Materials for Wind Turbine Blades, Loading and Manufacturing Methods

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Abstract: The paper is an overview on composite materials that are used in blades of a wind turbine. The manufacturing methods, type of loadings that a blade is subjected to are also discussed. The promising usage of natural hybrid composites for wind turbine blades and its recyclability for environmental concern are an important area of research.
Keywords: Hybrid composites, manufacturing methods

1. INTRODUCTION

The wellbeing of our environment has become a prime concern of every developed country. They are shifting from nonrenewable resources to increased dependency on renewable energy resources. Wind energy is one among them. The cumulative world wind power installed capacity upto the year 2015 is 432,883 MW. The European Union seeks to develop 20 % of its energy consumption through expanding wind power plants.

In the year 1988 the first wind turbine for producing electricity was installed in Cleveland Ohio, USA, by Charles F. Brush and in Denmark in 1889 by Poul La Cour. [1, 2]The production of electricity using wind turbine made up of steel blades in the year 1941 in USA failed after few hundred hours of its intermittent operation. The failure indicated the important role material plays in the reliable functioning of Wind turbines. The next development in this area was Gedser Turbine built by Johannes Jull showed remarkable increase in the lifetime of the turbine. It comprised of 3 blades that were built from steel spars, aluminum shells and wooden ribs, installed at Gedser coast in Denmark in 1956 -1957. The years beyond 1970 saw an increased rise in blades built of composite materials. [3, 4] The Gedser turbine functioned for 11 years without maintenance which was an achievement with greater implications resulting from using composite material.

Composite materials are a mixture of two or more chemically different materials combined macroscopically which have superior properties than the individual combining entities. Properties of the material are significantly different from its constituents. Composites are classified based on the nature of constituents in the matrix. They are particulate and fiber based composites. The particulate type has 2 sub categories as randomly oriented and preferred orientation. The fiber based composite has further sub categories- Single and multiple layered. Fiber has a very high aspect ratio, greater than 10,000. The fibers of a material are stronger than its bulk form.

2. LOADS ON A WIND TURBINE BLADES DESIGN

A blade of wind turbine is subjected to external loads. These are flapwise bending load, edgewise bending load, gravitational load, inertial and torsional load. The flapwise and edgewise bending loads cause tensile and compressive stresses. The bending moments caused by the above loads cause damage (fatigue) and failure in 97% of cases. The cyclic loadings due to turbulence, velocity variation, wind shear and pressure variation are also experienced by blades. Wind pressure causes flapwise loading and edgewise loading is caused by gravitational force and torque. The flapwise bending load can be resisted by introducing spar and internal webs inside the shell. The laminates at the leading and trailing edge carry the bending moment associated with gravitational load and they are subjected to tensile and compressive loads. The loading is position dependent along the surface of the blade. The very long blades deflect more, thus the gravitational load and stiffness of material becomes the prime design driver. The stiffness to weight ratio is of major importance. The behavior and material interface of composites are needed to be studied to improve the lifecycle of a wind turbine blade to 20-25 years. The world's longest wind turbine rotor blade, 88.4 m long blade is made of carbon/glass hybrid composites.

Composite materials are typically used in blades and nacelles of wind turbines. Generators, towers, etc. are manufactured from metals. Blades are the most important composite based part of a wind turbine, and the highest cost component of turbines. A wind turbine blades consists of two faces (on the suction side and the pressure side), joined together and stiffened either by one or several integral (shear) webs linking the upper and lower parts of the blade shell or by a box beam (box spar with shell fairings) . The flapwise load is caused by the wind pressure, and the edgewise load is caused by gravitational forces and torque load. The flapwise bending is resisted by the spar, internal webs or spar inside the blade, while the edges of the profile carry the edgewise bending. From the point of loads on materials, one of the main laminates in the main spar is subjected to cyclic tension-tension loads (pressure side) while the other (suction side) is subjected to cyclic compression-compression loads. The laminates at the leading and trailing edges that carry the bending moments associated with the gravitation loads are subjected to tension-compression loads. The aeroshells, which are made of sandwich structures, are primarily designed against elastic buckling. The different cyclic loading histories that exist at the various locations at the blades suggest that it could be advantageous to use different materials for different parts of the blade.

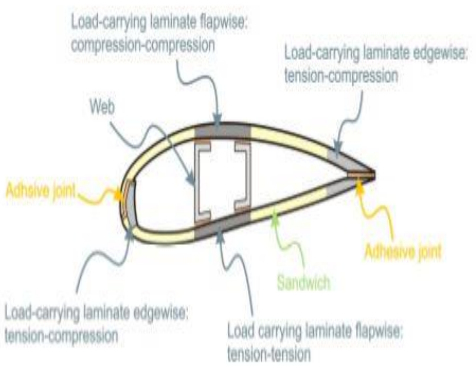

Fig. 1 Schema of a section of wind blade [5]

