

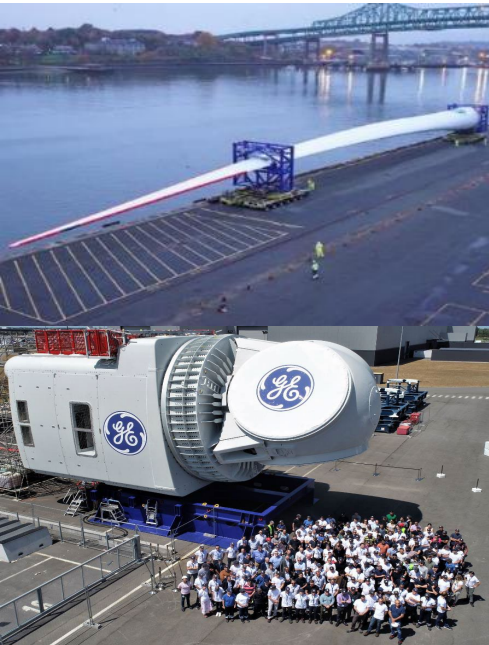
T04 - Carbon Fiber Material Design for Targeted Performance Enhancement

Tech. RD&T – Materials and Manufacturing

Robert Norris

Oak Ridge National Laboratory

August 3, 2021



FY21 Peer Review - Project Overview

Project Summary:

- Compressive strength of carbon fiber composites, being significantly lower than tensile strength, is the design-limiting factor for utilization in wind turbine blade spar caps
- Oak Ridge National Laboratory, Sandia National Laboratories, and Montana State University are developing and demonstrating tools for “designing” carbon fiber with enhanced compression strength:
 - Capability to produce larger diameter fibers at equivalent or lower cost than current products
 - Capability to modify fiber shape for enhanced interfacial and bending/buckling performance
- Results are expected to show that carbon fiber shape changes have the potential to cost-effectively increase compression strength by >25%

Project Start Year: FY 2020 (Q1)
Expected Completion Year: FY 2022
Total expected duration: 3 years

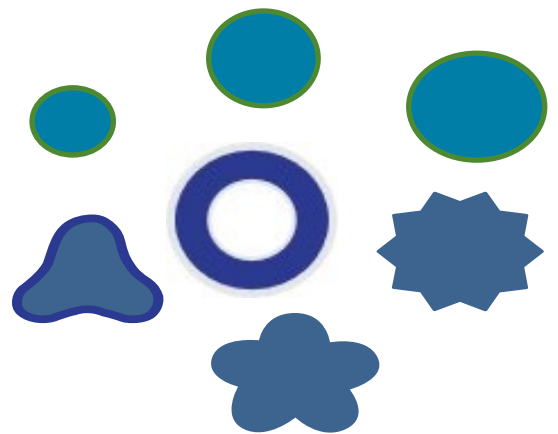
FY19 - FY20 Budget: \$645,000

Key Project Personnel:
Bob Norris, PI & Carbon Fiber M&P, ORNL
Brandon Ennis, Design Lead, SNL
David Miller, Testing Lead, MSU

Key DOE Personnel:
Michael Derby, PM
Benjamin Hallissy, Technical Lead

Project Objective(s) 2020:

- Provide baseline and >15% larger diameter carbon fiber samples to project team to initiate composite test development
- Perform analytical comparisons of potential fiber geometries to predict composite compressive performance.
- Demonstrate failure mode characterization through mechanical testing of baseline carbon fiber material



Project team is assessing various approaches to designing and producing carbon fibers with varying geometry with potential to cost-effectively improve compressive performance for carbon fiber materials for the wind industry

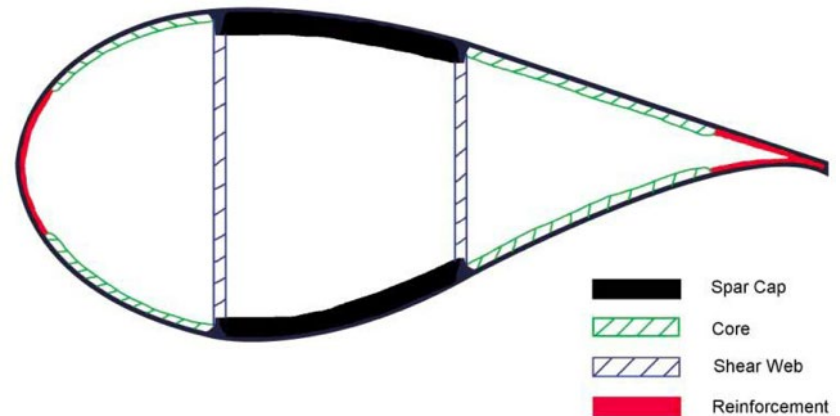
Overall Project Objectives (life of project):

- Demonstrate alternative shapes/sizes for carbon fiber that enable designing fibers to cost-effectively enhance compressive strength

Project Impact

Overall goal: Increase the value of carbon fiber composite specific to wind industry such that it is the preferred reinforcement for wind turbine blade spar caps, reducing the LCOE of wind energy.

