STRENGTH DISTRIBUTION COMPARISON OF AEROSPACE AND WIND ENERGY CARBON FIBER REINFORCED EPOXY

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Abstract

As wind turbines continue to grow in size, the wind energy industry increasingly looks to carbon fiber composites as a way to meet demanding weight and stiffness requirements. In general, wind energy carbon fiber tends to be large-tow standard-modulus carbon fiber manufactured as economically as possible. This focus has the potential to produce properties and property distributions unique to wind energy material. Property distribution information is critical for predicting the reliability of wind turbines. Unfortunately, limited distribution data is available and even less addresses behavior unique to the wind energy industry. In this study 90° off-axis tensile strength distributions were measured from micro-tensile tests performed on wind energy and aerospace preimpregnated carbon/epoxy. This data highlights any unique characteristics of wind energy material that must be taken into consideration during the design process. In addition, specimen microstructures were imaged using fluorescent optical microscopy to identify microstructural defects that may influence the strength distributions. This could lead to the identification of processing parameters that could improve reliability of wind turbines in the future.

Key Words: Property distributions, Reliability, Carbon Fiber, Composites, Microstructure, Defects

Introduction

As wind turbines continue to grow in size, the wind energy industry increasingly looks to carbon fiber composites as a way to meet demanding weight and stiffness requirements. Transitioning to carbon fiber poses some unique challenges. As with other composites there are a variety of manufacturing methods including wet hand layup, filament winding, and the use of preimpregnated (prepreg) material [1]. There are also additional processing considerations for carbon fiber because it can be difficult to wetout and fiber alignment is critical for consistent compressive strengths [2]. To address these difficulties many manufacturers rely on the more consistent and expensive prepreg material [2]. This material still requires a supply of large tow standard modulus carbon fiber which has been difficult to create [3]. Furthermore, wind energy carbon fiber material tends to be made as economically as possible because the costs can still be 10 to 20 times greater than the more commonly used E-glass [2][3]. This unique focus on large tow standard modulus carbon made as economically as possible could produce properties and property distributions which are unique to wind energy material.

Understanding property distributions is of critical importance because many design codes require property distribution data in order to properly dimension a structural component for a needed reliability [4]. Furthermore, developing methods to predict the reliability of wind turbines is a current area of study [5]. Unfortunately, limited property distribution data exists and even less focuses on wind energy material. In this study transverse tensile strength distribution data for wind energy and aerospace grade carbon/epoxy preimpregnated materials were collected. This enabled the comparison of the two and the identification of any behavior unique to the wind energy material. The distributions were collected on micro-tensile specimens, which permitted a large number of tests to be conducted with a minimum amount of material. For each failure, the microstructure at the location of the break was imaged using fluorescent optical microscopy. Identification of microstructural defects on or near the fracture surface showed the effect of defects on failure initiation. Better characterization of the relationships between defects and strength distributions could lead to improved processing techniques and improve the reliability of wind turbines in the future.

Testing

Flat plates $[0]_4$ of wind energy carbon/epoxy prepreg (Zoltek Panex 35 carbon and Hexcel M9.7 epoxy resin) were manufactured. Flat plates $[0]_{16}$ of aerospace material (AS4 carbon fiber and Hexcel 3501-6 epoxy) manufactured previously at the University of Wyoming were used. These layups produced similar thicknesses with the average wind energy material thickness being 2.28 mm and the average aerospace material thickness was 2.38 mm. Micro-tensile specimens were then cut from the flat plates using an OMAX 2652 jet machining center. The micro-tensile specimen geometry, in millimeters, is shown in Figure 1. This geometry was chosen to produce a uniform stress distribution in the gage section of the specimen as calculated by a finite element analysis shown in Figure 2. Fifty specimens were cut for each material. Then the gage section of each specimen was polished by hand with wet silicon carbide sand paper starting with a grit of 320 and ending with a grit of 600. This allowed for the imaging of the microstructure after the specimens were broken. The width and thickness of each specimen were measured at three locations in the gage section such that an average cross-sectional area could be calculated. Each specimen was then broken in an ADMET dual screw micro-tensile tester with a crosshead rate of 0.0965 mm/min which corresponds approximately to a strain rate of 0.01/min which is suggested by ASTM 3039 [6] for determining the tensile properties of fiber reinforced polymers. During testing the force and displacement were recorded. The maximum measured loads and the average cross sectional areas were used to calculate ultimate transverse tensile strengths. After each specimen was fractured a series of images of the fracture location, highlighted in red in Figure 3, were taken under epi-fluorescence with a Zeiss Axio.A1 optical microscope. These images were then stitched together in Photoshop CS6 so that a single image of the entire fracture path was obtained.

