U.S. DEPARTMENT OF ENERGY
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

2021 PROJECT PEER REVIEW
U.S. DEPARTMENT OF ENERGY
WIND ENERGY TECHNOLOGIES OFFICE

Oak Ridge National Laboratory
Sandia National Laboratories
Montana State University

T04 - Carbon Fiber Material Design for Targeted Performance Enhancement

Tech. RD&T – Materials and Manufacturing

Robert Norris
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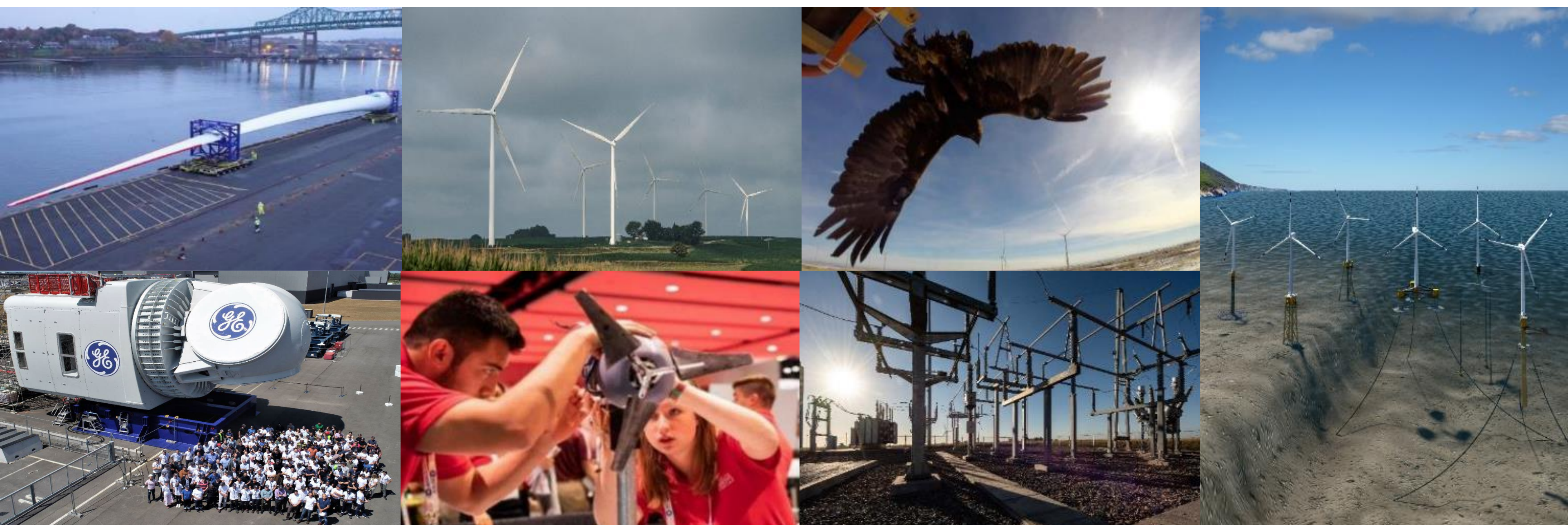
August 3, 2021



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

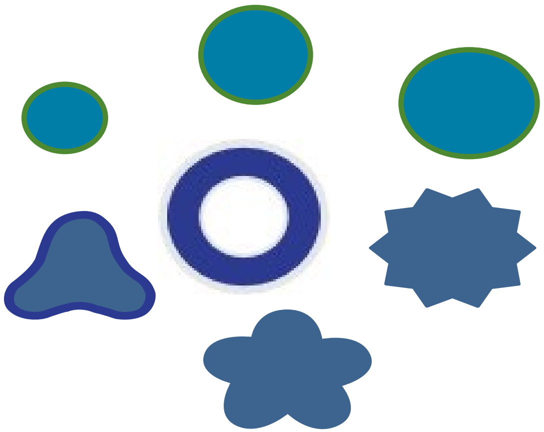
Key DOE Personnel:
Michael Derby, PM
Benjamin Hallissy, Technical Lead

