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Application of E-type Glass Fiber Reinforced Plastic with Epoxy matrix in Wind Turbine Blades

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Abstract — *Wind energy is one of the important renewable energy generation resources for the solution of global energy problem. Wind turbine blades experiences wind and gravity loading which are critical factors for the performance of the consideration for the materials used. E-type Glass Fiber with Epoxy matrix possesses high stiffness, low density and good fatigue resistance along with low cost, which makes them good candidate for the selection of wind turbine blade material. In this paper, mechanical properties of E-type Glass Fiber with Epoxy matrix composite materials are discussed with future challenges for materials in the field of wind turbines*.

Keywords- *Wind Turbine Blade, GFRP, E-type Glass Fiber, Epoxy Matrix*

INTRODUCTION

In present days engineering products, there is a high demand being placed on components made of fiber reinforced plastics (FRP). Fiber reinforced plastic (FRP) composites have been widely used in engineering application such as power generation equipment, automotive, aircraft and manufacture of spaceships and sea vehicles' industries due to their significant advantages over other materials. These are an economical alternative to stainless steel and other materials in highly corrosive industrial applications. They provide high specific strength/stiffness, superior corrosion resistance, light weight construction, low thermal conductivity, high fatigue strength, ability to char and resistance to chemical and microbiological attacks. As a result of the widening range of applications of these materials, its study has become a very important subject for research [1, 2].

WIND TURBINES

Wind powered systems have been widely used since the tenth century for water pumping, grinding grain and other low power applications. The available wind resource is governed by the climatology of the region concerned and has a large variability from one location to the other and also from season to season at any fixed location. Wind power devices are now used to produce electricity, and commonly termed wind turbines. The orientation of the shaft and rotational axis determines the first classification of the wind turbine. A turbine with a shaft mounted horizontally parallel to the ground is known as a horizontal axis wind turbine or (HAWT). A vertical axis wind turbine (VAWT) has its shaft normal to the ground [3, 4].

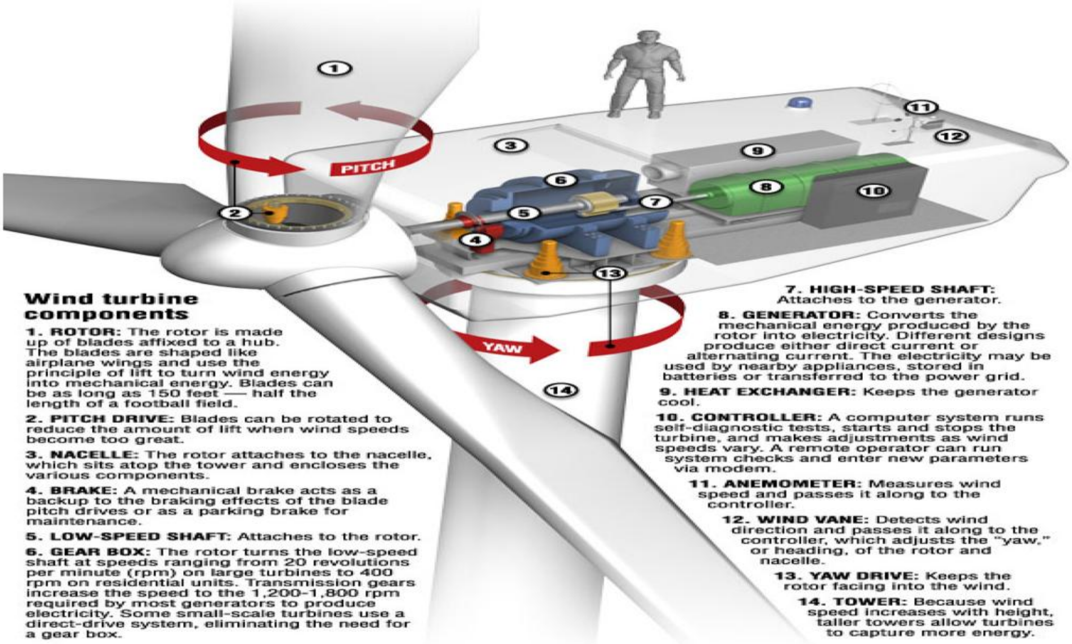

Fig. 1 Typical configuration of a modern large scale wind turbine (www.desmoinesregister.com)

Loads applied on blades

The most important load cases are dependent on individual designs. The main sources of blade loading are listed below [5]:

