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Wind Turbine Blades Design and Analysis Considering Dynamic Condition

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ABSTRACT

Wind turbine configuration is the method involved with planning the details and type of a wind turbine to get energy from the wind. A wind turbine establishment comprises of the accompanying frameworks expected to catch the wind's energy. They are turbine, which changes over mechanical pivot into electrical power, different frameworks to begin, pause and control the turbine. Most of industrial turbines are of level pivot wind turbines. On the turning cutting edges the diffusive power increments as a square of rotational speed. This makes this design touchy to over speed. The force of the wind increments straight forwardly with the block of the breeze speed. So that, the wind turbine ought to be endure a lot higher burdens to produce power. At high wind it has the ways for diminishing force. There are different ways of restricting the power assuming the breeze speed is surpassed. It is intended to create power between the cut-in speed and cut-out speed of 3–4 m/s and 25 m/s individually. This paper manages the design and evaluation of previously mentioned type wind turbine by thinking about dynamic condition.

Key words: wind turbine, dynamic analysis, aerodynamic performance and tip speed ratio.

1. INTRODUCTION

The aerodynamic performances (APs) are used to determine the shape and dimensions of the wind turbine blades (WTBs). In this wind turbine (WT) the wind movement is not straight forward. The air flow is varying in the airfoil section; this causes air to be deflected by the WT to extract energy. For efficient power generation the speed of the wind turbine blade (WTB) should be maintained within the designed speed and torque limits controlled. The design of WTBs has been reviewed in section 2. Section 3 has included structural analysis and aerodynamic analysis. Finally, conclusions have been presented in section 4. This paper could have tremendously helped the researchers and utility engineers to develop wind energy (WE) in the world.

2. DESIGN OF WTBs

The WTBs have subjected to complex and operational loadings during their entire periods of service. The optimal design approaches and design parameters have been presented as follows:

Chen et al. have performed the structural optimization of a 2 MW composite WTB (CWTB) using finite element analysis (FEA) and particle swarm optimization (PSO) algorithm. The essential mass reduction has been optimized for the structural design [1]. Liao et al. have developed a multi-criteria design model for the optimization of blade layers using FAST and an improved PSO algorithm. The optimum results have been validated with the focus software. The optimal model has an alternate design approach [2]. Chattot has studied the effect of a blade tip modifications on the performance using vortex model. The new blade tip design has improved the aerodynamic performance (AP) [3]. Maheri et al. have analyzed the effect of bend-twist adoptive blade (BTAB) on its structural behavior. The BTAB has improved the overall performance than that of an ordinary old design customs [4]. Ashuri et al. have prepared an integrated aerodynamic and structural design of blade of off-shore wind turbine generators (WTGs). The optimized design process has decreased the levelized cost of WE by 2.3% [5]. Lee et al. have examined the influence of design parameters such as pitch angle, rotational speed and swept radii on the AP of two WTBs rotating in counter direction using a modified Blade element momentum theory (BEMT). The design parameters such as blade pitch angle, rotational speed and swept radii have influenced on power coefficient and complex aerodynamic interactions [6]. Le has described the effect of various loads experiencing on WTBs during its operation. The centrifugal forces, bending moments and bending stresses have been produced on the blade due to the following loads such as normal load, gust load and gyroscopic load [7].

Jung et al. have designed a 750 kW wind turbine generator (WTG) with the help of the IEC61400-1and Germanischer Lioyd standard. The stresses have been calculated at the blade root and hub connection. The fatigue life has also been calculated using the Miner’s rule and the Goodman diagram [8]. Bak has explained the innovations in design of horizontal axis wind turbine blade (HAWTB). The following constraints have been considered for the aerodynamic design. They are such as choices of rotor control, rotor size, airfoil types and number of blades [9]. Bechly and Clausen have described the structural design of a WTB made of FG composite material using FEA based on the blade element theory (BET). The new structure has been analyzed with the following parameters such as bending stress, static bending, twisting deflections and tip deflections [10]. Henriques et al. have designed a new blade airfoil using a pressure load inverse methodology. This new design has improved the lift force acting on the blade and it has reduced the unfavorable pressure gradient developing on the suction side. The results have been obtained by the wind tunnel experiment and it has agreed with the computational results [11]. Barnes et al. have designed a specific low wind speed (LWS) WTB for the improvement of its structural performance. The new design has seen stiffer, lighter and lower cost than that of conventional one. The standard high wind speed (HWS) blade has been less efficient in LWS sites [12].

