CW 2019 CompositesWorld

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Evaluation of Low-Cost Carbon Fiber Materials for Use in Wind Turbine Blade Design Seminar

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Oak Ridge National Laboratory
Montana State University

Topic
Project overview and results
Material selection and discussion
Carbon fiber cost modeling
Material mechanical testing
Next steps and related project activities

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Sandia National Laboratories

OAK RIDGE National Laboratory

MONTANA STATE UNIVERSITY

Optimized Carbon Fiber Composites for Wind Turbine Blades

Project Approach and Summary

November 19, 2019

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David Miller (MSU)

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Optimized Carbon Fiber for Wind Energy Project

Sandia National Laboratories

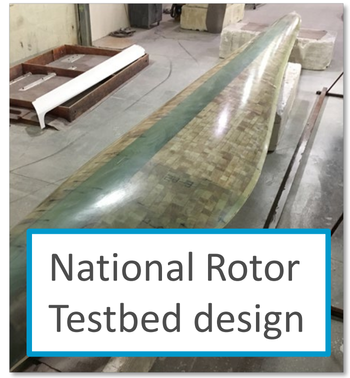
OAK RIDGE National Laboratory

MONTANA STATE UNIVERSITY

The objective of this project is to assess the commercial viability of cost-competitive, tailored carbon fiber composites for use in wind turbine blades.

- Wind turbine blades have unique loading criterion, including nearly equivalent compressive and tensile loads
- The driving design loads for wind turbines vary for high and low wind speed sites, and based on blade length and weight – producing distinct material demands
- Composites for wind turbines are selected based on a cost-driven design, compared to the performance-driven aerospace industry

Project Overview – Team and Capabilities



National Rotor Testbed design

Bend-twist coupled blade design

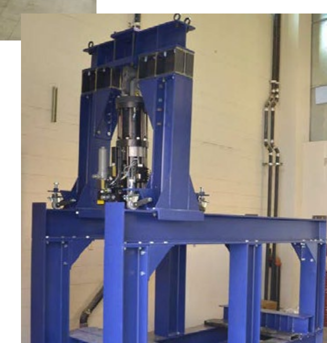
Sandia National Laboratories

- DOE's designated rotor design group
- Experience in design, manufacturing, and testing of novel blade concepts

Carbon Fiber Technology Facility

Oak Ridge National Laboratory

- Composites development/applications and Leadership in DOE Low Cost Carbon Fiber Program
- Carbon Fiber Technology Facility for technology demonstration/licensing opportunities
- Cost-modeling utilized to guide focal activities



Substructure test frame

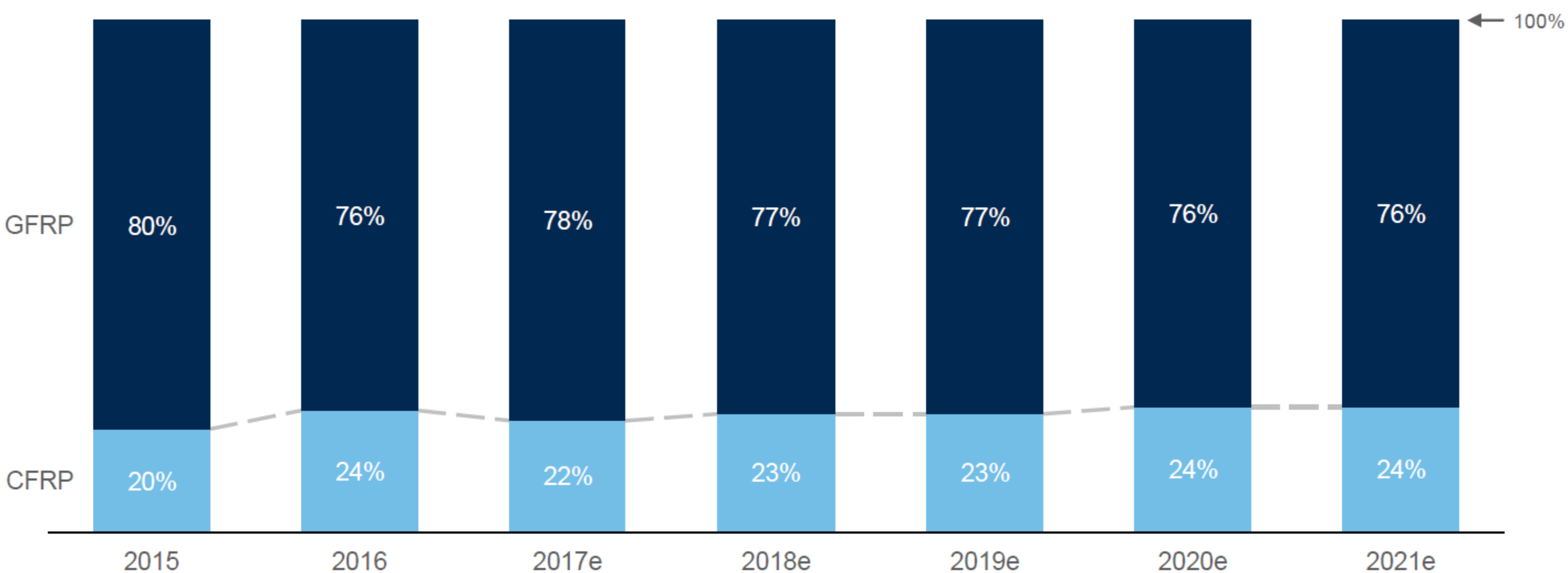
Montana State University

- Nearly 3 decades of experience and expertise in testing of composite materials for the SNL/MSU/DOE database
- Failure analysis methodologies utilized to characterize material failure progress during testing and post-mortem

Wind Turbine Blade Material Trends

- Despite industry growth in blade length, carbon fiber usage in wind turbine spar caps is not predicted to grow in the foreseeable future
- Stated reasons by turbine OEMs include price concerns, manufacturing sensitivities, and supply chain limitations/concerns
- High-modulus glass fiber has been pursued as an alternative

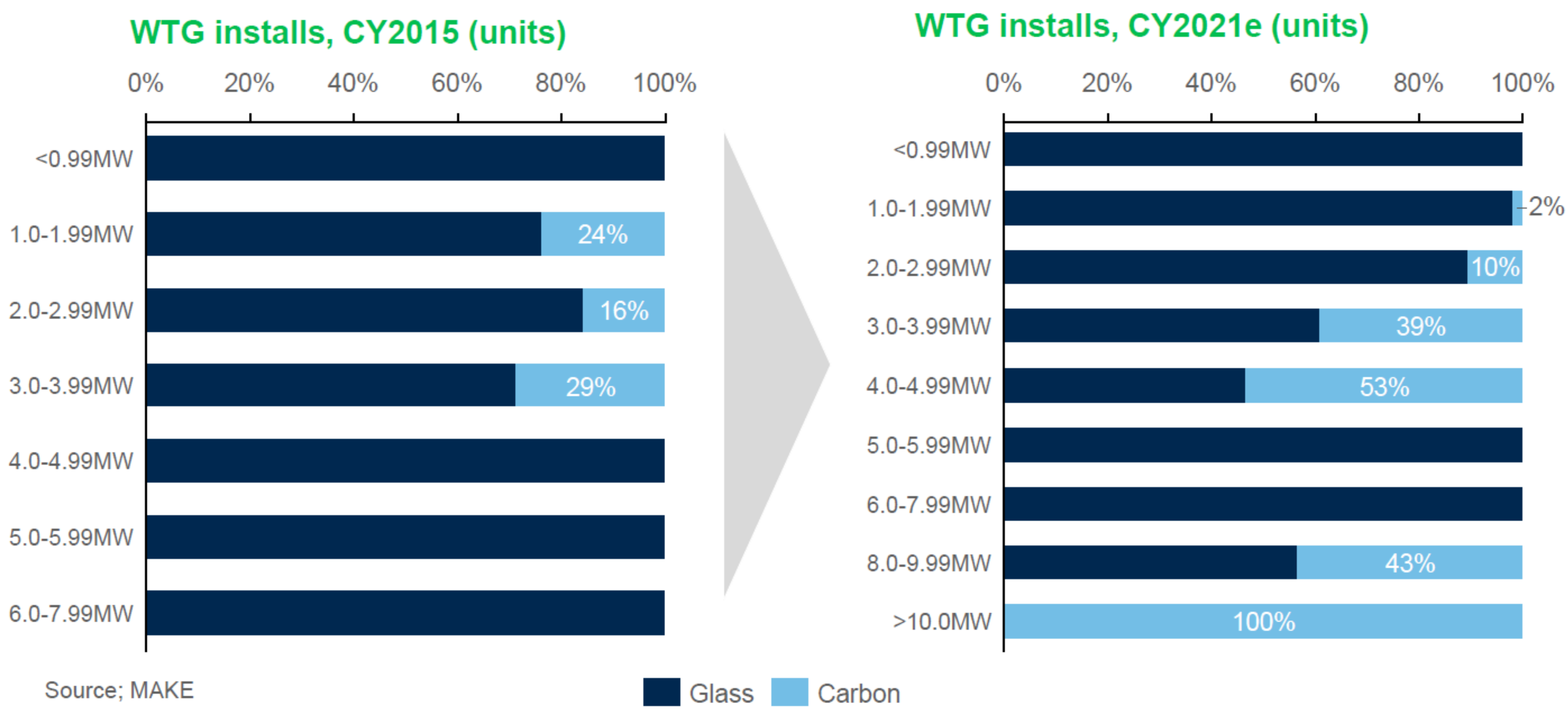
Global wind turbine installations, 2015-2021e (GW)



Source: MAKE

Wind Turbine Blade Material Trends

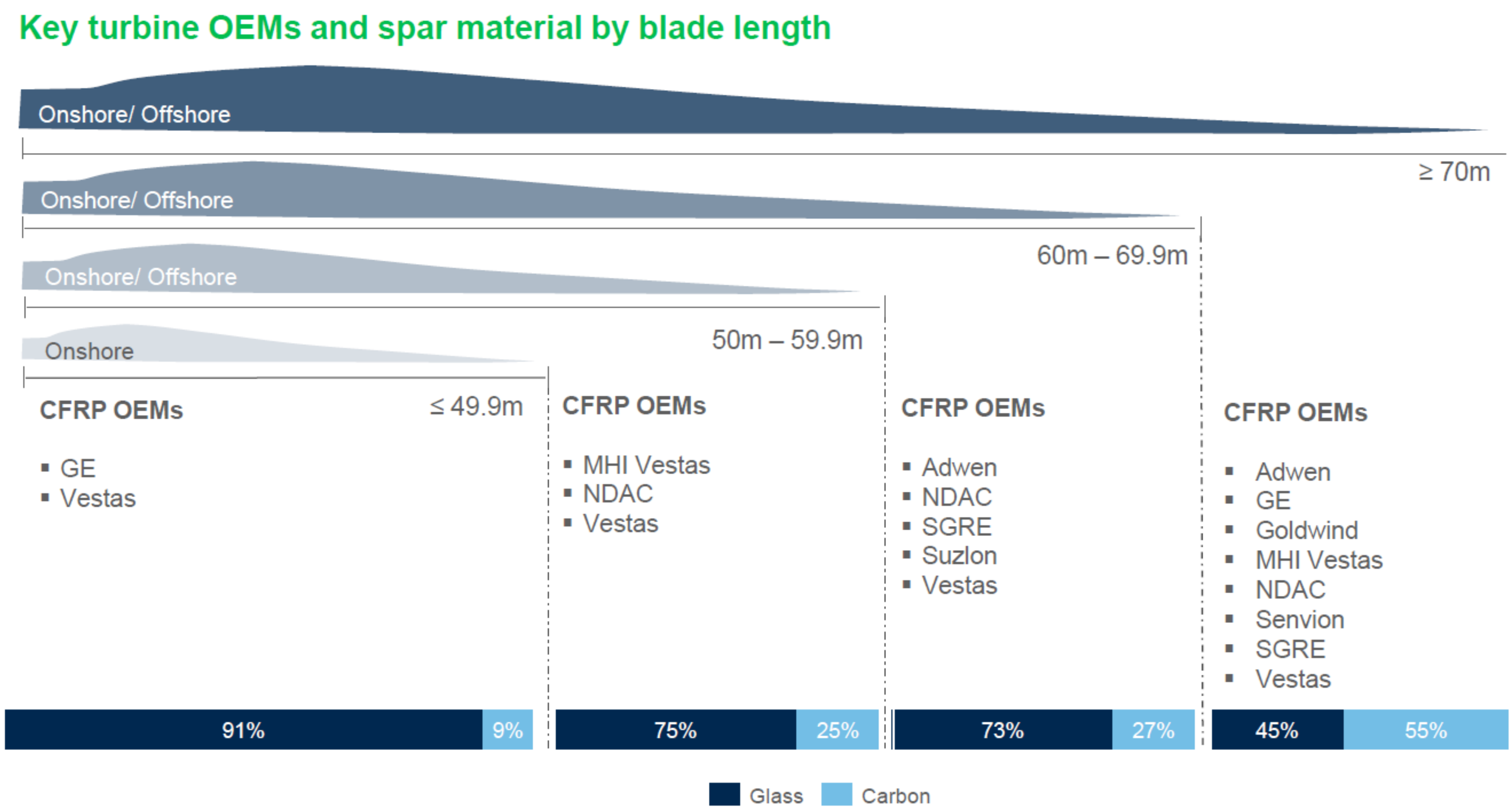
- In 2015, none of the installed 4-8 MW wind turbines utilized carbon fiber
- The usage of carbon fiber in blade designs is expected to increase for large, land-based machines and offshore wind turbines



Source; MAKE

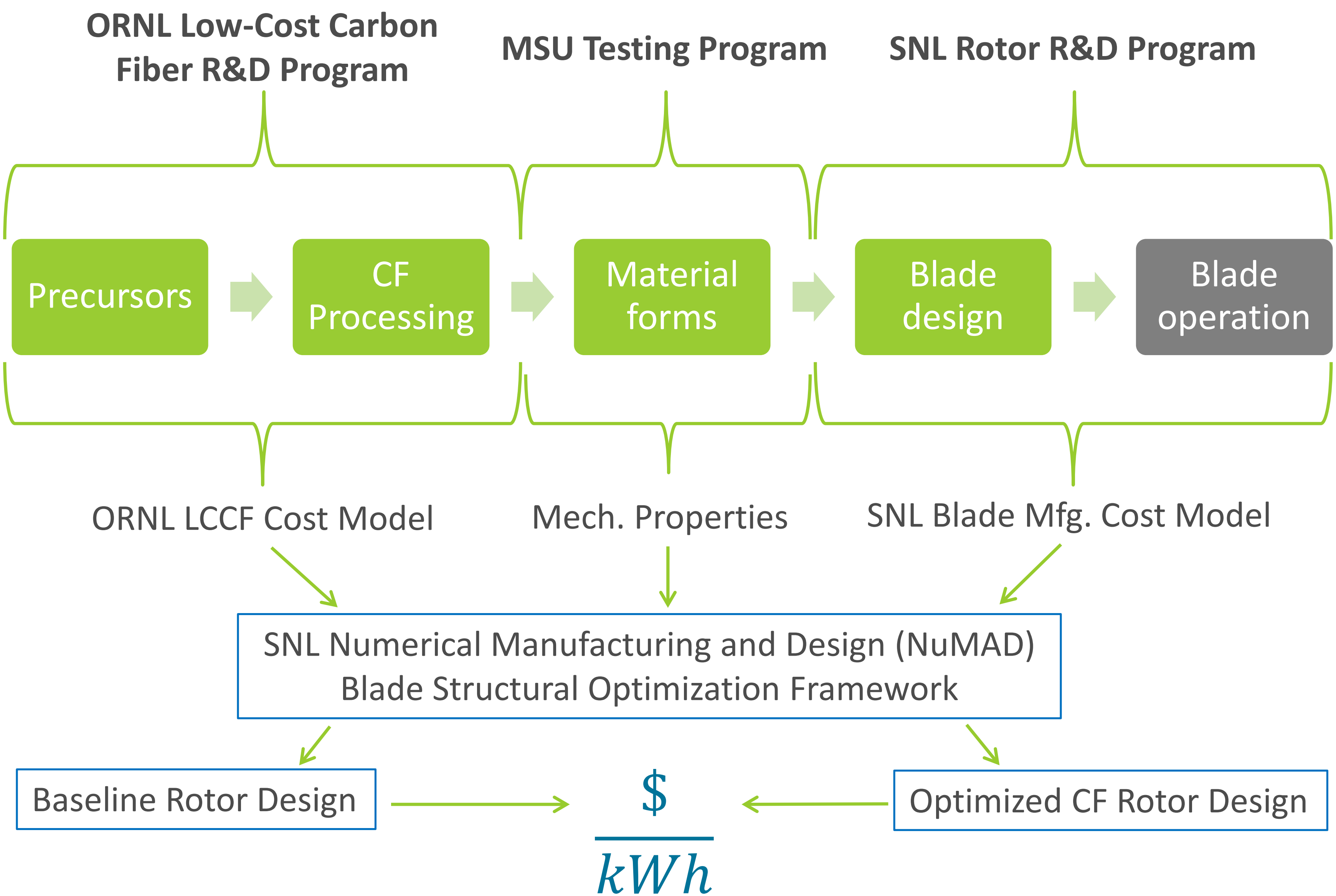
Wind Turbine Blade Material Trends

- Carbon fiber blade designs produce a system value by reducing the blade and tower-top weight, however, OEMs have identified ways to design blades at all available lengths using only glass fiber



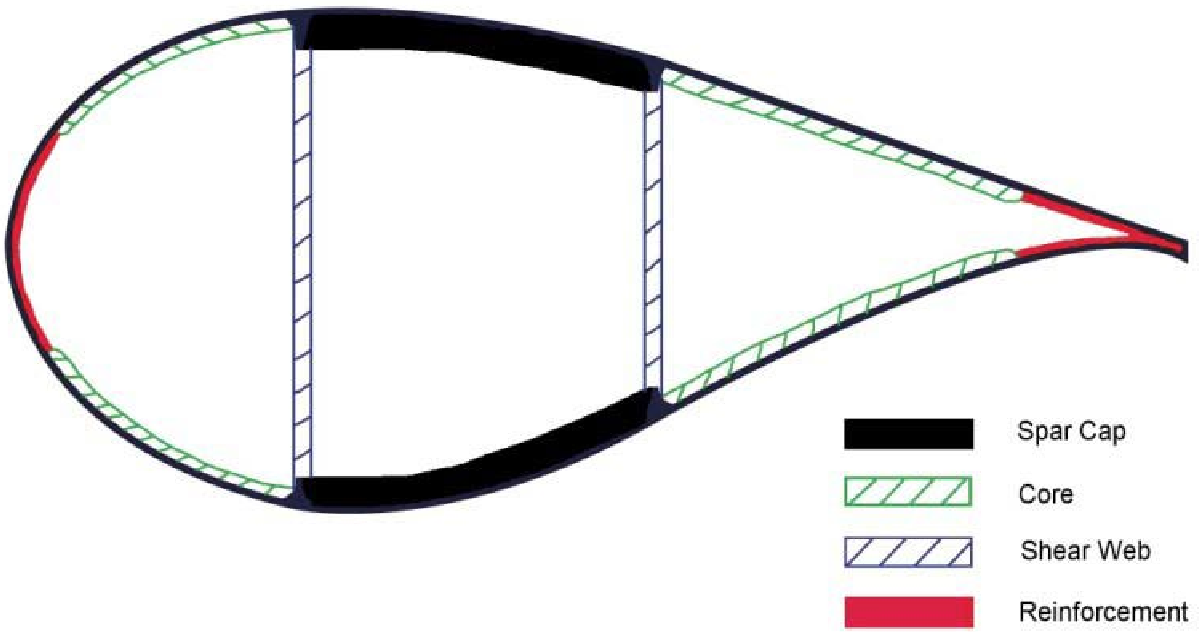
Note: % use of spar material on “current” and “prototype” turbine platforms in the market
Source: MAKE