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

Overall Project Objectives (life of project):

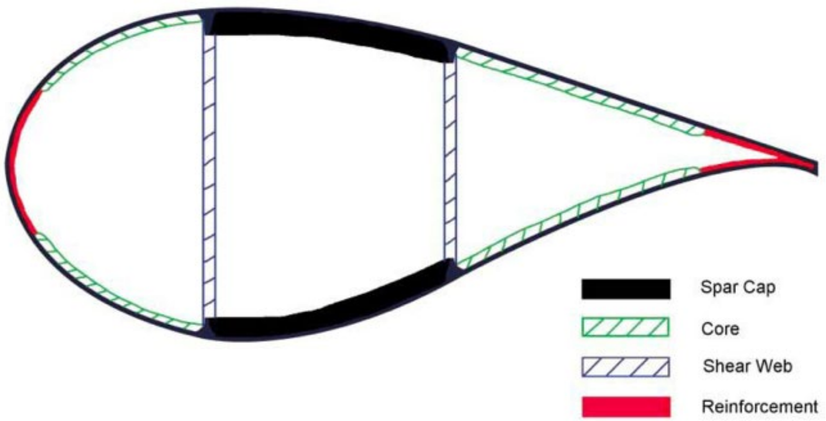
- Demonstrate alternative shapes/sizes for carbon fiber that enable designing fibers to cost-effectively enhance compressive strength



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

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 modulus[1].
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.

[1] Ennis, 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

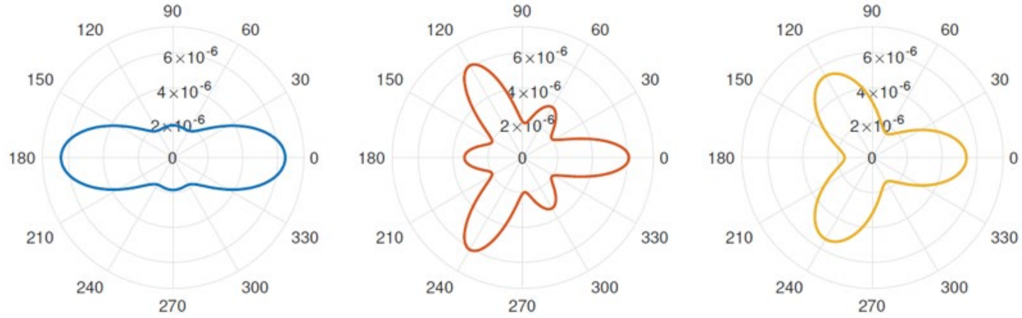
Year 1 (FY20-21) Focus on Larger Diameter Fibers

- 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



(a) Four lobe optimal shape (b) Six lobe optimal shape (c) Three lobe optimal shape

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

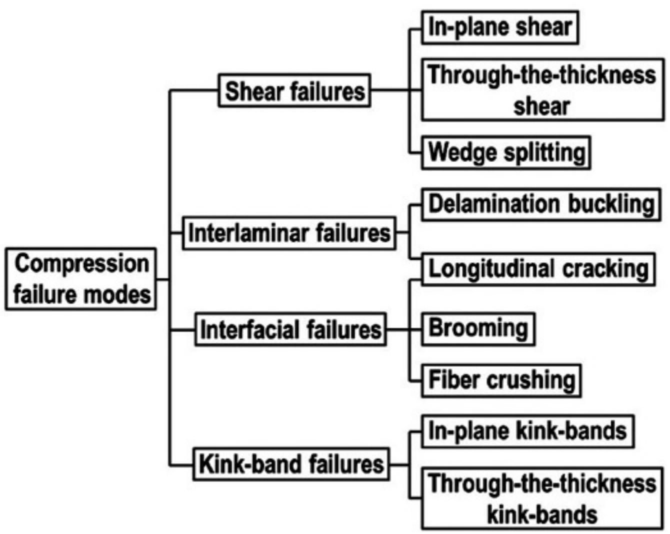
- Complete testing and assessment of failure mechanisms to understand effects of different shapes versus effects of manufacturing/testing
- Develop and implement techniques to produce/provide carbon fibers having a hollow cross section
- Better optimize shape, fiber size, or perhaps fiber post-treatment 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.