Zangenberg et al. have discussed about the blade such as the design process, technology and composition of materials. The fibrous composite preform has carried the loads as a main laminate of blade [13]. Tang et al. have analyzed the performance of stall-regulated HAWT. Its performance has been varied with the wind speed and design parameters such as tip speed ratio (TSR), rated wind speed, rotor diameter and blade geometry [14]. Saqib Hameed and Kamran Afaq have analyzed a straight bladed 1kW vertical axis wind turbine (VAWT) using analytical and numerical modelling. The following parameters have been determined. They are such as solidity, aspect ratio, pressure coefficient, deflection, bending stresses and structural strength. The optimized blades have reduced the blade deflections, bending stresses and the cost [15]. Mohamed et al. have considered an improved design of a classical Savonius turbine using an obstacle plate shielding the returning blade. The modified approach has increased 40% of output power at the TSR of 0.7 and the self-starting capability of the turbine [16].

Analyses of WTBs

The analysis is required to determine the ability and strength of WTBs. The blades should withstand the extreme wind load, structural load, operational load, inertial load and stresses acting on them. The following sub-sections deal with structural and aerodynamic analysis of WTBs.

3. STRUCTURAL ANALYSIS OF WTBs

The WTBs should have a high ultimate strength. It is essentially required to monitor the structural health of WTBs. This section briefly describes the factors such as forces, stresses, damages and failures happening on the WTBs as follows: Bacharoudis and Philippidis have examined the stresses, strength and stability of a CWTB under the extreme load conditions using a thick-shell 3D FEM. The properties of the blade materials have been measured at the ply level of the laminates [17]. De Goeij et al. have implemented the concept of bending-torsion coupling for the design of CWTB. The torsional deformation, blade configuration and the stress concentration have been analyzed for the passive pitch-control [18]. Tan et al. have studied the fracture behaviour of CWTB materials by using spiral notch torsion test with the help of fractography and FEA. They have also determined the following properties such as tensile stress, torsional shear stress and fracture toughness [19]. Soker has analyzed the loading effects and dynamics using cycle counting methodology. The WTBs have been subjected to various loads such as aerodynamic load, inertia load, gravitational load and gyroscopic load [20].

Molholt Jensen and Branner have described an overview of the structural design process of WTB. It has dealt with the design principles, failure mechanisms and failure modes of WTBs [21]. Duenas-Osorio and Basu have studied the acceleration response at the top of the WTGs using a dynamic model. The shut-down criteria have been established based on wind speed. The shut-down criteria has reduced the acceleration and damages [22]. Toft and Sorensen have described a reliability based design process for WTBs with stochastic models. The partial safety factors (PSFs) have been determined for the blade structural safety [23]. Ronold and Larsen have analyzed the reliability and safety of WTB at ultimate loading using a probabilistic model. The probability of failure has been calculated at the flap wise direction. The reliability analysis has been used to calibrate the PSFs of WTG design [24].

Carbone and Afferrante have assessed the throw risk of WTBs due to failure. The safe and unsafe areas have been located based on a novel computationally efficient method [25]. Vitale and Rossi have determined power output from the WTG using a software tool. It has also been helped to calculate the distribution of forces acting along the span of blade [26]. Liu et al. have investigated delamination growth on the FG-CWTBs using optical coherence tomography. The crack growth inside the composite material has been measured based on an optimized signal processing algorithm [27]. Mandell et al. have studied the effects of resinand reinforcement variations on fatigue resistance. The static and fatigue property variations have been determined during the test. The ply delamination has been identified as a critical damage mechanism [28].