Project Approach and Key Deliverables



Project Overview – Study Definition

- This project has studied the impact of novel and commercial carbon fiber materials on the main structural member of blades, the spar cap



Material Testing

Material testing performed using industry baseline carbon fiber material and ORNL low-cost textile carbon fiber materials:

- **Industry baseline** (50k tow)
- **ORNL Low-cost carbon fiber**:
  - Precursor #1: Kaltex 457k tow
  - Precursor #2: Taekwang 363k tow

Materials have been tested in **(1) aligned strand infused** and **(2) pultruded** composite forms

- MSU aligned strand to minimize manufacturing bias and enable direct material comparison
- Pultrusion considered as the true form for carbon fiber in wind turbine blades

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Lot Analysis for K20-HTU

Lot Number: TE4571150808

	Average	Standard Deviation
Tensile Strength (Ksi):	385.4	20.4
Tensile Modulus (Msi):	37.5	0.7
Elongation (%):	1.03	0.05
Linear Density (g/m):	14.71	2.18
Size (%)	1.18	0.38
Density (g/cc)	1.788	0.004
Date of Manufacture:	August 2015	

ORNL Material Properties for Kaltex Precursor (above) and Taekwang precursor (below)

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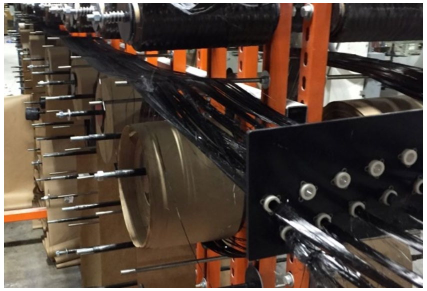
Lot Analysis for T20-C

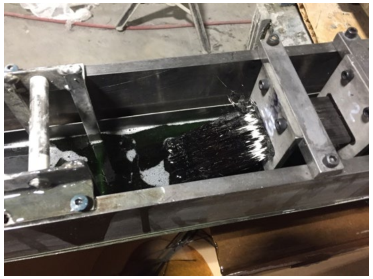
Lot Number: TE3631170205

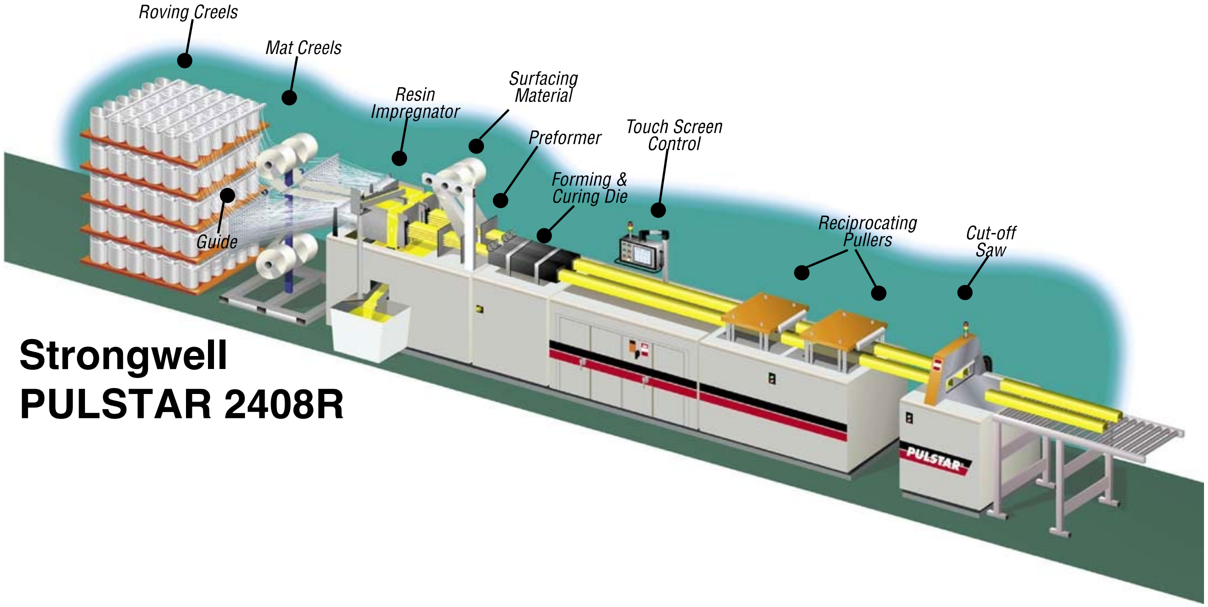
	Average	Standard Deviation
Tensile Strength (Ksi):	389.5	9.3
Tensile Modulus (Msi):	36.8	0.3
Elongation (%):	1.08	0.03
Linear Density (g/m):	11.46	0.49
Size (%)	1.36	0.32
Density (g/cc)	1.720	0.003
Date of Manufacture:	February 2017	

Material Testing

- The project team worked with a third-party pultruder to obtain pultruded samples of the CFTF heavy-tow materials
- No obvious differences from the Industry Baseline carbon fiber







Strongwell PULSTAR 2408R

Material Testing

1. Pultruded composite samples

Material	Composite Form	Layup	V_F [%]	E [GPa] 0.1-0.3%	UTS [MPa]	%, max	UCS [MPa]	%, min
ORNL K20 (Kaltex)	Pultrusion (third-party)	(0), 112017-5	51	123	846	0.69	-769	-0.64
Zoltek PX35	Pultrusion (third-party)	(0), 112017-6	53	114	1564	1.33	-897	-0.79
	Pultrusion (Zoltek)	(0)	62	142	2215	1.47	-	-
				138	-	-	-1505	-1.20

2. Aligned strand, infused composite samples

Material	Composite Form	Layup	V_F [%]	E [GPa] 0.1-0.3%	UTS [MPa]	%, max	UCS [MPa]	%, min
ORNL T20 (Taekwang)	Aligned strand	$(0)_5$ and $(0)_{10}$	50	126 (4)	968 (54)	0.75 (0.05)	-869 (46)	-0.69 (0.04)
ORNL K20 (Kaltex)	Aligned strand	$(0)_5$ and $(0)_{10}$	47	112 (6)	990 (49)	0.84 (0.06)	-872 (108)	-0.77 (0.10)
Zoltek PX35	Aligned strand	5.1 tows/cm	51	119 (4)	1726 (93)	1.48 (0.08)	-906 (44)	-0.74 (0.04)

Material Testing

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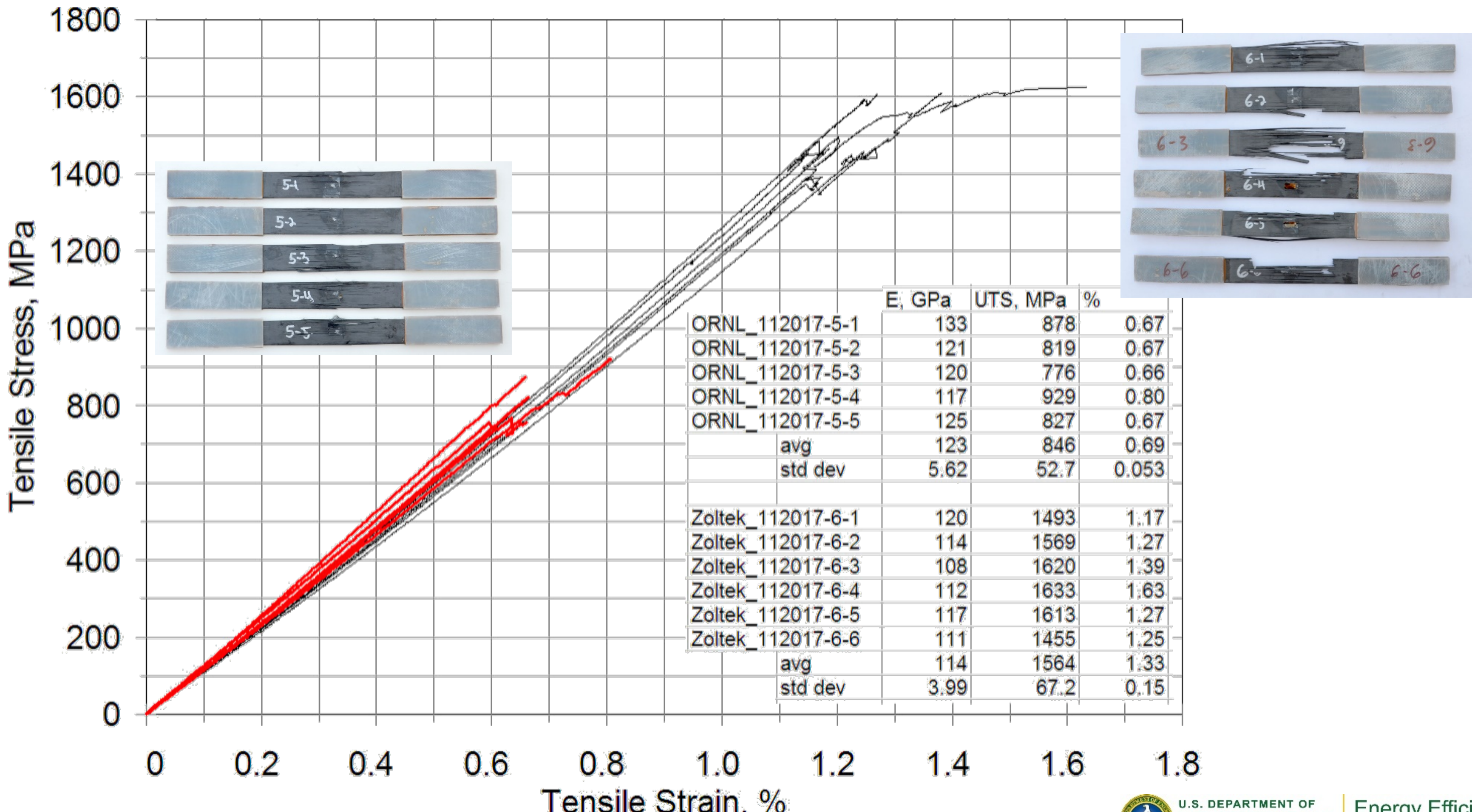
Material Testing

Tensile tests on 112017-5 (ORNL T20) and 112017-6 (PX35) materials

- Ultimate tensile strength is substantially degraded in the heavy-tow fibers, however, compressive strength is more critical for wind turbine blade design



	E, GPa	UTS, MPa	%
ORNL_112017-5-1	133	878	0.67
ORNL_112017-5-2	121	819	0.67
ORNL_112017-5-3	120	776	0.66
ORNL_112017-5-4	117	929	0.80
ORNL_112017-5-5	125	827	0.67
avg	123	846	0.69
std dev	5.62	52.7	0.053
Zoltek_112017-6-1	120	1493	1.17
Zoltek_112017-6-2	114	1569	1.27
Zoltek_112017-6-3	108	1620	1.39
Zoltek_112017-6-4	112	1633	1.63
Zoltek_112017-6-5	117	1613	1.27
Zoltek_112017-6-6	111	1455	1.25
avg	114	1564	1.33
std dev	3.99	67.2	0.15

Material Testing

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Material Testing

Aligned strand, infused composite samples

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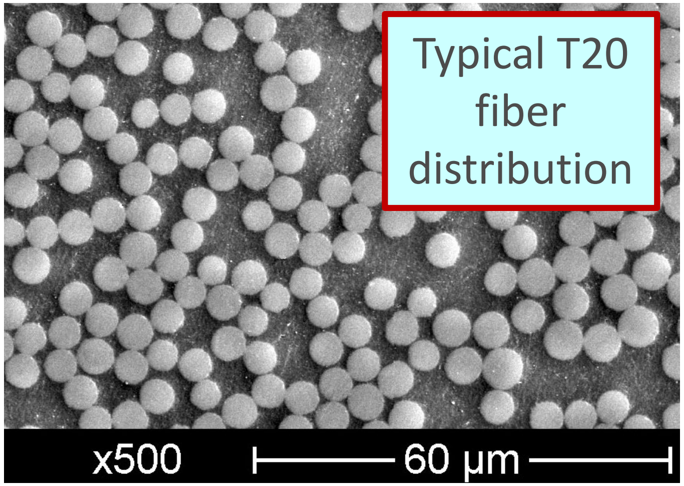
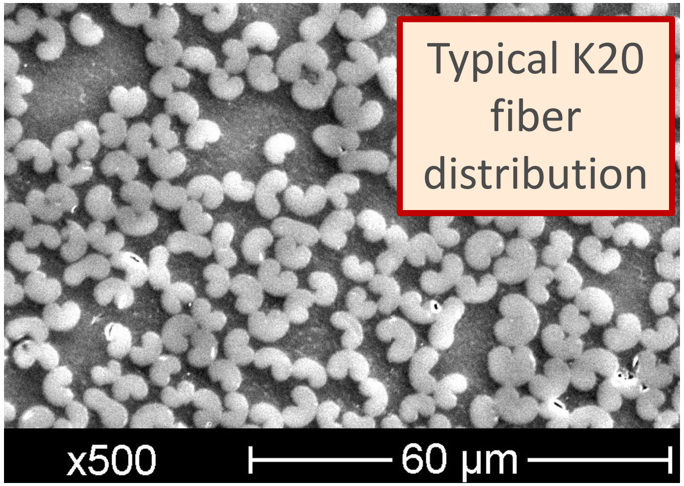
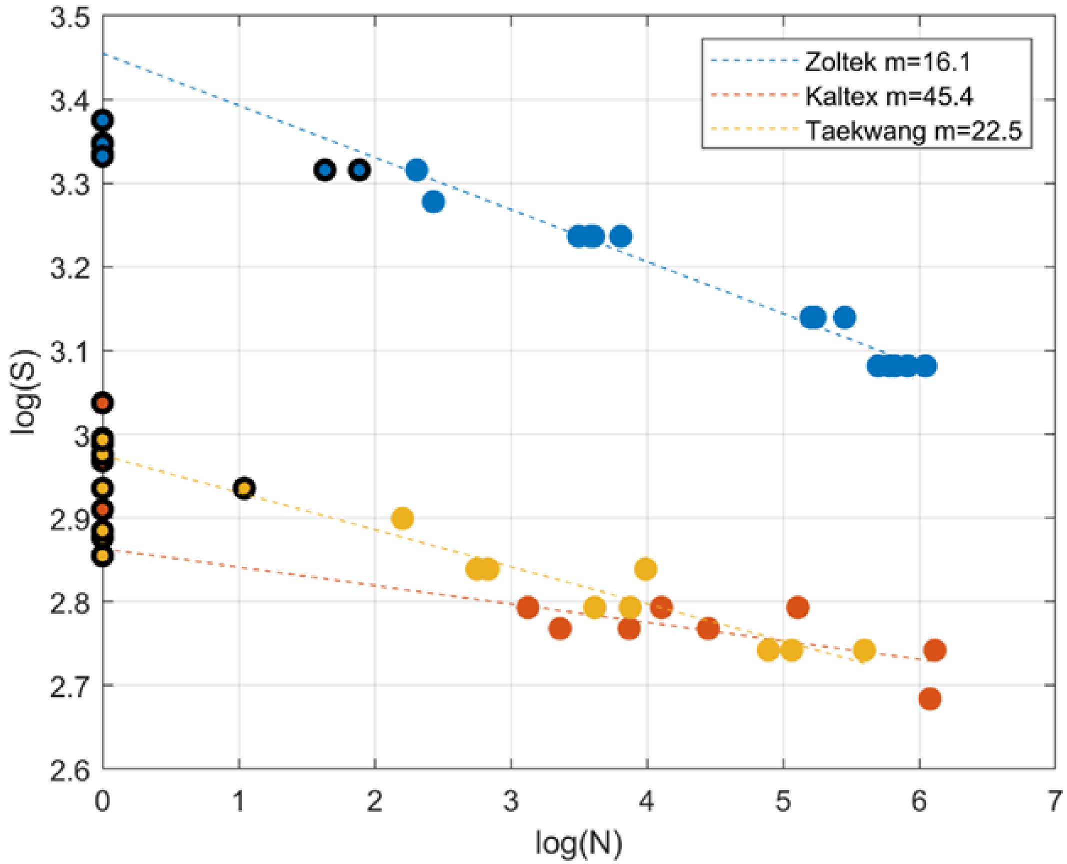
- ORNL Kaltex precursor has smaller fibers, heavier-tow, and kidney shaped fibers
- The non-round K20 material has approximately 6% higher UCS, but with greater variability (in early tests)





Material Testing

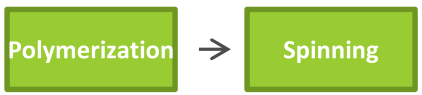
- Tension-tension fatigue tests at a single load cycle (R=0.1) were performed to compare the fatigue characteristics
  - **Zoltek 62% fiber volume fraction pultrusion** compared with the **textile carbon fiber materials in ~50% fiber volume fraction infusions**
- The textile carbon fiber materials were relatively fatigue insensitive



Carbon Fiber Cost Modeling

Precursor model (Baseline -- 7500 t/year line capacity)

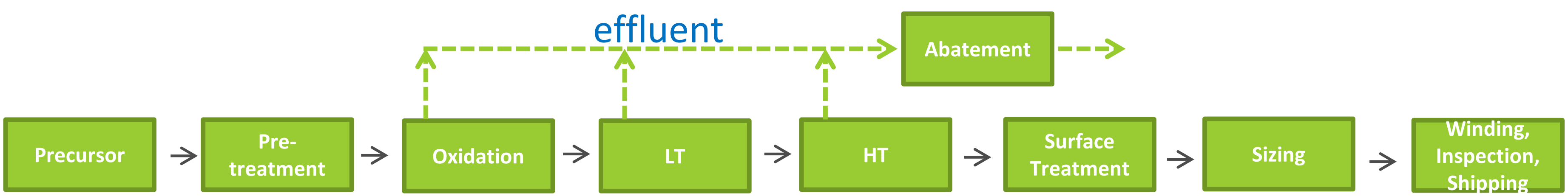
Evaluate precursor manufacturing at the level of two major process steps:



- User may examine any production volume from 1 - 45,000 t/y (7,500 t/y and 45,000 t/y used as low and high production volume)
- Test sensitivity of key parameters such as spin speed, process yield, raw material costs and ratios, energy vector costs, etc.