Mass of a blade increases cubically with respect to the length of the blade. The centrifugal and gravitational forces increase in magnitude owing to increasing length of blade. Gyroscopic loads are generally less intensive than gravitational and centrifugal loads. Operational loads depend upon pitching, yawing and are critical during emergency stop. Gyroscopic and operational loads can be controlled within permissible limits by adjusting parameters of the system. Blades that can withstand aerodynamic and gravitational loads are assumed to withstand gyroscopic and operational loads. [6]

2.2.1 Aerodynamic Load

Lift and drag forces of the blades aerofoil section generate aerodynamic load. It depends on wind velocity (V_W), blade velocity (U), surface finish, angle of attack (α) and yaw. Blade twist and pitch depend on angle of attack. The angle of attack is the angle made by the relative wind with the chord of the aerofoil section. The lift and drag forces are resolved into thrust (T) in the direction of rotation and reaction forces (R). The magnitude of reaction forces is high and acts in the flatwise bending plan and can cause deformation in the blade. Blade element momentum (BEM) theory is applied to obtain the drag and lift forces. The aerodynamic forces are summed over the length of the blade to calculate the reaction forces. [6]

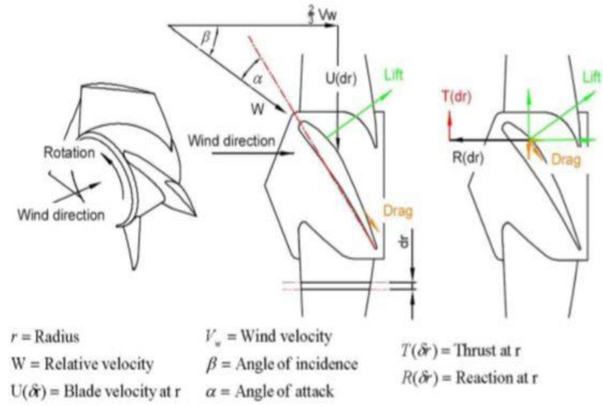

Fig.2.4 Aerodynamic forces generated at a blade element [6]

2.2.2 Gravitational and Centrifugal load

Gravitational centrifugal forces depend upon mass. They increase with diameter in a cubical fashion. Therefore, turbines which have a diameter under ten meters have negligible inertial loads, while for 20 meters and 70 meters and above inertial loads are moderate and critical respectively. The gravitational force equals mass times the gravitational constant, and its direction remains constant which is towards the center of the earth. It causes an alternating cyclic load case. The centrifugal force is a product of square of rotational velocity and mass. It always acts radially outward. [6]

3. COMPOSITES FOR WIND TURBINE BLADES

3.1 Fibers

Glass and carbon fibers. E glass fibers are typically mixed in thermosetting resin to produce turbine blades. The stiffness of the composite depends on the stiffness of fibers and their volume percentage. The volume percentage of fiber if 65 and above may lead to reduced fatigue stiffness of composite. This is due to the existence of dry regions between fiber and resin [7]. The other fibers which have more stiffness than glass fibers are aramid, basalt and Carbon fibers. S glass fibers have superior properties than E glass. S glass has higher tensile and compressive strengths than E glass fibers. Also, S glass fibers are costlier. Carbon fibers have lesser density than glass fibers but are stiffer. This has led to the development of lighter and stiffer turbine blades. Compressive strength of carbon fibers is less than glass fibers.

Aramid and Basalt fiber. Aramid is aromatic polyamide. Like carbon fibers high strength and stiffness are its characteristics along with lower compressive strength. They absorb moisture and degrade due to UV radiation. Basalt fibers are stiffer and lighter than glass fibers. They have been mixed with carbon fibers to produce hybrid composite. [8]

Hybrid composites. These composites are formed by mixing two or more fibers in a resin or a matrix. Since carbon fibers are expensive yet their small percentage with fibers like glass, aramid etc. can form a hybrid composite with superior mechanical properties. Though Carbon fibers have lower ultimate strain, hybrid composite of carbon and glass fibers has larger ultimate strain. Ong and Tsai demonstrated full replacement by carbon fibers would lead to 80% weight saving and cost increase by 150%, while a partial replacement (30%) would lead to only 90% cost increase and 50% weight reduction for a 8 m turbine.[9]. Additional investigations are required for the optimal composition of the materials.

Natural fibers. They are abundantly available, environmentally friendly and of low cost. On the contrary they absorb moisture and have low thermal stability [10]. Eg- Sisal, jute, flax, bamboo etc. Holmes et al. [11] demonstrated that bamboo-poplar epoxy laminate has high strength and durability. In a series of investigations, a group of Nepali, Danish and Australian scientists studied the applicability of different timbers for wind turbines, and demonstrated that the turbines with wooden blades represent a reliable and low cost option for the developing countries. [12]

3.2 Matrix

Typically, thermosets (epoxies, polyesters, vinyl esters) or (more seldom) thermoplastics are used as matrices in wind blade composites.

