CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

In the following section an introduction to Wind electric generators is given. A comprehensive review of literature regarding blades of WEG, problems encountered in present blade material and the feasibility of carbon fibres were included. Structural optimization techniques have been discussed.

1.2 INTRODUCTION

Electricity is indispensable for our life. It is very vital for industries. Small scale industries and big factories are run by electricity. If there is power failure the products cannot be produced, and it will hamper the economic development of any country. Science and technology of a country will develop only with the availability of electricity. Mass media such as T.V., internet, mobile phones can be operated only with the help of electricity. To put in a nutshell, the well being of the people of a country and its economic development solely depends on the per capita consumption of electricity. The global demand for electricity is predicted to increase by 80 percent between 2013 and 2030.

The consumption of electricity is thus growing rapidly and the fossil fuels of earth is depleting. If there is short supply of coal or diesel the production of electricity will be reduced in thermal power plants. The atomic power stations are a threat to human life. As long as it is safe everything goes
well. But if any mishap happens the radiation will cause unutterable loss to humanity. The drawbacks from fossil fuels such as air pollution, acid rain, greenhouse gas effects, change of climate, floods, unpredictable rainfalls and droughts, health problem of living beings, are normally not included in calculations of electricity costs. When cost calculations are made considering these factors, renewable energy sources produce cheaper electricity. So, more electricity should be produced from renewable energy. Wind energy is the most promising source of renewable energy. It is a free fuel with no emission of pollutants. Wind is cost-effective renewable energy resource.

Global wind energy council (2013) depicts that wind farms generate between 17 to 39 times as much power as they consume, but nuclear power plants consume 16 times more power and coal power plants consume 11 times more power. For every kWh of wind energy used, approximately 696g of Co₂ will be avoided. A WEG will produce up to 80 times more energy than is used to build, install, operate, maintain and decommission it. It is predicted by the council that 8 to 12% of the amount of global electricity could be supplied by wind power in 2020.

The amount of electricity generated from a WEG depends upon the hub height of WEG, wind speed and the dimensions of the aeroturbine. An aeroturbine consist of blades and a hub. The hub is used to join the blades with the slow speed shaft of a WEG as shown in Figure 1.1. As the wind speed doubles, the power produced by a WEG increases by eight times. Longer blades with efficient aerodynamic profile capture more wind. As the rotor diameter of WEG doubles, the power increases four times. But, the weight of a blade increases with the cube of the rotor diameter. The components of a WEG such as bearings, shafts, gears, will be affected if the weight of blades exceeds the limit. During working, blades are subjected to rapidly varying wind loads from different directions. These loads are
transmitted to all the above components. However, the tower and foundation should be designed and manufactured to support the WEG.

Figure 1.1 Parts of a WEG

Blades of a WEG are made up of advanced composite materials as the properties of these materials can be decided by the designer. A blade should have less weight with better properties. Figure 1.2 shows the parts of a WEG blade. Root of the blade is joined with the hub. Root and lightning
arresters are the region of blade which are made up of metals. Detailed description about blade is given in the section 1.4.

1.3 OBJECTIVES OF THE THESIS

The objectives of this research can be summarized as follows:

- Investigate the influence of SiC filler with different weight fractions (0, 5, 10 wt. %) on mechanical properties of GF reinforced silane treated epoxy matrix composites.

- Investigate the influence of SiC filler with different weight fractions (0, 5, 10 wt. %) on mechanical properties of GF reinforced silane treated isoresin matrix composites.

- Investigate the influence of SiC filler with different weight fractions (0, 5, 10 wt. %) on mechanical properties of CF reinforced silane treated epoxy matrix composites.
• Investigate influence of SiC filler with different weight fractions (0, 5, 10 wt. %) on mechanical properties of synthesized CF reinforced silane treated isoresin matrix composites.

• Optimize the mechanical properties of prepared composites using MINITAB software to identify the optimal material for a WEG blade.

• Model a wind electric generator blade using Pro-E software and perform finite element analysis for the optimal composite using ANSYS software.

1.4 LITERATURE SURVEY

Presently research in wind energy is focused on weight reduction of blades by using suitable composites. Several researches have been carried out to improve the properties of composites by varying the type, dimensions and orientations of fibre, modifying the resin, improving the manufacturing process. Many researchers diversify their work towards hybrid composites, natural fibre composites, nano composites to obtain an optimal composite for WEG’s. To understand the current research problem, a through literature review have been done concerning optimization, GF reinforced composites, CF reinforced composites; some of them is presented below.

1.4.1 Wind Electric Generator

Leung & Yang (2012) describes that wind power is the only renewable resource which offers a developed technique, and proven profitable prospects. Presently, wind turbines are also applied in large-scale electricity generation. They predict that, wind energy will provide 5% of the world’s energy in 2020. They observed that, during the last decade, the world’s wind
power generation capacity has been growing with an average annual growth of about 30%.

Vestas (2013) 8.0 MW- WEG has a blade with length 80m and weight 35 tons. As carbon fibres are used, the blades are slimmer, stiffer and lighter. Loads on turbine components are reduced which makes the turbine more efficient, the added advantages are smaller foundations and better logistics.