1. Aerodynamic
2. Gravitational
3. Centrifugal
4. Gyroscopic
5. Operational

The load magnitude will depend on the operational scenario under analysis. If the optimum rotor shape is maintained, then aerodynamic loads are unavoidable and vital to the function of the turbine. As turbines increase in size, the mass of the blade is said to increase proportionately at a cubic rate. The gravitational and centrifugal forces become critical due to blade mass. Gyroscopic loads result from yawing during operation. They are system dependant and generally less intensive than gravitational loads. Operational loads are also system dependant, resulting from pitching, yawing, breaking and generator connection and can be intensive during emergency stop or grid loss scenarios. Gyroscopic and operational loads can be reduced by adjusting system parameters. Blades which can withstand aerodynamic, gravitational and centrifugal loads are generally capable of withstanding these reduced loads [5].

MATERIAL REQUIREMENT FOR WIND TURBINE BLADES

Desirable Properties

The operational parameters and loading conditions lead to the following requirements focused on stiffness, density, and long-time fatigue:

- high material stiffness is needed to maintain optimal aerodynamic performance,
- low density is needed to reduce gravity forces,
- Long-fatigue life is needed to reduce material degradation.

The optimal design of the rotor blades is today a complex and multifaceted task and requires optimization of properties, performance, and economy.

The combined result of the design process and the materials can be illustrated in the form of rotor blade weight as a function of rotor blade length, as presented in Figure 2. The lower end of the curve represents the relatively short blades of length 12–15 m, as were common in the early years of wind turbine design (1980s). The points represent rotor blades of increasing length, as developed until the present. An empirical curve is shown for the points representing blades with lengths below 40m, giving a power law with an exponent of about 2.6; this is lower than expected for a simple up-scaling of the design on a volume basis (exponent 3), but it corresponds more closely to up-scaling of only two dimensions (length and thickness, exponent 2). This rather low exponent is a good indication of the high quality of the design

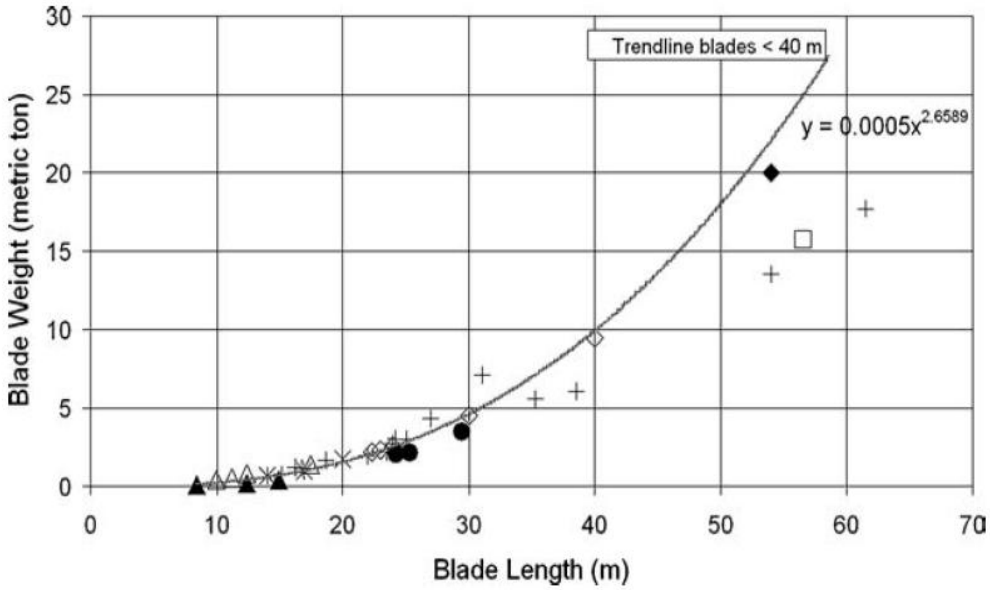

Fig. 2 Development in rotor blade weight versus length Symbols indicate different manufacturers and processing technologies

process. Three recent and very long rotor blades of 54 to 61.5m (2), plotted in Figure 2, show the further improvement in the design process by the points being below the extrapolated empirical curve.

