Cost-Effective Carbon Fiber Material Design for Targeted Performance Enhancement

2022 Sandia Wind Blade Workshop

Project Team/Leads
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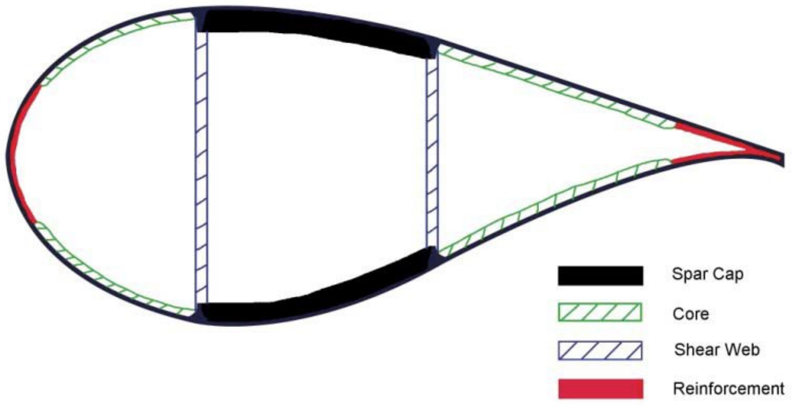
Alternative Materials for Wind Blade Manufacturing

- Spar caps are logical application of carbon fiber in blades
  - The key structural blade element providing both stiffness and strength to blade



  - Loading is mostly longitudinal taking advantage of max fiber orientation in that direction
  - Pultrusion can produce spar cap profile very cost-effectively off-line allowing easy insertion in blade assembly

- Optimized Carbon Fiber project identified pathways for low-cost carbon system increasing composite compressive strength per unit cost for a similar modulus[1].
- Tensile strength capacity currently under-utilized with cost penalty due to significant compression performance deficits; utilization of carbon fiber must be fully optimized by increasing its cost-specific compressive strength
- ***This work will be useful with both textile and conventional precursor!***

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

Key Optimized Fiber Project Composite Data Comparison

Table 2-2. Select testing results of MSU aligned strand infusion composite forms (standard deviation shown in parenthesis) [1].

Material	Layup	V_F (%)	E (GPa) 0.1-0.3%	UTS (MPa)	% Strain, max	UCS (MPa)	% Strain, min
Zoltek PX35	5.1 tows/cm [0]	51	119 (4)	1726 (93)	1.4 (0.08)	-906 (44)	-0.74 (0.04)
Kaltex	$[0]_5$ $[0]_{20}$	47	112 (6)	990 (49)	0.84 (0.06)	-863 (108)	-0.77 (0.10)
Taekwang	$[0]_5$ $[0]_{20}$	50	126 (4)	956 (63)	0.74 (0.05)	-869 (46)	-0.69 (0.04)
	$[90]_5$	52	7.8 (0.6)	31.7 (4)	1.13 (0.08)		

Table 2-3. Select testing results of pultruded composite forms (standard deviation shown in parenthesis) [1].

Material	Layup	V_F (%)	E (GPa) 0.1-0.3%	UTS (MPa)	% Strain, max	UCS (MPa)	% Strain, min
Zoltek	Commercial, [0]	62	142 (3) 138 (9)	2215 (77)	1.5 (0.10)	-1505 (38)	-1.21 (0.05)
	Commercial, [90]	62	9.13 (0.1)	50.1 (8)	0.58 (0.11)		
	Third-party, [0]	53	114 (4)	1564 (67)	1.33 (0.15)	-897 (67)	-0.79 (0.06)
Kaltex	Third-party, [0]	51	123 (6)	846 (53)	0.69 (0.05)	-803 (26) -769 (73)	-0.65 (0.02) -0.63 (0.06)

OAK RIDGE
National Laboratory

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Carbon Fiber Design Project Overview in a Nutshell

- Objective
  - Demonstrate alternative shapes/sizes for carbon fiber that enable
    - Designing fibers to cost-effectively enhance compressive strength
    - Reducing the LCOE of wind energy with CF as preferred spar cap reinforcement
- 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
  - Project team is 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%***

Fiber Geometry vs Fiber Performance/Processing

- Compressive performance of CF composites is generally thought to be ~20-45% deficient. For same section, compressive performance always significantly trails tensile performance in CF composites.

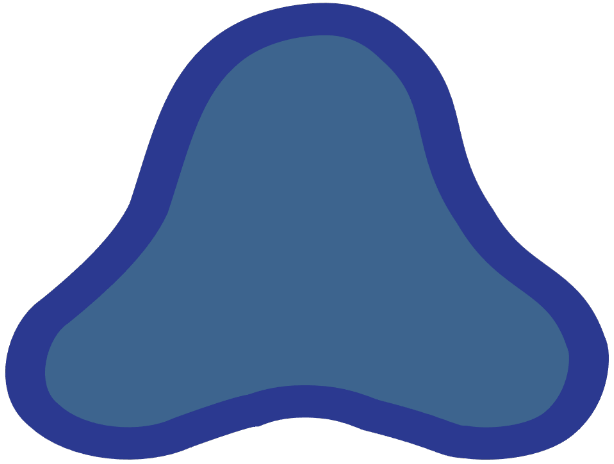
- Small diameter – small buckling resistance via Euler buckling theory

$$F_b = \frac{\pi^2 \, E \, I}{(K \, L)^2} \qquad\qquad I = \frac{\pi}{64} \boldsymbol{D^4}$$

- Larger diameter should enhance the buckling element of compression performance significantly, causing shift in failure mechanism.

- Advanced conversion technology may mitigate concerns about conversion economics associated with oxygen diffusion pathways in larger diameter.

- Other shape modifications can also enhance fiber inertia as well as conversion economics.