1. Optimized Carbon Fiber project (FY17-FY19) identified pathways for low-cost carbon system with a higher value than glass fiber or commercial carbon fiber by increasing composite compressive strength per unit cost for a similar modulus¹.
2. Current spar cap configurations under-utilize tensile strength capacity due to significant compression performance deficits with cost penalty.
3. Baseline cost per weight of carbon fiber is about 10X that of fiberglass; utilization of carbon fiber must be fully optimized by increasing its cost-specific compressive strength
4. This project will demonstrate the potential to achieve increases in compression strength of 25% or more, resulting in a reduction of spar cap material cost of greater than 50% through optimization of heavy tow textile carbon fiber materials compared to an industry baseline.



¹Ennis, BL, Norris, RE, et.al. **Optimized Carbon Fiber Composites in Wind Turbine Blade Design**, Sandia National Laboratory report SAND2019, 14173, November 2019.

Program Performance – Scope, Schedule, Execution

Overall Project Approach/Plan

Year 1 (FY20-21) Focus on Larger Diameter Fibers

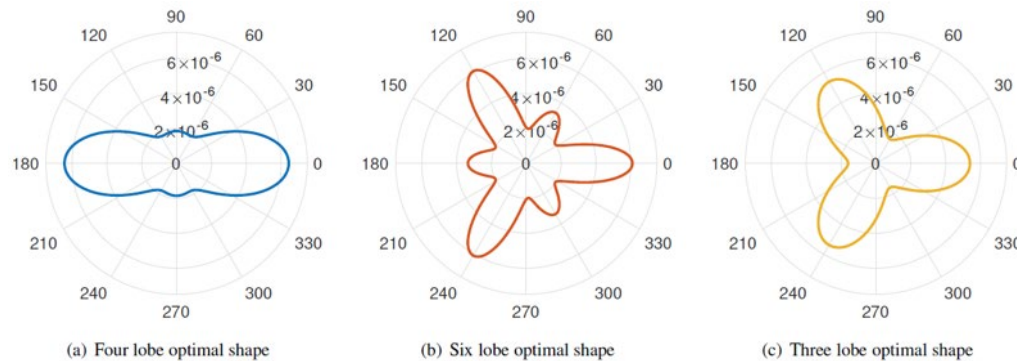
- Develop and implement techniques to produce/provide carbon fibers with different diameters, but similar precursor chemistry/molecular weight and carbon fiber mechanical and physical properties to assess shape/size effects on compressive performance
- Develop predictive analytical model for compressive performance to assist in distinguishing shape/size effects found in testing from other manufacturing and testing artifacts
- Develop sample manufacturing and testing techniques to best utilize small quantities of custom-manufactured samples and facilitate analysis of failure mechanisms
- Develop shape configuration model to facilitate comparison and optimization of various shapes based on inertial effects, wetting perimeter, likely fiber packing, etc.



Program Performance –Scope, Schedule, Execution (cont)

Year 2 (FY21-22) Focus on Carbon Fiber with Alternative Shapes

- Complete testing and assessment of failure mechanisms to understand effects of diameter/greater fiber inertia versus manufacturing/testing effects
- Develop and implement techniques to produce/provide carbon fibers having different shapes



Year 3 (FY22-23) Focus on Combining Lessons from First 2 Years and Evaluating Hollow Fibers