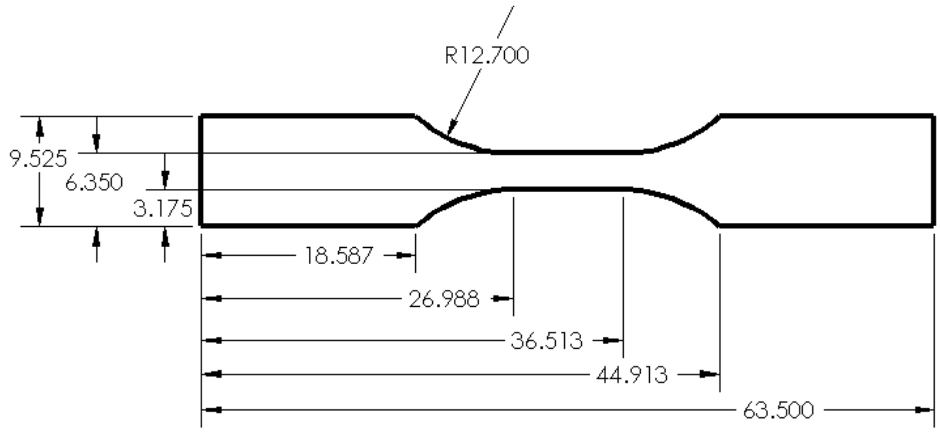


Figure 1: Micro-tensile specimen geometry dimensions in mm

Figure 2:Micro-tensile specimen stress distribution from finite element model

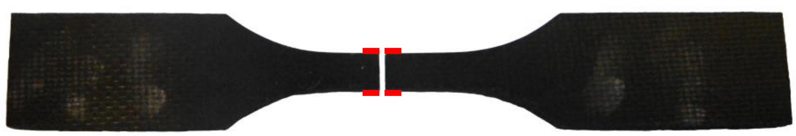


Figure 3: Actual micro-tensile specimen with imaged areas highlighted in red

Distribution Analysis

Several distributions could be fitted to the strength data, and Phillipidis et al. [4] showed that for filament wound CFRPs the normal, log-normal, Weibull, gamma, and asymptotic extreme value distribution type I, gave equally reasonable results based on the Kolmogorov-Smirnov test. However, for brittle materials such as carbon fibers and composites it is common to use a Weibull distribution [4][7][8]. The standard Weibull distribution function for strengths takes the form of [8],

$$F(\sigma) = 1 - \exp\left[-\left(\frac{\sigma}{\sigma_0} \right)^{\rho} \right] \quad (1)$$

where ρ is the Weibull shape parameter, σ_0 is the Weibull scaling parameter, and σ is the strength. The general Weibull distribution can be altered to account for size effects of the composites but for this initial study the basic two parameter distribution was used [7][8]. The Weibull parameters were estimated by a least squares regression to a Weibull plot. The Weibull cumulative distribution values, F(σ) in equation 1, for the collected strengths ordered from smallest to largest can be estimated as p-quantiles as [8],

$$P = \frac{(i-0.5)}{n} \qquad 2$$

where $i=1,2,\ldots n$ is the ith value and n is the total number of samples. Equation 1 can be rearranged substituting in the quantile approximation such that,

$$\ln(-\ln(1-P)) = \rho\ln(\sigma) - \rho\ln(\sigma_0)\ . \qquad 3$$

If the data follow a Weibull distribution it will appear linear when *ln(-ln(1-P))* is plotted against the *ln(σ)* and the slope of a best fit line will approximate the shape parameter *ρ* and the scaling parameter σ_0 can be calculated from the intercept of the line of best fit.