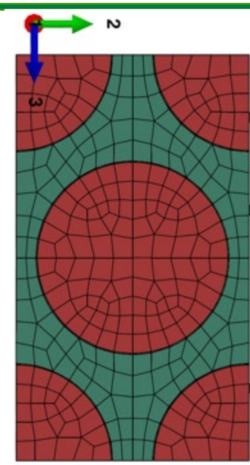
Program Performance – Accomplishments & Progress

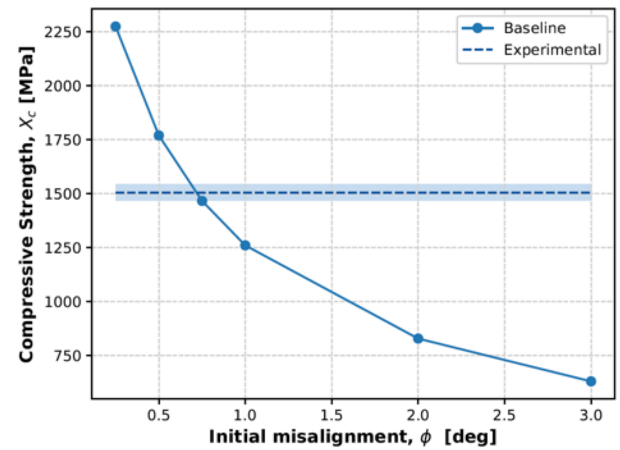
- 1) Predictive analytical model for compressive performance and the 2) shape configuration assessment model have been developed and papers prepared for submission.

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

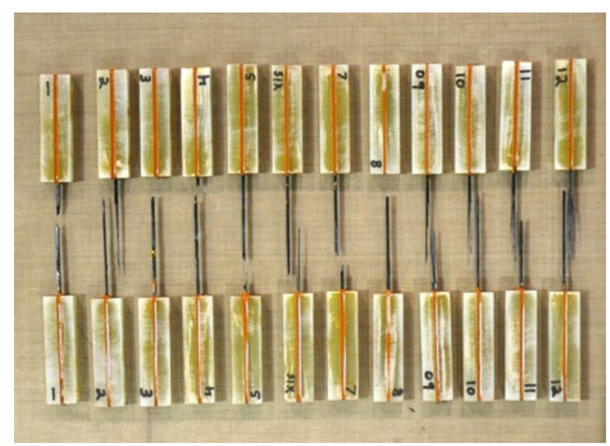
$$\mathcal{O}_{eff}(w_p) = \frac{I_{eff} + w_p p_s}{C_s}$$