Thermosets. It is the most commonly used matrix for composite, around 80% composites are based on thermoset polymer matrix. They offer higher fluidity, less curing time thus lesser processing time. Initially, polyester was in use for developing turbine blades. Large turbine blades saw an increase in usage of Epoxy resin. Even lesser curing time, and energy efficient production of composite is an exciting area of research. However, thermoset matrix cannot be recycled owing to degradation at temperatures above their melting temperatures. Thermoplastics (as differed from thermosets) have melting temperatures lower than their decomposition temperatures, and, thus, can be reshaped upon melting. While the fracture toughness of thermoplastics is higher than that of thermosets, fatigue behavior of thermoplastics is generally not as good as thermosets, both with carbon or glass ber. [13]

Thermoplastics. Thermoplastics are the prominent alternatives for the thermosets matrices. Thermoplastic composites are easily recycled and on the other hand due to high viscosity it needs high temperature for processing and it is tedious to manufacture large parts. Some of the other disadvantages include the possibility of automatic processing, elongation at fracture and unlimited shelf life of raw materials.

Nanoengineered polymers and composites. By adding nanomaterial in the matrix enhances the mechanical properties of the composite material. As per the study even a 0.5% of addition of Nano Reinforcement in the polymer matrix improves the fatigue resistance, fracture and shear toughness upto 80%. [14, 15]Loos, Manas Zloczower and colleagues developed various wind turbine blades with secondary carbon nanoparticles reinforcement and shown that the addition of a little amount of carbon nanotube increases the lifetime of the blade upto 1500% [16] Koratkar and colleagues calculated graphene as a secondary reinforcement for the Nano modification of wind turbine composites, and presented that graphene helps in improving the strength, long-life turbine blades for the wing industry.[17] It has been observed that in some cases ,the usage of nano modified polymers as matrix have shown to degrade the mechanical properties like strength and toughness.it was exhibited that the high investments for the gains of the lifetime of the composited is justified. Nevertheless the economic challenges against the Nanoengineered wind turbines are used

4. MANUFACTURING OF WIND TURBINE BLADES

Wind turbine blades were often produced using the wet hand lay-up technology in open molds during the initial days of wind energy conversion. Rollers and brushes were used to impregnate glass fibers. A rotor blade consists of two aeroshells adhesively bonded together through webs or spars. Hand layup method could produce small and medium sized blades. This method poses some challenges. These are high labor costs, relatively low quality of products. [18] Vacuum infusion and Prepreg technologies improved the quality of manufacturing. The Prepreg technology utilizes pre-impregnated composite bers, which contain matrix material bonded to them. The Prepregs are then formed into complex shapes. Resin infusion technology however is the most widely used to manufacture large wind rotor blades. In this method bers are aligned in closed and sealed mold, and resin is injected into the mold cavity under pressure.

The resin is allowed to wet the fibers, then the entire material is cured using heat. Resin Transfer Molding (RTM) and Vacuum Assisted Resin Transfer Molding (VARTM) are two types of resin infusion methods. In RTM resin is injected inside the mold under a high pressure while in Vacuum assisted resin transfer molding resin is injected inside the old at a pressure below atmospheric. SCRIMP (i.e., Seemann Composite Resin Infusion Process) a variation of Resin infusion method was developed in late 1980s and is suitable for producing large and thick parts. The vacuum assisted resin transfer molding (VARTM) is the most common manufacturing method for manufacturing of wind turbine rotor blades. In this method, layers of fabrics of dry bers are aligned in the direction along the length of the blade, and positioned on mold parts along with polymer foams for sandwich structures. Ply drop process makes the blade thick at the root section as the plies starting at the root section terminates partly towards the end of the blade. Subsequently, the fabric is covered by a vacuum bag and made air-tight. After this low viscosity resin flows inside and over and underneath the fabric wetting it. Thereafter, the resin is left for curing at room temperature. [18] Usually, wind turbine blades are made up of two aeroshells with a load-carrying box (spar) or internal webs that are then bonded together. This manufacturing method VARTM is suitable for upscaling, as the number of resin inlets and vacuum suction points can be increased. There exist challenges with upscaling- fibers remain non-wet, formation of wrinkles at double-curved areas, many layers of dry fabrics must be kept in place and should not slip relative to each other. The blade is thick at the root section. After manufacturing, the blades undergo quality control and manufacturing defects are repaired. The blades require a huge amount of material so their processing should be such that processing results in minimum defects. Materials properties should be such that damages and larger manufacturing defects can be tolerated. Prepreg process is more expensive than infusion process. However, the Prepreg composites have more stable, better and less variable mechanical properties than the composites produced by resin infusion. The Prepreg method of producing composites is relatively environmental friendly, and controlling the materials properties and higher volume content of bers is possible. [18]

5. CONCLUSION

The most expensive component of a wind turbine are its blades. The power produced by a wind turbine is ideally proportional to square of length of a blade. The manufacturing and handling of a blade requires extensive care owing to high material cost and size. Commonly used composite material for a wind turbine blade is glass-epoxy composite. The natural fibers are gaining importance in composites for their environmental friendliness and relatively good mechanical properties. The matrix material which can cure faster and at lesser temperature is an area of research. The interface between the fiber and matrix requires more research. Recyclability of blades to bring them to some other use have also been reported. There is a shift in inspection of blades from manual ways to automation which can well manage the maintenance and timely operation of wind turbines.

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