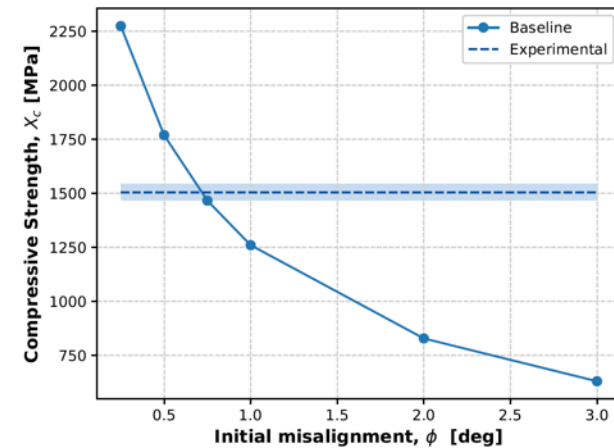
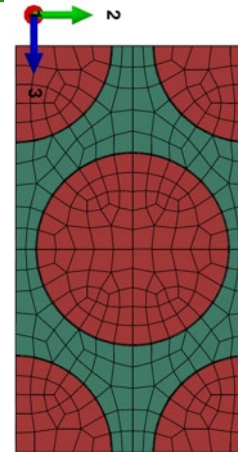
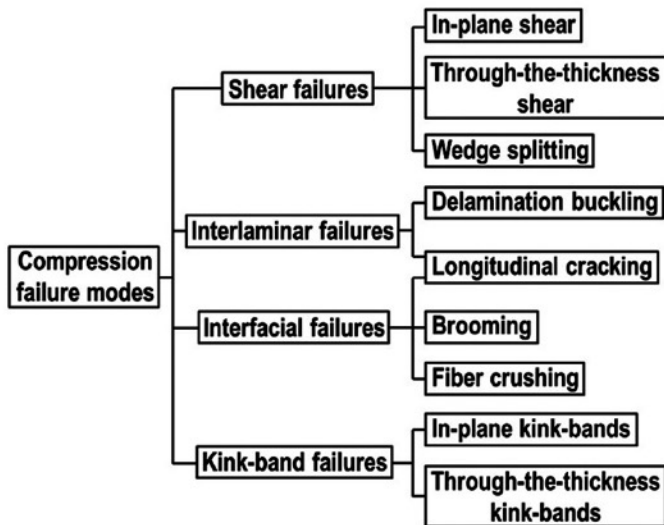
- Complete testing and assessment of failure mechanisms to understand effects of different shapes versus effects of manufacturing/testing
- Develop and implement techniques to produce/provide carbon fibers having a hollow cross section
- Better optimize shape, fiber size, or perhaps fiber post-treatment approaches from early work if deemed to be a more promising implementation approach.
- Results will be made available to wind industry and fiber production stakeholders and best pathways to commercialization will be identified.

Program Performance – Accomplishments & Progress

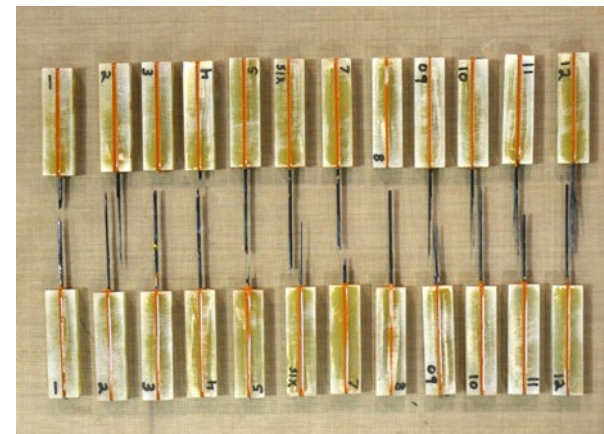
- 1) Predictive analytical model for compressive performance and the 2) shape configuration assessment model have been developed and papers prepared for submission.

$$\hat{r} = \frac{r(\theta)}{h} = 1 + S \left(\left(\cos^2\left(\frac{k}{4}\theta\right) \right)^n + R \left(\sin^2\left(\frac{k}{4}\theta\right) \right)^n \right)$$