The materials properties requirements of high stiffness, low weight, and long fatigue life can be used to perform a materials selection, initially looking at all materials. The property combinations presented in Reference (7) are illustrative for a first selection of potentially usable materials classes. In a simplified form, the diagram of stiffness versus density in

Figure 3 shows the procedure to be used (8). For details of materials selection, see Reference (7). The mechanical design of a rotor blade corresponds nominally to a beam, and the merit index is for this case

$$M_b = E^{1/2}/\rho$$

where E is the material stiffness and ρ is the material density. Lines of constant M_b are superimposed on the diagram, and materials that fulfill the criterion (partially or completely) are on the line and to the upper-left of the line. The two lines shown in Figure 3 are arbitrary and illustrate lines of materials that are equally good in terms of stiffness and density for a cantilever beam. The lower of the two lines indicates that potential candidates materials are wood, composites, porous ceramics, metals, and ceramics. The lower line has a merit index of $M_b = 0.003$ with units of E in GPa and ρ in kg/m^3.If the merit index is doubled to $M_b = 0.006$, the upper line is valid. This line indicates that candidate materials are woods, composites, and ceramics.
A second criterion is stiffness on an absolute scale; a stiff material causes less deflection of a cantilever beam than does a flexible material. In the diagram of Figure 3, a stiffness criterion corresponds to a horizontal line.

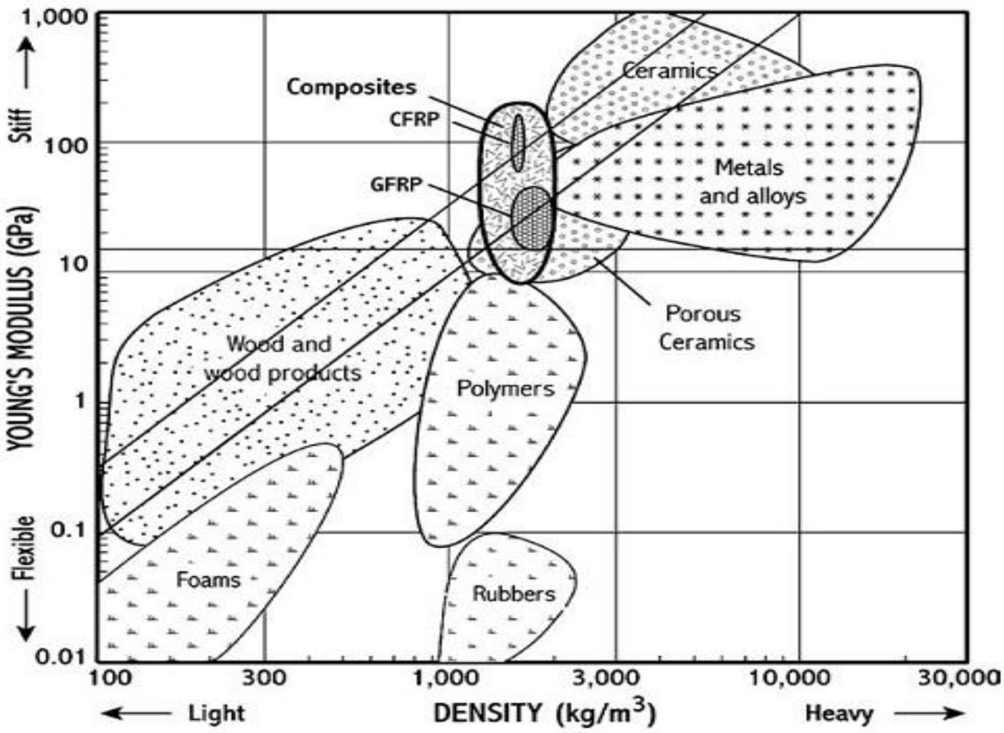

Fig. 3 Diagram showing stiffness versus density for all materials.

(The merit index for a beam $M_b = E^{1/2}/\rho$ is represented by sloping lines with M_b equal to 0.003 (lower line) and 0.006 (upper line). The criterion for absolute stiffness E = 15 GPa is indicated by the horizontal line (4). Development in rotor blade weight versus length Symbols indicate different manufacturers and processing technologies)

Deflection considerations are related to rotor blade geometry and dimensions, as well as to the overall design of tower and rotor, in particular the blade deflection when the rotor blade passes the tower. A sensible deflection requires a material stiffness of 10–20 GPa; for illustration, the line for E = 15 GPa is drawn in Figure 3. Materials on or above this line satisfy the criterion, and it is seen that most woods, some composites, and some porous ceramics are excluded. In terms of materials strength, i.e., resistance against long-time fatigue loads, and extra high loads, it is also important to consider materials fracture toughness. The toughness in relation to density is collected in a similar diagram, which can be found in Reference (7). The merit index for high fracture toughness and low density shows that candidate materials are woods and composites.