Results

Although fifty specimens for each material were broken, some tests failed near the grips or the grips slipped such that there were 41 successful tests on the wind energy material and 39 successful tests on the aerospace material. The average transverse tensile strength for Panex35/M9.7 was found to be 71.4 MPa with a sample standard deviation of 4.65 MPa. The average transverse tensile strength for AS4/3501-6 was 63.9 MPa with a sample standard deviation of 5.72 MPa. The strength distributions are shown in Figure 4. Weibull parameters for each of these distributions were estimated from Weibull plots, shown in Figure 5, and the linear behavior suggests that a Weibull distribution is appropriate for the data. The calculated Weibull parameters for the wind energy material were a shape parameter of ρ=18.4 and a scaling parameter σ_0=73.5. The aerospace material had a shape parameter of ρ=13.65 and σ_0=66.4. These values are comparable to those found by Philipidis et al. [4] for a +/-45 filament wound carbon epoxy which had a shape parameter ρ=11.2 and scaling parameter σ_0=64.3.

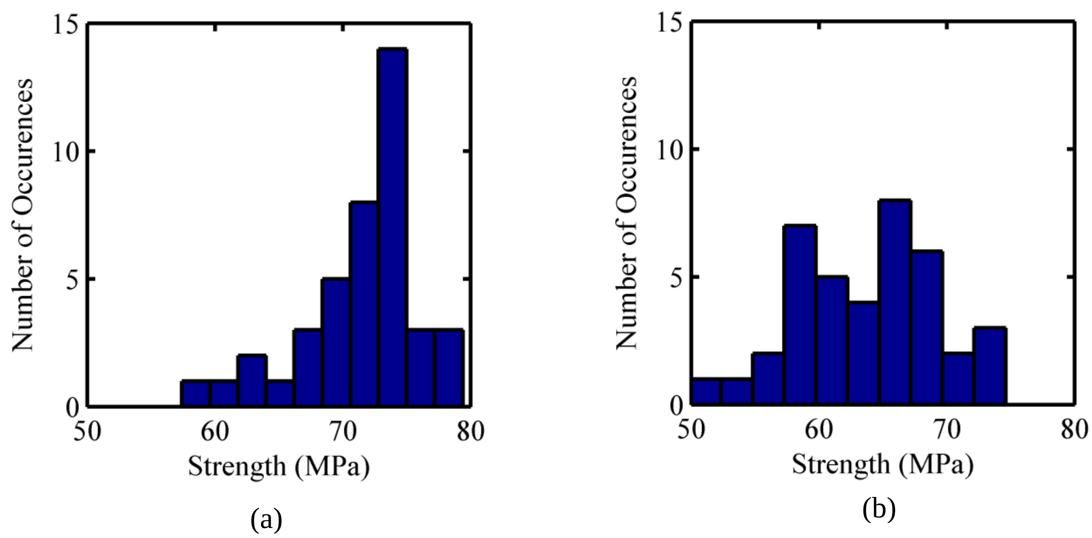
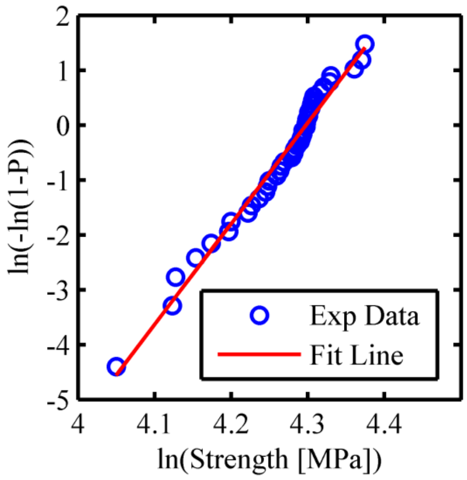
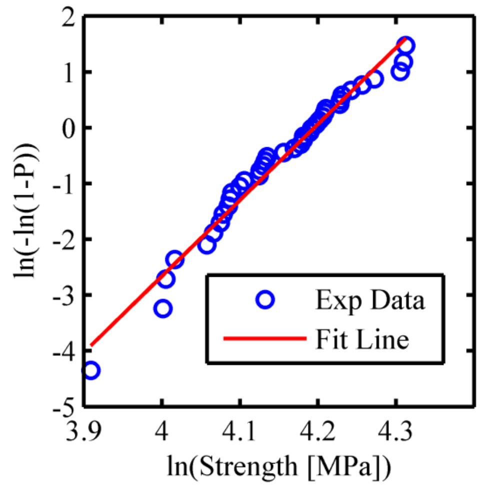