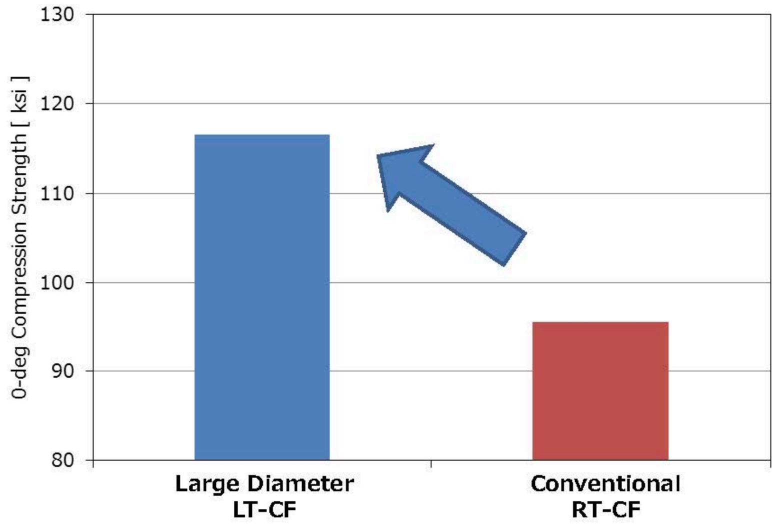
Carbon Fiber Diameter Selection is a Function of Generally-Accepted Tradeoffs

- Carbon fiber diameter is smaller than that of fiberglass
  - Carbon fiber is typically 4.5-8.5 microns
  - Fiberglass is typically 15-25 microns
- Processing Observations
  - Conversion: Oxidative stabilization is tied directly to diffusion pathway and rates which are generally *proportional to fiber diameter* <u>*squared*</u>
  - Composite Processing: Smaller diameter inhibits resin infusion
- Performance observations
  - Tensile strength of carbon fiber trends up with smaller diameter – compression relationship appears somewhat reverse
  - Higher properties are also a function of cross-sectional uniformity

Mitsubishi Found Improved Compression/Bending at Larger Diameters

◆ Improvement of Compressive Strength

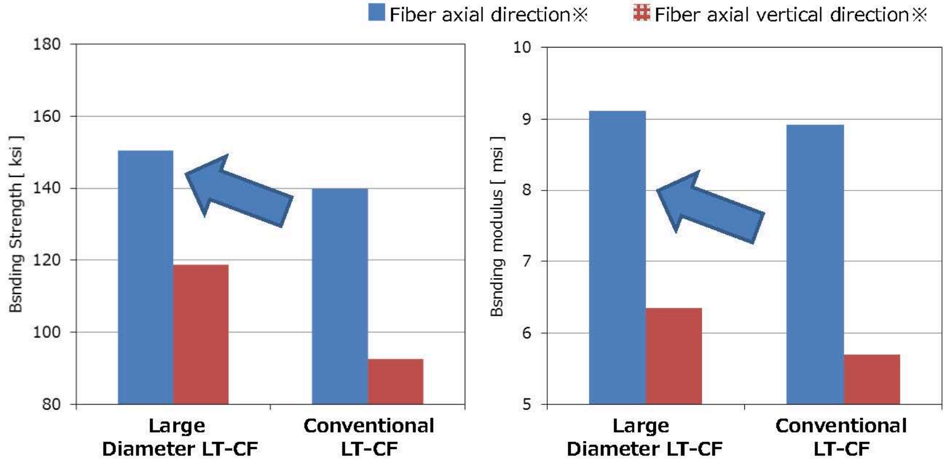
Resin: polyamide(nylon6)



0-deg CS of large diameter LT-CF is higher than conventional RT-CF, too.

◆ Mechanical properties of RTM panel

○Bending Strength ○Bending Modulus



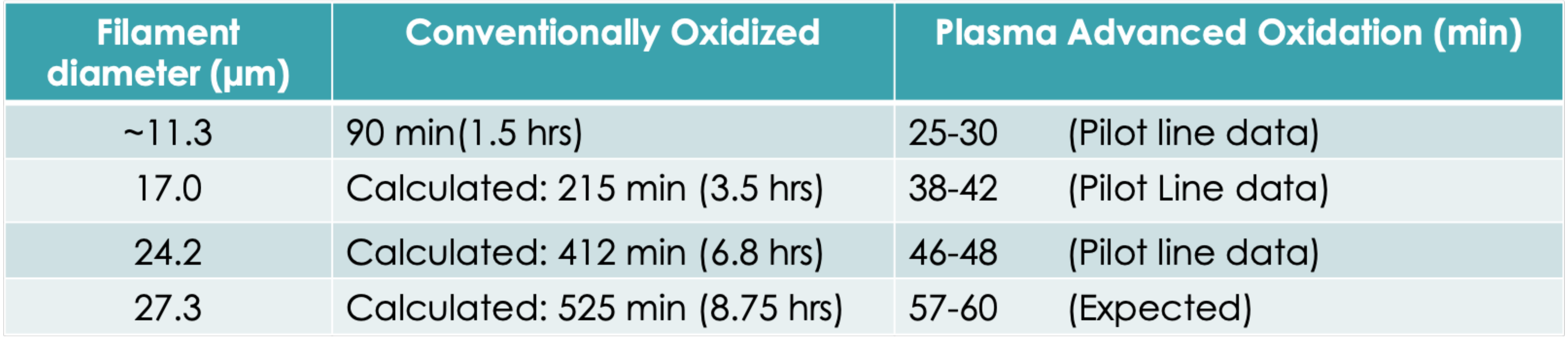
※Based on fiber axial direction of RTM panel surface

The bending strength and modulus of large diameter LT-CF are approximately 10% higher than those of conventional LT-CF

From presentation "Expanding carbon fiber industrial applications with newly developed large-diameter carbon fiber", Steven Carmichael and Yusuke Shinmen, Mitsubishi Rayon, November 2016

Recent Progress with Larger Diameter Fibers

- IACMI/ORNL/4XT/Dralon project initiated evaluation primarily as means to enhance throughput utilizing advanced (plasma oxidation) conversion
- Precursor produced in diameter ranges from less than 12 to approximately 30 microns – Dralon says large diameter precursor production works well
- Tensile properties appear as good or better than other textile fiber options
- Conversion has been unexpectedly fast:



Filament diameter (µm)	Conventionally Oxidized	Plasma Advanced Oxidation (min)
~11.3	90 min(1.5 hrs)	25-30 (Pilot line data)
17.0	Calculated: 215 min (3.5 hrs)	38-42 (Pilot Line data)
24.2	Calculated: 412 min (6.8 hrs)	46-48 (Pilot line data)
27.3	Calculated: 525 min (8.75 hrs)	57-60 (Expected)

Overall Project Approach/Plan – Leverages ORNL CF Capabilities

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

- Develop techniques to produce/provide carbon fibers with different diameters, but ***similar precursor chemistry/molecular weight and carbon fiber mechanical properties***
- Develop predictive analytical model for compressive performance to assist in distinguishing shape/size effects in testing from other manufacturing and testing artifacts
- Develop 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.