Carbon Fiber model (Baseline -- 1500 t/year line capacity)

Evaluate carbon fiber manufacturing at the level of nine major process steps:



- User may examine any production volume from 1 - 18,000 t/y (economies of scale for a fully utilized carbon fiber lines between low and high production volume)
- Test sensitivity of key parameters such as line speed, residence times and temperatures of oxidation, LT, and HT, precursor cost, etc.

Carbon Fiber Cost Modeling

- The ORNL heavy-tow carbon fiber material is estimated to cost between 38-57% less than the industry baseline
- The (current) scenario represents the material processing as tested
- The (full-utilization) scenario is accounting for realistic commercial processing

PARAMETER	BASELINE	HEAVY TEXTILE TOW (current)	HEAVY TEXTILE TOW (full-utilization)
Precursor Cost	$3.63/kg	$2.24/kg	$2.24/kg
Tow Size	50K	457K	457K
Tow linear density (g/m)	3.7	15	15
Tow Spacing	24 mm	50 mm	24 mm
Strands/Line	120	58	120
Line Speed	9 m/min (211 kg/hr)	7 m/min (338 kg/hr)	8.45 m/min (843 kg/hr)
Annual Prodn. Volume	1500 tonnes/yr	2400 tonnes/yr	6000 tonnes/yr
Capital Investment	$58MM	$58MM	$58MM
Final Fiber Cost	$17.98/kg	$11.19/kg	$7.82/kg

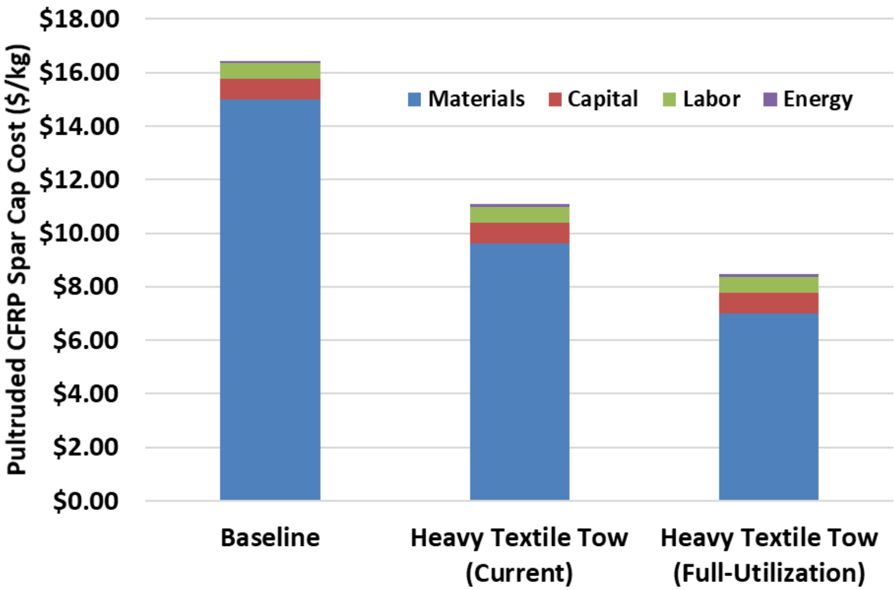
Carbon Fiber Cost Modeling

Parameter	Baseline $/kg (%)	Heavy Textile Tow (full-utilization) $/kg (%)	Reduction %
Materials	$8.09 (45.0%)	$5.05 (64.6%)	38%
Capital	$6.62 (36.8%)	$1.91 (24.4%)	71%
Labor	$2.06 (11.5%)	$0.47 (6.0%)	77%
Energy	$1.20 (6.7%)	$0.39 (4.9%)	68%
TOTAL	**$17.98 (100%)**	**$7.82 (100%)**	**57%**

- ✓ Lower precursor cost -- High output textile grade acrylic fiber used for clothing application today vs. specialty acrylic fiber
- ✓ Lower capital cost – Higher production capacity (heavy tow and higher conversion speed) for a significantly lower cost and simpler similar sized capital equipment available today (largest share of total cost reduction)
- ✓ Lower energy and labor cost – Economies of scale from an increased throughput

Pultruded Composite Cost Model

- Pultrusion is arguably one of the most stable, repeatable and cost-competitive composite manufacturing processes of continuous fiber composites
- A pultrusion cost model was developed as part of the project to enablecost comparisons of the manufactured blade
- Pultruded form model input properties were estimated using the testing results and cost estimates and models from the project work



$$E = V_f E_f + (1 - V_f) E_m$$

$$S_{ut} \approx S_{ft} T_f \left[V_f + (1 - V_f) \, {}^{E_m}\!/_{E_f} \right]$$

$$S_{uc\,(vf2)} \approx \left({}^{S_{uc}}\!/_{S_{ut}} \right)_{vf1} S_{ut\,(vf2)}$$

Model Input Values for Spar Cap Materials

- Carbon fiber composites have significantly higher properties than fiberglass

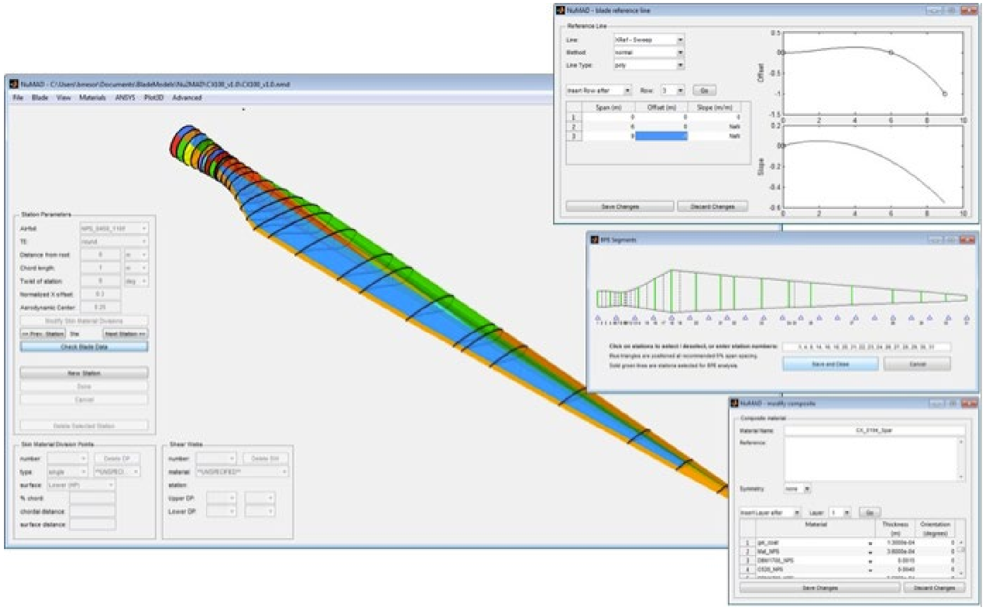
Material	Vf	E [GPa]	UTS [MPa]	UCS [MPa]	Cost [/kg]
Industry Baseline CFRP pultrusion	0.68	157.6	2427.3	-1649.2	$16.44
Heavy-Tow CFRP pultrusion	0.68	160.6	1508.5	-1315.0	$8.38 - $11.01
Fiberglass infusion	0.55	42.8	1169.7	-743.5	$2.06

- The heavy-tow carbon fiber shows cost-specific improvements in mechanical properties over the industry baseline carbon fiber over the cost estimate range

Material	UTS(MPa)/$/kg	%	UCS(MPa)/$/kg	%	E(GPa)/$/kg	%
Industry Baseline	147.6	**100**	-100.3	**100**	9.6	**100**
Heavy-Tow (full-utilization)	180.0	**122**	-156.9	**156**	19.2	**200**
Heavy-Tow (current)	137.0	**93**	-119.4	**119**	14.6	**152**
Fiberglass infusion	437.9	**297**	-311.7	**311**	20.8	**217**

Wind Turbine Blade Optimization

- **Blade structural optimizations** have been performed with blade material cost minimization as the objective
- The **impact of material choices** has been assessed using the developed cost estimates and mechanical properties
- Derived trends of material properties vs. cost will be used to more broadly address the question of **which properties matter most** for particular blade designs

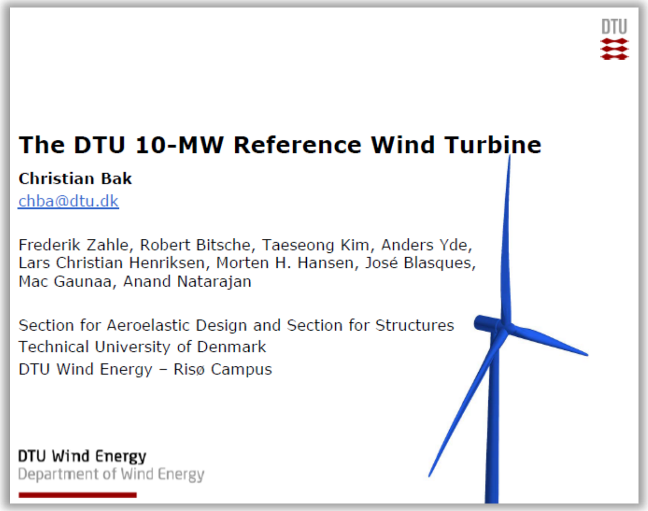


Wind Turbine Blade Optimization

Structural and material optimizations have been performed using **two reference blade models**, representative of industry trends:

1. High wind resource (IEC class I-B), large wind turbine representative of future offshore wind turbines; **IEA 10 MW** aerodynamic design
2. Low wind resource (IEC class III-A), high energy capture wind turbine typical of development for the low wind speed sites across the U.S.; **SNL3.0-148** aerodynamic design

Ensures that the results cover the differences from driving load conditions and machine type


DTU

The DTU 10-MW Reference Wind Turbine

Christian Bak
chba@dtu.dk

Frederik Zahle, Robert Bitsche, Taeseong Kim, Anders Yde, Lars Christian Henriksen, Morten H. Hansen, José Blasques, Mac Gaunaa, Anand Natarajan

Section for Aeroelastic Design and Section for Structures
Technical University of Denmark
DTU Wind Energy – Risø Campus

DTU Wind Energy
Department of Wind Energy


Exceptional service in the national interest

Sandia National Laboratories

Wind Turbine Blade Reference Model for the U.S. Low Wind Resource Regions

Brandon L. Ennis and Christopher L. Kelley

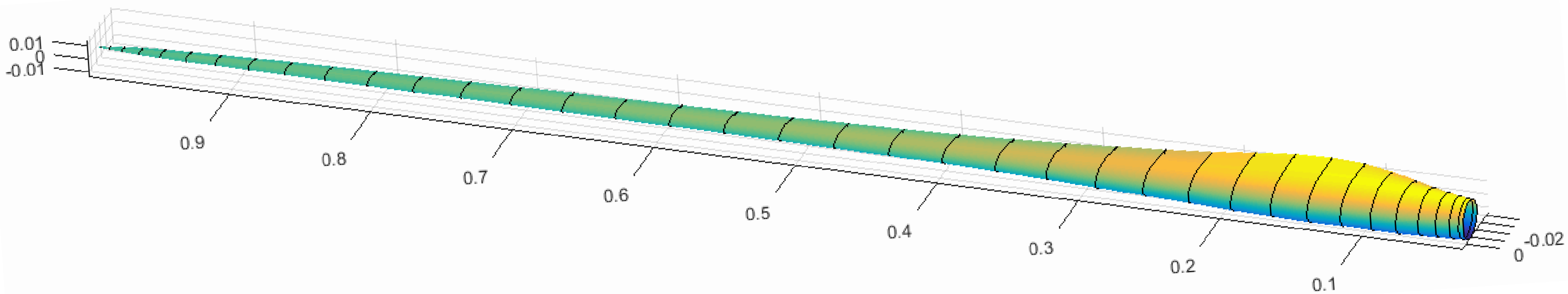
ENERGY NNSA

Blade structural optimization performed using NuMAD to produce **blade structural designs**:

- (**s1**) All-fiberglass reference design
- (**s2**) Industry baseline reference design
- (**s3**) Heavy-tow textile carbon fiber reference

SNL3.0-148 Reference Blade Model

Publicly available reference model that is representative of the industry shift towards high energy capture wind turbines for land-based sites.

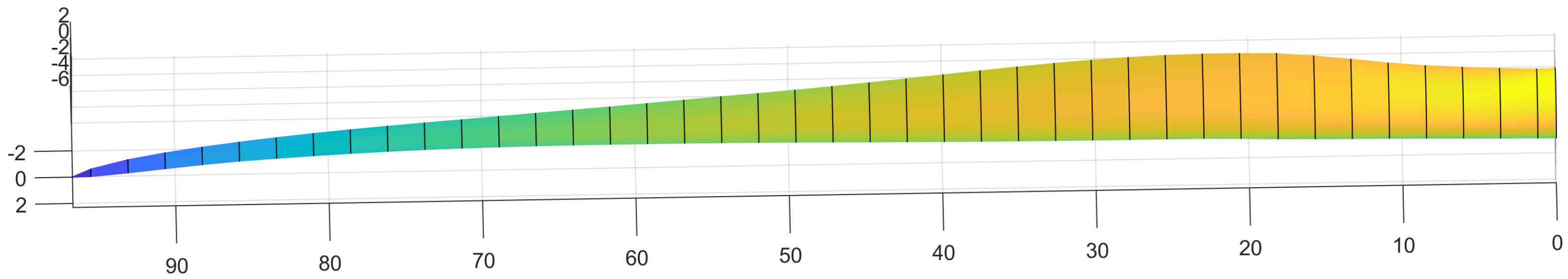


- 3 MW power rating
- 148 m turbine diameter
- 72 m blade length
- 175 W/m^2 specific power
- Class III-A site
- TSR = 9

- Blade solidity = 2.85%
- Lightly loaded tip
  - Matches the root bending moment of the "optimal" induction design (a=1/3) while increasing energy capture through a longer blade
- 30 year design life

IEA10.0-198 Reference Blade Model

Publicly available reference model that is representative of increasing machine rating and blade length typical for offshore sites.



- 10 MW power rating
- 198 m turbine diameter
- 96.7 m blade length
- 325 W/m² specific power
- Class I-B site
- TSR = 9
- Blade solidity = 3.5%
- High-induction Region 2 design
  - Design operation has induction exceeding the aerodynamic “optimal” design (a=1/3)
- 25 year design life

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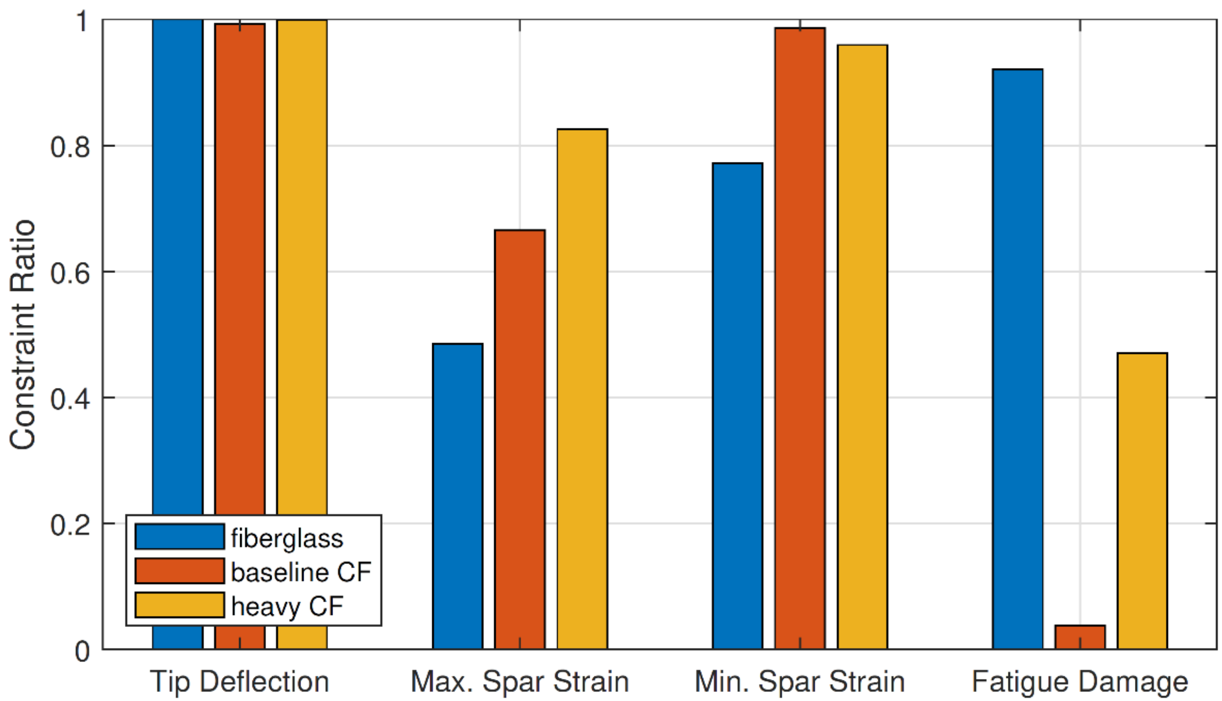
Blade Optimization Results

- Reduced set of the most relevant design load cases were simulated within the optimization
  - IEC DLC 1.4: extreme coherent gust with wind direction change
  - IEC DLC 6.1: 50-year extreme wind model (turbine parked)
  - IEC DLC 1.2: normal turbulence model (fatigue analysis)
- Solve for spar cap material layup along the blade length
- Minimize spar cap material subject to constraints:
  - Design tip deflection of less than 20% of the blade length
  - Tensile and compressive failure strain limits
  - Spar cap fatigue damage not exceeding design life
- Blade shell material sized from global buckling checks performed offline (outside of the optimization)

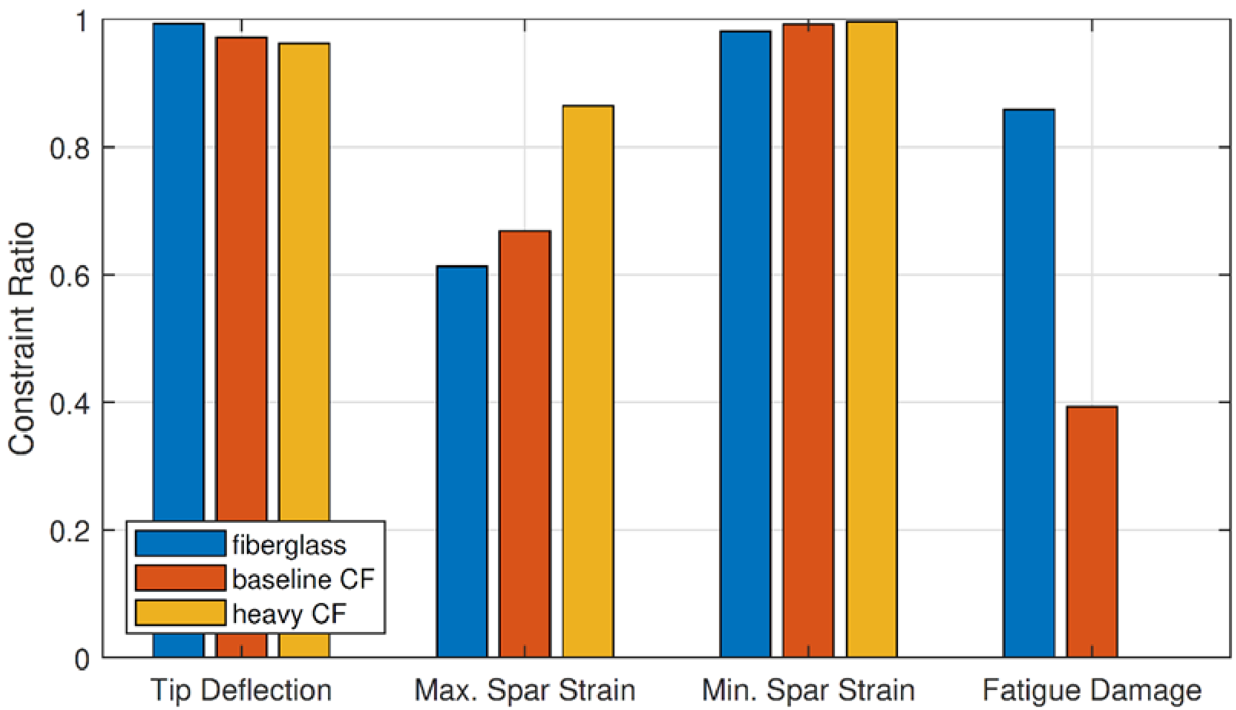
SNL 3MW Constraint Results

- This low wind-resource turbine is stiffness driven for the fiberglass spar
- The two carbon fiber materials nearly simultaneously meet the deflection and compressive strain limits
- The fiberglass design is fatigue-driven which drives the material demand up to meet the design life