Figure 4: Transverse tensile strength distribution comparison of a) wind energy (Panex 35/M9.7) b) aerospace (AS4/3501-6)



(a)



(b)

Figure 5: Weibull plot comparison for a) wind energy and b) aerospace material

In general the failure mechanism for both materials seemed to be very similar. Typical failures are shown in Figure 6 and Figure 8. A transverse crack would quickly propagate across the width of the specimen, travelling through the matrix and following the outlines of fibers suggesting an interfacial failure mechanism. The area outlined in Figure 6 has been blown up to illustrate the fracture path and is shown in Figure 7. One major difference between the two materials is that the wind energy material had a thermoplastic grid on top of each ply to aid in alignment and air removal during cure—these are termed alignment fibers. For the aerospace material, no unique features were observed to consistently nucleate failure. In contrast, 60% of the failures of the wind energy material occurred at an alignment fiber and 80% of these occurred at an alignment fiber located on the surface such as that shown in Figure 8. Five wind energy material specimens and four aerospace material specimens failed at a void location. Approximately 78% of these failures were below the average strength. Typically, the crack would run along the void and finish cracking at a different longitudinal location as shown in Figure 9. A unique feature was observed in the weakest wind energy specimen. Two alignment fibers were closely and transversely aligned such that cracking occurred through two alignment fibers as shown in Figure 10. Thus, a clear correlation between defect microstructure and strength scatter is established.

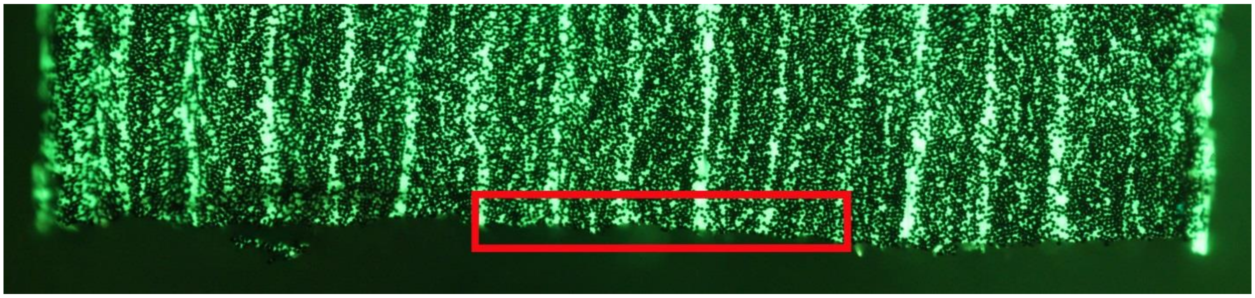


Figure 6: Imaged microstructure of typical fractured aerospace micro-tensile specimen

