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Thermoplastic Materials for Wind Turbine Blade Design

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ABSTRACT

As wind-generation capacity increases globally, blade manufacturers turn their attention to lighter and larger blades. Blade design requirements of high stiffness, high strength to weight ratios and excellent fatigue performance, are becoming the main focus of optimizing blade manufacturing. This study investigates a thermoplastic material, PEEK with 40% carbon fillers, as a replacement for thermoset composites, the dominant material in blade design. Injection molded thermoplastic PEEK CF40 structures and vacuum-bagged E-glass/epoxy laminates are compared in order to decide upon the applicability of thermoplastic materials in blade manufacturing. Experimental tensile and flexure testing of these structures, as well as finite elements analysis using ABAQUS/CAE, show the superiority of PEEK CF40 as compared to E-glass/epoxy composites. Overall, PEEK CF40 can potentially provide up to 28% reduction in weight and higher stiffness without significant reduction in elongation.

1. INTRODUCTION

One of the most important sources of renewable energy today is wind power, which is growing at an average rate of 30% annually with a worldwide installed capacity of 282, 275 MW (WWEA 2012). Wind energy has a promising long-term potential with an approximate value of 40 times the current electricity demand (WWEA 2012).

As wind-generating capacity increases globally, blade manufacturing is focused more and more on lighter and larger blade construction, to capture more energy from the wind and enable maximum production. Optimizing the materials used in blade manufacturing is very important in order to fulfill the expectations of lighter weight and lower cost structures. The main material requirements for blade design are high stiffness to weight ratios, high strength to weight ratios, and an excellent fatigue performance (Brondsted 2005). Composite materials can provide these properties and they are the primary choice in the wind turbine blade industry (Brondsted 2005).

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Thermoplastics provide higher toughness, faster processing, unlimited shelf life of the semi-raw materials, a clean working environment, and easier recycling (Brondsted 2005). However, blade designs may include thermoplastics as matrix components of the composite structure, but an all-thermoplastic blade manufactured by injection molding has not been realized yet due to the manufacturing challenges they present: high processing temperatures (149°C to 260°C) requiring high temperature resistant tooling, and faster heating and cooling rates to achieve sufficient crystallization process (Brondsted 2005).

This paper investigates the applicability of thermoplastic materials to wind turbine manufacturing, by examining their strength and stiffness to weight ratios through experimental testing and finite element analysis.

2. MATERIAL SELECTION AND MANUFACTURING

The most widely used matrix material in blade manufacturing is thermosets. Polyesters, vinyl esters and epoxies having stiffness values of 3-4 GPa and densities of 1.1-1.3 g/cm^3, are the most commonly used thermosets (Talreja 2000 & Brondsted 2005).

Glass fibers having a moderate stiffness, high strength, and moderate density, provide a good combination of properties as reinforcing agents, and therefore are most widely used fibers in blade manufacturing (Pyrz 2000). The increasing length of the blade has led to use of other materials such as carbon fibers, which are currently used in the spar and structural elements of wind blades longer than 45 m (Brondsted 2005). The high stiffness and low density of carbon fibers allow for a stiff and light blade design with a thinner profile. This study compares the mechanical properties of a thermoset composite reinforced with E-glass fibers to thermoplastic Polyetheretherketone (PEEK) with 40% carbon fillers.

Most commonly used large-scale blade manufacturing techniques are wet lay-up, pre-preg, and resin infusion. For this study E-glass/epoxy laminates were prepared by vacuum bagging, while PEEK CF40 samples were injection molded.

3. SPECIMENS AND TESTING

The thermoset and thermoplastic specimens were tested both under tension and flexure, in order to determine and compare their strength and stiffness. ASTM D638 and ASTM D790 standards were used to determine the geometry of the materials for tensile and flexure testing, respectively.

Type I specimen geometry was chosen for the tensile test (ASTM D638). 12-layer composite laminates made of woven E-glass fiber fabric and epoxy using vacuum bagging were cut into beams 12.7 mm wide and with a gage length of 25.4 mm. The thickness of the specimens varied between 3.7 mm and 4.2 mm. PEEK CF40 specimens were injection molded into tensile test specimens (dog bones) 10 mm wide, 75 mm long and approximately 4.2 mm in thickness.

For the flex test, a span length to thickness ratio of 16:1 was used. The thickness of the 12-layer laminates (60 mm wide and 120 mm long) needed to be in the same range as the thickness of the PEEK CF40 dog bones, which were used for flexure testing as well tensile testing. The average thickness of the composite specimens for flex test was 3.2 mm.