Siemens (2013) 6.0 MW-WEG shown in Figure A1.2 has a blade with length 75m and weight 25 tons. Even though this blade was manufactured by the manufacturer’s patented integral blade process by avoiding glued joints, adhesive or seams; as glass fibres were used in the blade, the weight was more. If carbon fibres were used for these longer blades, the blade could be 20 percent lighter.

Gamesa (2013) is using carbon fibres to manufacture lighter blades with better strength and excellent dynamic behaviour for their 4.5 MW-WEG. As a consequence of this the load transmitted to other components was also less.

Zoltek (2012) illustrates the implementation of carbon fibres in blades. They suggest that, if carbon fibres were used to manufacture blades longer than 45m, then a less robust turbine and tower components are sufficient to withstand the reduced loads during working. The cost savings by using these components shall justify the additional cost of carbon fibres. As, carbon fibres are used in blades of wind turbines manufactured by Vestas and Gamesa; the entire system cost is less than a similar system with a blade using glass fibre alone. At the outset, the replacement of glass fibre with carbon fibre enabled Vestas, to increase the blade length up to 5m without any additional weight. Thus, retrofitting existing turbines with extremely large
blades without increasing weight can be possible by using carbon fibres. As a rough rule of thumb for weight reduction, if carbon fibres were used in spar cap of blades, it would weigh 20 percentage lesser than a similar blade made entirely with glass fibres. A 100m long blade made entirely with glass fibre weighs around 50 tons. If weight savings of 25 percentage was achieved by incorporating carbon fibres in these blades, then there would be a weight savings of 12.5 tons. As weight savings are more important, the possibility of using carbon fibres in shell and trailing edge are in research.

Liaoa et al (2012) studied the parts of a blade. They describe that blade is a multilayer structure which consist of spar caps, shear web and shell. Spar cap weigh around forty percent of blade weight. Blade mass is directly proportional to blade cost. Further, more mass of a blade will affect the remaining components of wind turbine by exerting additional loads. The spar cap is the main part of a wind turbine blade which bears heavier loads and bending moment. Optimization of shape, size and proper placement of fibres within the material are some methods to alter the material properties of blade. However, altering material properties may include the complexity of the design problem.

Attempts have been made by Sharma & Wefzel (2010) to manufacture cost effective blades. A 3.2m long blade was aero elastically tailored and fabricated by using low cost vacuum assisted resin transfer moulding. High tow fabrics can be used in this method. This method is cost effective, as it does not depend on stimulation tools for manufacturing.

Sagol et al (2013) evaluated the effect of surface roughness on wind turbine blades. Due to inclusion of dust, dirt, ice and attrition of insects, the roughness of the exposed blades gets affected. This results in poor efficiency of wind turbine due to changes in flow of air. To prevail over this, a
numerical algorithm was being used to predict the power performance and the flow characteristics in the presence of surface irregularities.

Ryu et al (2012) made a one year survey regarding the structural characteristics of wind turbine blades which were operating in hilly complex sites. They studied the mechanical loads at root of rotor blades. They also evaluated the fatigue resistance of blades using finite element simulation.

Attempts have been made by Rashedi et al (2012) to study the material selection strategy for wind turbine blade and tower as per Ashby’s method. This was based on the basis of inherent structural boundaries and probable design objectives. After investigating several composites for wind turbine blade and tower they conclude that carbon fibre reinforced composites are the excellent materials for blade if cost factor is neglected.

Grujicic et al (2009) investigated the design, performance, material selection of a 1MW wind turbine blade using computer aided tools. They developed a computer program to generate geometrical modeling and a finite element input deck. A procedure for blade material selection is developed to identify optimal material for given requirements such as durability, weight reduction. They conclude that carbon fibre reinforced composites are suitable materials for a blade rather than E glass fibre reinforced composites. They observed that epoxy may not be a suitable matrix for these composites.

Zhu et al (2012) developed a mathematical model to optimize the design for a wind turbine blade. The model is practiced to minimize the blade mass for reducing the cost of blade. The number of layups of the material for spar cap is the design variable. Strength, stiffness and stability of the blade are the constraint conditions. The design is optimized in ANSYS software by considering the objective and constraint conditions. They found that the
optimization design resulted in 7.2% of the blade mass reduction, the stress and strain of blade is reasonable with nil resonance.

Wu & Young (2012) developed a simple iterative method to design the structure of a blade. They have arranged the composite materials in an optimal way by developing a GUI interface to attain good mechanical strength. The geometrical model of the blade was constructed using visualization interface method. A simple iterative method was also developed to design the structure of blade.

Buckney et al (2013) applied a topology optimization technique for a 45m wind turbine blade. Their objective was to reduce the cost of energy by improving the structure of a blade through weight reduction. They developed structural shape factors for non symmetric sections to evaluate structural concepts. They found that trailing edge reinforcement and spar cap topology are suitable methods in maximizing stiffness.