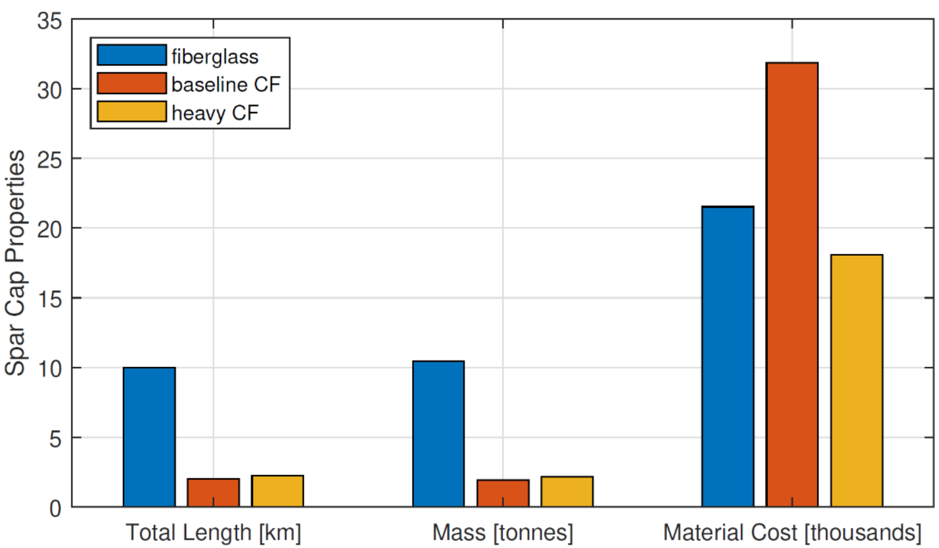
IEA 10MW Constraint Results

- The large offshore turbine is strength-driven for the fiberglass design
- Similar to the 3 MW design, the material compressive strength is what drives the design (not tensile strength) for the study materials
- The fatigue life of the two carbon fiber spar caps are over double the design life for both the 3 MW and 10 MW turbines

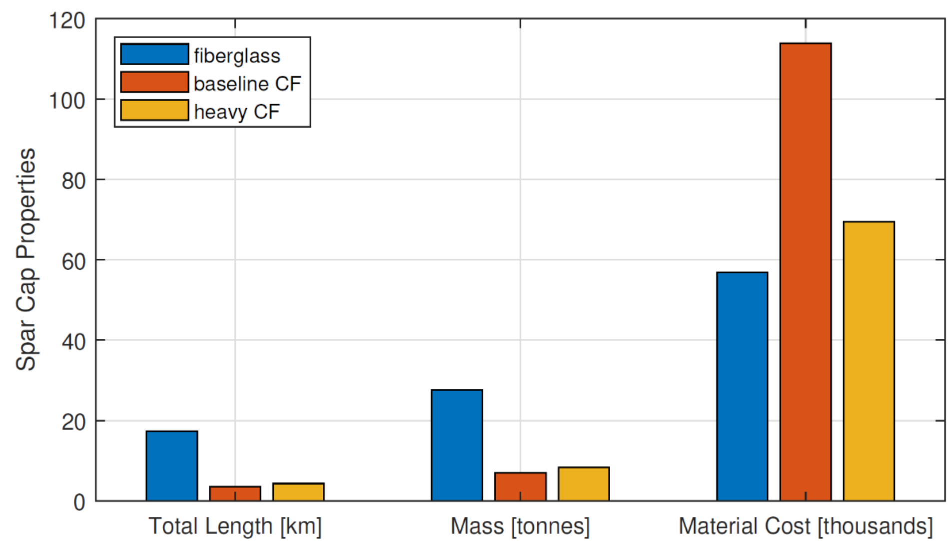


Spar Cap Comparison with Material and Turbine Type

- The optimized spar caps with the heavy tow textile carbon fiber have a 39-43% reduction in material cost compared to the industry baseline carbon fiber
- The heavy tow textile carbon fiber is found to be the optimal material for the 3 MW wind turbine over fiberglass for this fatigue driven design
- Carbon fiber pultrusions will likely have lower manufacturing costs due to the reduced number of layers required



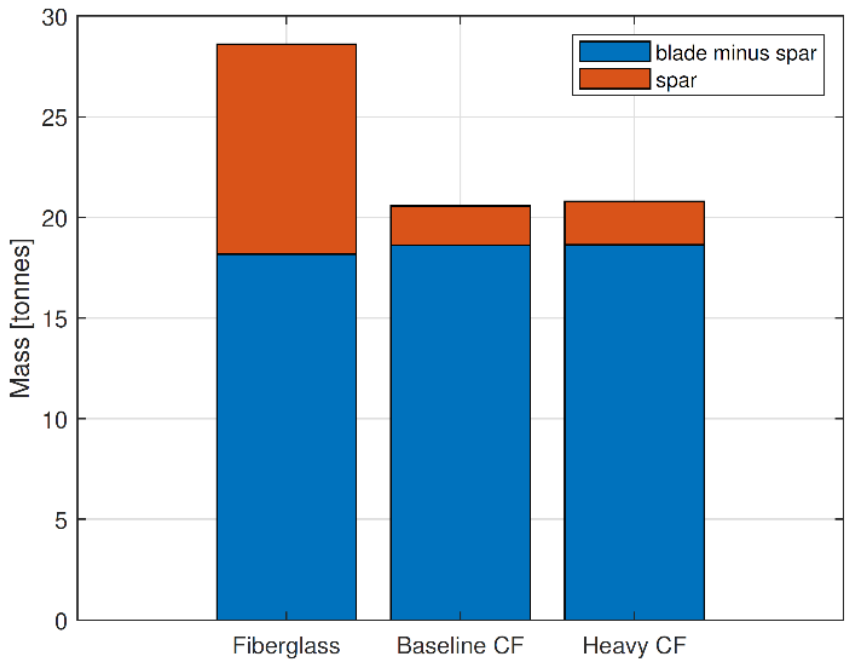
3 MW, Land-based Spar Cap Properties



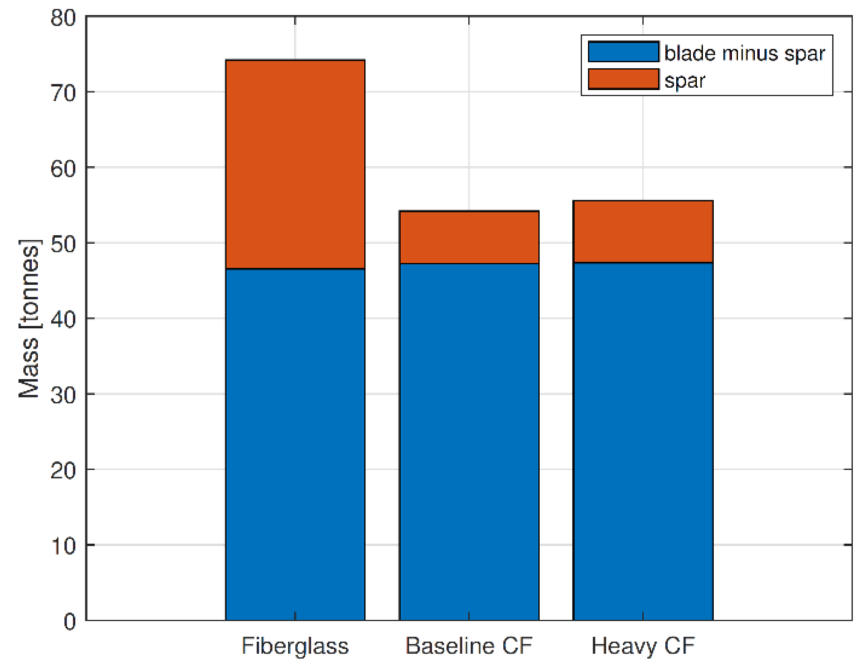
10 MW, Offshore Spar Cap Properties

Spar Cap Comparison with Material and Turbine Type

- The novel heavy tow textile carbon fiber blade is 25-27% lower mass than the fiberglass design for the two wind turbine models
- Carbon fiber spar caps produce a system benefit due to the lower blade mass which reduces the cost of the drivetrain and support members
  - This is not quantified in the spar cap material cost comparison, but is an added benefit over the fiberglass designs



3 MW, Land-based Blade Mass Comparison



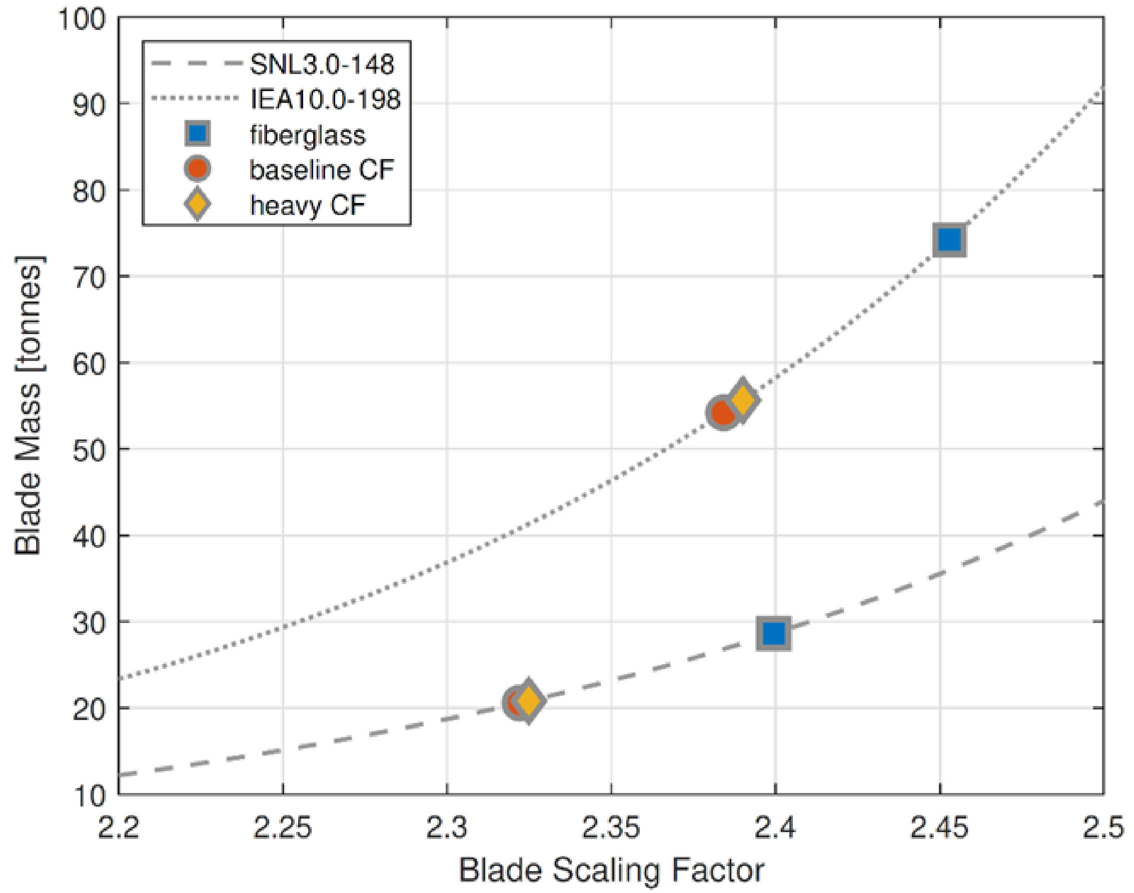
10 MW, Offshore Blade Mass Comparison

Blade Optimization Mass Results

- Blade mass scales with blade length to a power greater than 2

$$m_{blade} = L_{blade}{}^{x}$$

- Increasing blade length has been correlated with reductions in the levelized cost of wind energy
- Blade designs with carbon fiber spar caps enable longer blades by controlling mass



Blue square is fiberglass baseline
Red circle is industry baseline carbon fiber
Yellow diamond is heavy-tow textile carbon fiber

Summary

- The heavy-tow textile carbon fiber material has improved cost-specific strength and stiffness compared to the industry baseline carbon fiber
  - 56% increase in compressive strength-per-cost and 100% increase in modulus-per-cost
  - Results in 39-43% lower blade spar cap material costs compared to baseline carbon fiber in the two reference models
- Carbon fiber blade designs have lower mass which produces system benefits on the drivetrain and structural components and bearings
  - The novel textile carbon fiber has a 27% and 25% lower blade mass for the 3 MW and 10 MW reference turbines, respectively, compared to fiberglass spar cap designs
  - Enables longer rotors which capture more energy for low wind speed sites
- Improved fatigue properties of carbon (specifically of heavy tow study material) enables a longer fatigue life than fiberglass designs
  - The CFTF Kaltex material has a fatigue slope of m=45 for a (R=0.1) tension-tension test
  - The two carbon fiber spar caps retain a high end of life value due to their fatigue resistance which may be beneficial for recycling or extending turbine design life
- Carbon enables slender blade designs to be more cost effective
  - more aerodynamically efficient (energy gains, reduced thrust loads)
  - utilizes less shell material for slender, thin airfoil designs

Summary

- Without further innovation, carbon fiber will continue to be utilized in certain wind turbine designs and represent a share of the industry
- Turbine OEMs continue to meet the load requirements of even the largest blades using all glass designs, motivated by the high cost of carbon fiber
- An innovative carbon fiber material purposefully optimized for the unique demands of a wind turbine likely offers a more ideal solution than current, large-production carbon fiber or glass fiber alone
- This project has started to address the perceived material gap through an assessment of the effect of a range of materials on blade cost

Oak Ridge National Laboratory

Alternative Carbon Fiber Materials and Processing Selection for Wind Turbine Blade Applications

Bob Norris

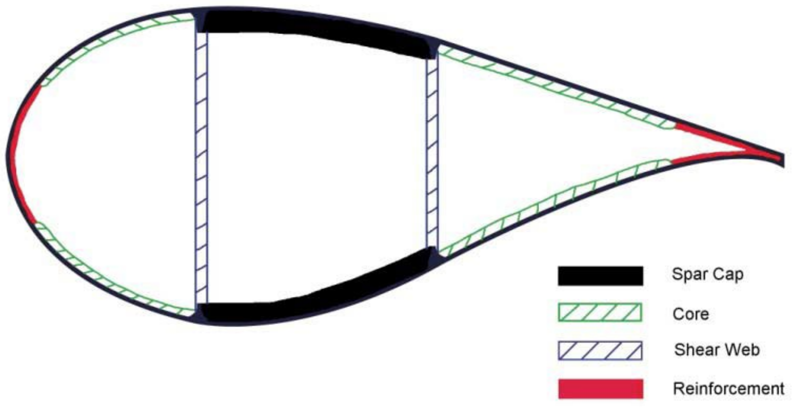
Evaluation of Low-Cost Carbon Fiber Materials for use in Wind Turbine Blade Design Seminar

Carbon Fiber 2019, Knoxville, TN

November 19, 2019

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

- Textile Carbon Fiber (TCF)
  - Acrylic fibers produced for textiles are similar chemically to those produced specifically as carbon fiber precursors, but significantly less expensive
  - Large existing availability from under-utilized textile capacity

Common Carbon Fiber Opportunities, Issues and Needs

Civil Infrastructure
Rapid Repair and Installation, Time and Cost Savings

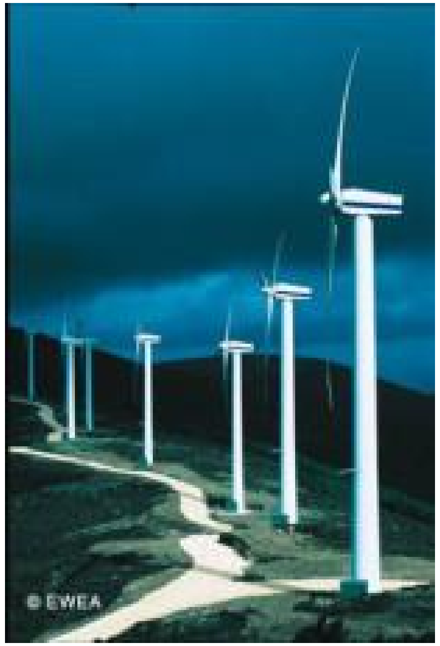
Fiber Cost
Fiber Availability
Design Methods
Manufacturing Methods
Product Forms