Advanced Oxidation System (right) makes larger diameter CF cost-effective in production. CFTF (far right) facilitates production of larger (demo-scale) samples

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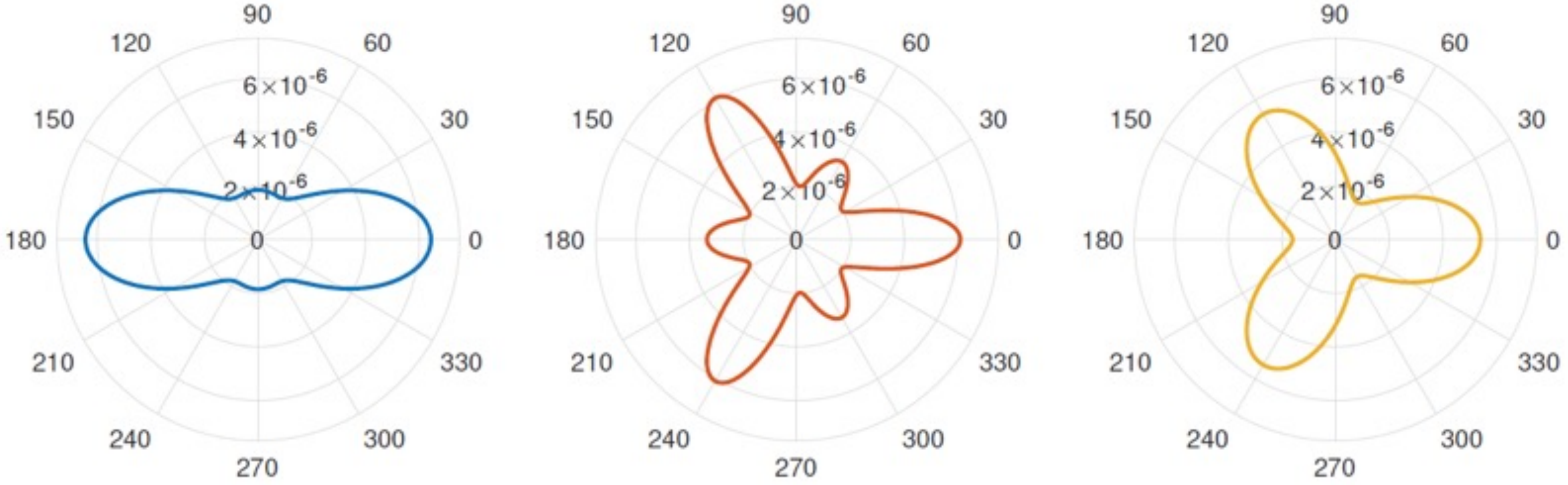
Overall Project Approach/Plan (cont)

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

Overall Project Approach/Plan (cont)

Unique ORNL Lab Capabilities Being Utilized - Precursor Wet Spinning (Left) and Precursor Evaluation System (Right)

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 techniques to produce/provide carbon fibers having a hollow cross section
- As budget permits, utilize results from Years 1 and 2 to better optimize shape, fiber size, or perhaps fiber post-treatment approaches from early work
- Results made available to wind industry and fiber production stakeholders; pathways to commercialization will be identified.

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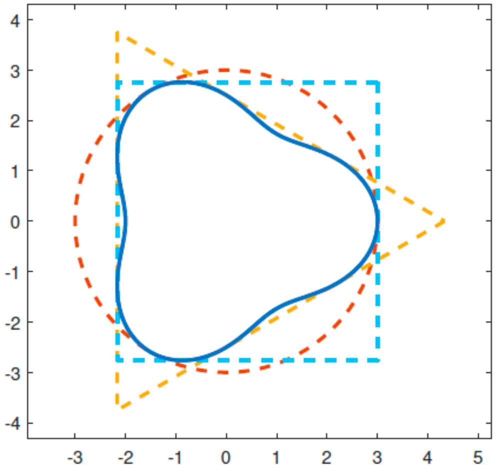
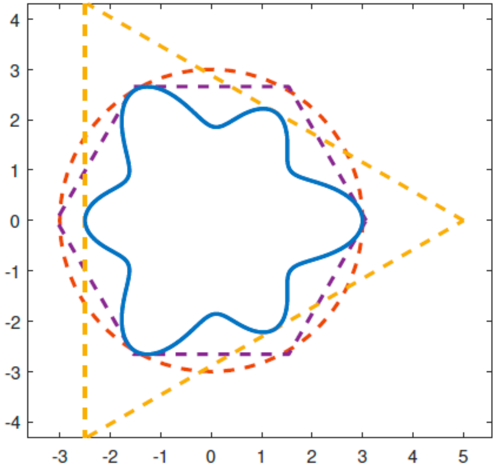
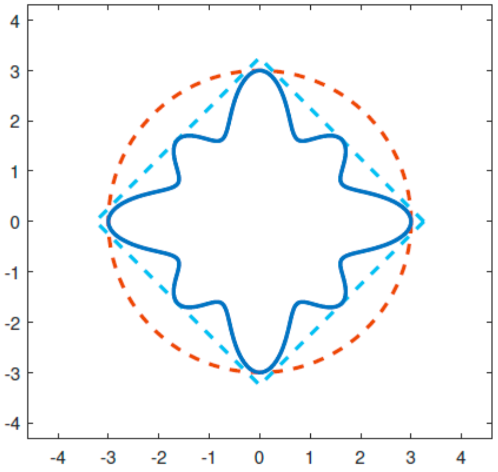
Fiber Shape Design Approach