Chen et al (2013) designed a 2MW wind turbine blade by using new airfoil families. A finite element model was developed for the blade. Fluid structure interaction method is introduced as per the blade element momentum theory. Finite element analysis and particle swarm algorithm was used to locate spar cap properly and to select blade thickness for optimizing the blade structure.

Sandia (2004) describes the material and manufacturing processes of large blades and the trends in blade manufacturing. Specifications for very long blades are developed to guide the initial design. Using this design, parametric analyses are performed to prove the stiffness of blade. They observed that if fibreglass spar were replaced with hybrid carbon/glass fibre composite, mass of composite decreases. Preliminary designs are implemented in the transferred mid-span region. Problems according to these
designs are identified. Thin coupon test on standard specimens show that, the specimen has good tensile strength. Larger tows with stiffer fibres are essential to achieve good fatigue and compressive strength. Also the transition of carbon and fibreglass shows different properties with different arrangements of ply. Better properties are observed by this fibre change.

John et al (Sandia 2010) analyzed static and fatigue performance of wind turbine blade materials by considering the fatigue failure of blade. They observed an increase in stress and strain during tension. The initial damage of blade is due to resin matrix cracking. They identified that matrix cracking decreases the stiffness of longitudinal and multidirectional laminate. They observed more damage for reversed loading than tension or compression for all laminates. Shear effects is most important in biax laminates. The lifetime of multidirectional laminates shows same properties and strain levels of biax fabric layers. Under fatigue loading ply delaminating is observed in carbon fibre laminates.

Attempts have been made by Sandia (2011) to improve the reliability of wind turbine blades. They studied the failure of wind turbine blades and suggest the following remedial measures:

(i) Test has to be conducted to study the performance of blade.

(ii) Non destructive evaluation techniques have to be used for blade monitoring.

(iii) The effect of flows and their contribution to the entire structure should be understood.
(iv) Analytical and experimental analogs should be developed for damage growth and residual strengths necessary for blade reliability.

DTU (2012) developed a Beam Cross section Analysis Software (BECAS) for cross section analysis of wind turbine blades. Finite element models were also studied. For the future design of wind turbine blades, it provides data in an intelligent manner. Numerical calculations and experiential measurements satisfy the results obtained by the analysis. They conclude that as BECAS predicts geometrical and material induced couplings with less error, it can be used as an efficient tool for analysis.

Rajakumar & Ravindran (2012) studied the aerodynamic performance analysis of wind turbine blades. They identified that the maximum aerodynamic efficiency can be obtained, if the blade is twisted according to a profile with different angle of attack. Suitable attack angle and twist angle increases the performance of the blade. They observed that rotational velocity of a turbine maximizes its power coefficient. A mathematical code for generating power coefficient curve was also developed.

Rajakumar & Ravindran (2010) created a NACA 4420 airfoil profile using DESIGNFOIL software. They modeled the wind turbine blade in Solid works software and calculated the lift and drag forces at various sections. They have observed that at 5° angle of attack the lift/drag ratio is maximum. Computational fluid dynamic analysis was also done to understand the feasibility for its application in a wind turbine blade. The results were found to be in good agreement with the wind tunnel experimental values.

Rajadurai et al (2008) created a NACA 4412 airfoil profile using NACA coding. They modeled the wind turbine blade in Solid works software
and calculated the lift and drag forces at various sections. They performed free vibration analysis to validate the blade model. They evaluated the various forces acting on a wind turbine blade at different wind velocities. Fatigue life of the blade was estimated from stress ratio to the number of cycles to failure expression. They proposed a reliable failure criterion for assessing the cruciality of blade during service.

The growth in size of WEG was predicted by European wind energy association (2009) and Peter et al (2011) as shown in Figure 1.3.

![Figure 1.3 Growth in size of WEG](image)

**Figure 1.3 Growth in size of WEG**

### 1.4.2 Glass Fibre Composites

Yuanjian & Isaac (2008) investigated the behavior glass fibre reinforced polyester matrix composites on low velocity impact. They observed more damage in glass fibre laminates with 45° fibre orientation than
$0/90^\circ$ fibre orientation of laminates during low velocity impact. They observed that the fatigue performance of a composite is related with the post impact residual tensile strength.

Zangenberg et al (2012) examined unidirectional glass fibre for damage progression when exposed to tension fatigue. They observed that for different fibre volume fractions the failure models are same. The fibre volume fractions make remarkable changes in fatigue life time as well as damage progression. Stiffness loss is caused due to the backing layers, which form stress concentration that breaks the fibre in axial load carrying bundles.

Shah et al (2013) investigated blades made of flax reinforced polyester composites and E-glass fibre reinforced polyester composites. The flax reinforced polyester blade is found to be 10% lighter than E-glass reinforced polyester blade. E-glass blade posses more flexural rigidity compared to flax blade. Deflection is high for flax blades. They conclude that flax can be a structural replacement for E-glass.

Dong et al (2012) described the flexural properties of hybrid composites which are reinforced by S-2 glass and T 700S carbon fibre. The specimens were made by hand layup process with intra ply configuration added to carbon laminate. Compressive mode of failure was observed in these composites. The results show that flexural modulus decreases with S-2 glass fibre percentage.