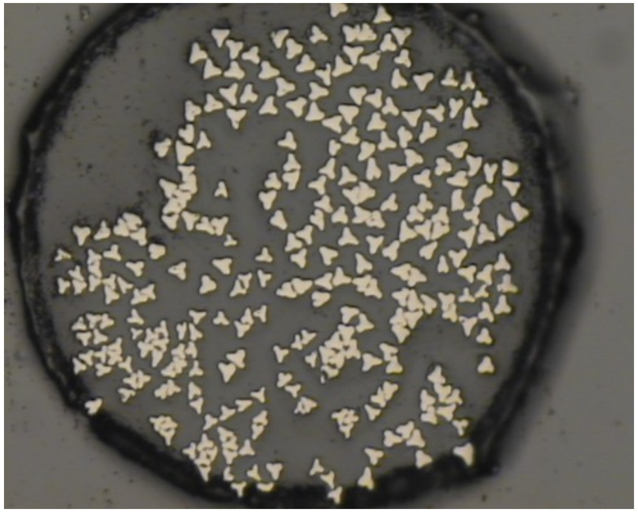


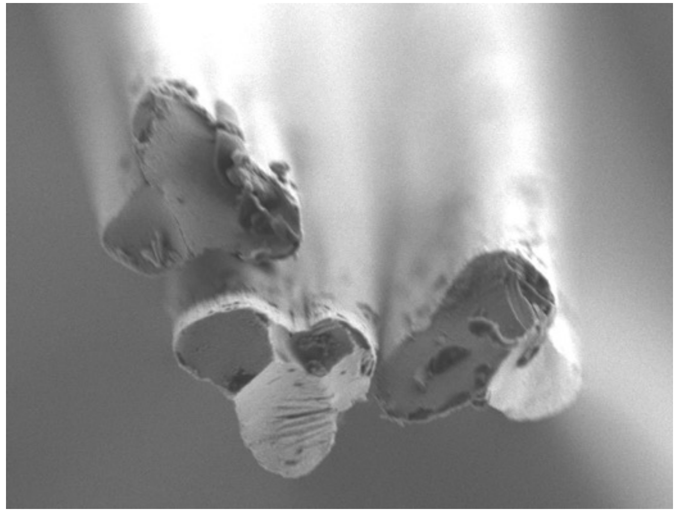


- Basic techniques were established for approaches to best utilize small quantities of custom-manufactured samples and facilitate analysis of failure mechanisms,

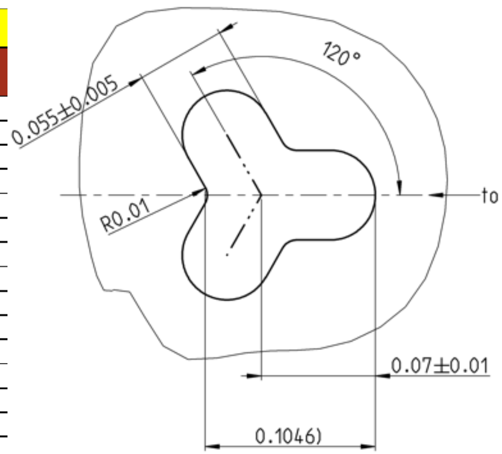


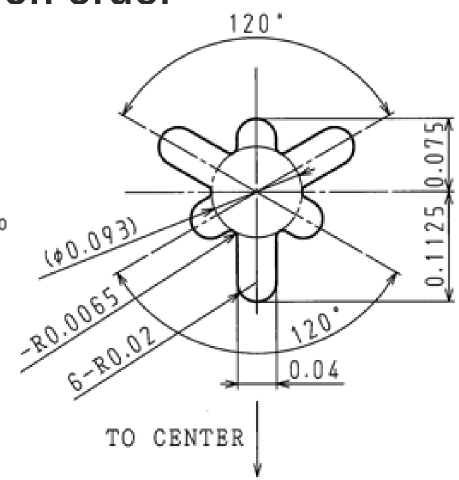
Program Performance – Accomplishments & Progress (cont.)