(a) Three lobe shape packing fit



(b) Six lobe shape packing fit



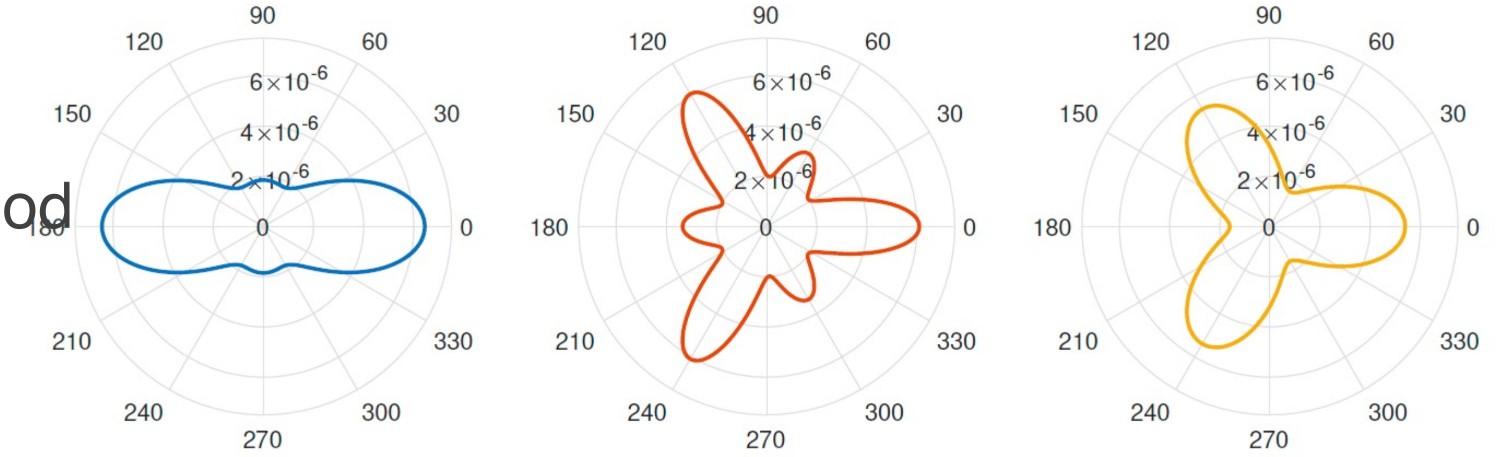
(c) Eight lobe shape packing fit

B. L. Ennis, H. S. Perez, R. E. Norris, "Identification of the Optimal Carbon Fiber Shape for Cost-Specific Compressive Performance", Materials Today Communication, Volume 33, December 2022, 104298.

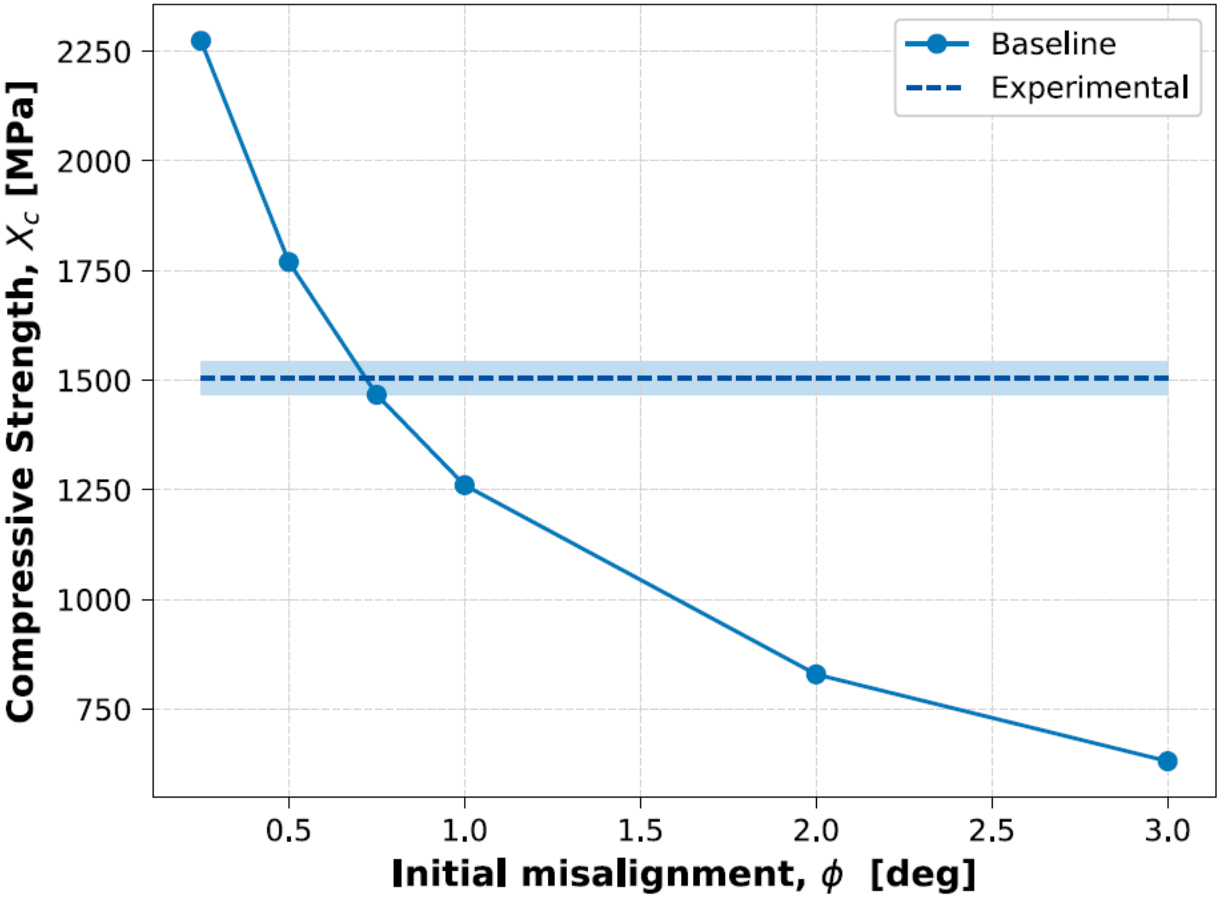
- A shape function has been formulated to generate arbitrary shapes using four independent variables where cross-section area is normalized to circular reference:
  - Number of lobes (k)
  - Amplitude of lobes (S)
  - Relative amplitude of alternating lobes (R)
  - Curvature/steepness of lobes (n)
- A penalized objective function approach is taken in order to include additional affects of fiber geometry
  - Fiber packing - ability for the fibers to align and pack together (62-69%) is important for the cost-effectiveness of the composite
  - Manufacturability – engineering judgement on what is most "makeable"