EI – Tayeb & Mostafa (1996) examined the wear properties of glass fibre reinforced polyester matrix composites for various loading conditions and sliding speed. Different orientations such as cross laminar and inter-laminar were used for the study. Lowest values of friction coefficients are obtained in cross laminar configuration; as soft components are entrapped between the fibres.
A hunch-up-technique has been implemented by Tsai and Wooh (2001) to investigate the hygric behaviour of woven glass/epoxy composites. Ficks law is used to define the expression for one dimensional moisture absorption and diffusion on the material. The hunch-up method is used to find the distance of aerially constrained laminate. From the hunch up distance the coefficient of moisture expansion was correlated. Properties such as distribution of moisture, maximum concentration, diffusion rate, induced elongation can be easily calculated by this method.

Raj et al (1982) studied the impact strength and mode of fracture of glass fibre reinforced epoxy composites. Five samples were tested and the average value is taken into account. It was found that the impact strength also increases with curing time like tensile strength, flexural strength etc. They conclude that irrespective of the composition of composites; the impact strength increases with curing time.

Velmurugan & Solaimurugan (2007) investigated the effect of plain stitching by using untwisted fibre rovings. Traditional laminated composites suffer extensive damage due to plain stitch. As there are no cross threads in these composites, it has resin rich pockets. The fibre damage is less by locked stitch and modified lock stitch. Due to the absence of resin rich pockets, less fibre damage and uniform distribution of fibres in this stitch; improved tensile, shear and impact strength was accomplished.

Boger et al (2008) suggest a new approach in condition monitoring composites. It is by direct measurement of the material property without using additional sensors. Epoxy resin was modified with two different types of carbon nanotubes and with carbon black, in order to achieve an electrical conductivity. Glass fibre reinforced composites were synthesized with these modified epoxies by resin transfer moulding. Specimens were cut from the prepared materials and tested by incremental tensile tests and fatigue tests.
The inter-laminar shear strength was measured. They observed that the mechanical properties vary according to the distribution of nano particles in the epoxy matrix.

Khan & Kumar (2011) studied about machining glass fibre reinforced composites. Specimens were prepared using a filament winding process. The machining properties are studied using two different alumina cutting tools. It is found that with respect to the cutting speed, gradual progressive abrasive wear is produced on the tool. The abrasive wear is quite smooth and less if SiC whisker reinforced alumina cutting tool was used. The wear is more for Ti mixed alumina cutting tool. Surface resistance varies due to the inherent variation of surface roughness of matrix and fibre. More surface finish is achieved by using SiC whisker reinforced alumina cutting tool than that of Ti mixed alumina cutting tool.

Hao et al (2012) implemented electrochemical impedance spectroscopy for studying the barrier properties of the coatings containing different volume fractions of ultra-short glass fibres. Different volume fractions of ultra-short glass fibres containing epoxy coating were prepared. They observed that hardness, transition temperature, and adhesion of the epoxy coating could be increased with the addition of ultra-short glass fibres. A reduction in coefficient of thermal expansion of the coating is the added advantage.

Bozkurt et al (2007) investigated the mechanical properties of non-crimp glass fibre reinforced clay filled epoxy nano composites. X-ray diffraction results obtained from natural and modified clays indicate that the intergallery spacing of the layered clay increases with surface treatment. The tensile properties have minor effect on clay loading. Due to the improved interface between glass fibre and epoxy matrix, flexural property increases.
The glass transition temperature of the composite is also affected by the addition of clay. Mechanical properties of nano composite laminate were found to increase by the addition of clay particle.

Manjunatha et al (2010) described the effect of incorporating 10 wt. % of well-dispersed silica nano particles on an unhydride cured thermosetting epoxy polymer. For the nano particle modified epoxy the stress controlled tensile fatigue behaviour was studied. The plastic void growth absorbs energy and increase the fatigue life of the modified epoxy. They observed that the nano particle modified epoxy shows three times higher fatigue than the normal epoxy.

Ellyin & Kujawski (1995) investigated unidirectional and multi directional glass fibre reinforced composites at room temperature for tensile and fatigue test. For unidirectional fibres the rate effect is significant in tensile and fatigue loading. Studies show that there is a large difference between the strength and ductility of unidirectional and multi directional fibres. They observed that unidirectional glass fibres are weak in tensile and fatigue strength.

Yuan et al (2007) studied the spall strength of two different types of glass fibre reinforced polymer composites. They observed that the spall strength tend to decrease with increasing levels of normal shock compression. Moreover, superposition of shear-strain on the normal shock compression was found to be highly unfavourable for spall strength. The E glass fibre reinforced composite was found to have a much higher level of spall strength under normal shock compression, combined compression and shear loading when compared to the S glass fibre reinforced composite. The maximum spall strength of the E glass fibre reinforced composite was found to be 119.5 MPa, while the maximum spall strength for the S glass fibre reinforced composite was only 53.7 MPa.
Attempts have been made by Srivastava and Pawar (2006) to understand the effect of adding fly ash filler to E-glass fibre reinforced epoxy matrix composites. They studied the solid particle erosion behavior of these composites with different impingement angle and particle velocity. Tests were carried out with impingement angles such as 30°, 90° and also varying velocities such as 24, 35, 52 m/s. They observed that hardness, density and tensile strength decreases when fly ash filler is used in the composite. Wear rate is found to be maximum at impingement angle of 60°. Erosion efficiency varies from 0.17% to 6%. The SEM analysis shows that the erosion damage is due to the removal of broken fibres followed by the removal of resin. They also observed that ash fillers resist the crack growth formation.