Abd-Elhady et al. have experimentally evaluated the air-termination systems for rotating WTBs based on IEC-61400-24 standard for lightning production. The proposed system has shown quality lightning protection [29]. Rodrigues et al. have presented the computer simulations by using electro-magnetic transients program (E-MTP) to avoid indirect effects of lightning. This model has been used to protect the WTG, transformer and nearby area [30]. Rodrigues et al. have studied the lightning strokes, lightning effects and lightning protection on WTGs. The E-MTP has been applied to protect the WTG from lighting strokes [31]. Da Silva Melo and Da Silveira Neto have performed an integral analysis on VAWT system. The following performance parameters have been determined such as wind velocity, angle of attack, lift, drag forces, torque and power generated and power coefficient [32]. The structural analysis of CWTBs is integrated by the following fatigue analysis of WTBs.

Aerodynamics Analysis of WTBs

The aerodynamic is the most preeminent subject for design and operations of WTBs. The sub-sections of this section have been explained with the following analyses such as:

Aerodynamics of HAWTBs

The aerodynamic design, lift force, and drag forces, flow analysis and performance of WTBs have been reviewed as follows: Habali and Saleh have designed a new blade with the combination of two airfoils. It has been installed and tested on a 15kW WTG. The test has resulted on desirable power coefficient of 41.2% [33]. Bak has described the aerodynamic design process. The performance has been varied based on the rotor size, types of airfoil, number of blades and aerodynamic shape of the blades [34. Sharifi and Nobari have developed an aerodynamic code for the prediction of aerodynamic of HAWT using BEMT. The new innovative algorithm has been proposed to predict the optimum pitch angle distribution along WTBs for the maximum power extraction [35]. Sedaghat and Mirhosseini have described the aerodynamic of a 300 kW HAWTB using BEMT. The suitable parameters have been considered for the maximum lift to drag ratio and also for the best interactions of wind and blade structure [36]. Lanzafame and Messina have analyzed the fluid dynamics using a mathematical model based on BEMT. It has helped for the maximum performance even at LWS operation [37]. Hansen et al. have reviewed the aerodynamics with the following methods such as BEMT, CFD, vortex method, panel methods and structural modelling. The yaw analysis could be 10-20 times more expensive than that of steady state axial flow computation. The structural models have been done based on classical beam theory because of the rigidity of turbine components [38]. Lanzafame and Messina have predicted the performance of a HAWTB with the aerodynamic post-stall and brake state models using the numerical code based on BEMT. The results of the brake state model have agreed to the experimental data [39]. Lee et al. have performed aerodynamic analysis using an improved strip theory. The AEBs have also been determined and validated with the NREL 5 MW model [40].

Macquart et al. have studied load rejections from WTB using a micro-tab dynamic model. The predicted transient aerodynamic coefficients have shown consistency with the experimental data. The results have also indicated the frequencies of load rejection impact on the fatigue life of blade [41]. Sayed et al. have performed the aerodynamic simulations for the different blade profiles using CFD based on finite volume approach. It has helped to obtain the optimum blade profiles, angle of attack and power output from the WTG and it has also calculated the aerodynamic loads acting of WTG [42].

Puterbaugh and Beyene have established a parametric study on WTB to predict the geometric response using moment area method. A mathematical model has also been derived to predict material deformation with aerodynamic forces. The aerofoil has been modelled as a non-prismatic cantilevered beam [43]. Maheri et al. have considered the magnitude and the direction of the aerodynamic force acting on a WTB for the efficient meshing. The result has shown a considerable improvement of the mesh efficiency in the chord-wise mesh size [44]. No TS et al. have studied the blade pitch control system, AP of a new WTG based on hybrid simulation software FORTRAN and MATLAB. In this new system, the generator has been located vertically inside the tower [45]. Bottasso et al. have studied the lift force using lifting line model. The lift forces have been found varying with different angles of attack and shapes of blades [46]. Sedaghat has presented an innovative magnus type HAWT for the development of wind energy. The attractive magnus effect has augmented the lift force [47].