Materials for Rotor Blades

The combined materials performance criteria identify the candidates for rotor-blades as woods and composites. Woods are potentially interesting because of their low density, but their low stiffness makes it difficult to limit the (elastic) deflections for very large rotor blades. Even wood materials with cellulosic fibers all aligned in the major load-bearing directions are close to the maximum performance possible for wood. Furthermore, wood is a natural material and thus environmentally attractive, but at the same time difficult to obtain in reproducible and high quality, which is a requirement for stable and economical manufacturing of rotor blades and thus economically attractive wind energy. Partly for these reasons, composites have until now been most extensively used.

Fibers

The materials science basis for these composites and their potential use is the existence of strong and stiff fibers (9–14) and compliant and easily processable polymers, such as thermosets and thermoplastics (15). The strong and stiff fibers are themselves not usable for structural purposes; their good properties can be exploited only as an important component of composites. Nonetheless, it is important to describe the fibers even if the composites are the real structural materials for rotor blades. By far the most widely used fibers are glass fibers. In recent years carbon fibers have become of increasing interest because of the requirements presented by the ever-larger rotor blades and the decreasing price of carbon fibers. Other potentially interesting fibers are aramid, polyethylene, and cellulose, all of which have moderate mechanical properties, and low or very low densities. Key data for these fibers and their composites are collected in Table 1.

GLASS FIBERS

Glass is generally composed of SiO_2, Al_2O_3, and smaller amounts of other oxides (9–11). The atoms of Si and O form a lattice with no crystallographic order, and glass fibers are therefore amorphous with isotropic properties, e.g., stiffness and thermal expansion. Glass fibers are produced in several chemical compositions, for specific purposes. The glass fiber called type E (electrical) is the most widely used for composites. Glass fibers have diameters normally in the range of 10 to 20 µm and are produced from molten glass by pulling fibers from spinnerets into bundles of hundreds to thousands of individual fibers. Their surfaces are normally coated immediately with a polymer sizing, typically a silane compound, to protect the fiber against cracks and adhered water; the sizing, which is a multi component compound, is also designed to improve the bonding of the glass fiber surface to the polymer matrix, typically a thermoset, and thereby enhance the properties of the composite.

	Fibers			Composites					
Type	Stiffness E_f GPa	Tensile strength σ_f MPa	Density ρ_f g/cm^3	Volume fraction V_f	Orientation θ	Stiffness E_c GPa	Tensile strength σ_c MPa	Density ρ_c g/cm^3	Merit $E_c^{1/2}/\rho_c$
Glass-E	72	3500	2.54	0.5	0°	38	1800	1.87	3.3
				0.3	Random	9.3	420	1.60	1.9
Carbon	350	4000	1.77	0.5	0°	176	2050	1.49	8.9
				0.3	Random	37	470	1.37	4.4
Aramid	120	3600	1.45	0.5	0°	61	1850	1.33	5.9
				0.3	Random	14.1	430	1.27	2.9
Polyethylene	117	2600	0.97	0.5	0°	60	1350	1.09	7.1
				0.3	Random	13.8	330	1.13	3.3
Cellulose	80	1000	1.50	0.5	0°	41	550	1.35	4.7
				0.3	Random	10.1	170	1.29	2.5

Table 1. Composite materials based on the fibers listed and a polymer matrix with properties E_m = 3 GPa, σ_m = 100 MPa, and ρ_m = 1.2 g/cm^3. The composite properties are calculated from the simple composite theory (law of mixtures); the orientation factor is 1 for aligned composites and 1/3 for random composites

Glass fibers for composites have a good combination of properties: moderate stiffness, high strength, and moderate density, as listed in Table 1.

CARBON FIBERS

Carbon fibers (5–7) are composed of nearly pure carbon, which forms a crystallographic lattice with a hexagonal shape called graphite. The crystallographic structure and anisotropy of graphite dictates the arrangement of the hexagonal planes, such that the planes must be oriented parallel to the fiber axis in order to achieve useful properties of the fibers. In all carbon fibers there is a high degree of alignment of the graphite planes, which varies somewhat depending on the type of fiber and its production method.

The carbon fibers are produced by two different methods. The first and most widely used method starts with polyacrylonitrile (PAN) fibers. These textile fibers are oxidized, stretched, and finally heat-treated at temperatures of 1500 to 2500◦C. The second method starts from natural tar, which contains the graphite units in a random mixture. Various processing steps lead to the production of fibers through spinnerets, which ensure alignment of the graphite planes and thus again the required properties of the fibers. Both methods include rather expensive raw materials and

numerous and expensive processing steps.
Carbon fibers for composites have an excellent combination of very high stiffness, high strength, and low density, as listed in Table 1. However, the use of carbon fibers in a hybrid combination with glass fibers has today placed focus on carbon fibers with moderate to low stiffness and relatively high failure strain, so that the carbon fibers can share the loads and deform in concert with the glass fibers of moderately high failure strain.