Tewari et al (2003) studied the solid particle erosion of unidirectional carbon and glass fibre reinforced composites. The impingement angle is varied from 15° to 90° at different fibre orientations such as 0°, 45° and 90°. Steel balls with diameter 300 µm to 500 µm and a velocity of 45 m/s were used in the erosion test. The eroded surfaces were examined by SEM. It was observed that the maximum erosion occurs at 60° impingement angle and it depends on the fibre orientation. More erosion is observed during the normal impact than parallel with respect to the fibre. Erosive rate is higher for glass fibre composite than carbon fibre composite. Fractographic analysis revealed that erosion is due to matrix microcracking and fibre matrix debonding.

Suresha et al (2010) investigated the wear and friction behavior of glass fibre reinforced epoxy composites with and without silicon carbide filler. The test is conducted by varying the sliding distance keeping the load and velocity constant. They found that wear rate increases with the sliding distance; but it is not maintained in the same gradient. Coefficient of friction is found to be the same over a wide range of sliding distances. While running in wear very few broken fibres are noticed, the breakage of fibres and
interface separation takes place at later stage, i.e. in the severe wear region. Agglomeration and disorientation of broken fibres are seen in the steady state region. The wear rate reduces to 14-20% by the addition of SiC fillers at higher sliding distance. The SiC filled glass-epoxy composites have better wear behavior.

A study performed by Grujicic et al (2010) details the challenges in manufacturing cost effective wind turbine blades. They optimized the design of cost-effective glass fibre reinforced epoxy matrix composite blade for a 5MW horizontal axis wind turbine. They found that the blade stiffness functional requirements, fatigue-controlled durability and quasi-static strength could not be achieved simultaneously. More blade stiffness could be obtained by increasing the spar-cap thickness but it is not mass-effective as glass fibres were used. Adding additional glass fibres to increase the stiffness of blade will lead to the failure of the blade. They concluded that, if laminates made using advanced composites were used in spar cap of a wind turbine blade it will increase the stiffness of blade.

Newer methods have been devised by Kumar et al (2011) to replace the conventional thermal curing by the infrared radiation post curing. They observed that more stress is formed in the conventional method since it lags in uniformity; the outer layer absorbs more heat than the inner layer. In infrared curing process volumetric heating is done so the curing will be uniform resulting in reduced stress. Within the laminate there will be no uncured resins. The SEM tests shows that the fibre-matrix interfacial bonding is similar in thermal and infrared curing. They suggest that infrared curing could be employed for glass fibre reinforced epoxy matrix composites.

Dong & Davies (2012) studied hybrid composites reinforced with S-2 glass and T700S carbon fibre in an ultra ply configuration. The test results show that, the flexural modulus increases as the span to depth ratio increases.
They obtained an S curve for the flexural modulus and hybrid ratio plot. The maximum strength depends on stacking configuration. The maximum hybrid effect is observed when the volume fractions are around 50%. When compared with the full carbon and glass configurations the strength increases as 43.46% and 85.57%.

Overgaard et al (2010) developed a modeling strategy for the structural analysis of three dimensional laminated composite structures in geometric and material related instabilities. For identifying crack formations and the propagation of delamination, localized sub-plane control strategy was used. Finally the adopted methods was established in generic laminated composite wind turbine blade and correlated.

Gu (2006) experimented textile composites for structural applications. Stacking orientations of the woven fabric layer is one of the major factors which influence the mechanical properties of the woven fabric reinforced composites. The laminates with various fabric crossing angles were manufactured using vacuum assisted resin infusion technique. By conducting flexural and tensile tests they identified that flexural and tensile strength was highly influenced by the orientation of the fabric in laminates.

Mariatti & Chum (2005) manufactured five type GF reinforced composites using hand lay-up technique by varying the ratio of resin and fibre. The correlation of the resin and fibre ratio with physical and flexural properties was analyzed. They also examined the effect of water absorption on the flexural properties of the prepared composites. They observed that the properties of these composites depend on the ratio between resin and fibre.

Attempts have been made by Joshi et al (2010) to improve the properties of glass particulate reinforced epoxy matrix composites. They observed that the experimental coefficient of thermal expansion was found to
be less than theoretical coefficient of thermal expansion; due to adhesion between epoxy and the glass particulates. It was also investigated that a simple rule of mixtures overestimate the CTE values because it does take into account the good adhesion between the particulates and the matrix.