4. RESULTS AND DISCUSSION

4.1 Experimental Testing

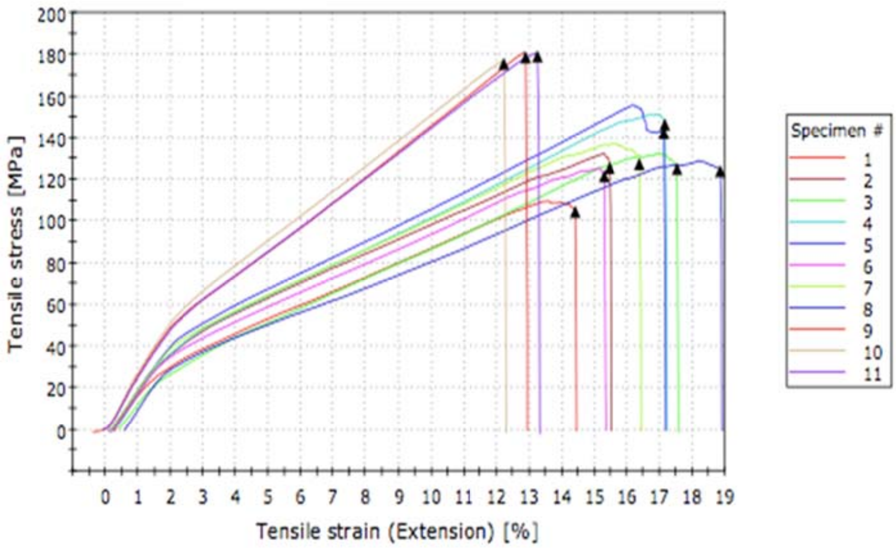
Tensile Testing Both E-glass/epoxy and PEEK CF40 were tested to obtain the stress-strain behavior of the materials (Fig. 1). An INSTRON 3366 load frame was operated with a load cell of 10 kN at 5 mm/min. Specimens were loaded until fracture. Data was obtained from a total of 11 specimens for each material.

The average ultimate stress of the thermoplastic material (PEEK CF40) is almost 1.5 times that of the thermoset composite. The thermoplastic also appears much stiffer by a factor of approximately five. Table 1 gives a summary of the average properties of the two materials determined by tensile testing.

Table 1: Mean Tensile Properties of E-glass/epoxy and PEEK CF40 Specimens

Material	Ultimate Tensile Stress [MPa]	% Elongation	Tensile Modulus [GPa]
E-glass/epoxy	146	15.5	2.28
PEEK CF40	220	3.24	10.3

Flexure Testing 5 thermoset and 10 thermoplastic specimens of the materials being investigated were also tested under 3-point bending conditions at 2 mm/min using the same INSTRON frame and load cell. Measurements were taken at multiple points on the specimens and Fig. 2 shows the test data for both materials. Table 2 summarizes the mean values of the ultimate flexure stress and the flexure modulus, which is used as an indication of the stiffness of both materials when flexed. During testing it was observed that PEEK CF40 is relatively a brittle material when compared to the E-glass/epoxy composite laminates.



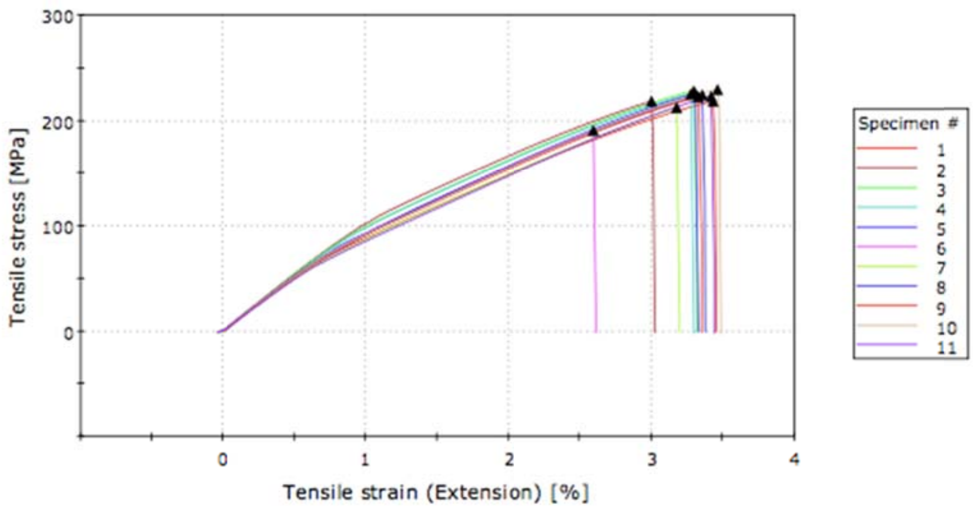


Fig. 1 Stress-strain curves of E-glass/epoxy (top) and PEEK CF40 tensile specimens (bottom)

