T600	RT 900
		RT 900	RT 900	MAT T600	RT 900	MAT T600
			MAT T600	RT 900	MAT T600	RT 900
			RT 900	MAT T600	RT 900	MAT T600
				RT 900	MAT T600	RT 900
				RT 900	RT 900	MAT T600
					MAT T600	RT 900
					RT 900	MAT T600
						RT 900
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Mass(kg)	0.72	0.93	1.34	1.54	1.96	2.16

Fig.11 Arrangement of layers(Stanciu*et al*, 2016)

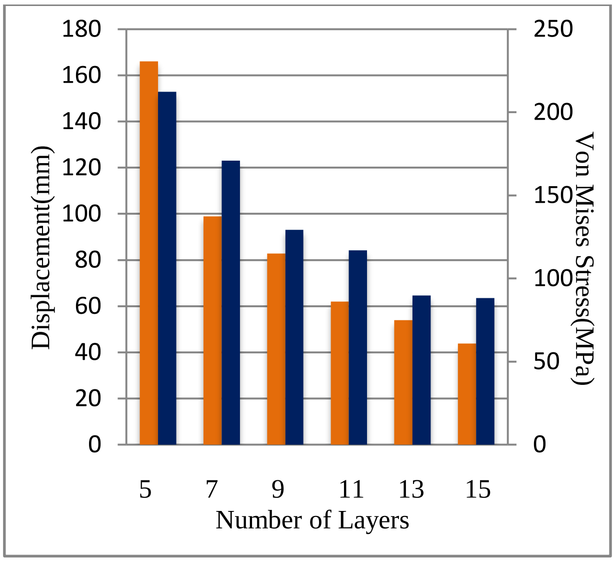


Fig.12 Displacement and stress variation for each compositepackage

For baseline analysis, it has been observed from Fig.12that, as we increase number of layers from 5 to 15 value of displacement as well as stress tends to decrease but mass ofthe blade increase approx. 3 times which causes increase in cut in wind speed.

Hence number of layers should keptminimum to minimize mass of blade at the same time thedesign must be safe.Further analysis examined the bladehaving 9 layers whose arrangement is shown in Fig. 11.

3. Numerical Results

Baseline analysis of 9 layers with axial and tangentialload, unidirectional orientation leads to following results ofdisplacement and Von Mises stress due to combined effect ofboth axial as well as tangential forces.

Fig.12 represents displacement of rotor blade undergiven boundary conditions of forces at 15m/s wind speed.Maximum displacement of 82.83mm occurs at the tip of theblade and it decreases along theroot. As portion near root isfixed to the hub,displacement is less near root.

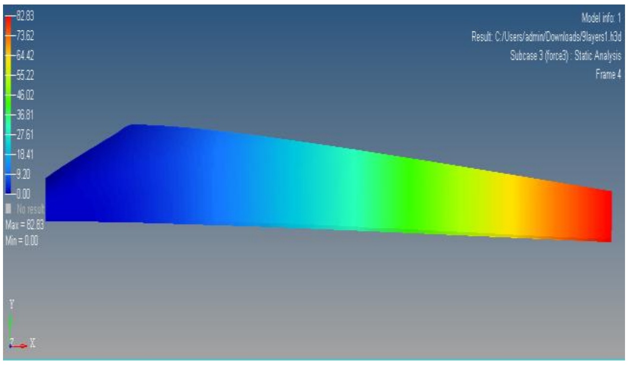


Fig.13 Displacement of blade before optimization

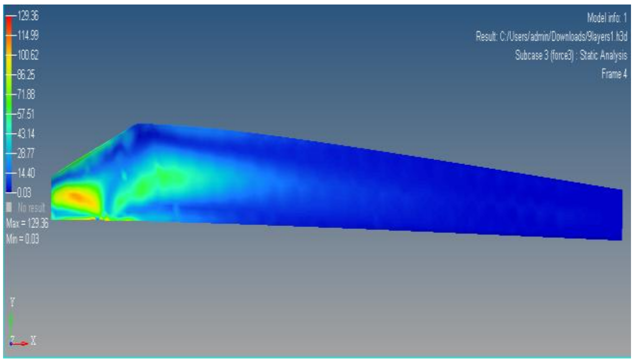


Fig.14 Von Mises Stress before optimization

Another parameter check for static analysis is Von Misesstress which are used to check the whether material will withstand given loading conditions. Maximum Von mises stressobserved from Fig.14 is 129.36 MPa which occurs near root of blademainly due to axial load.

After performing baseline analysis on turbine blade,next stage is performing optimization with the objective minimization of mass. Hypermesh-OptiStruct program is usedfor optimization which considers response function as mass.For avoiding failure, stress constraint value has been givenas 420MPa which is maximum value of stress that glass fibrecan withstand. Optimization process keeps the number oflayers and orientation constant. Varying parameter is thicknessof layer.

Optimization leads to results of displacement and stressas shown in Fig. 15 & 16:

It has been seen from Fig.15 that optimized blade maximumdeflection is 110.88mm which is more than the conventional blade. Hence for the same loading conditions due to minimization of blade weight, displacement is as we wereoptimizing for weight without constraint of displacement.