Gupta et al (2001) investigated the effect of adding flyash as filler material with glass fibre reinforced epoxy matrix composites. They observed an increase in impact strength of the composites due to the inclusion of filler material. Fractographic analysis was done to understand the failure modes. For impact fracture, failure depends upon the interfacial strength of filler and matrix material. They conclude that for short fibre composites, the fibre length should always be considered for deciding specimen dimensions and aspect ratio.

Lindsey et al (1995) studied the mechanical properties of unidirectional glass fibre reinforced polyester laminates. They observed that the fibre-matrix interface influenced the mechanical properties of these laminates.

Liu et al (2012) determined the shear properties of glass fibre reinforced epoxy matrix composites for structural applications. They modified the matrix of the composite by adding multi-walled carbon nanotubes and n-butyl glycidyl ether in the matrix of these composites. Hot-press process was used to fabricate glass fibre reinforced unmodified and modified epoxy resin composites. They observed an increase in interlaminar shear strength of the composite with modified matrix. The results are supported by SEM studies.

Taniguchia et al (2012) determined the tensile properties of E-glass fibre by fibre bundle testing under a high strain rate. The results confirm that tensile strength and fracture strain of E-glass fibre is directly proportional to strain. The tensile strength of E-glass fibre depends on fibre diameter. The
smaller diameter fibres have greater strain rate addiction. Impact tensile strengths of glass and carbon fibres were investigated. They confirmed that tensile strength of high-strength glass fibres increases with the strain rate, but tensile properties of carbon fibre were independent with strain rate.

Ismail et al (1999) investigated the influence of unsaturated polyester resin on the physico-mechanical properties of the sand-polyester composites. The samples were prepared at different ratios such as 5% to 30% of unsaturated polyester to sand it is further subjected to \(\gamma\)-irradiation between 10 and 100 kGy. The compressive strength is directly proportional to unsaturated polyester resin. This is attributed to adhesion between the sand and unsaturated polyester under the effect of \(\gamma\)-irradiation. Infrared spectra confirmed the appearance of new bands due to the formation of SiC bond.

Suresha et al (2010) studied the friction and dry sliding wear characteristics of glass and carbon fabric reinforced vinyl ester composites. They conducted tests by varying the sliding distance with constant velocity. They observed that wear rate increases with the sliding distance. Coefficient of friction is found to be constant for wide range of sliding distances. They noticed few broken fibres during wear; interface separation took in the severe wear region. Carbon fabrics have more wear resistance than glass fabrics, it also reduces friction coefficient. They conclude that carbon fibre reinforced vinyl ester composites have better wear resistance and less coefficient of friction than glass fibre reinforced vinyl ester composites.

1.4.3 Carbon Fibre Composites

Composites world (2009) predicts the size of future WEG as shown in Figure 1.4. The blade weight of a 10MW–WEG is predicted to be 37 tons if it is made by utilizing CF.
Sandia (2013) builds and evaluates innovative and efficient large blades for WEG. Their present work focused on the development of a 100-meter blade for a 13.2 MW WEG. They have developed a 100-m blade using carbon spar cap known as SNL100-01. This is a modification to the baseline 100-m blade known as SNL100-00 which was made entirely using glass
fibres with similar blade geometry but the blade weight and cost was very high. The SNL100-01 design weighs around 74,000 kg, which is 35% less comparing SNL100-00 due to the addition of new spar cap, additional amendments such as reduction in spar thickness and thin blade root were made. Although efforts were made to reduce weight, further possibilities still exist to reduce the weight of SNL100-01; as the design was not optimized.

Gamstedt et al (2002) studied the adaptability of unsaturated polyesters in a carbon fibre composite by synthesizing unsaturated polyester resins with different ratios of maleic anhydride, o-phthalic anhydride and 1, 2-propylene glycol as precursors. It was found that the interfacial shear strength of untreated carbon fibres increases with increasing degree of unsaturation of polyester resin; this can be controlled by using relative amount of maleic anhydride. Strongest interface was obtained in polyester resin with the highest relative amount of maleic anhydride.

Feih & Mouritz (2012) conducted experiments on carbon fibre reinforced epoxy composites at elevated temperatures. They observed that the fibre modulus is not affected when the composite is heated in an inert atmosphere this was due to the absence of surface oxidation. They observed that the reduction in fibre strength was proportional to temperature.

Gao et al (2004) investigated the nature of interphases of CF reinforced epoxy composites with respect to surface features, fracture and adhesion. They determined the variation of adhesive and attractive forces on oxidized surfaces of high modulus and intermediate modulus carbon fibre. They conclude that interphases influence the mechanical properties of hybrid composite.
Ray (2006) evaluated the effect of temperature on shear strength of carbon fibre reinforced epoxy composites and glass fibre reinforced epoxy composites in hygrothermal conditions. Mechanical tests were performed to identify the influence of environmental damage in relaxation process. Finally they conclude that higher temperature generated during hygrothermal ageing increases moisture intake and alters the threshold of delamination.

Berbinau et al (1999) examined the microbuckling failure of unidirectional carbon fibre laminates loaded in compression. By successive testing they observed that the fibres undergo bending without failure in tension in their convex side; and the fibres failed in compression on their concave side.