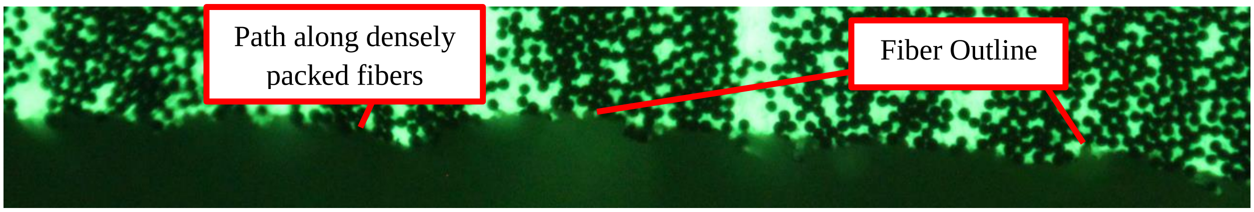


Figure 7: Zoomed in view of area highlighted in red in figure 6 illustrating fracture path

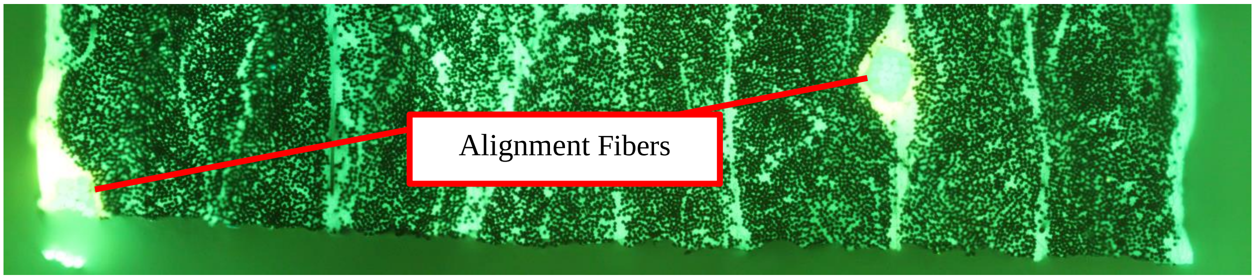


Figure 8: Imaged microstructure of fractured wind energy micro-tensile specimen

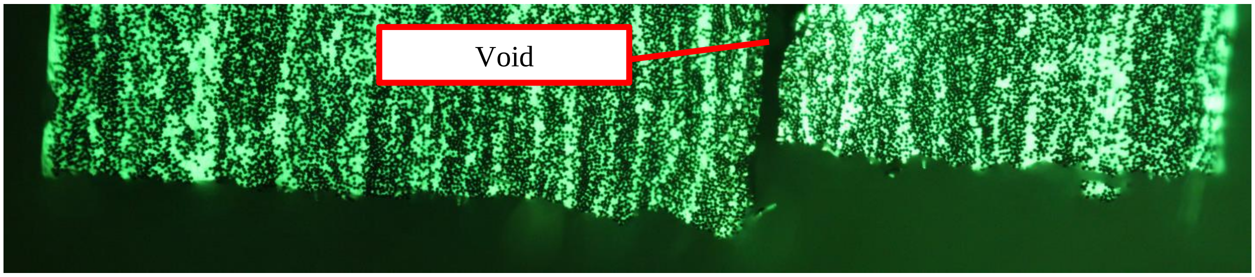


Figure 9: Imaged microstructure of fractured aerospace material at void

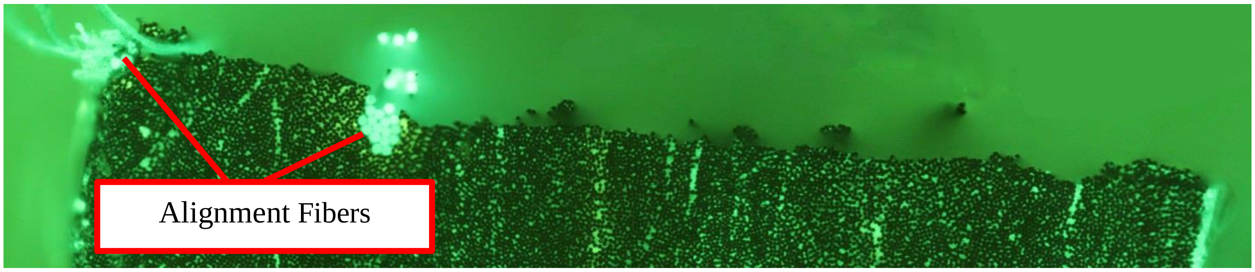


Figure 10: Imaged microstructure of weakest wind energy specimen

Discussion

The average ultimate tensile strengths for both materials are larger than typical reported values. This is due to the small specimen size, as composites typically show an increase in strength with a decrease in material volume due to their relatively brittle and flaw-sensitive nature [7][9]. These strengths are not unreasonable for the specimen size and with additional testing could potentially be linked to predict strengths for different specimen sizes using an altered Weibull distribution. The average strength of the wind energy material was higher than that of the aerospace material. Image analysis estimated the fiber volume fraction of the aerospace material to be approximately 64% and the wind material to be about 75%. This is larger than standard values and a standard constituent content test is required to validate this estimate, but this could explain the difference in observed strength.

Strength variation in the wind energy material, as measured by the standard deviation and Weibull shape parameter, was less than the aerospace material, which suggests that more conservative reliability considerations than those for aerospace materials are unnecessary. This is surprising given the presence of visible microstructural defects (alignment fibers) throughout the microstructure that commonly nucleated failure due to stress concentration. However, the smaller scatter in strength may be directly linked with these defects. Because the alignment fibers are relatively uniform in size, the strain concentrations they give rise to will also be more uniform. These relatively high uniform strain concentrations may dominate over smaller strain fluctuations induced by, for example, variation in local fiber volume fraction. Thus, a more uniform failure stress is observed.