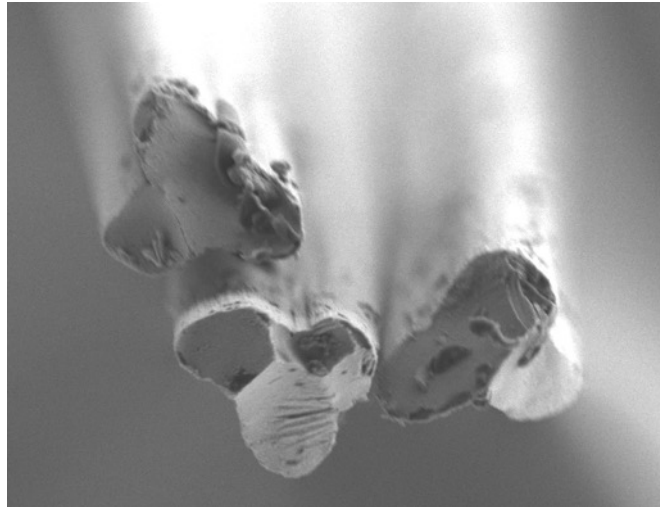
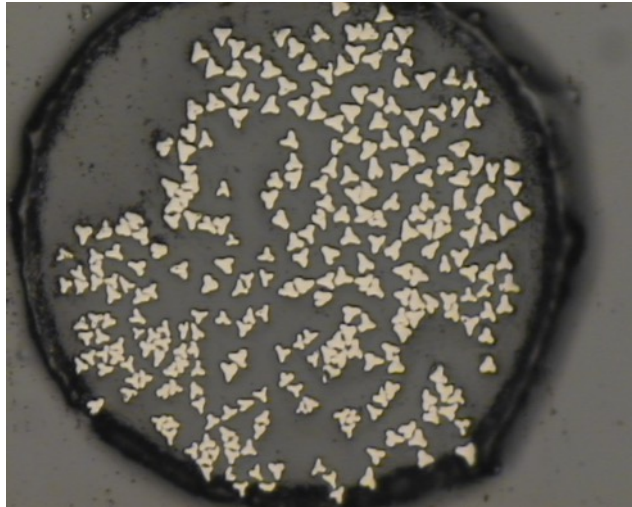
$$\mathcal{O}_{eff}(w_p) = \frac{I_{eff} + w_p p_s}{C_s}$$



- Basic techniques were established for approaches to best utilize small quantities of custom-manufactured samples and facilitate analysis of failure mechanisms,

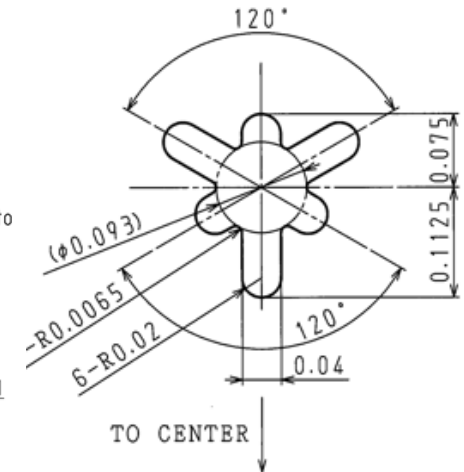
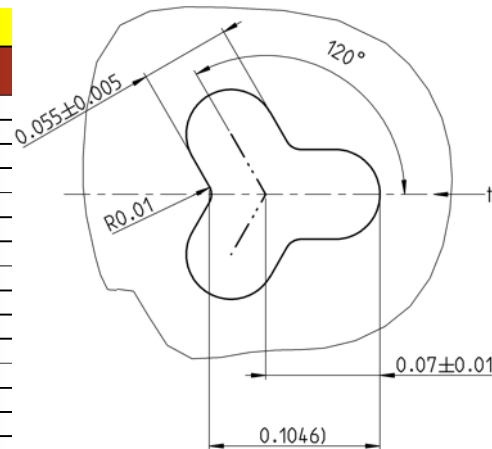


Program Performance – Accomplishments & Progress (cont.)



- A spinneret for producing tri-lobal shaped fiber has been designed/received and is being utilized for making samples
- A six-lobed spinneret is on order

	Single Filament Testing				Strand Testing			
	Diameter (μm)	Peak Stress (Ksi)	Modulus (Mpsi)	Strain (%)	Peak Stress (Ksi)	Modulus (Mpsi)	Strain (%)	Calculated Diameter
	7.03	495.4	29.9	1.59	470.2	34.39	1.37	7.05
	7.11	474.5	30	1.52	456.1	34.50	1.32	7.00
	7.21	523.9	30.1	1.66	478.3	34.39	1.39	7.00
	7.11	495.5	30	1.58	438.7	34.24	1.28	7.06
Average	7.12	497.3	30.0	1.59	460.8	34.38	1.34	7.03
	6.91	477.1	29.9	1.53	465.1	34.57	1.35	7.02
	6.82	459.9	29.7	1.49	440.5	35.24	1.25	6.99
	7.53	444.8	30.4	1.42	442.6	34.76	1.27	6.96
	7.5	472.4	30.4	1.49	431.3	34.67	1.23	7.06
Average	7.19	463.6	30.1	1.48	444.9	34.81	1.28	7.01
	9.32	455.1	31.3	1.41	435.1	34.64	1.22	9.41
	9.49	428.4	30.8	1.34	420.2	34.48	1.22	9.39
	8.91	491.6	31.9	1.49	448.1	34.41	1.16	9.42
	9.74	444.7	30.6	1.39	476.3	34.62	1.38	9.45
Average	9.37	455.0	31.2	1.41	444.9	34.54	1.25	9.42
	9.38	485.4	31.2	1.5	481.8	34.55	1.39	9.67
	9.28	471.9	31.3	1.46	477.3	34.39	1.39	9.45
	8.93	503.7	31.5	1.55	481.2	34.70	1.39	9.45
	9.53	507.1	31	1.56	527.2	34.99	1.51	9.66
Average	9.28	492.0	31.3	1.52	491.9	34.66	1.42	9.56