Burlibasa and Ceanga have analyzed the wind speed turbulence created by shaping filter in large WTG using a rated non-parametric frequency model. It has helped for the simulation of large WTGs. The model has considered the following parameters such as wind speed, rotational speed of shaft, turbulence intensity and turbulence length [48]. Li et al. have described the WTG aerodynamics using CFD based on RANS and detached Eddy simulation (DES) turbulence models. At wind speed greater than 25m/s and lower than 15m/s the DES has been appeared to produce better and poor results respectively. The following parameters have been estimated. They are such as: angle of attack, total power, thrust, average force moments, normal force coefficient and pressure coefficient [49]. Melius et al. have analyzed the boundary layer flow of a model WTGs using wind tunnel and Fokker-Planck equation (FPE). The result has indicated a good agreement between experimental data and numerical solutions in the far-wake region. The turbulent flow has been governed by FPE [50]. Kristensen and Frandsen have studied the atmospheric turbulence component of the wind using a kinematical model. It is used to clarify the dynamic loads acting on WTBs due to turbulent wind speed [51]. Lubitz has investigated the impacts of ambient turbulence on power production of SWTS. The change of wind speed and turbulence has changed the energy production [52].

Lin and Shieh have studied the aero dynamical interference of an upwind WTG using SST k-w turbulence model based on Navier-Stokes solver. The following simulation results have been obtained; the velocity in the field, lift force coefficient of blade, the movement of stagnation point of tower and the skewed wake of tower [53]. Lynch et al. have described the unsteady motion of rotating WTBs using an efficient actuating blade model. It has predicted the root and tip vortex location and the blade strength [54]. Lee et al. have analyzed the effect of local shear flows around WTG airfoils using CFD simulations based on BEMT and have also proposed a lift correction model for the load analysis. The following parameters have changed the lift coefficient. The parameters are such as: the shear rate, chord length and reference inflow [55]. Da Silva et al. have implemented the shear flow model in CWTBs using an analytical solution based on FEM. The results have shown similar discretization with the shear flow on an actual blade [56].

Janajreh et al. have carried out an aerodynamic flow analysis for the down-stream WT (DSWT) using K-epsilon model. The blade static pressure and aerodynamic forces have been calculated with various wind speeds and wind incident angles. The DSWT and flapping rotor blades have been considered for the best performance [57]. Liu et al. have studied the aerodynamic flow field around S809 WTG airfoils using CFD method and reduced order method (ROM) under dynamic stall condition. The computational cost by ROM is lesser than that of CFD method. The study has also effectively predicted the nonlinear hysteretic feature of the airfoil [58]. Clausen and Wood have studied the flow behind a WTG using phase-locked averaged measurements model. The axial vorticity contours have been found for the operating conditions [59]. Kamoun et al. have performed an accurate airfoil analysis on WTB profiles using singularities method. It has shown the best AWCs. The result has been validated with the data available in the airfoil catalogue [60].

Ronsten has calculated the static pressure distributions of HAWT using wind tunnel based on Lanchester-Prandt lifting line theory. The following parameters have been measured. They are such as: the angle of attack, lift coefficient, drag coefficient and tip loads [61]. Sicot et al have experimentally investigated the effects of the rotation and turbulence on a WTB stall mechanisms using the wind tunnel tests. The pressure of the flow separation point on the rotating blade has been reduced with the influence of free stream turbulence levels. The results have shown the lift augmentation [62]. Kamoun et al. have presented the in-viscid velocity field and potential function distributions around the WTB contour using the singularities method. The design procedure has been used to optimize the blade geometry and also to obtain good aerodynamic characteristics (ACs) [63]. Hu et al. have simulated the stall-delay phenomenon (SDP) of HAWT using CFD code based on integral boundary layer equations. The SDP has accurately predicted the load and performance [64].