Hydrogen Storage
Only Material With Sufficient Strength/Weight

Power Transmission
Less Bulky Structures
Zero CLTE

Oil and Gas
Offshore Structual Components

Wind Energy
Needed for Longer Blade Designs



Vehicle Technologies
Necessary for 50+% Mass Reduction

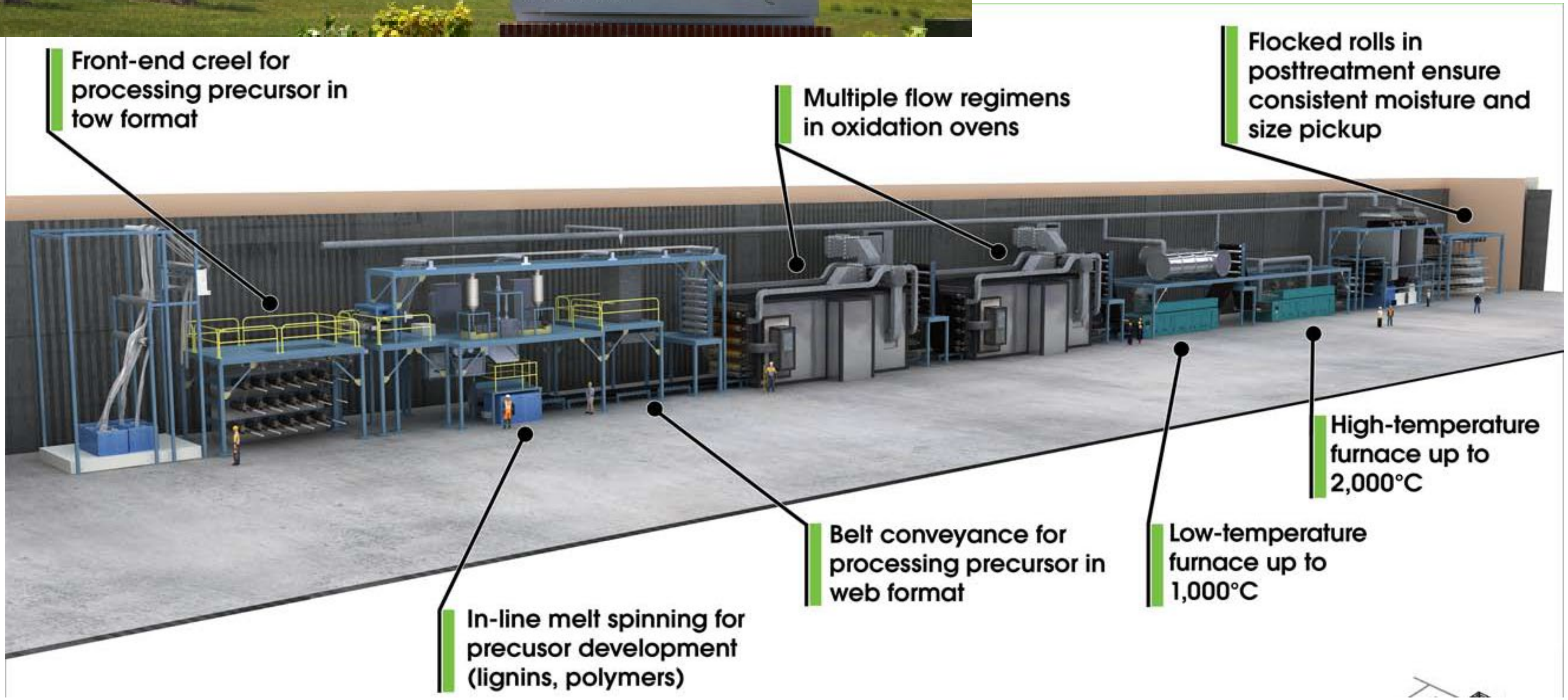
Economic Tradeoffs are Key

- Carbon fiber is traditionally produced from PAN fiber developed and produced specifically as carbon fiber precursor
  - Aerospace is typically 0.5K to 24K tow and 700ksi strength and above
  - Industrial is typically 24K to 80K, and 500 ksi strength to about 700 ksi
  - Modulus for both is typically 33Msi and above; above 45Msi, strength typically drops even as cost increases
- DOE Low Cost Carbon Fiber (LCCF) Program
  - *Automotive "drivers"* insisted fiber strength was relatively secondary to COST and specific stiffness
  - Original (and largely sustained) goals were cost of $5-7/lb or better, modulus 25 Msi min, strength 250 ksi min, and strain 1% min

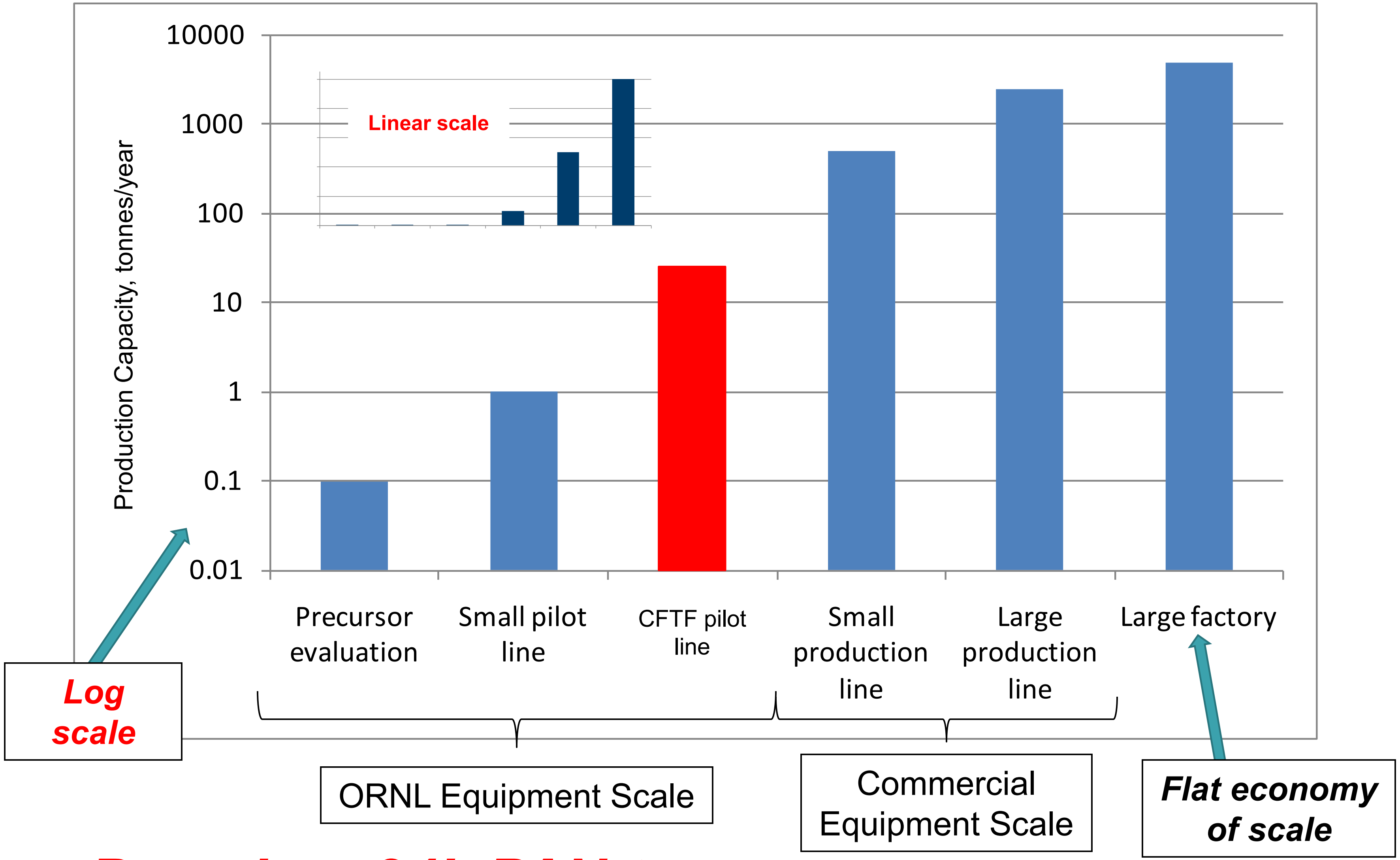
Oak Ridge National Laboratory

ORNL Carbon Fiber Technology Facility

- 25 tonnes/yr carbon fiber production capacity
- Multiple precursors and material forms
- Demonstrate technology scalability
- Produce fibers for material and process evaluation

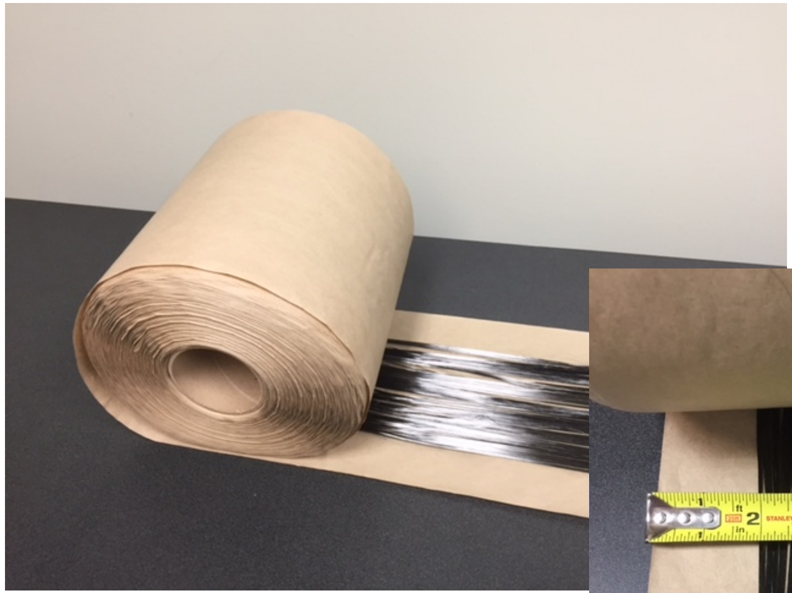


ORNL Carbon Fiber Line Scale - Capacities



Based on 24k PAN tows

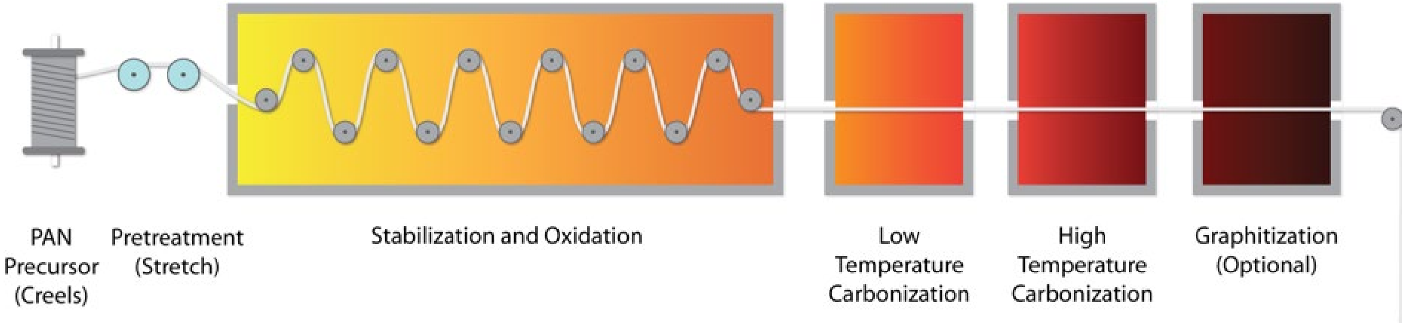
CFTF Recent Focus has Been Demonstration of Textile-Based Carbon Fiber

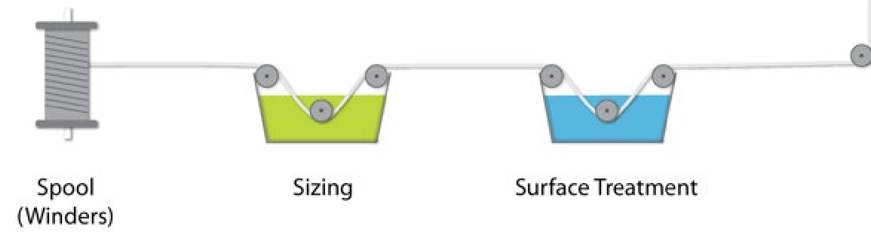


- Kaltex
  - Mexican textile PAN producer
  - Standard product is 457K tow
- Taekwang
  - Korean textile PAN producer
  - Standard product is 363K tow
- Others
  - Dralon, MonteFibre, and a few others have supplied materials for initial evaluation
  - Most sampling has been PAN/MA although we have had very good results with PAN/VA as well

Evaluating Potential for Lower Cost Carbon Fiber

- ORNL has demonstrated various TCF routes to lower cost
  - Kaltex, Taekwang, and the other "precursors" show much potential as development continues
  - Several licenses have been announced and others are considering going into production
  - Still opportunity to influence product characteristics such as form and fiber stiffness among other factors
- This project provides feedback to industry on market needs and cost/performance tradeoffs
  - Experimental work in pultrusion provides independent data and processing experience





Textile Precursor May be Boxed or Spooled

Example CFTF Fiber Data

Lot Analysis for K20-HTU

Lot Number: TE4571150808

	Average	Standard Deviation
Tensile Strength (Ksi):	385.4	20.4
Tensile Modulus (Msi):	37.5	0.7
Elongation (%):	1.03	0.05
Linear Density (g/m):	14.71	2.18
Size (%)	1.18	0.38
Density (g/cc)	1.788	0.004
Date of Manufacture:	August 2015	

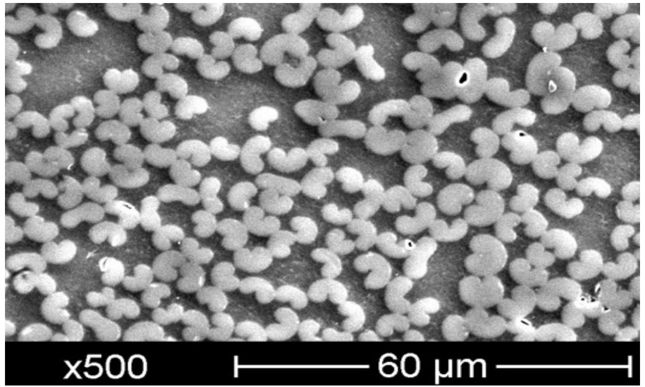
- Fiber properties for Kaltex and Taekwang are remarkably similar
- Taekwang fibers are much more round

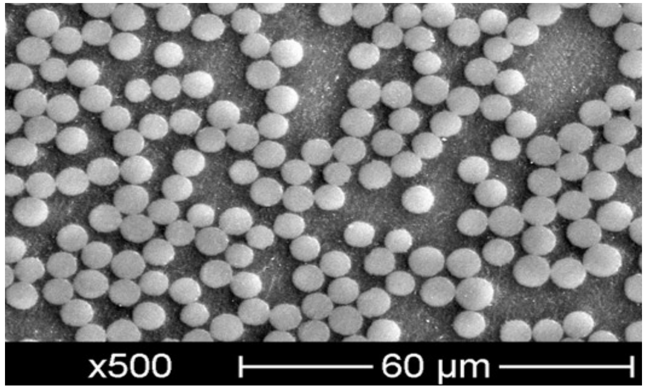
Lot Analysis for T20-C

Lot Number: TE3631170205

	Average	Standard Deviation
Tensile Strength (Ksi):	389.5	9.3
Tensile Modulus (Msi):	36.8	0.3
Elongation (%):	1.08	0.03
Linear Density (g/m):	11.46	0.49
Size (%)	1.36	0.32
Density (g/cc)	1.720	0.003
Date of Manufacture:	February 2017	

Kaltex-based fiber





Taekwang-based fiber

Comparison with Similarly Marketed Zoltek Fiber

	SI	US
Tensile Strength	4137 MPa	600 ksi
Tensile Modulus	242 GPa	35 msi
Density	1.81 g/cc	0.065 lb/in3
Fiber Diameter	7.2 microns	0.283 mils
Yield	267 m/kg	397 ft/lb
Spool Weight	5.5 kg, 11 kg	12 lb, 24 lb
Spool Length	1500 m, 3000 m	1640 yd, 3280 yd

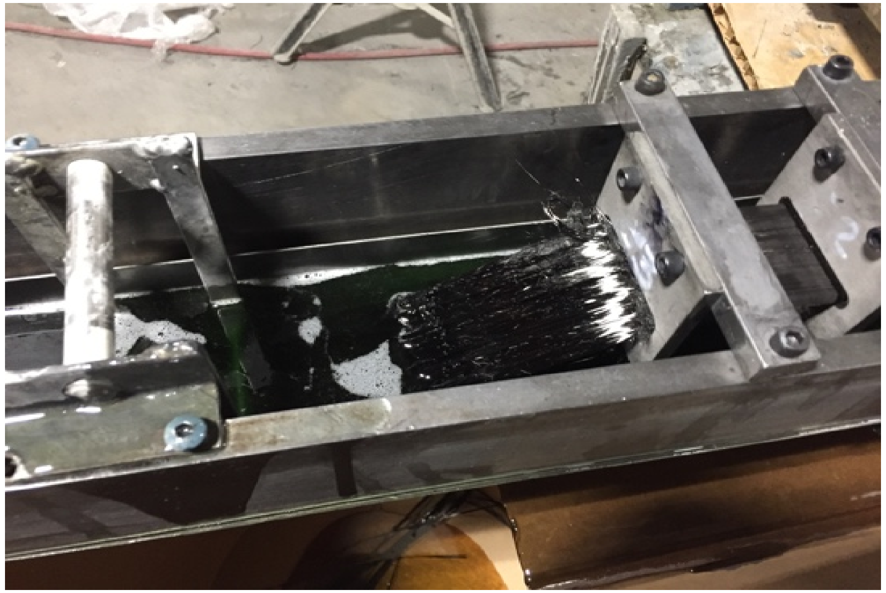
- Note that comparing tow count is somewhat misleading since the effective fiber diameters for the CFTF variants are smaller than for Zoltek. Linear densities are "more" comparable

Parameter	Zoltek	Kaltex	Taekwang
Tow Filaments	50,000	457,000	363,000
Filament Ratio	1	9:1	7:1
Linear Density (g/m)	3.7	14.7	11.5
Linear Density Ratio	1	4:1	3:1

Pultrusion Advantages vs Other Forms

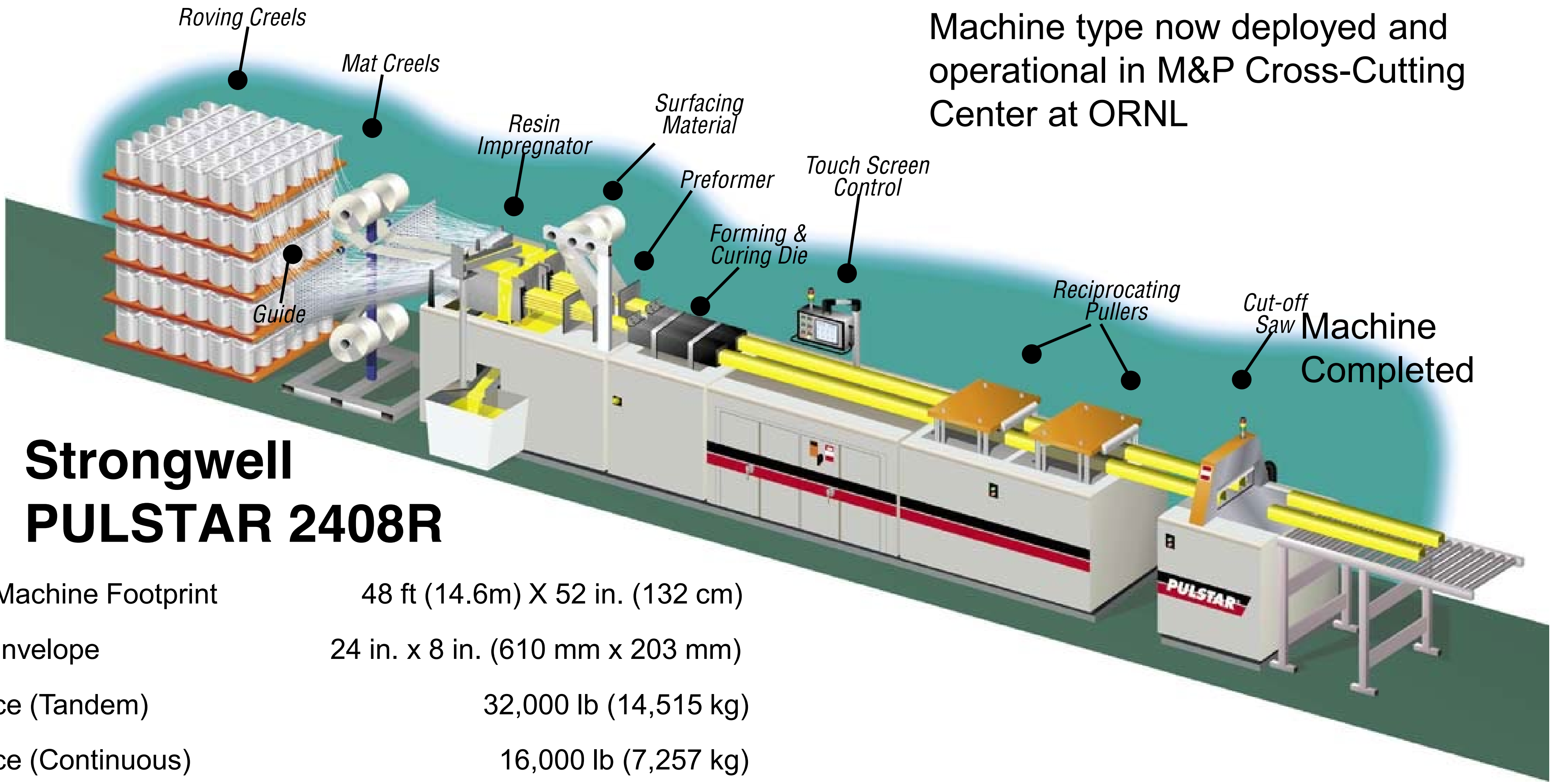
- Greater automation, less dependent on operators for consistency
- Higher fiber orientation/straighter fibers
- Low waste
- Higher fiber fraction
- Low cost material forms – less handling

CFTF material being dipped through resin and pulled through the pultrusion die.