Attempts have been made by Pérez-Pacheco et al (2013) to understand the effect of moisture inclusion on mechanical properties of unidirectional carbon fibre and epoxy laminates under moist environments. They observed that incorporating silane coupling agent in the matrix favours fibre-matrix adhesion; it also improves the mechanical properties of laminates and reduces the effect of humidity during tensile loading.

Han & Chung (2012) studied the effect of incorporating fillers in carbon fibre composites. They observed that the filler inclusion is more effective for crossply laminates than unidirectional laminates. They conclude that addition of filler increases the interlaminar interface thickness and mechanical properties of the composite.
Sandia (2006) reports the fabrication, testing and analysis of anisotropic carbon/glass hybrid composites. The specimens were made using vacuum assisted resin transfer moulding. Properties such as density, fibre volume fraction and void fraction of composites were tested. They observed that end constraints affect the results of shear modulus. For carbon fibres oriented at 15° for two-thirds of the laminate volume, maximum extension with least loss in axial tensile stiffness is obtained. The predictions made by maximum strain criteria are found to fail for laminates which respond nonlinearly to loading. For anisotropic laminates, the tensile modulus result is correlated according to the classical lamination theory.

Lee & Soutis (2007) investigated the compressive strength of CF reinforced epoxy composites. They failure mechanism were studied by using optical micrographs. They observed that the failure of thicker specimens was due to geometric discontinuity which resulted in premature failure of composites. Hence, the compressive strength was less. They conclude that multidirectional quasi-isotropic composites with a distributed ply stacking sequence have to be used to evaluate the unidirectional compressive strength and size effects on composites.

Pe´rez-Pacheco et al (2011) investigated carbon fibre reinforced epoxy matrix composites in thermal environment. They analyzed the heterogeneity of the matrix for the effective mechanical properties of the composite. The development of an interphase was studied. They observed that even though the composite had poor mechanical properties, fibre–matrix interface failure did not occur.
Yang et al (2013) analyzed a large composite wind turbine blade. They evaluated the response of blade during loading and found that shell debonding from the adhesive joints is the failure mechanism which leads to blade failure. They used a video metric technique to identify the deformation of the blade. The parts of a blade are also illustrated by them as shown in Figure 1.5.

**Figure 1.5 Parts of a long WEG blade**
Bazhenov & Kozey (1991) analyzed the compression fracture of unidirectional carbon fibre-reinforced composites. They studied the effect of volume fraction, tensile strength, temperature and stress concentrators on the compression strength and fracture mode of the composites. They observed longitudinal splitting of carbon fibres during compression initiates the failure of the composites. They observed new failure mode of composites.

Harris et al (1971) investigated the fracture toughness of carbon fibre reinforced polyester matrix composites. They analysed the effect of moisture on fracture toughness of composites by exposing the composites to steam. Fractographic analysis was made to identify the mode of fracture. The results were analysed according to various theories of fracture of composites.

Compositesworld (2007) reports that as longer blades are being used in WEG as they increase the swept area. If carbon fibre is used in blades with optimal aerodynamic design; the blades would be slimmer. The weight of CF reinforced blades would be 30 percent lesser than a traditional blade made up of GF reinforced in polyester matrix composites. A 59m long blade of Vestas 3 MW WEG weighs 12.6 tons. But a 61.5m long blade of Repower 5MW WEG weighs 18 tons as the manufacturer uses GF reinforced blades supplied by LM Glasfibre. Higher specific stiffness of carbon fibre provides the possibility to manufacture slimmer blades which will reduce the cost of energy further.

Vestas (2012) utilized improved carbon fibre technology and structural shell design to manufacture a 62 m long blade for their 3.3 MW WEG. The weight of this blade is 20 percent lesser than the existing 54.65 m blade for the same WEG.
Suresha et al (2006) investigated tribological properties of CF reinforced epoxy matrix composite by comparing it with GF reinforced epoxy matrix composites. The sliding velocity is varied from 2 to 5m/s and the loads are varied from 20 to 80 N in a pin-on-disc set up. They observed that the wear behavior of CF composites are excellent than GF composites, because CF improves self lubricating property of composites.

Kumaresan et al. (2011) investigated the friction and dry sliding wear behavior of carbon fabric-reinforced silicon carbide filled epoxy composites. The weight fraction of silicon carbide filler was varied in the order of 0%, 5% and 10 % so as to obtain composite samples of three different compositions. Carbon fabric-reinforced epoxy composites with silicon carbide filler were prepared by hand lay-up technique followed by compression moulding. They observed that incorporating silicon carbide fillers in carbon epoxy composites improve the mechanical properties of composites. Carbon fibre and fine silicon carbide particles not only form a hard phase in the soft polymer matrix but also strengthen the combination of the interface between the reinforcement and the epoxy matrix thus they increase the elastic modulus of this composites. Also, increase in silicon carbide filler content in the carbon epoxy composite enhanced the tensile strength, Young’s modulus, and surface hardness, and decreased the elongation at break.