Matrix Materials

The polymeric composites with the above mentioned fibers have matrices of polymers, typically thermosets or thermoplastics (15). Both are rather soft and flexible (low stiffness of less than 4 GPa), and their main purpose is to bind the fibers together so that they can act in concert and give a functional composite for structural purposes. The toughness and especially failure strain is moderate for thermosets, 5–8%, and large for thermoplastics, 50–100%, and the matrices thus induce toughness in the composites, in particular via energy absorbing mechanisms related to the interface. The early composite materials for rotor blades were glass fibers combined with polyester, a material, as well as a processing method, taken from the boat industry. The easy availability of materials and processing was part of the reason for the rather fast development of rotor blades and wind energy in the early years.
The thermosets most used are polyesters, vinylesters, and epoxies. All have stiffness values of 3–4 GPa and densities of 1.1–1.3 g/cm^3 and thus match the fibers reasonably well. The thermosets go through an irreversible curing reaction, which implies a contraction giving internal stresses in the composites.
The thermoplastics for composites for rotor blades have been under development over the past 10–15 years. The properties have also rather low values: stiffness values of 1–3 GPa, and densities of 0.9–1.4 g/cm^3. The interest is centered on the potential recycling of thermoplastic polymers, and this has been investigated, although no clear procedure has been established for recycling of thermoplastic polymer composites. The thermoplastics go through a melting and solidification process during processing, which is potentially fast. The solidification also introduces a thermal contraction leading to internal stresses; these could be high because of the rather high melting point/processing temperature for thermoplastics, and better thermoplastics typically have higher melting points. The internal stresses, of whatever origin, affect the mechanical properties often detrimentally.

Composite Materials

The fibers and the matrix are combined into the composite (13, 14, 16–19). Many combinations and mixing ratios are possible, and the composite properties, most generally, are governed by the fibers, the matrix, and the interface established between these (normally) two components. Properties of fibers and matrices are, of course, important, and so are the ways in which they are arranged in the composite. The important parameters are their relative amounts, often described by the fiber volume fraction, and the spatial orientation of the fibers. As a simple illustration,
the stiffness of the composite Ec is controlled and calculated according to

$$E_c = \eta \cdot V_f \cdot E_f + V_m \cdot E_m,$$

where E is the stiffness (elastic modulus), V is the volume fraction, η is an orientation factor for the fibers, index f is fiber, and m is the matrix. For a perfect composite with no porosity, $V_f + V_m = 1$. The orientation factor is equal to 1 for aligned parallel fibers loaded along the fiber direction; for a randomly oriented fiber assembly in two dimensions (in a plane; often called a fiber-mat) the orientation factor is 1/3.
A range of values, listed in Table 1, illustrates the simple, basic mechanical properties of composites based on the various fibers mentioned above. The fibers are normally the dominant contributor to the composite properties, and for ease of comparison, all composite properties are calculated for a matrix of thermoset with parameters E_m = 3GPa, σ_m = 100 MPa and ρ_m = 1.2 g/cm^3.For each composite based on a given fiber, the first line describes a composite with 50 volume% fibers, fully aligned η = 1, whereas the second line describes a composite with 30 volume% fibers arranged in a random planar mat.
In Table 1 the first column lists the typical fiber properties and the following columns list the calculated composite properties. The final column shows the elastic merit index for a cantilever beam, as discussed above. It is clear from the composite stiffness that all aligned fiber composites have rather high values, whereas nearly all random fiber composites have stiffness below the limit of 15 GPa (discussed above).

CONCLUSIONS

Glass fiber composites have moderate properties and were selected widely because of easy availability, low cost compared to other fiber materials and known processing technology. The other potential composites are slightly better, and only carbon fiber composites show significant improvements over the well-established glass fiber composites. The modern materials are in most cases a combination of glass fibers and carbon fibers in a hybrid construction. Selected parts of the rotor blade are made from the hybrid composites on a macro scale, typically the outer weight critical elements, made in carbon fiber composites, or the hybrid aspects can be on the material structure level where glass and carbon fiber are intermixed on a layer basis or perhaps even on the basis of individual fiber bundles or fibers. This hybrid concept is often a compromise between the improved performance of carbon fibers and the high cost of carbon fibers. .

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