Typical Pultrusion Machine Specifications

Machine type now deployed and operational in M&P Cross-Cutting Center at ORNL



Machine Completed

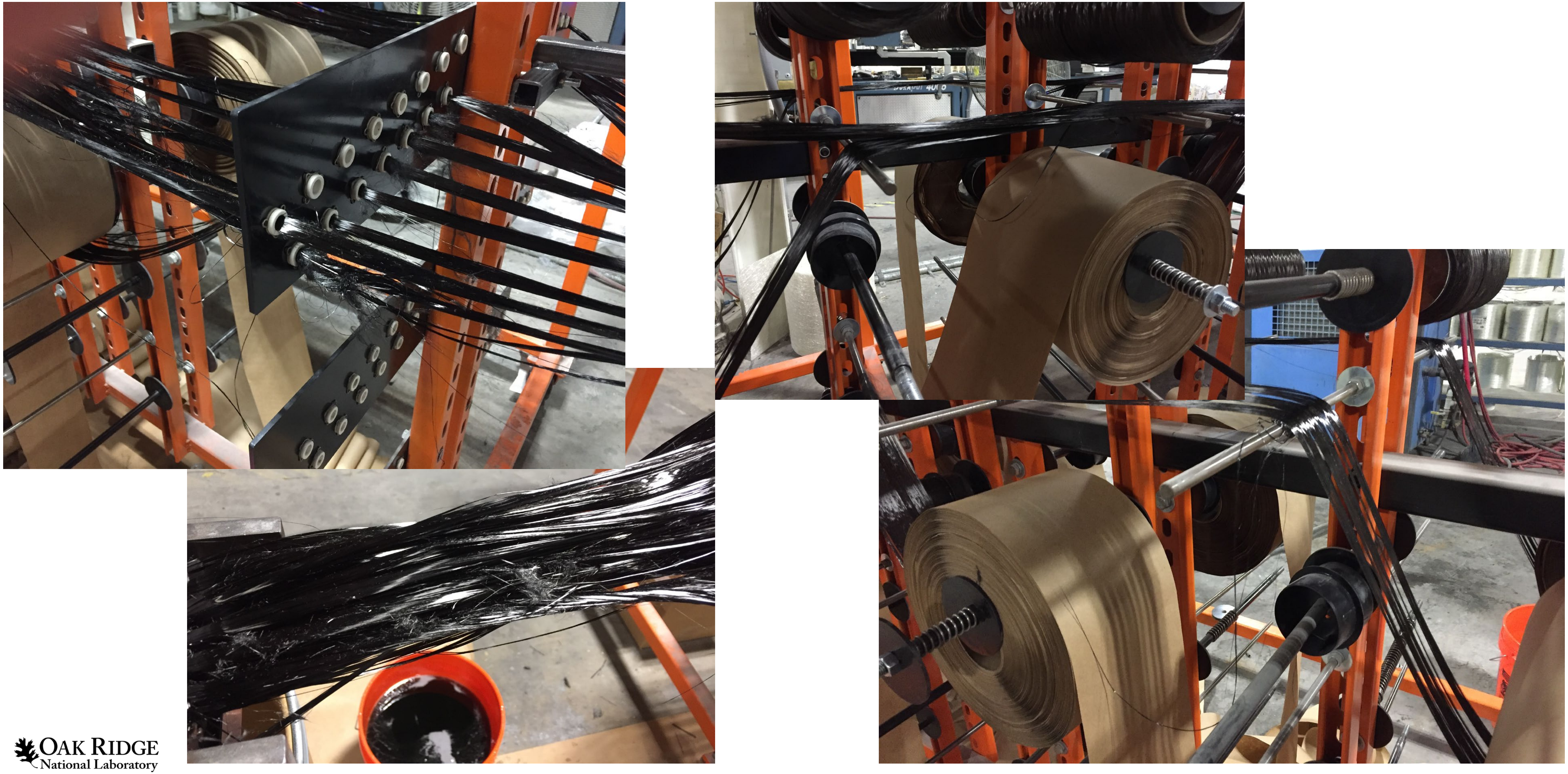
Strongwell PULSTAR 2408R

Overall Machine Footprint	48 ft (14.6m) X 52 in. (132 cm)
Profile Envelope	24 in. x 8 in. (610 mm x 203 mm)
Pull Force (Tandem)	32,000 lb (14,515 kg)
Pull Force (Continuous)	16,000 lb (7,257 kg)
Clamp Force	24,000 lb (10,886 kg)
Speed Range	1-120 in./min (2-305 cm/min)

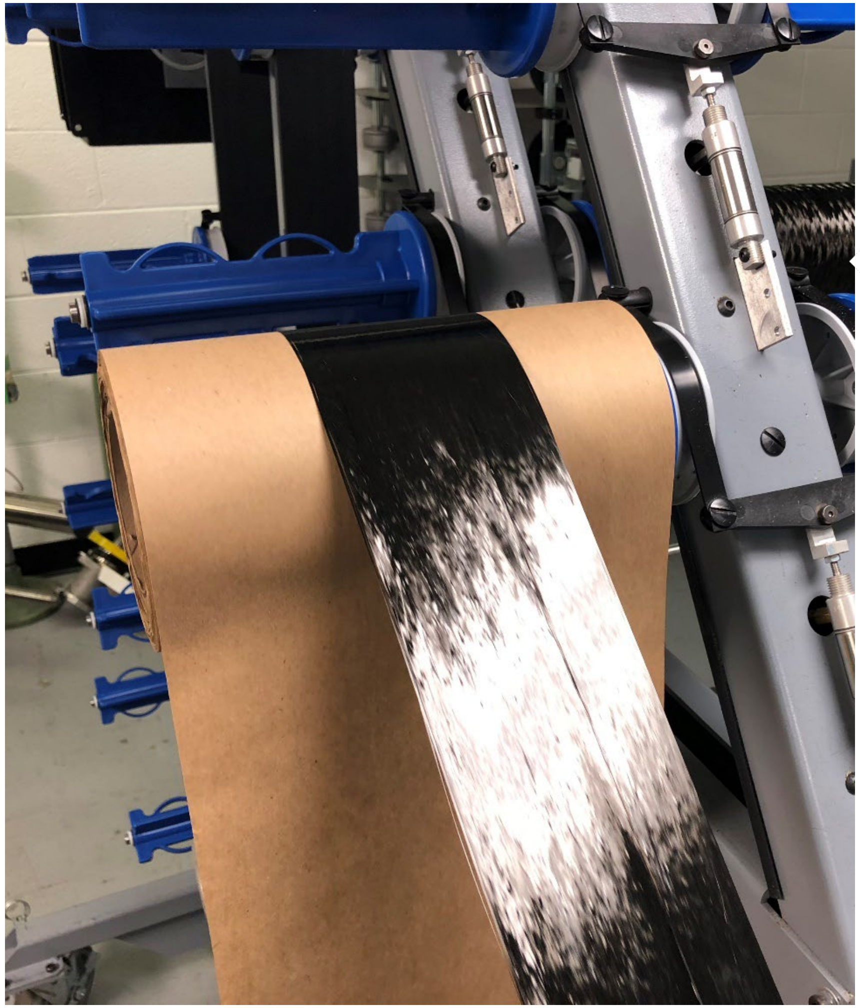
https://www.youtube.com/watch?v=qfHrw2s893Q

IACMI Pultrusion Machine as Installed for Operation

Processing This Tow Can be Done in Spite of Challenges



IACMI/McCoy Spooling Approach Should Enhance Handling Significantly



From

To

Key Project Composite Data Comparison

	Layup	V_F, %	E, GPa 0.1-0.3%	UTS, MPa	%, max	UCS, MPa	%, min	UCS, MPa Back-out[1]
Zoltek PX35[2]	Single tow	52	126	2193	1.59	-	-	-
	5.1 tows/cm	51	119	1760	1.48	-	-	-
ORNLL CCF T20-C tow[2]	$(0)_5$	52	121	978	0.78	-	-	-
	$(90)_5$	52	7.77	31.7	1.31	-	-	-
	$(0)_{10}$	52	124	-	-	-573	-0.47	-
	$(0/90)_{3S}$	50	67.4	-	-	-475	-0.73	-893
	(0), 112017-4	51	-	-	-	-	-	-
	(0), 112017-5	51	123	846	0.69	-784	-0.64	-
PX35	(0), 112017-6	53	114	1564	1.33	-897	-0.79	-
Zoltek FCE2.0 -200	(90)	62	9.13	50.1	0.58			
	(0) with tabs	62	142	2215	1.47	-	-	-
			138	-	-	-1516	-1.10	-

[1]High-Performance Composites, May 2006, Dr. Donald Adams
www.compositesworld.com/articles/back-out-factors, BF = $2E_{11}/(E_{11} + E_{22})$
[2]Resin system: Hexion 135/1366, 24h @20°C+12h@70°C

Some of the IACMI Data Comparing Composite Systems

Property (Cross-ply)	LCCF (E sized) (73% V_f) / Urethane	LCCF (U sized) (73% V_f) / Urethane	LCCF (66% V_f) / Epoxy	Zoltek (68% V_f) / Epoxy
Tensile strength(MPa)	441 (64 ksi)	457 (66.3 ksi)	548 (79.5 ksi)	1001 (145.2 ksi)
Tensile modulus (GPa)	82 (11.9 Msi)	85 (12.3 Msi)	84 (12.2 Msi)	77 (11.1 Msi)
Compression Stress (MPa)	379 (55 ksi)	351 (50.9 ksi)	456 (66.1 ksi)	479 (69.5 ksi)
Compression Modulus (GPa)	76 (11 ksi)	80 (11.6 Msi)	72 (10.4 Msi)	69 (10 Msi)
Flexural strength (MPa)	602 (87.3 ksi)	620 (90 ksi)	655 (95 ksi)	758 (109.9 ksi)
Flexural Modulus (GPa)	60 (8.7 Msi)	69 (10 Msi)	73 (10.6 Msi)	75.5 (10.9 Msi)
ILSS (MPa)	31 (4.45 ksi)	26 (3.7 ksi)	45 (6.5 ksi)	52 (7.5 ksi)

General Observations for CFTF Baseline Materials

- Cost with TCF approaching $1/lb versus conventional precursor costs of ~$3/lb and up largely due to larger tow and less QA
- Larger tows – fewer creel positions required, lower labor for both fiber production and composite manufacturing
- Fiber modulus is relatively selectable from 33 Msi to 40 Msi
- Strength seems to be relatively stable approaching 400 ksi

however

- Users have "learning curve" in handling larger tows
- Current issues with non-uniformity (fuzz, cross-overs, packaging, etc.) are being worked at CFTF and precursor providers

Highlights of Relevant Product Evaluation, Formatting Improvements and Applications Development

- A number of organizations are evaluating properties
- Dow/Ford conducted preliminary evaluation of prepreg
- McCoy/ORNL/UT/Chomarat project working to improve fiber formatting
- ORNL pultruded 2 product versions at Martin to provide data for ORNL/Sandia Wind project study
- Prescott project demonstrated preliminary prepreg fabbed into panel at ORNL and tested at UT as initial part of larger project
- ORNL/UT/TPI/Strongwell/Huntsman/MonteFibre/Others initiating project to demo and evaluate TCF spar cap for wind

Commercialization Summary

- Interest in the Textile-Based Carbon Fiber businesses - organizations represented here are still moving forward
- Another group is commercializing advanced conversion equipment as well as planning production scaleup themselves
- Existing carbon fiber manufacturers continue introducing new products and enhancing price/performance tradeoffs
- DOE programs (IACMI, Wind, etc.) are supporting opportunities to facilitate implementation kicking off new work on compressive performance and pultrusion demonstrations
- Results of this work are targeted towards providing tools to assist carbon fiber product development and end user utilization

DOE Optimized Carbon Fiber Project Carbon Fiber Cost Modeling

Sujit Das

Carbon Fiber 2019 – CompositesWorld Conference

Knoxville, TN

November 19, 2019

Carbon Fiber Cost Modeling -- Objectives

- Increasing blade length and turbine trend (lowers energy cost) requires use of lightweight materials (e.g., carbon fiber composites) in the blade design
- Limited availability of types carbon fiber suited for the demanding aerospace industry applications today has resulted in a high material cost barrier for wind industry
- Development of suitable types of carbon fiber materials are necessary to optimize its wind specific performance requirements and cost
- Develop manufacturing cost models for both carbon fiber (e.g., Low-cost heavy textile tow) and its polymer composites (e.g., pultrusion)
  - Estimated carbon fiber epoxy composites functional cost vs. mechanical properties are inputs used for the blade design optimization studies
  - Focus on cost sensitivity among various types (i.e., properties) of carbon fiber and its composites to facilitate optimization between performance and cost
  - Price is a temporal metric as dictated by the prevalent market supply and demand dynamics (focus here on the cost difference for performance vs. cost optimization)
  - Cost allows to identify major drivers of competitiveness of a manufacturing technology

Cost Modeling Framework

Annual Production Volume (t/y)

Production Line → f(m/c hourly rate)

Process Step
(Manufacturing Cost: $/kg)

Product
Manufacturing Cost ($/kg)

Material (Price, Qty.)

Labor (Rate & Qty.)

Energy (Rate & Qty.)

Equipment & Tooling ($, Discount, Life)

Building (Rate, ft^2)

Technical and economic parameters sensitive to technology, e.g., Temp. → Furnace rating → Energy (kWh)

∑Process Step Cost

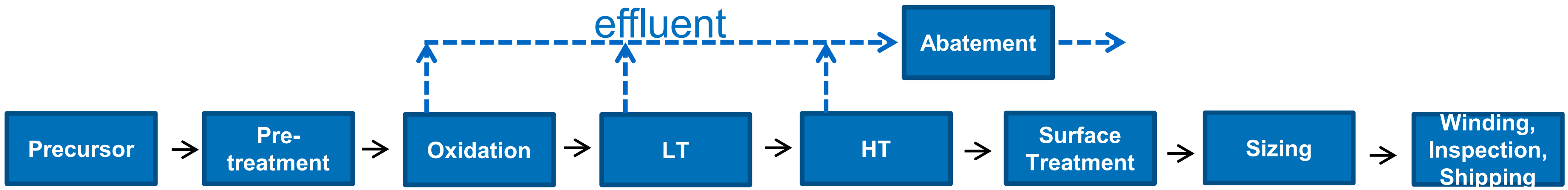
- Material
- Capital
- Labor
- Energy

- *Material*
- *Capital (Installation, Maintenance, Insurance, Taxes)*
- *Labor (Direct & Indirect)*
- *Energy*

- Focus on product direct manufacturing *cost* and not *price*
- Allows to estimate the *cost* impacts of alternative technologies without consideration of *price* impacts (depends on SG&A and Profit driven by market dynamics

ORNL Carbon Fiber Cost Modeling Framework

- CF model (Baseline -- 1500 t/year line capacity)
  - Evaluate carbon fiber manufacturing at the level of nine major process steps



  - User may examine any production volume from 1 - 18,000 t/y (economies of scale for a fully utilized carbon fiber lines between low and high production volume)
  - Test sensitivity of key parameters such as line speed, residence times and temperatures of oxidation, LT, and HT, precursor cost, etc.
- Economies of scale savings from operating two lines in one building, indirect labor, project engineering, and energy efficiencies

Major Carbon Fiber Processing Parameter Assumptions

Parameter	Value
Yield	Chemical: 0.48; Mechanical: 0.95; Total: 0.45
Total Labor	9 FTE/shift
Total Capital Eqpt. Investment	$58MM (installed)
Furnace Temp. & Time (Oxidation time reduced for full-utilization Heavy Textile Tow Carbon Fiber)	Oxidation: 250C for 90 min.; Low Temp.: 700C for 1.5 min; High Temp.: 1400C for 1.5 min

ORNL CF Model – Assumptions(Underlying)

- All high-level assumptions can be easily modified to test different scenarios
- Equipment installation cost reduces from 20% to 15% of equipment capital cost under high production volume from reduced project engineering activity
- Indirect labor costs assumed to decrease from 40% to 15% of total direct labor costs under high volume
- Electricity and natural gas are 2018 industrial prices (source EIA)
- General HVAC and lighting costs assumed $1.25/sq ft/yr (source CBECS)
- N_2 generated onsite, included under capital and energy costs for carbonization

Parameter	Value
Capital	
Lifetime of Equipment	15 years
Lifetime of Building	30 years
Cost of capital	7%
Installation (% of equipment) – low, high volume	20%, 15%
Maintenance (% of equipment)	3%
Insurance (% of equipment)	1%
Taxes (% of equipment)	1%
Startup, contingency, and working capital (% of installed capital)	20%
Building construction cost	$150/ft^2
Labor	
Direct labor $/hr (fully burdened)	$28
Indirect labor (% of total direct labor cost) – low, high volume	40%, 15%
Energy and Utilities	
Electricity	$0.10/kWh
Natural gas	$5.00/MMBtu
HVAC, lighting	$1.25/sq ft/yr