- 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





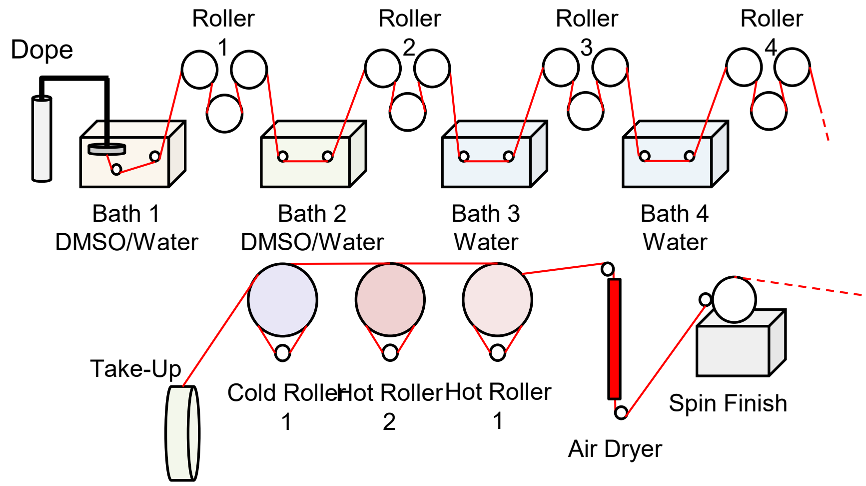
	Single Filament Testing				Strand Testing			
	Diameter (µm)	Peak Stress (Ksi)	Modulus (Mpsi)	Strain (%)	Peak Stress (Ksi)	Modulus (Msi)	Strain (%)	Calcculated Diameter
	7.03	495.4	29.9	1.59	470.2	34.39	1.37	7.05
	7.11	474.5	30	1.52	456.1	34.50	1.32	7.00
	7.21	523.9	30.1	1.66	478.3	34.39	1.39	7.00
	7.11	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

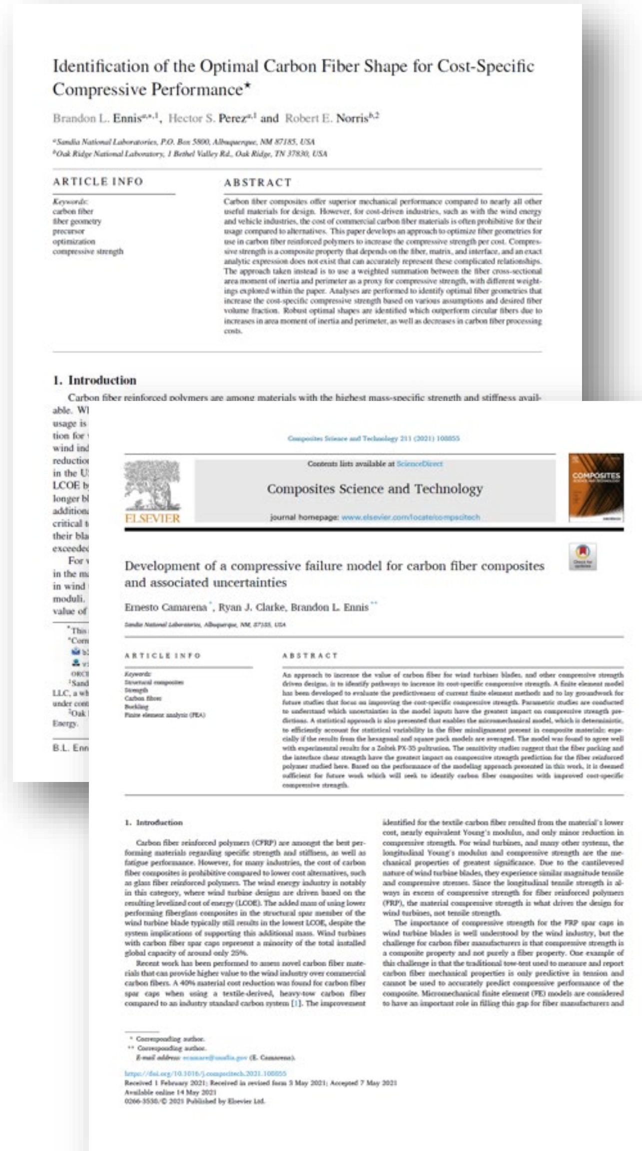


- Evaluate, select, and implement cost-effective means for producing hollow fibers
- Identify optimal fiber geometry pathways based on cost versus performance results for enhancing compression performance of carbon fiber composites
- Communicate findings to stakeholder and facilitate pathway to commercial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



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.