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Tenguria et al. have investigated the AP using an optimal rotor theory. The suitable blade geometry has been obtained from the optimum chord and twist distribution of the blade [65]. Varol et al. have developed a new kind of steering aerofoils to increase rotational speed. The rotational speed has been increased by 32% by the optimum distance and optimum angle of the airfoils [66]. Tenguria et al. have designed NACA twisted airfoils for a 5 kW HAWT based on the BEMT. The maximum stress and power coefficient have been estimated for the blade segment [67]. The knowledge of aerodynamic is required for wind power augmentation by the new aerodynamic design of blade. The following sub-section deals with aerodynamics of VAWTs.

Aerodynamics of VAWT blades

Danao et al. have simulated the AP using RANS based on CFD numerical simulation. The turbine has given slight improvement on performance at higher frequencies (>Hz) of operations [68]. Beans has performed an aerodynamic analysis for multi-bladed DTVAWT using a performance model. The variation of power coefficient and blade normal force has been predicted for the upwind and downwind turbines [69]. Castillo Tudela has analysed the design and aerodynamic of a VAWT blade using momentum based model. The wood has been considered as an apt material for further improvement with the help of computer algorithm [70]. Rolland et al. studied the AP of a VAWT using a CFD simulation turbulence modelling technique. The simulated data have been validated with the experimental data with the help of a wind tunnel. The study has also been used to identify the out of operational range of turbines [71]. Deglaire et al. have developed an analytical model to study the flow around a moving profile of VAWT based on conformal mapping techniques. The blade pressure distribution and aerodynamic forces have been determined faster and more accurately than standard panel methods [72]. Kacprzak et al. have investigated the performance of STVAWT by means of quasi 2D flow prediction using ANSYS CFX. The flow structure and the wake have been identified from the investigation. They have also determined the performance parameters such as: the power coefficient, torque coefficient and torque variation [73]. Reupke and Probert have carried out the dynamic-torque test on a slatted-blade STVAWT. The modified turbine has increased the torque at low rotational speed [74]. Castelli et al. have evaluated the AP of DTVAWT using a CFD model based on BEMT. The flow field characteristics have been investigated with different values of TSRs. The AP has been predicted by a powerful design and optimisational tool called CFD [75].

Selvan Nambi and Joselin Herbert conducted case study for obtaining wind energy data. From that collected data the parameters required for designing the WTB for static analysis were finalized. For analyzing the dynamic performance of the wind turbine blade the parameters were taken from the same blade in which the static analyses were carried out [76].

By considering the references [77-79] the design and analysis were carried out using blade element momentum theory.

The blade lengths were varied from 13m to 15m and the corresponding power were calculated for lift type and drag type WT. For that design the power various from 208 kW to 277 kW for lift type and 106 kW to 141 kW for drag type WT. In both the cases as the blade length increases there is a gradual increase in power production as shown in Fig 1 & 2.

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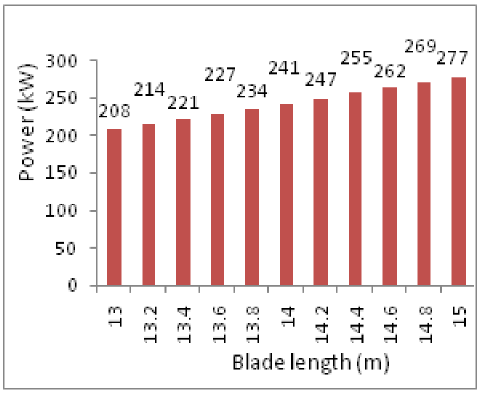

Figure 1 lift type wind turbine

Figure 2 drag type wind turbine

For the same change in blade length the torque increase for both the lift and drag type blade. The torque values various from 43 Nm to 57 Nm for lift type and its value ranges 22 Nm to 29 Nm for drag type blade as shown in Fig 3 & 4.