ORNL CF Model – Production Volume Scale Up

- Replicating production lines in parallel, incrementally as demand increases, appears most representative of current industry practice
- Little to no purchasing discounts on capital equipment are anticipated as long as industry standard is to add capacity incrementally, in parallel
- Purchasing discounts on capital equipment <u>might</u> be available if a high-volume plant were built all at once, but this appears to be the least likely event
- Purchasing discounts on key raw materials (monomers) also expected to be limited due to their availability at commodity prices for the range of CF production volumes under consideration
- With limited discounts on capital equipment and raw materials, production volume cost curves are expected to be relatively flat, with savings confined primarily to:
    - Reduced floor space capital costs when operating two CF lines in one building
    - Reduced indirect labor
    - Reduced project engineering costs as new lines are essentially similar to previous lines
    - Energy efficiencies

Major Baseline 50K Tow Carbon Fiber Cost Modeling – Input Parameters

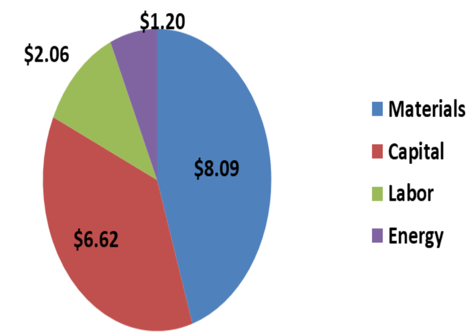
Parameter	Value
Annual Fiber Production Volume	50k Tow fiber @ 1,500 tonnes/year
Tow linear density	3.7 g/m
Tow spacing	24 mm
Precursor Cost	$3.63/kg
Line Speed	8.98 m/min
Total Energy	41 kWh/kg
Yield	Chemical: 0.48; Mechanical: 0.95; Total: 0.45
Total Labor	9 FTE/shift
Total Capital Eqpt. Investment	$58MM (installed)
Furnace Temp. & Time	Oxidation: 250C for 90 min.; Low Temp.: 700C for 1.5 min; High Temp.: 1400C for 1.5 min

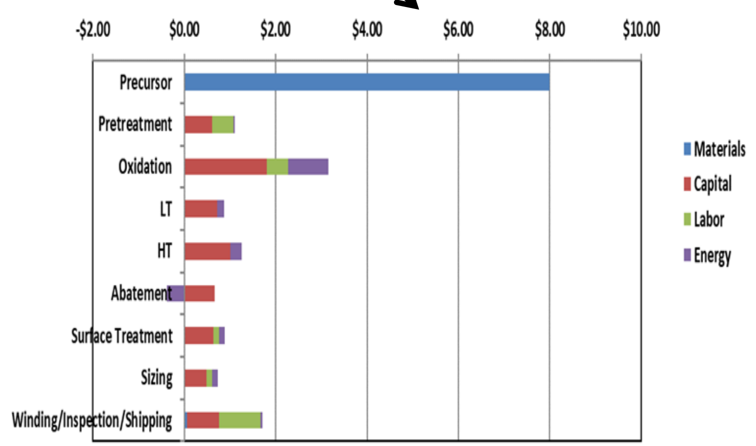
Input parameter assumptions were based on the collaboration with the equipment manufacturers and the fiber industry OEMs

Baseline Commodity PAN – Carbon Fiber Cost

- Cost drivers are **high "as-spun" precursor cost ($8.00/kg CF) coupled with low conversion yield (48%)**
- $16.62/kg under high production volume (18,000 t/y)
- Highly sensitive to precursor cost, dictated by AN and oil prices
- Capital cost has the largest share after Materials – economical only at a higher production volume
- Oxidation is the most expensive and fiber conversion line speed determinant step (250°C for 90 min)
- High sensitivity to electricity prices drives CF manufacturers to states with low electricity cost: WA, WY, SC, AL, TX, TN

Baseline CF
1500 t/y Plant
$17.98/kg





HEAVY TEXTILE TOW CARBON FIBER – Assumptions (1)

- ✓ Three scenarios considered:
  - ✓ Baseline – Commercial grade textile PAN
  - ✓ Heavy Textile Tow (current): ORNL CFTF Current Technology
  - ✓ Heavy Textile Tow (full-utilization): ORNL CFTF Technology Potential

PARAMETER	BASELINE	HEAVY TEXTILE TOW (current)	HEAVY TEXTILE TOW (full-utilization)
Precursor Cost	\$3.63/kg	\$2.24/kg	\$2.24/kg
Tow Size	50K	457K	457K
Tow linear density (g/m)	3.7	15	15
Tow Spacing	24 mm	50 mm	24 mm
Strands/Line	120	58	120
Line Speed	211 kg/hr (9 m/min)	338 kg/hr (7 m/min)	843 kg/hr (9 m/min)
Annual Prodn. Volume	1,500 tonnes/yr	2,400 tonnes/yr	6,000 tonnes/yr
Capital Investment	\$58M	\$58M	\$58M
Final Fiber Cost	\$17.98/kg	\$11.19/kg	\$7.82/kg

HEAVY TEXTILE TOW CARBON FIBER – Assumptions (2)

- ✓ Lower precursor cost -- High output textile grade acrylic fiber used for clothing application today for heavy textile tow vs. specialty acrylic fiber (Baseline)

- ✓ Heavy Textile Tow (current): Annual Output (2400 tonnes vs. 1500 tonnes – Baseline)
  - Higher linear density (3.4 g/m vs. 15 g/m – Baseline)
  - Lower line speed of 7 m/min vs. 9 m/min (Baseline) causes less increased output

- ✓ Heavy Textile Tow (full-utilization): Higher Annual Output (6000 tonnes/year)
  - Tow space decrease (same as baseline 24 mm)
  - 33% reduction in oxidn. time (60 min vs. 90 min) – benefits of exothermic reaction
  - Increasing line speed from 7 m/min to 9 m/min due to additional stretching

HEAVY TEXTILE TOW CARBON FIBER -- COST

PARAMETER	BASELINE $/kg (%)	HEAVY TEXTILE TOW (current) $/kg (%)	HEAVY TEXTILE TOW (full-utilization) $/kg (%)
Materials	$8.09 (45.0%)	$5.05 (45.2%)	$5.05 (64.6%)
Capital	$6.74 (36.8%)	$4.10 (36.7%)	$1.91 (24.4%)
Labor	$2.06 (11.5%)	$1.25 (11.2%)	$0.47 (6.0%)
Energy	$1.21 (6.7%)	$0.78 (7.0%)	$0.39 (4.9%)
TOTAL	**$17.98 (100%)**	**$11.19 (100%)**	**$7.82 (100%)**

✓ Major drivers for Low-cost Heavy Textile Tow Carbon Fiber

- Low precursor cost and materials cost has the largest share of fiber cost
- Economies of scale from a higher throughput due to higher linear density precursors using the same capital investments and labor
- A significantly higher 57% fiber cost reduction opportunity under full-utilization (vs. 38% reduction for current) due to similar tow spacing and line speed as Baseline
- Exothermic fiber conversion process has the potential for a lower energy cost

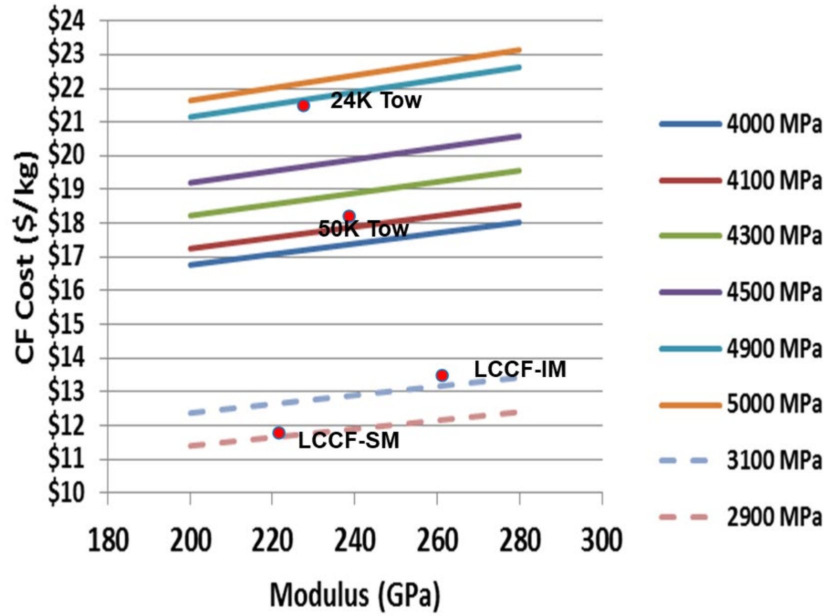
Fiber Cost Sensitivity to Mechanical Properties -- Approach

- Fiber tensile strength and modulus only considered – without conisderaiton of any interdependency between them
- Improved fiber tensile strength dependent on the precursor quality/cost – *improved polymer filtration, higher molecular weight polymers, porosity and residual solvent content reduction, smoother surface fibers through dry jet spinning etc.*
- Fiber *tensile strength* dependency is based on its 24K tow vs 50K tow estimated costs (mainly precursor) having similar fiber modulus:
  - 50K Tow (PX35) - $18.11/kg: Tensile Strength: 4137 MPa; Tensile Modulus: 242 GPa
  - 24K Tow (T700S) - $21.71/kg: Tensile Strength: 4900 MPa; Tensile Modulus: 230 GPa
- Tensile Strength dependency for a wide range estimated based on the linear extrapolation of difference in costs of precursor and fiber conversion
  - 50K Tow (PX35): Raw Precursor: $3.63/kg; Fiber Conversion: $10.11/kg
  - 24K Tow (T700S): Raw Precursor: $5.04/kg; Fiber Conversion: $10.61/kg
- Fiber modulus depends on LT (Tension and Temp. Increase) and HT (Residence Time and Stretch Increase)
  - LT Temp. Increase (1.78 MSI/100^{o}C)
  - *HT Furnace Residence Time Increase* (0.085 MSI/sec)

OAK RIDGE National Laboratory

Large Tow vs. Heavy Tow CF Cost Sensitivity

Carbon Fiber	Modulus (GPa)	Strength (MPa)
Zoltek (50K Tow)	242	4137
LCFF-SM (Heavy Tow/Std. Modulus)	224	2913
LCCF-IM (Heavy Tow/Intermediate Modulus)	265	3140



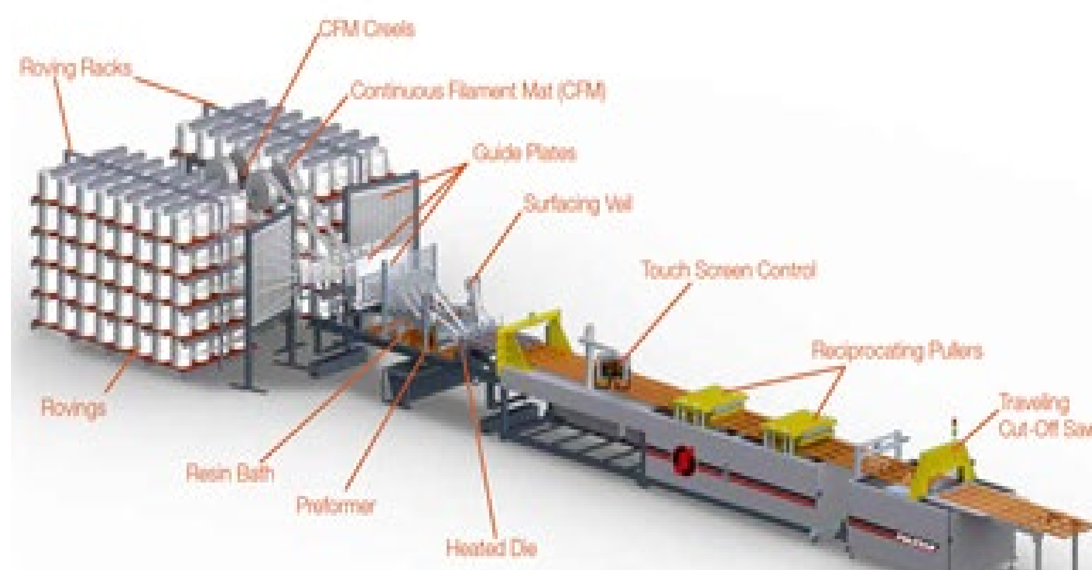
$$\textit{Carbon Fiber Cost}\left(\frac{\$}{kg}\right) = -6.45 + 0.005 * \boldsymbol{UTS} + 0.016 * \boldsymbol{E}$$

- Linear fiber cost sensitivity to its properties
- Fiber cost is more sensitive to change in its strength than modulus without any consideration of interdependency between them (limited empirical data availability)
- Estimated Heavy Tow SM CF cost of $11.19/kg lies lower than estimated large tow cost relationships
  - LCCF-SM: ~$11.75/kg -- LCCF-IM: ~$13.25/kg

Source: Vaidya et al. (2017). "Technology Update: Mechanical Properties of Low-Cost Fiber versus Zoltek Fiber Composites – Benchmarking," IACMI, Knoxville, TN

Pultruded Carbon Fiber Spar Cap

- Carbon fiber is used primarily in the spar, or structural elements (e.g., trailing edge) or skin for blades longer than 45m
  - ✓ Vestas Wind Systems: 54.6m
  - ✓ GE Energy: 48.7m
  - ✓ LM Wind Power: 73.5m
  - ✓ IACMI: 9m (Pultruded)
- Pultrusion is a manufacturing (*pulling*) process for producing continuous lengths of FRPC structural shapes with constant sections of highest unidirectional loading reinforcement properties
- Saturated reinforcements in a resin bath are shaped by a performer and pulled through a heated die – resin cure is initiated by the die heat, setting off a catalytic reaction – resulting in a rigid, cured profile corresponding to the die cavity shape



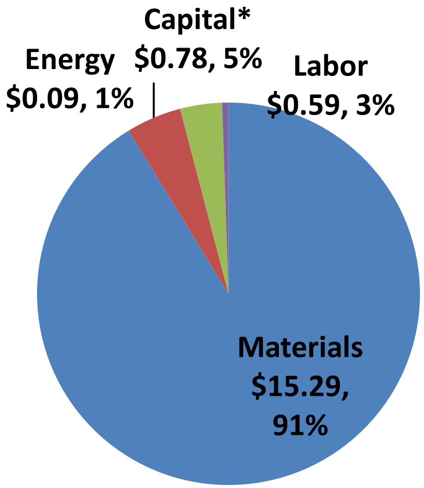
Strongwell PULSTAR Pultrusion Machine

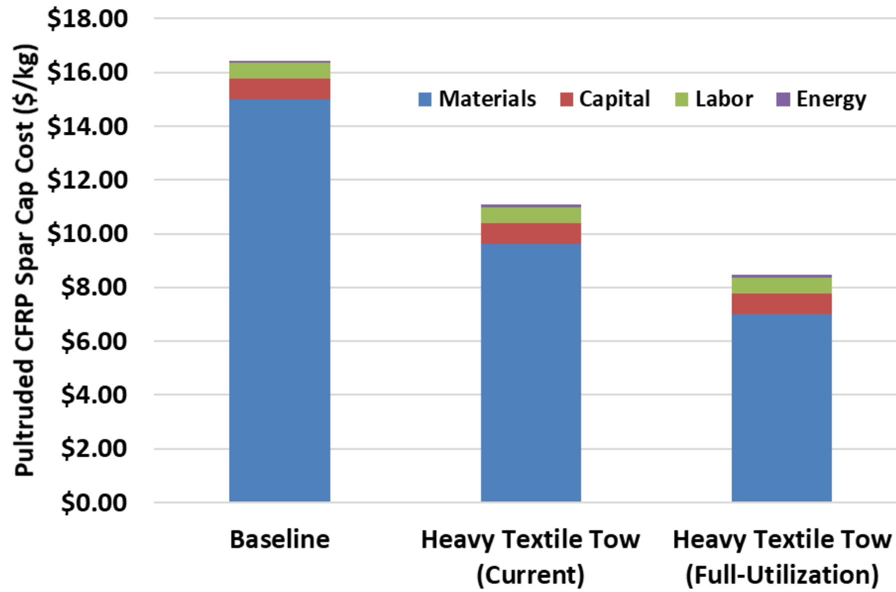
Pultruded CF Spar Cap Cost Estimation

- Major Assumptions (Focus on *Cost* and not *Price*):
  - Spar Cap Size: 61.5m blade
  - Spar Cap Weight: 807.5 kg/part or 1615 kg/blade (2 spar caps per blade)
  - Annual Production Volume: 1850 parts Material Composition: Carbon Fiber (68 vol.%, 75 wt.%); Epoxy Resin (32 vol. %, 25 wt.%)
  - Material Cost: $18.11/kg (Baseline 50K Tow); $3.63/kg* (Epoxy Resin)
  - Total Capital Investment: $1.5M
  - Labor (#): 2 per shift for a 24-hr continuous operation
  - Yield: 99.7% (Material); 97% (Pultrusion Process)

* Low volume and high temperature performance requirements of prepreg results in a higher epoxy resin cost of $8.50/kg vs. $3.63/kg assumed for standard liquid epoxies for turbine blades

Pultruded CF Spar Cap Cost





Total Part Cost: $16.75/kg
: $27,050/spar cap

*Capital Cost includes Tooling and Facility cost

- Total spar cap cost in terms of ($/kg) with assumed 75 wt.% fiber is lower than the baseline fiber cost ($18.11/kg) as the added pultrusion processing cost is less than the effect of considerably lower resin cost ($3.63/kg) in a part
- Material contributes to the largest share (91%) of total spar cap cost
- Heavy-textile tow carbon fiber spar cap costs are estimated to be ~33% and ~49% lower under "Current" and "Full-Utilization" scenarios, respectively (Low material cost is the driving factor as processing cost is assumed to be the same)

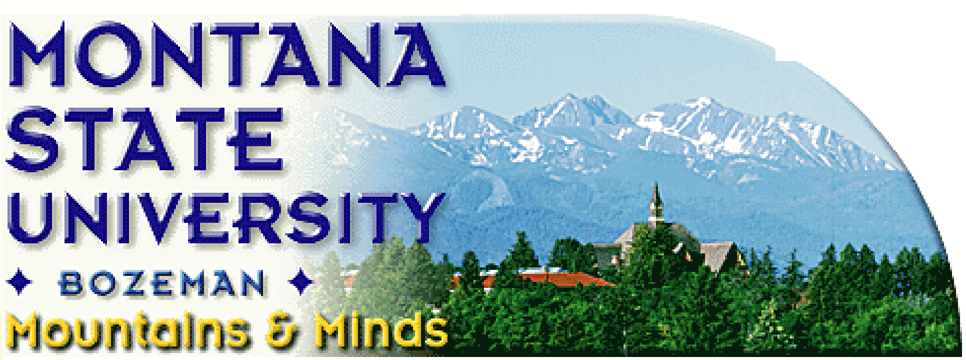
Preliminary Findings..