Table 2: Mean Flexural Properties of E-glass/epoxy and PEEK CF 40 Specimens

Material	Ultimate Flexural Stress [MPa]	Flexural Modulus [GPa]
E-glass/epoxy	164	7.7
PEEK CF40	276	16.2

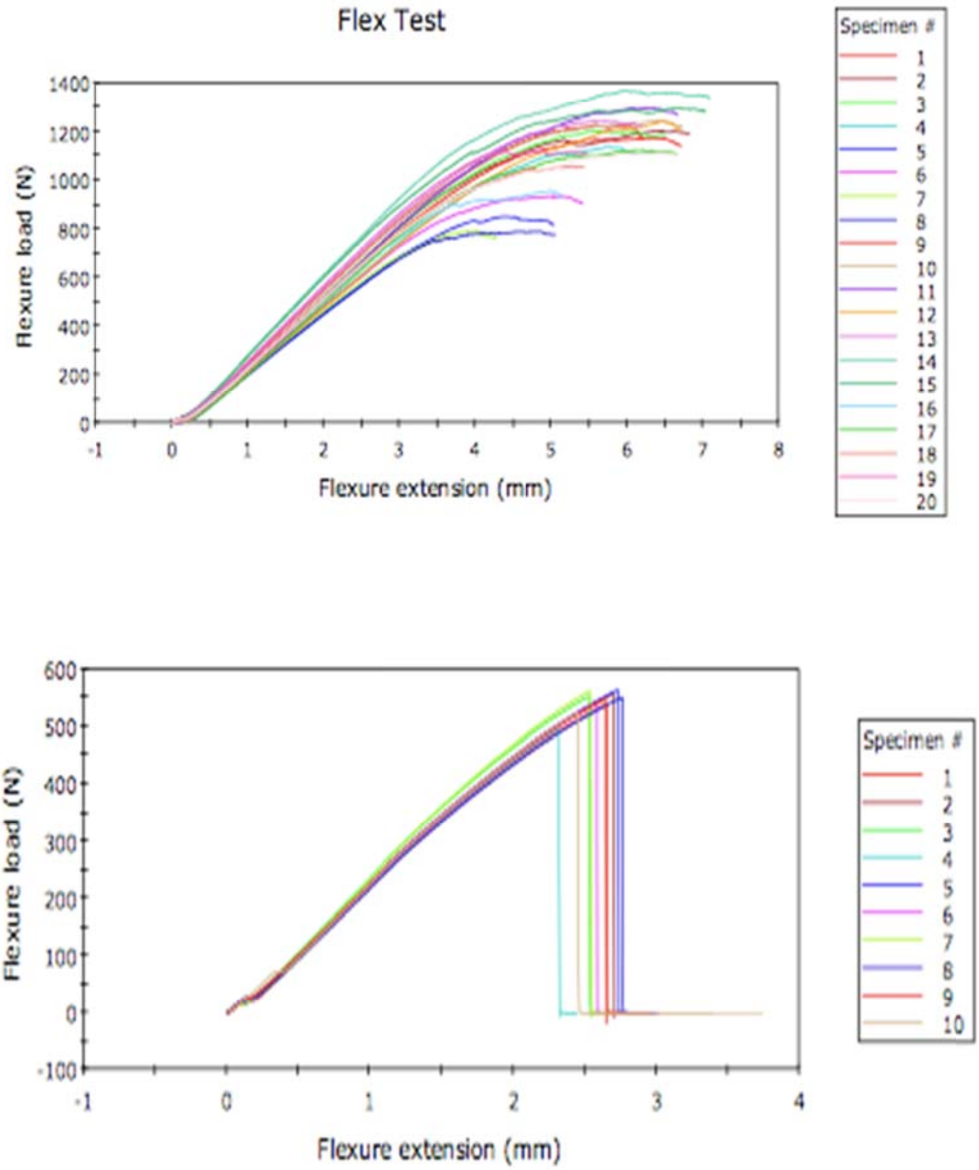


Fig. 2 Load-displacement curves of E-glass/epoxy (top) and PEEK CF40 flexural specimens (bottom)