Optimal Carbon Fiber Shape for Cost-Specific Compression

- 4 lobe or “peanut” shape:
  - Best performer if using effective area moment of inertia with consideration of fiber packing factor (FPF) and perimeter
  - When using the minimum area moment of inertia for the fitness evaluations the 4 lobe shape is worse than a circular fiber
- 6 lobe shape is best performer for FPF where perimeter is weighted for the compressive strength proxy
- 3 lobe shape is a great average performer for FPF when reducing perimeter weighting
  - Considered the most robust shape based on manufacturability and likelihood of achieving fiber volume fraction



Compression Failure Modeling



- Compression failure modeling is being employed to better understand failure mechanisms to enhance predictions and interpret test data
- A micromechanical failure modeling approach has been developed using commercial tool ABAQUS®
- Finite element modeling compressive strength predictions (shown for square pack) depend strongly on fiber misalignment for these idealized simulations

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Samples for Fiber Size Effects Studies

- Precursor was produced using same formulation by textile partner Dralon at 2.2 dtex, 3.3 dtex, and 5.5 dtex (about 14.4μ, 17.7μ, and 23.9μ)
- Precursor was oxidatively stabilized by 4XT and carbonized/post-treated at CFTF achieving carbon fiber diameter of 5.8μ, 7.0μ, and 9.5μ – diameter differences of >20% for each group and >60% largest to smallest
- Fiber tensile mechanical properties across all 3 groups were remarkably comparable

	Carbon Fiber Measured Properties			
	Calcculated Diameter	Peak Stress (Ksi)	Tensile Modulus (Msi)	Strain (%)
	5.78	477.0	34.56	1.38
	5.82	476.3	34.71	1.37
	5.84	440.9	34.57	1.28
	5.76	475.8	34.61	1.37
	5.87	469.1	34.61	1.36
	5.62	474.5	34.56	1.37
	5.86	425.2	35.37	1.21
	5.82	459.9	34.93	1.32
Average	**5.80**	**461.8**	**34.74**	**1.33**
	7.05	470.2	34.39	1.37
	7.00	456.1	34.50	1.32
	7.00	478.3	34.39	1.39
	7.06	438.7	34.24	1.28
Average	**7.03**	**460.8**	**34.38**	**1.34**
	7.02	465.1	34.57	1.35
	6.99	440.5	35.24	1.25
	6.96	442.6	34.76	1.27
	7.06	431.3	34.67	1.23
Average	**7.01**	**444.9**	**34.81**	**1.28**
	9.41	435.1	34.64	1.22
	9.39	420.2	34.48	1.22
	9.42	448.1	34.41	1.16
	9.45	476.3	34.62	1.38
Average	**9.42**	**444.9**	**34.54**	**1.25**
	9.67	481.8	34.55	1.39
	9.45	477.3	34.39	1.39
	9.45	481.2	34.70	1.39
	9.66	527.2	34.99	1.51
Average	**9.56**	**491.9**	**34.66**	**1.42**

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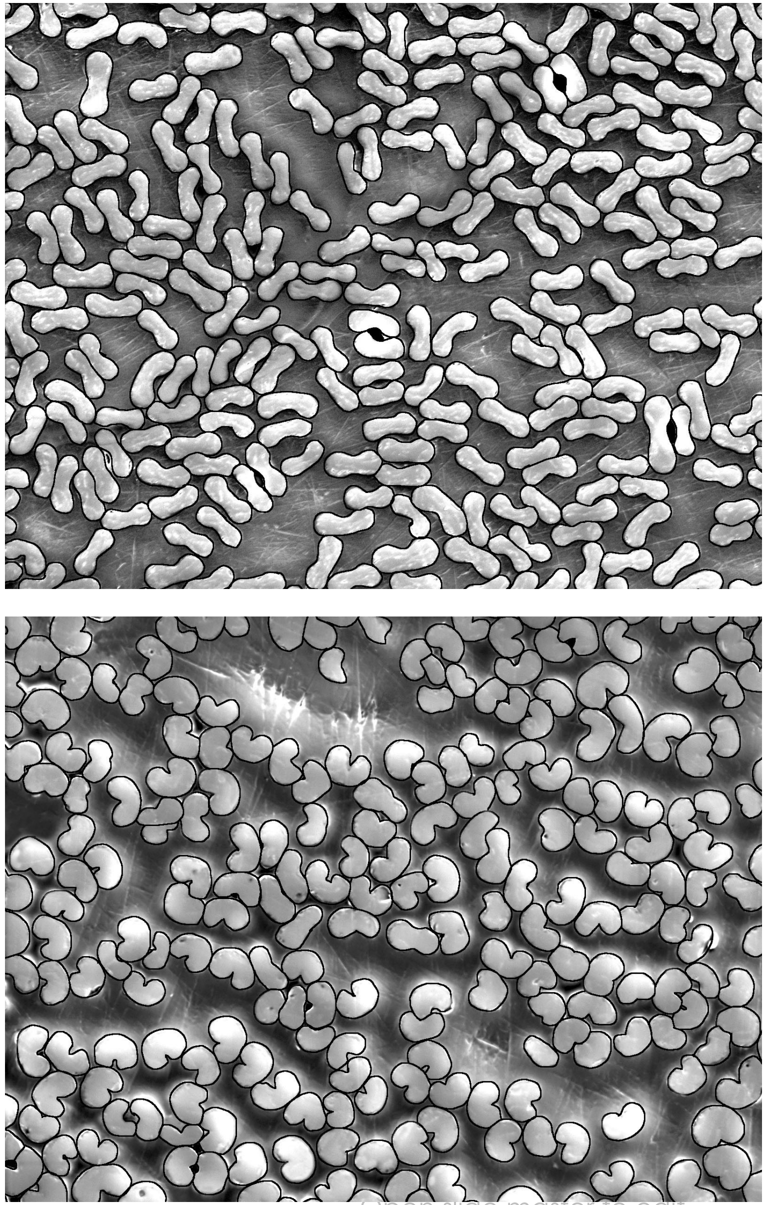
Data Trends Support Case for Alternative CF in Blades