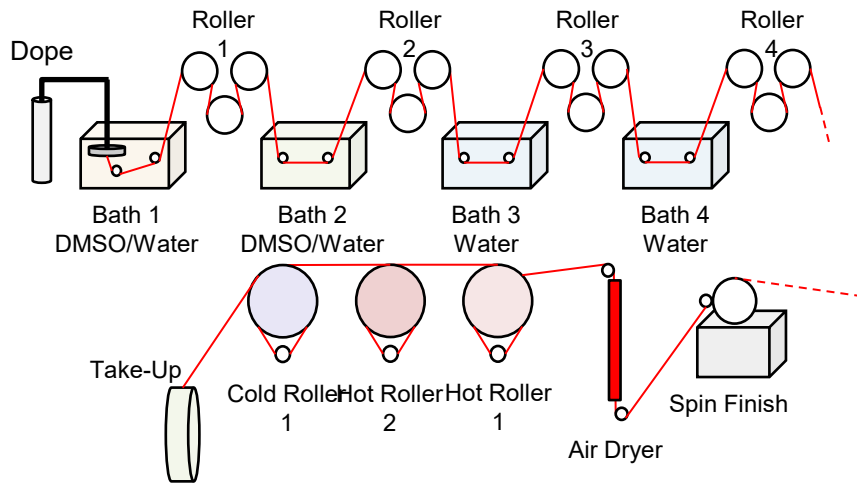


- Comparable 7 and 9 micron carbon fiber samples have been manufactured/delivered

Project Performance - Upcoming Activities

Key planned upcoming activities include:

- Compression testing/failure analysis to assess the performance of larger diameter fibers
- Convene industry advisory panel to review progress and plans and get their recommendations for making our approach most relevant to their potential adaptation.
- Optimization and scale up spinning and conversion of tri-lobal fibers and other shapes based on very promising approach already demonstrated; testing to assess shape effects on compression



- Evaluate, select, and implement cost-effective means for producing hollow fibers
- Identify optimal fiber geometry pathways based on cost versus performance results for enhancing compression performance of carbon fiber composites
- Communicate findings to stakeholder and facilitate pathway to commercial implementation

Stakeholder Engagement & Information Sharing

Ongoing and planned activities for stakeholder engagement

- Papers on the predictive modeling and fiber shape comparison analysis prepared for submission
- Industry advisory panel being established with carbon fiber suppliers for ensuring approach is relevant
- Team briefed multiple DOE offices funding carbon fiber on opportunities for collaboration.
- Members have key DOE/IACMI interaction roles
- Results on compressive performance to be documented for public release, targeting a high impact trade publication (such as JEC or CompositesWorld) in addition to technical publications on various subtasks.

Identification of the Optimal Carbon Fiber Shape for Cost-Specific Compressive Performance*

Brandon L. Ennis^{a,*}, Hector S. Perez^{a,1} and Robert E. Norris^{b,2}

^aSandia National Laboratories, P.O. Box 5800, Albuquerque, NM 87185, USA

^bOak Ridge National Laboratory, 1 Bethel Valley Rd., Oak Ridge, TN 37830, USA

ARTICLE INFO

Keywords:
carbon fiber
fiber geometry
precursor
optimization
compressive strength

ABSTRACT

Carbon fiber composites offer superior mechanical performance compared to nearly all other useful materials for design. However, for cost-driven industries, such as with the wind energy and vehicle industries, the cost of commercial carbon fiber materials is often prohibitive for their usage compared to alternatives. This paper develops an approach to optimize fiber geometries for use in carbon fiber reinforced polymers to increase the compressive strength per cost. Compressive strength is a composite property that depends on the fiber, matrix, and interface, and an exact analytic expression does not exist that can accurately represent these complicated relationships. The approach taken instead is to use a weighted summation between the fiber cross-sectional area moment of inertia and perimeter as a proxy for compressive strength, with different weights explored within the paper. Analyses are performed to identify optimal fiber geometries that increase the cost-specific compressive strength based on various assumptions and desired fiber volume fraction. Robust optimal shapes are identified which outperform circular fibers due to increases in area moment of inertia and perimeter, as well as decreases in carbon fiber processing costs.