Zoltek (2010) differentiates blades manufactured by utilizing CF and blades manufactured only by GF. From Figure 1.6, It is evident that the weight of blade utilising CF is less.
1.4.4 Optimization

Kazanci (2004) studied the properties of seven carbon fibre reinforced micro composites, prepared by using stiff and flexible epoxy resin. The composites were tested for short-term and long-term strength tests. Some of his findings are:

(i) Properties of resin decide the mechanical behaviour of composites.

(ii) Stiff epoxy produces stronger and creep rupture resistant composites.

(iii) Stiff epoxy is stronger than the flexible epoxy.
He concludes that, besides matrix stiffness, fibre/matrix interaction and adhesion have strong effect on the mechanical properties of these microcomposites.

Ross (1996) describes that the experiments in Taguchi techniques were planned in such a way to estimate simultaneously two or more factors which possess their ability to affect the resultant average or variability of particular product or process characteristics. To accomplish this in a valuable and statistically proper method, levels of the factors are varied in a strategic manner.

Bottasso et al (2011) describe a procedure for design optimization of wind turbines. Aerodynamic shape optimization was done first, followed by structural blade optimization. Both methods were combined to get an optimum solution. This procedure is implemented in a computer program and further confirmed by optimization of a large wind turbine.

An integrated optimisation methodology was proposed by Park et al (2009) to optimise the manufacturing cost and the structural performance, the weight of laminates. Resin transfer moulding process was used for manufacturing. The fibre, the number of layers, the fibre orientation angle and layup, fibre volume fraction are optimised to minimise the blade weight and the cost of composite structure. Relation between cost of composite material and weight savings were discussed. The optimisation methodology forms a reference to cheap material selection in the design stage of wind turbine blade.

Jureczko et al (2005) describes the state of art in determining the optimal shape and material for blade. They found that computation of
aerodynamic load is complex as number of constraints and objectives have to be satisfied. An improved genetic algorithm was used for optimizing the objective functions. The authors considered the blade optimization as a multi-criteria optimum design. They developed a computer program package to optimize the wind turbine blade according to a number of criteria. Different blade models were created by means of an ANSYS, the dimensions of the blade model was also varied.

Song et al (2011) implemented MATLAB tool for optimum design of the blades in a 20KW the horizontal axis wind turbine blade. According to the space coordinate transformation theory; the space coordinates of the blade elements have been calculated. Solid Works and ANSYS softwares were combined to establish the blade model to describe shape and layup of the composite blade. The dynamic performance of the blade was checked by modal analysis; this provides a reference for structure design and analysis. This study has been successfully applied to production of 20KW composite wind turbine blades.

Zehnder & Ermanni (2006) developed a methodology for global optimization of composite structures. It consists of a flexible and robust optimization engine using evolutionary algorithms. The methodology is validated by optimizing the stiffness of a sailing boat within given weight and cost limits. The method is suited for the solution of real-world problems which gives optimized design output which is easy to manufacture.

Maalawi & Badr (2003) categorized practical families of horizontal-axis wind turbine blades, which are optimized to produce the largest possible power output. They developed a computer program to automate the overall
analysis procedures. A practical methodology has been presented for generating optimized blade configurations, which are supposed to produce maximum possible power output.

Park et al (2003) made a detailed study about weight minimization of laminates. They proposed a genetic algorithm based optimization methodology to minimize the weight of a composite structure with structural and process constraints. The thickness of laminates was considered as a design objective to be minimized.

Challis (2010) developed a discrete level topology optimization code to minimize the conformity of loaded structure.

Talischi (2012) used a matlab code for structural topology optimization. The characteristics of this code is its modular structure. The analysis and algorithm are separated from topology optimization formulation. Various steps taken in creating optimal shape is reviewed. Numerical examples were discussed to illustrate the capabilities of the generated code.

Radhika et al (2011) describes response surface as a valuable technique to deal with responses influenced by multi-variables. It is formulated for process optimization and detection of optimal combination of the parameters for a given response. This method significantly reduces the number of trials that are required to model the response function compared with the full factorial design of experiments.

Baradeswaran et al (2013) discuss that the objective of this technique is to find out the possible interaction between the factors.
1.5 OUTLINE OF THE THESIS

The contents of the thesis are as follows:

Chapter 1 is an introduction to WEG and it deals with literature review.

Chapter 2 describes the details of materials, experimental and testing methods of this investigation.

Chapter 3 illustrates the results and discussion of experiments performed.

Chapter 4 describes about optimization of experimental values and finite element analysis of the created NACA4412 blade profile.

Chapter 5 presents conclusions from this investigation and feasible future work.
Figure 1.7 Methodology for the present work
1.6 SUMMARY

Justification for choosing the topic of research is described; the objective of the present study is narrated. From the literature survey, it is evident that weight reduction is vital for longer blades. High performance carbon fibres should be used in optimal proportion in optimal parts of a WEG blade to avoid failure as shown in Appendix 1. Optimization is essential to choose the composite material as per the application. Analysis has to be performed on the composite material to simulate their behavior in different working conditions.