Summary of ASTM D6641 Standard Compression Tests
Ultimate Compressive Strength Average and Standard Deviation

Fiber	V_F*	E, GPa	$(0)_n$			$(90/0)_{ns}$ using BF factor		
			UCS, MPa	Std. Dev.	Strain, %	UCS, MPa	Std. Dev.	Strain, %
AS4A	0.64	148	-1028	80	-0.69	-987	58	-0.67
IM7 (unsized) IM7G	0.58 0.62	159 162	-818 -991	73 139	-0.51 -0.61	-1301 -1254	92 65	-0.82 -0.78
PX35	0.59	143	-971	78	-0.68	-1163	98	-0.81
T300	0.60	139	-846	45	-0.61	-1291	130	-0.93
T600 (fabric)	0.63	133	-796	38	-0.60	-1079	85	-0.81
4XT Dolan 5.8 micron	0.58	139	-942	40	-0.68	-1081	43	-0.78
4XT Dolan 7.0 micron	0.59	141	-1112	37	-0.79	-1151	138	-0.82
4XT Dolan 9.5 micron	0.57	135	-1103	104	-0.82	-1216	64	-0.90
Dralon Dogbone	0.52	119	-1090	68	-0.92	-1122	49	-0.94
Kaltex Kidney Bean Small	0.52	136	-777	70	-0.57	-1026	92	-0.81
Kaltex Kidney Beam Medium	0.55	118	-1135	88	-0.96	-1119	104	-0.90

*V_F calculated from fiber modulus or matrix digestion. Back out factor (BF) $= 2E_{11}/(E_{11} + E_{22}) = 1.86 - 1.89$ for these laminates



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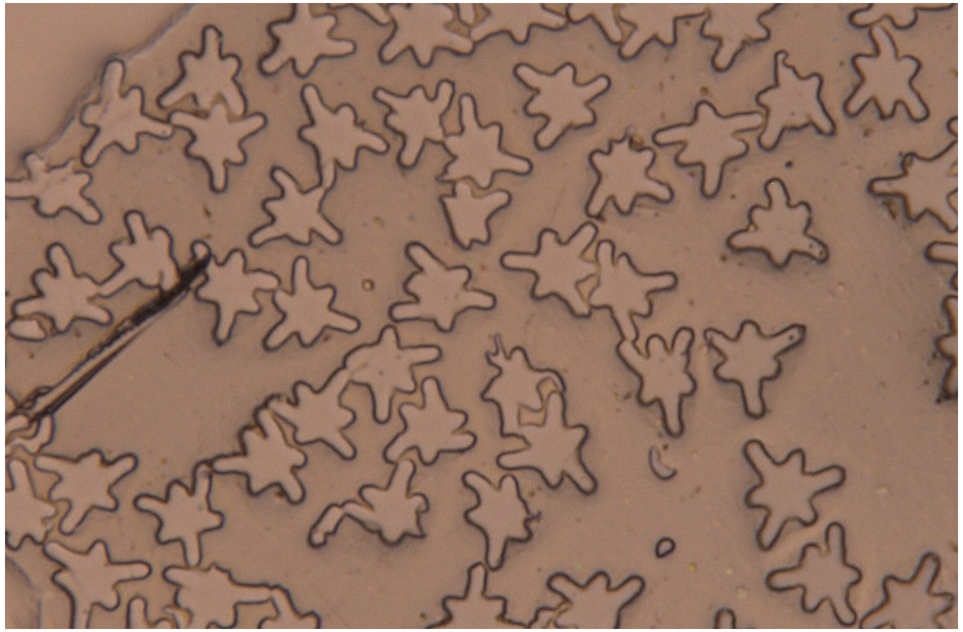
Unique CF Shapes Currently Being Developed/Evaluated

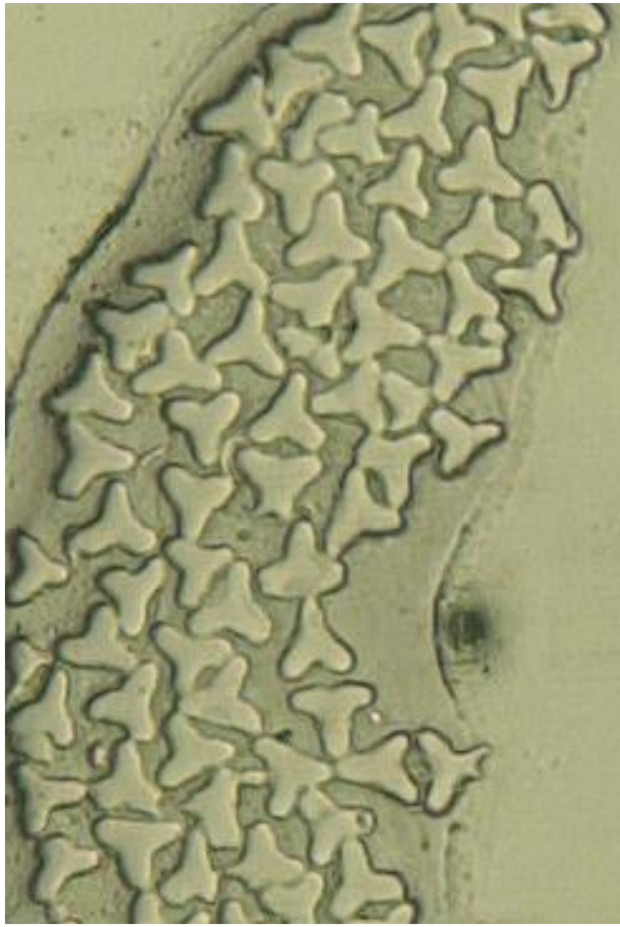
3-lobed Fiber Far Right

6-Lobed Fiber Below



Diameter	**Break.Stress**	**Modulus**	**Strain**
µm	Ksi	Mpsi	%
9.67	403.30	32.49	1.23
10.18	187.58		0.55
11.49	133.14		0.50
10.28	278.12	34.51	0.82
10.00	505.45	34.51	1.44
10.66	360.37	32.11	1.15
10.26	372.95	32.96	1.19
8.20	453.02	29.50	1.50
10.08	492.92	33.91	1.44
10.24	289.80	33.39	0.88
10.67	541.41	32.47	1.63
10.16	143.74		0.46
10.30	479.30	33.00	1.44
10.50	203.50	33.56	0.63
10.23	432.37	35.02	1.23
10.20	**351.80**	**33.12**	**1.07**
0.68	**137.57**	**1.46**	**0.40**