1. Introduction

Carbon fiber reinforced polymers are among materials with the highest mass-specific strength and stiffness available. Wind turbine blades are a prime example of this, with the use of carbon fiber in the leading edge and spar cap areas leading to significant weight and cost savings. This paper focuses on the optimization of carbon fiber reinforced polymers for cost-specific compressive strength.

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Development of a compressive failure model for carbon fiber composites and associated uncertainties

Ernesto Camareno^a, Ryan J. Clarke, Brandon L. Ennis^{a,*}

^aSandia National Laboratories, Albuquerque, NM 87185, USA

ARTICLE INFO

Keywords:
Structural composite
Strength
Carbon fibers
Finite element analysis (FEA)

ABSTRACT

An approach to increase the value of carbon fiber for wind turbine blades, and other composite strength driven designs, is to identify pathways to increase its cost-specific compressive strength. A finite element model has been developed to evaluate the performance of various fiber diameter methods, and to lay groundwork for future studies that focus on improving the cost-specific compressive strength. Parametric studies are conducted to understand which uncertainties in the model inputs have the greatest impact on compressive strength predictions. A statistical approach is also presented that enables the micro-mechanical model, which is deterministic, to accurately account for statistical variability in the fiber misalignment present in composite materials; especially if the results from the homogenized and representative models are averaged. The model was found to agree well with experimental results for a Zoltek FX-30 polyimide. The sensitivity studies suggest that the fiber geometry and the interface fiber strength have the greatest impact on compressive strength predictions for the fiber reinforced polymers studied here. Based on the performance of the analytical approach presented in this work, it is deemed sufficient for future work which will seek to identify carbon fiber composites with improved cost-specific compressive strength.

1. Introduction

Carbon fiber reinforced polymers (CFRP) are amongst the best performing materials regarding specific strength and stiffness, as well as fatigue performance. However, for many industries, the cost of carbon fiber composites is prohibitive compared to lower cost alternatives, such as glass fiber reinforced polymers. The wind energy industry is notable in this category, where wind turbine designs are driven based on the resulting levelized cost of energy (LCOE). The added mass of using lower performing fibreglass composites in the structural spar members of the wind turbine blade typically still results in the lowest LCOE, despite the system implications of supporting this additional mass. Wind turbines with carbon fiber spar caps represent a minority of the total installed global capacity of around only 25%.

Recent work has been performed to assess novel carbon fiber materials that can provide higher value to the wind industry over commercial carbon fibers. A 40% material cost reduction was found for carbon fiber spar caps when using a textile-derived, honeycomb carbon fiber compared to an industry standard carbon system [1]. The improvement

identified for the textile carbon fiber resulted from the material's lower cost, nearly equivalent Young's modulus, and only minor reduction in compressive strength. For wind turbines, and many other systems, the longitudinal Young's modulus and compressive strength are the mechanical properties of greatest significance. Due to the anisotropic nature of wind turbine blades, they experience similar magnitude tensile and compressive stresses. Since the longitudinal tensile strength is always in excess of compressive strength for fiber reinforced polymers (FRP), the material compressive strength is what drives the design for wind turbines, not tensile strength.

The importance of compressive strength for the FRP spar caps in wind turbine blades is well understood by the wind industry, but the challenge for carbon fiber manufacturers is that compressive strength is a composite property and not purely a fiber property. One example of this challenge is that the traditional two-net used to measure and report carbon fiber mechanical properties is only predictive in tension, and cannot be used to accurately predict compressive performance of the composite. Micro-mechanical finite element (FE) models are considered to have an important role in filling this gap for fiber manufacturers and

* Corresponding author.

¹ Corresponding author.

² Email address: rclarke@sandia.gov (R. Camareno).

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Key Takeaways and Closing Remarks

Project Impact: Developing practical tools for understanding and enhancing composite compressive performance applicable to a wide spectrum of carbon fiber products and applications beyond wind alone boosts opportunities.

Project Performance: Substantial progress continues with major accomplishments in *developing unique approaches and producing unique fibers and supporting tools* towards those goals despite COVID impacts.

Stakeholder Engagement: Team is executing an aggressive approach in making results known in various venues and engaging key industrial feedback.