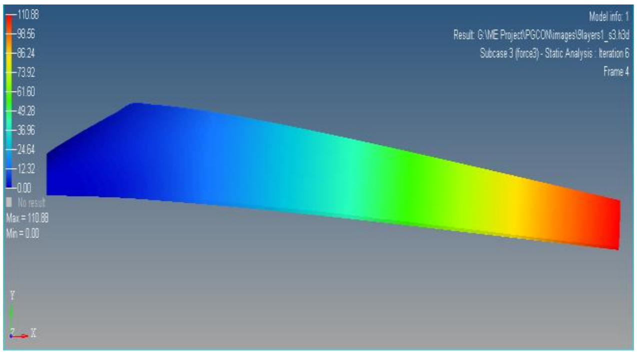


Fig.15 Optimized blade maximum displacement

Deflection of wind turbine blade under extreme loadscenario should be less than the clearance provided between blade tip and tower structure.

Fig 16 shows the maximum Von Mises stress value afteroptimization which is nearly 144MPa. This value is less thanultimate tensile stress of glass fibre i.e. 420MPa, the designof this blade is safe.

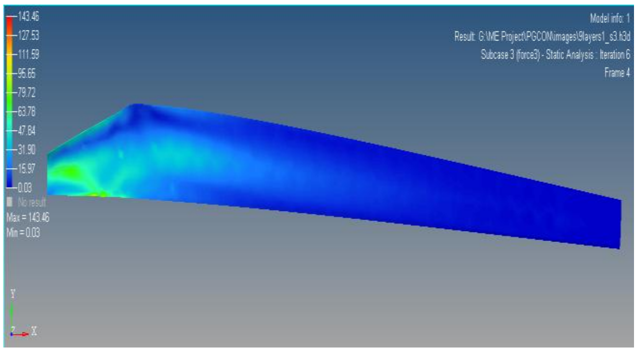


Fig.16 Optimized blade maximum stress

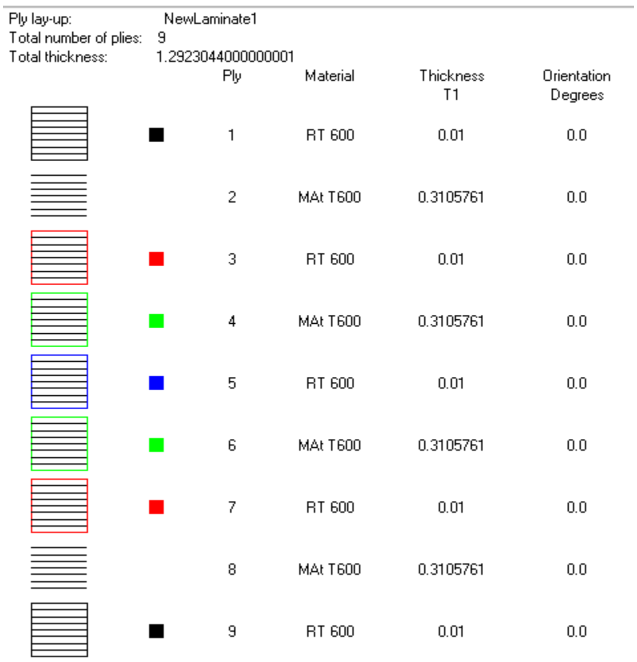
After optimization process, the new structure gives followingthickness of layers with unidirectional orientation asonly varying parameter is thickness.

New package gives 1.051 kg weight for single blade of wind turbine machine with total laminate thickness as 1.2923mm.

Table 2 gives the comparison between conventional blade i.e. the blade before optimization and new optimized blade.

Table 2 Results of optimization process

Parameter	Conventional Blade	Optimized Blade
Displacement(mm)	82.83	110.88
Von Mises Stress(MPa)	129.36	143.46
Weight(kg)	1.34	1.051



Ply lay-up: NewLaminate1
Total number of plies: 9
Total thickness: 1.2923044000000001

Ply	Material	Thickness T1	Orientation Degrees
1	RT 600	0.01	0.0
2	MAt T600	0.3105761	0.0
3	RT 600	0.01	0.0
4	MAt T600	0.3105761	0.0
5	RT 600	0.01	0.0
6	MAt T600	0.3105761	0.0
7	RT 600	0.01	0.0
8	MAt T600	0.3105761	0.0
9	RT 600	0.01	0.0

Fig.17 Optimized layer thickness

It has been seen from comparison that mass of turbineblade decreases which results in increase in displacement andstresses values.

4. Validation

Results obtained from numerical simulation on turbine blade are then validated with the author Stanciu Mariana Domnica et al who presented study on structural optimization of composite blade. Validation results for 1.5m length blade are given in Table 3:

Table 3 Validation of results with % error

Parameter		Paper result	Simulation result	% error
Von mises stress (Mpa)	Before optimization	119	129.36	8.7
	After optimization	125.15	143.46	14.63
Weight (kg)	Before optimization	1.25	1.34	7.2
	After optimization	1.04	1.051	1.05

14° twist has been given to the blade whereas the blade presented in the paper written by Stanciu Mariana Domnica et al is without twist. Hence there occurs error during validation. Though the experimental validation is always better way, it can be said that the methodology for minimization of weight is validated with the referred paper. Further, we can carry out experimentation work for validation of results

5. Conclusion

The main objective of research work was tominimizemass of turbine blade without failure. Work has been carriedout on 1.5m length blade with glass fibre as composite materialhaving 9 number of layers arranged in unidirectionalorientation. Numerical simulation on given blade has beendone in Hypermesh-OptiStruct solver which gives 21.5% decreasein weight due to thickness reduction from 1.651mm to 1.29mm with maximum displacement as110.88mm.

Optimization process fulfilled objective of reducing thewind turbine blade mass in terms of keeping the design safe. In future, the study can be carried out by using different materialfor blade such as carbon fibre, aramid fibre etc. withgiven boundary conditions remaining same.

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