Recent Fiber Data on 6-lobed Fiber



Working to Enhance and Scale Lobed and Hollow Fiber

- Tests of Initial Samples of 6-lobed Fiber Inconclusive
  - Overall mechanical tensile properties (notably stiffness) significantly lower than for previous fibers
  - Fiber fractions for the composite samples were lower as well
  - Sample quantities were limited due to high resource consumption (risk)
  - Lessons learned being used to scale 3-lobed fibers with less pronounced lobe shapes

Fiber Type	Fiber Fraction	Rods UCS, MPa	Coupons UCS, MPa	Rods: Percent of larger coupons UCS
AS4A	0.64	-628	-1028	0.61
IM7	.58	-675	-1301	0.52
IM7G	.62	-734	-991	0.74
PX35	.59	-787	-1163	0.68
T300	.60	-616	-1291	0.48
4XT Dolan 5.8 micron	.58	-641	-1081	0.59
4XT Dolan 7.0 micron	.59	-685	-1151	0.59
4XT Dolan 9.5 micron	.57	-824	-1216	0.68
Dralon Dogbone	.52	-752	-1122	0.67
Kaltex Kidney Bean Small	.52	-609	-1026	0.59
Kaltex Kidney Beam Medium	.55	-578	-1135	0.51
ORNL 6-Lobe	.42	-748	-652	1.15

- Somewhat surprisingly, some 6-lobe rod samples showed very competitive compressive strength

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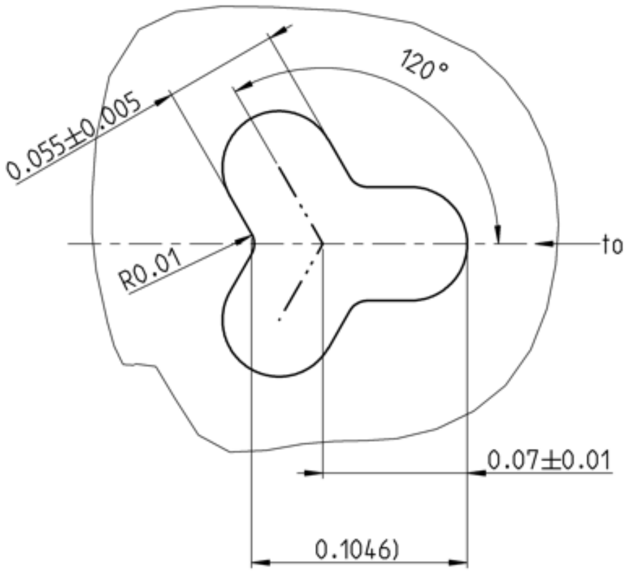
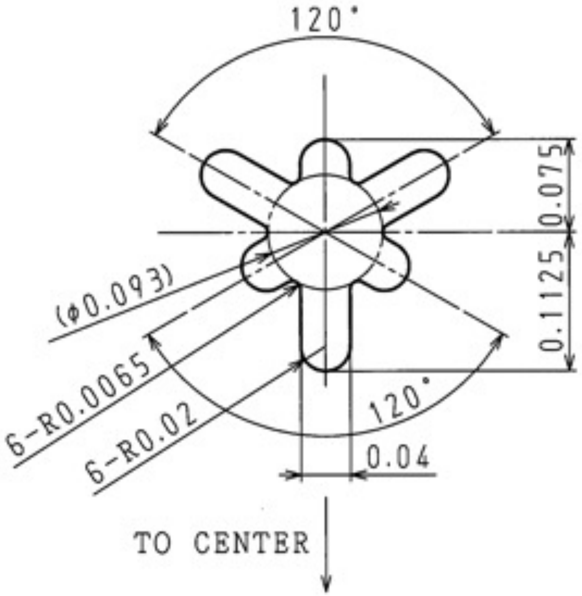
Designing Target Shapes Begins at the Spinneret/Spin Line

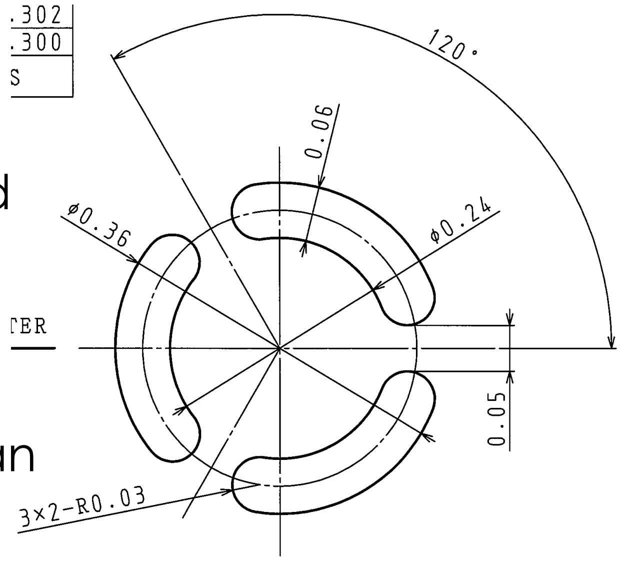
- We continue to evaluate a variety of detailed shapes/sizes to gain critical feedback on general shape utility and understand how variations on detail characteristics affect both manufacturability and robust performance
- Working with several spinneret producers, we have challenged their capabilities, knowing spinnerets are expensive, long-lead-time deliverables
- Tailoring spinning process is also key to tweak shape features and properties





Spinneret hole designs: Tri-lobal (far left, 6-lobes (left) and “3C” for Hollow Shapes

(We are also experimenting with an internally supported hollow shape)



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Related Issues and Activities

- Costs of producing even small amounts of precursor and then converting those at lab scale are very high; we are only beginning to exercise the available tools for implementation
- Fortunately, we have been able to leverage related work to provide significant technical background, facilities and some of the experimental materials – *thanks CFTF and 4 XT!*
- So far, we have also gotten adequate/comparable surface treatment and sizing processes as part of our partnering
- Close coordination and interaction with modeling and testing are required
- At this point, we do not have budget to explore effects of tow size, varying fiber fractions, surface treatments/sizing, etc.