Torque Vs Blade length

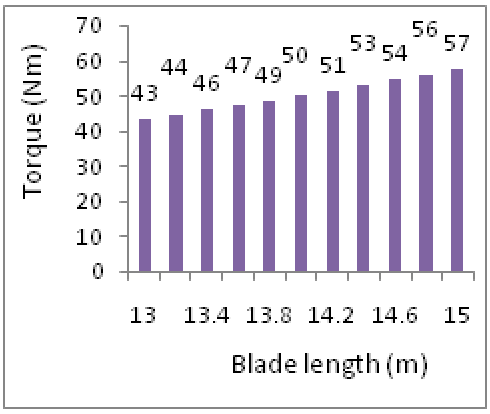

Figure 3 lift type wind turbine

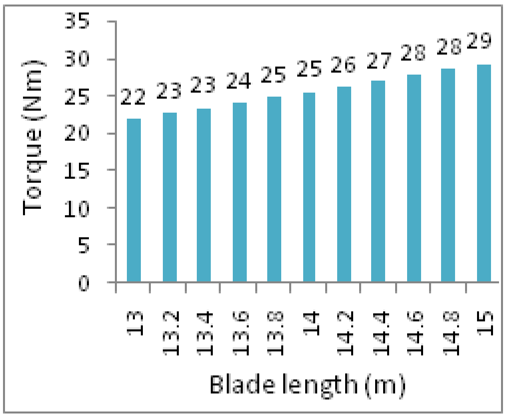

Figure 4 drag type wind turbine

There is a linear increase in tip speed ratio with respect to the increase in pitch angle as shown in Fig 5. For the constant angle of attack (α) of 8.04^0 as ϕ value increases Cx value increases as shown in Fig 6.

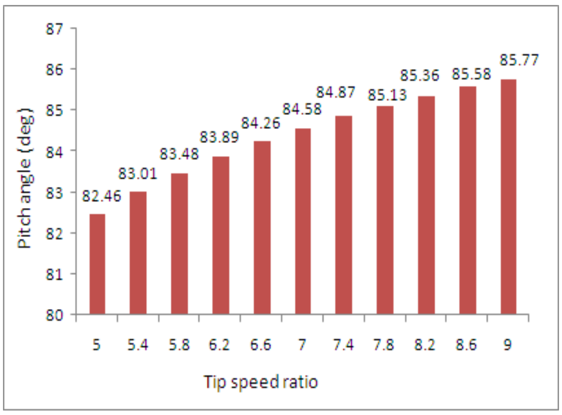

Figure 5 Pitch angle Vs Tip speed ratio for lift type wind turbine

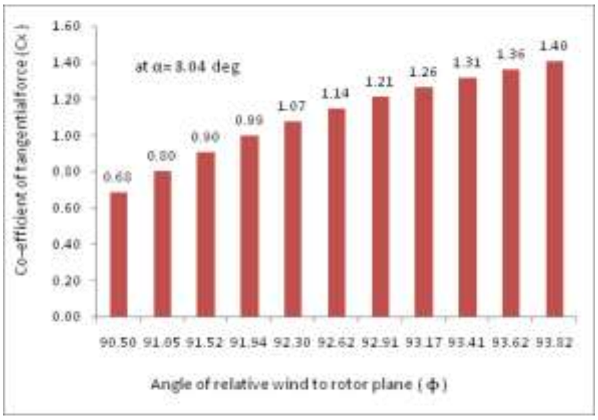

Figure 6 Co-efficient of tangential force (Cx) Vs (ϕ)

4. DYNAMIC ANALYSIS RESULT

Tsai-Wu Constants

Air density	Kg/mm^3	1.225 e-009
Specific Heat	mJ/kg.C	1.0064 e+006

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Thermal Conductivity	W/mm.C	2.42e-005
Viscosity	MPa s	1.7894e-011
Molecular Weight	Kg/mol	2.8966e-002
Thermal Accom Coefficient		0.9137
Velocity Accom Coefficient	mm/s	913.7