4.2 Finite Element Analysis

ABAQUS/CAE was used to perform beam analysis of 1 m long beams with a rectangular cross section (width of 0.10 m and thickness of 0.05 m). A solid continuum shell made up of a composite lay-up was created for the E-glass/epoxy composite having 185 layers each of 0.27 mm thickness. The beam structure for the thermoplastic design was assumed to be solid homogeneous.

Cantilever beam conditions were used to analyze the selected materials. The beam was fixed at one end and a concentrated load of 1 kN was applied on the other end. A mesh size of 15,625 plain stress elements (C3D8R) was used (Fig. 3).

Table 3 summarizes the results of the simulations, showing potential weight reductions up to 28% when the thermoplastic material is chosen. It can be shown that the thermoplastic material provides higher stiffness to weight ratios due to the carbon fiber fillers.

Table 3: ABAQUS/CAE analysis results

Material	Deflection [mm]	Mass [Kg]	Stiffness/Weight [N/mKg]
E-glass/epoxy	87.1	9.99	1.15×10^3
PEEK CF40	6.69	7.24	2.07×10^4

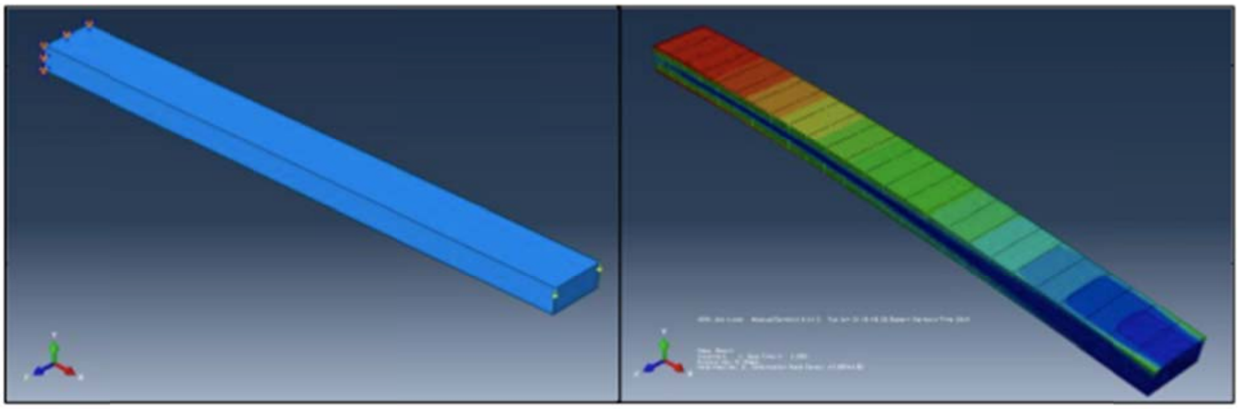


Fig. 3: ABAQUS/CAE beam design with applied constrains and loads (left) and final analysis results showing stress distribution and mesh (right)

A higher stiffness value of the blade material, as the one provided by PEEK CF40, is a very significant advantage to the blade shell design. One of the most important requirements for high stiffness is due to the damage that may be caused to the shell as the blade rotates around the tower. Materials of high stiffness help prevent such problems as well as increase the fatigue life of the blade shell.

5. CONCLUSIONS

Experimental tensile and flexure testing of E-glass/epoxy and PEEK CF40 beam structures, as well as finite elements analysis using ABAQUS/CAE, show the superiority of PEEK CF40 as compared to E-glass/epoxy composites. The measured ultimate tensile stress, tensile modulus and elongation for E-glass/epoxy composites and PEEK CF40 were 146 MPa, 2.3 GPa, 15.5% and 220 MPa, 10.3 GPa and 3.2%, respectively. The measured ultimate stress and modulus for E-glass/epoxy composites and PEEK CF40 in flexure were 164 MPa, 7.7 GPa and 276 MPa, 16.2 GPa, respectively. Overall, PEEK CF40 thermoplastic material can potentially provide up to 28% reduction in weight and higher stiffness without significant reduction in elongation.

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