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Phase 1 has Identified Unique Approaches to Design More Cost-Effective Carbon Fiber for Wind

- Several lower cost carbon fiber products achieve comparable compressive performance with some tensile deficits vs industry standards and even higher performance fibers
- Unique fiber geometry tools have been highlighted and potential advantages are being demonstrated at lab-scale
- Although data is limited due to quantities available in bench-scale fiber production, some shape vs performance trends are emerging
- Modeling results have identified certain shapes as likely dual winners by both increasing compressive strength while decreasing projected processing costs

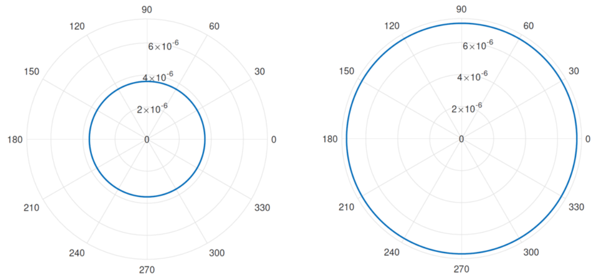
Planning Follow-on Fiber Development Work for Phase 2

- As stated earlier, we are only beginning to exercise the available tools for implementation
- Phase 2 will better optimize shape/fiber sizes of most promising approaches, building on promising findings from ongoing work
  - Focusing on best techniques to scale up and provide larger sample sizes to solidify data findings - open to industry teaming for scaling
- Open up experimental work to include characteristics held constant in Phase 1
  - Expand investigation to include effects of tow size, fiber fractions, etc
  - Evaluate alternative post-treatment approaches for wind products
- Model and experimentally validate combined effects of the above to balance tensile/compressive strengths and production economics

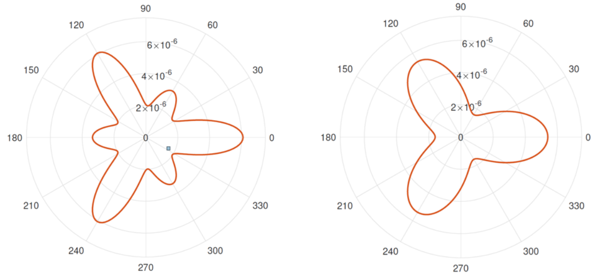
Follow-on “Phase 2” Proposal Modeling Tasks

Phase 1 Results

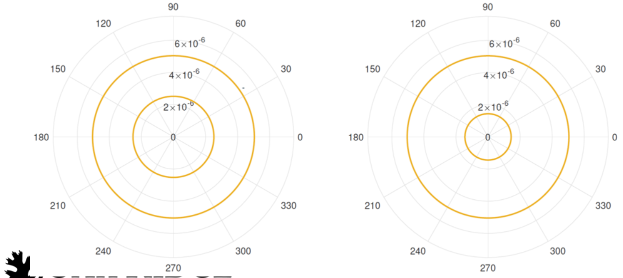
Size Effects



Shape Effects

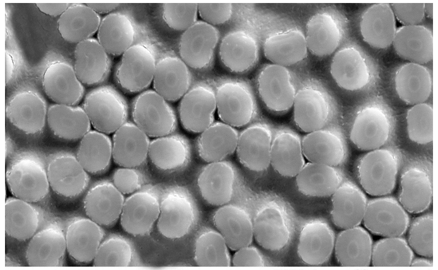


Hollow Effects



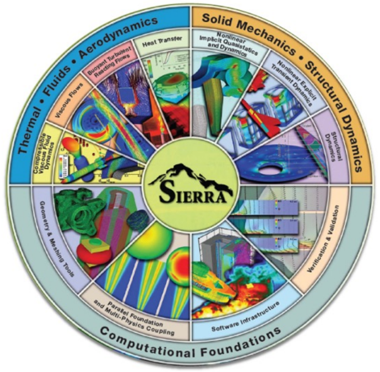
Additional Cost and “Tow” Effects

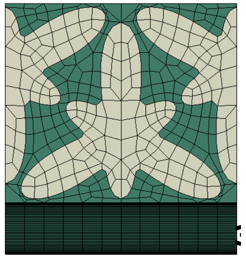
- Comprehensive cost relationships
- Achievable fiber volume fraction based on;
  - Tow size (number of fibers in a bundle)
  - Fiber geometry
  - Statistical packing
- Fiber alignment versus;
  - Fiber area moment of inertia



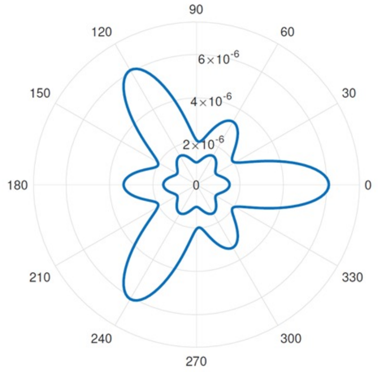
Phase 2 Scope

High-fidelity modeling and optimization





Combined Optimal Design of Carbon Fiber and Tow Properties



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Phase II Demonstration and Completion Activities

- Down-select 1 or 2 approaches to scale up to demonstration level
- Scale up precursor production internally or recruit potential precursor partner and utilize CFTF to produce CF quantities adequate for larger demo sections
- Produce and test CF composite sections more representative of actual spar cap sizes and construction methods
- Update detailed techno-economic modeling of alternative CF product manufacturing and associated spar cap production
- Conduct multiple direct outreach activities targeting CF manufacturer collaboration with blade producers to generate needed commercialization push/pull

Summary and Conclusions

- We understand that this is a complex study area and we are making a number of simplifying assumptions in modeling, fiber production, and testing
- Successfully produced very comparable carbon fiber with >60% diameter spread to evaluate diameter variation effects
- Production of alternatively shaped carbon fiber is progressing well, although production levels are challenging for internal capabilities. Pathway to hollow fiber shape is less clear
- Modeling and testing feedback and interaction are critical for producing and interpreting meaningful results
- We are excited to have advisory committee participation for exchange of plans/suggestions along this pathway - hope the group will consider implementing successful approaches