	0 deg (Epoxy S-GLASS UD)			**15 deg (Epoxy S-GLASS UD)**			**30 deg (Epoxy S-GLASS UD)**		
Minimum Total Deformation (mm)	0			0			0		
Maximum Total Deformation (mm)	1.5624			1.535			68.415		
Minimum Equivalent Stress (MPa)	1.3107 e-004			1.114e-005			4.0983e-003		
Maximum Equivalent Stress (MPa)	4.746 e-002			3.3513e-002			1.9048		
Minimum Equivalent Elastic Strain (mm/mm)	2.2116e-008			2.5322e-009			8.2432e-007		
Maximum Equivalent Elastic Strain (mm/mm)	6.9628e-006			7.2252e-006			2.982e-004		
Orthotropic Elasticity									
Young's Modulus direction (MPa)	x	y	z	x	y	z	x	y	Z
	50000	8000	8000	50000	8000	8000	50000	8000	8000
Poisson's Ratio	XY	YZ	XZ	XY	YZ	XZ	XY	YZ	XZ
	0.3	0.4	0.3	0.3	0.4	0.3	0.3	0.4	0.3
Shear Modulus (MPa)	XY	YZ	XZ	XY	YZ	XZ	XY	YZ	XZ
	5000	3846.1	5000	5000	3846.1	5000	5000	3846.1	5000
Orthotropic Strain Limits									
Tensile (Pa)	x	y	z	x	y	z	x	y	z
	2.44e-002	3.5e-003	3.5e-003	2.44e-002	3.5e-003	3.5e-003	2.44e-002	3.5e-003	3.5e-003
Compressive (Pa)	x	y	z	x	y	z	x	y	z
	-1.5e-002	-1.2e-002	-1.2e-002	-1.5e-002	-1.2e-002	-1.2e-002	-1.5e-002	-1.2e-002	-1.2e-002
Shear (Pa)	XY	YZ	XZ	XY	YZ	XZ	XY	YZ	XZ
	1.6e-002	1.2e-002	1.6e-002	1.6e-002	1.2e-002	1.6e-002	1.6e-002	1.2e-002	1.6e-002
Orthotropic Stress Limits									
Tensile (MPa)	x	y	z	x	y	z	x	y	z

	1700	35	35	1700	35	35	1700	35	35
Compressive (MPa)	x	y	z	x	y	z	x	y	z
	-1000	-120	-120	-1000	-120	-120	-1000	-120	-120
Shear (MPa)	XY	YZ	XZ	XY	YZ	XZ	XY	YZ	XZ
	80	46.154	80	80	46.154	80	80	46.154	80

5. CONCLUSIONS

The design and analysis were carried out for the selected wind turbine blade. The design work was done by blade element momentum theory and Ansys software was used for analysis. From this the following conclusions were obtained.

- With the increases in turbine size the labour and maintenance cost increase gradually. The wind farm turbine cost are minimized by limiting the strength of blade materials and requirements. In the optimal wind speed ratio during energetic gust of wind allows the wind turbine to improve energy capture.
- The noise of the wind turbine blades increases with higher blade tip speeds. For increasing the tip speed without increasing the noise would allow reduction the torque into the gear box and generator. It reduces the overall structural loads and their by reducing cost. The noise level reduction is linked the factors that abrupt stalling.
- In both the stall and pitch type wind turbine blade during the rotation the turbine blade and the tip will be visualised as flat surface. During the cut-out speed of wind the stall type turbine blade remains flat surface and its tip rotates to 90^0. But the pitch control type both the tip and blade rotates to 90^0.
- Tensile stress, compressive stress and shear stress are almost constant with respect to the direction of flow of wind.
- In relation with the direction of wind flow the following values such as Tensile strain, compressive strain and shear strain are almost constant.
- Upto 15^0 twist the max total deformation is nearly 1.5 mm but it rapidly rises to 68.415 mm for the 30^0 twist blade.
- Maximum equivalent stress increases with increase of twist angle.

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