In addition, the alignment fibers on the surface appear to dominate failure initiation more than those embedded in the composite, which suggests that interactions of defect strain fields with the surface cannot be ignored. The role played by the alignment fibers in failure initiation is further highlighted in that the lowest wind energy strength measured corresponded to the only specimen that cracked through two alignment fibers. This suggests that the alignment fibers can interact in such a way that could further decrease the strength. Fortunately, from St. Venant’s principle the alignment fibers must be relatively close together for this interaction to be significant, which is supported by the fact that several specimens fractured through one alignment fiber and the crack did not deflect to reach a nearby alignment fiber as shown in Figure 8.

In the aerospace material, linking specific strengths with defect structures was more difficult. In most instances there was no obvious defect around which failure occurred. The specimens that broke on the edges of the gage section tended to have slightly lower strengths than those that broke in the center of the gage section. It seems that the more homogenous aerospace material, with few visual defects and no inherent inclusion such as an alignment fiber, was more sensitive to macroscopic geometry than the wind material with its inherent alignment fiber inhomogeneities. This could also explain why the aerospace material transverse tensile strength tends to be more uniformly distributed than that of the wind energy material. This is a complicated problem but microstructural defects clearly play a role and are important factors contributing to strength distributions.

Conclusions

Transverse strength distributions for Panex 35/M9.7 and AS4/3501-6 carbon epoxy preimpregnated materials have been collected and Weibull distribution parameters for these distributions were estimated. Less scatter was observed in the wind energy material than the aerospace material, which suggests that more conservative reliability design requirements for the wind energy industry are unnecessary. Using micro-tensile specimens the microstructure of the fractured specimens was imaged using fluorescent optical microscopy. Some microstructural defects were identified, which included voids as well as alignment fibers. The wind energy data provide evidence that microstructural defects, such as alignment fibers, have the potential to interact and affect the strength of a component. Furthermore, these uniformly sized defects may actually reduce the scatter in the strength distribution by providing larger more uniform stress concentrations such that failure occurs at a more consistent level. Further work needs to be conducted to relate the findings on micro-tensile specimens to larger components, as well as to investigate if different processing parameters can affect defects and strength distributions so that reliability improvements can be made.

References

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