- Heavy textile acrylic carbon fiber and its polymer composites has a significant cost reduction potential in spar cap applications
- Future work is planned for
  - Consideration of the wind carbon fiber applications beyond spar caps
  - Improve the fiber cost sensitivity to its mechanical properties (tensile strength, modulus, and compressive strength)
  - Consideration of impacts of different precursor types and processing technologies (e.g. microwave assisted plasma oxidation) on fiber properties
  - Update the pultrusion composites manufacturing cost model and consideration of other potential carbon fiber manufacturing technolgies

OPTIMIZED CARBON FIBER COMPOSITES IN WIND TURBINE BLADE DESIGN :

MECHANICAL TESTING SUMMARY

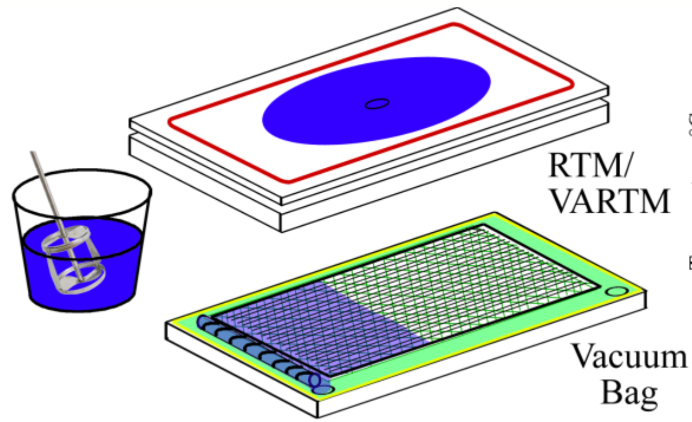
David Miller
Carbon Fiber 2019, Knoxville, TN
November 19, 2019



MONTANA STATE UNIVERSITY

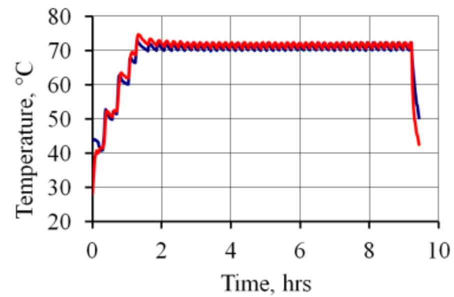
Mountains & Minds

MSU-Bozeman Composite Group Manufacturing and Material Characterization

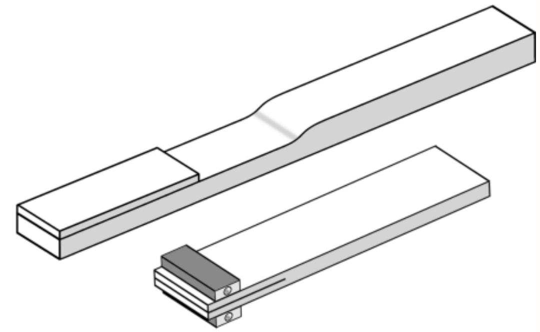


Mixing

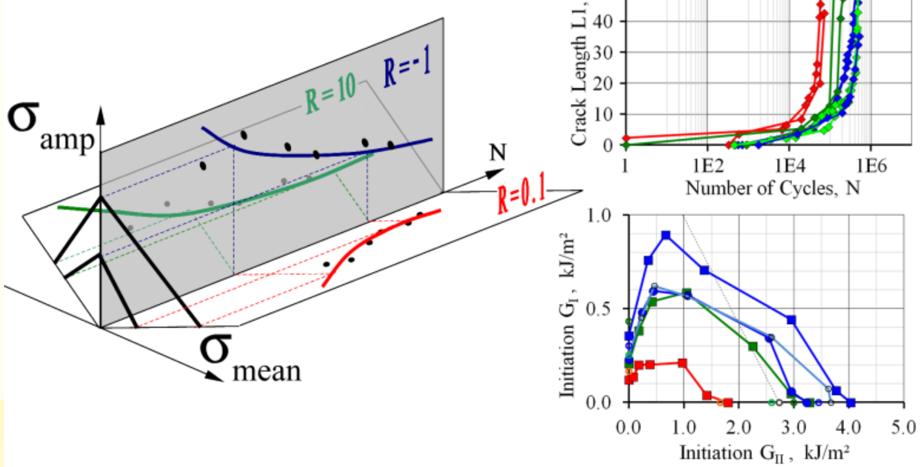
Infusion



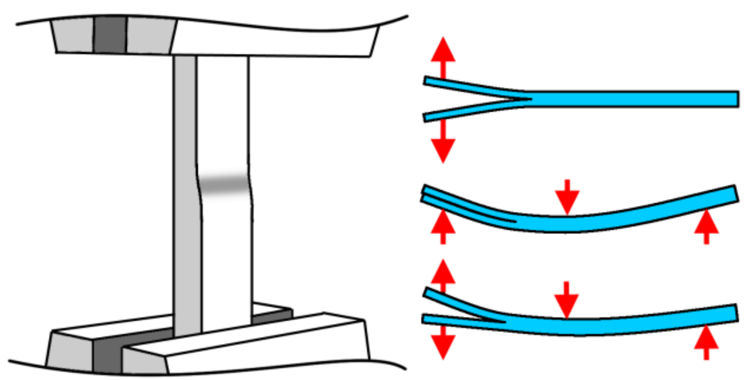
Curing and Post-curing



Coupon Preparation



Mechanial Perfomance Database

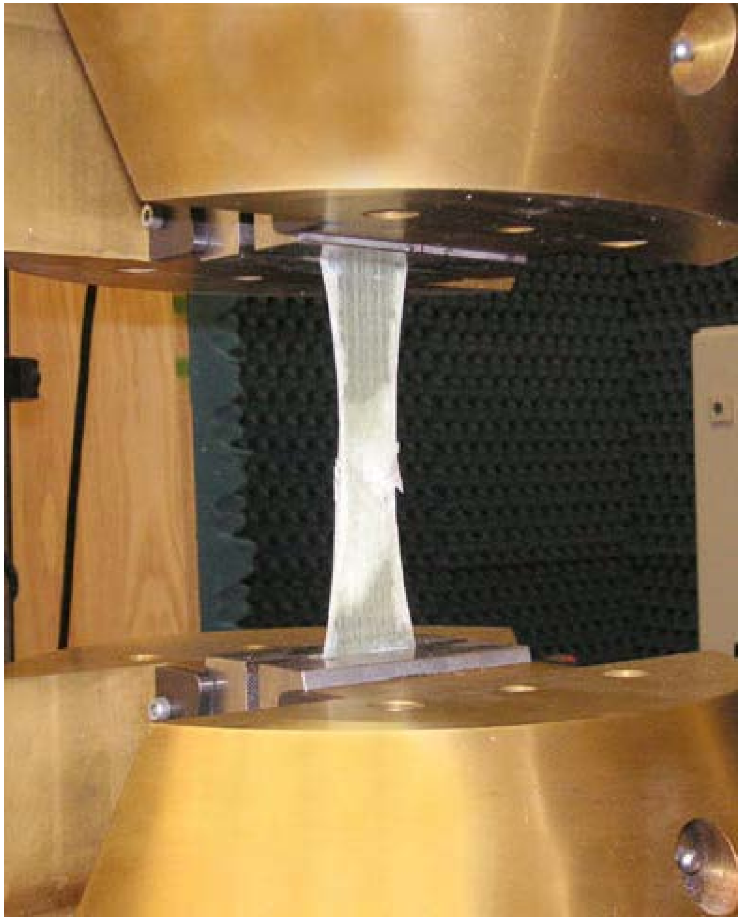


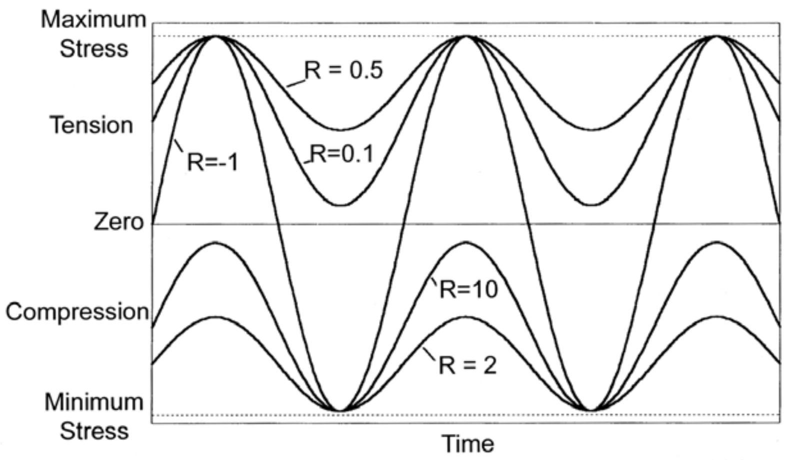
Mechanical Testing

Uniaxial Mechanical Testing

- Instron 4206 – 30,000 pound capacity servo electric, 30 inch stroke
- Instron 8562- servo electric, 100 kN (22,480 lb), 100 mm (4 inch) stroke
- Instron 8501- servo hydraulic, 100 kN (22,480 lb), 100 mm (4 inch) stroke
- Instron 8511- servo hydraulic, 10 kN (2,248 lb), 50 mm (2 inch) stroke
- Instron 8872- servo hydraulic, 25 kN (5,500 lb), 100 mm (4 inch) stroke
- Instron 8802 - servo hydraulic, 250 kN (56,000 lb), 150 mm (6 inch) stroke
- Instron 1350- servo hydraulic, 100 kN (22,000 lb), 100 mm (4 inch) stroke

- **DOE/MSU Fatigue Database for (Public, Sandia Website)**
  - Over 300 Materials
  - 16,000+ test results
  - Updates each March
  - Now Excel based
  - Trends analyzed in contractor reports (www.coe.montana.edu/ composites/)

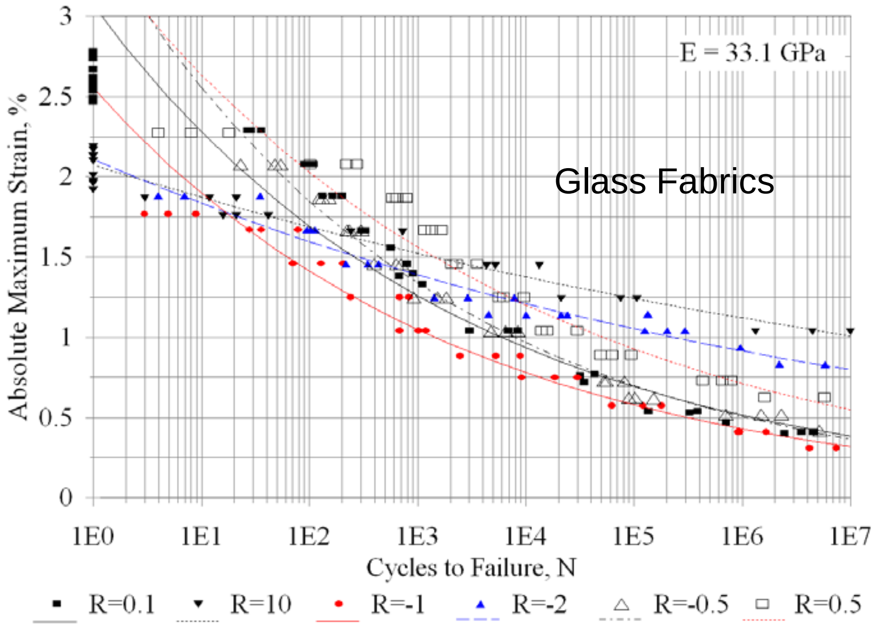


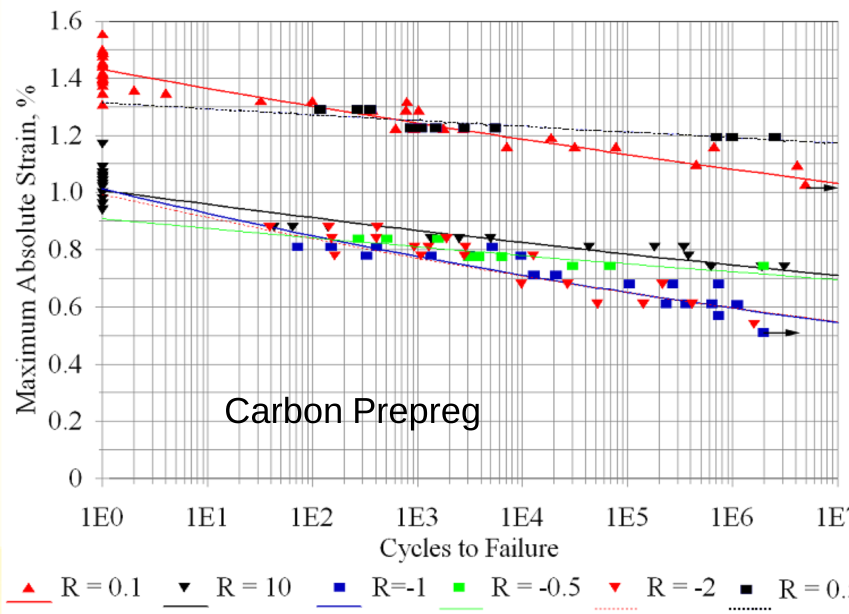


Constant Stress Amplitude Sine Waveforms for Different R-Values
R-Value = (Minimum Stress / Maximum Stress)

Standard Laminate Fatigue Typical Data

S-N Curves, MD Laminates
Effect of R-Value
Carbon vs Glass





Material Forms

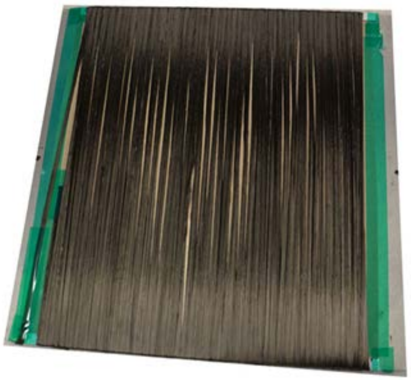
Composite form	Testing objective
MSU aligned strand infusion	Controlled process designed to minimize manufacturing bias and enable direct material comparison
Commercial pultrusion	Most representative process for commercial wind turbine blade spar cap material, used to understand the relative performance compared to MSU aligned strand infusions
Third-party pultrusion	Performed to identify if additional difficulties arise from pultruding the heavy-tow materials compared to the industry baseline, should not be used for actual mechanical performance

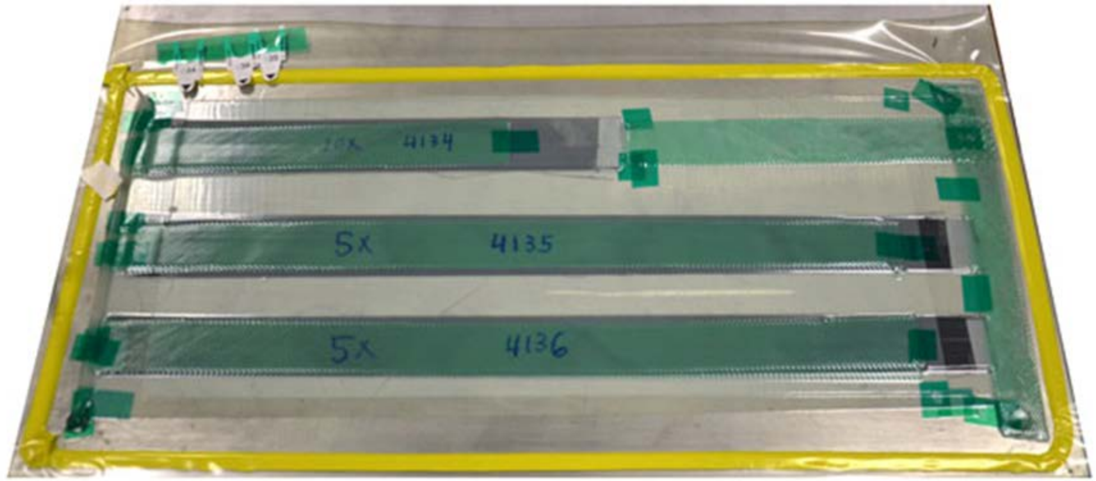
Material Forms

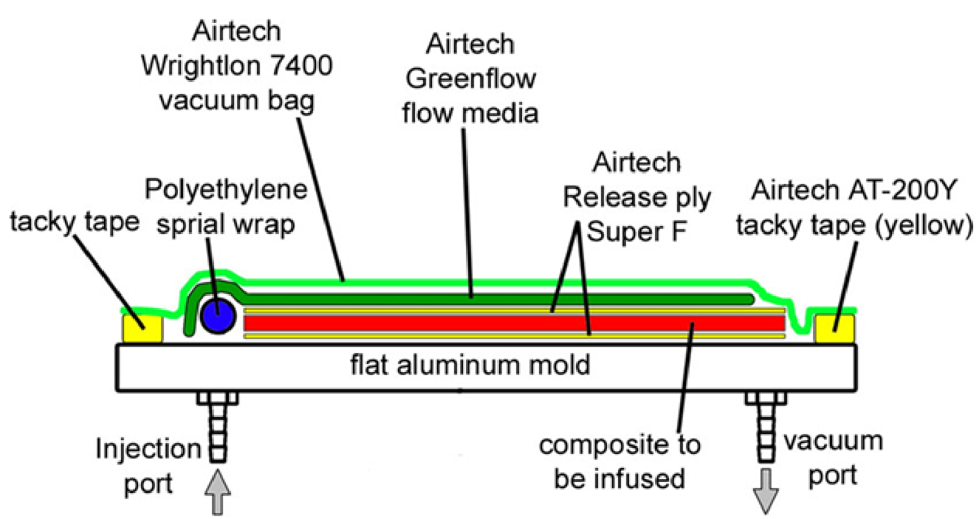
Dry fiber inputs	Roll labels	Tow fiber count
Taekwang T20C (low-cost)	TE3631170205 / TE3631170501	363K tow
Kaltex K20-HTU (low-cost)	TE4571150808 / TE4571180605	457K tow
Zoltek PX3505015T-13 (industry baseline)	SN 22224094, lot 4C22-6076	50K tow

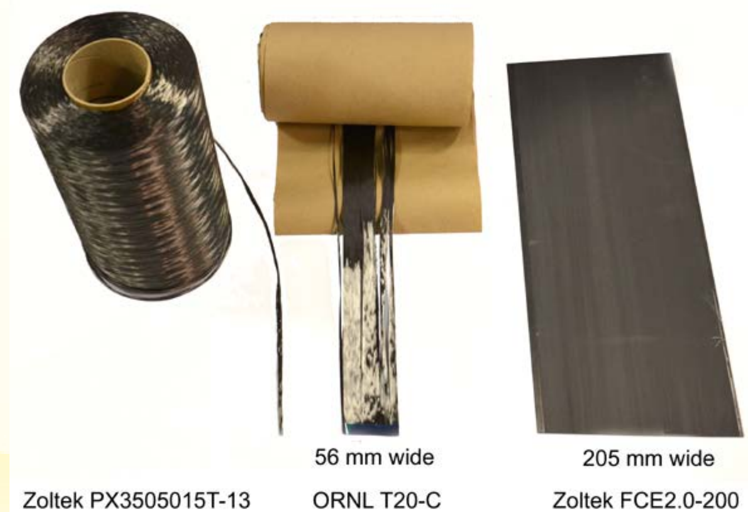
Label nomenclature	Fiber	Pultrusion	Supplied form
112017-4, 112017-5 (Kaltex pre-cursor)	K20-HTU	Third-party	50 mm wide x 3.5 mm thick
112017-6 (Zoltek)	PX-35	Third-party	
FCE2.0-200, 5T10-7017 (Zoltek)	PX-35	Commercial	205 mm wide x 1.87 mm thick

Material Forms

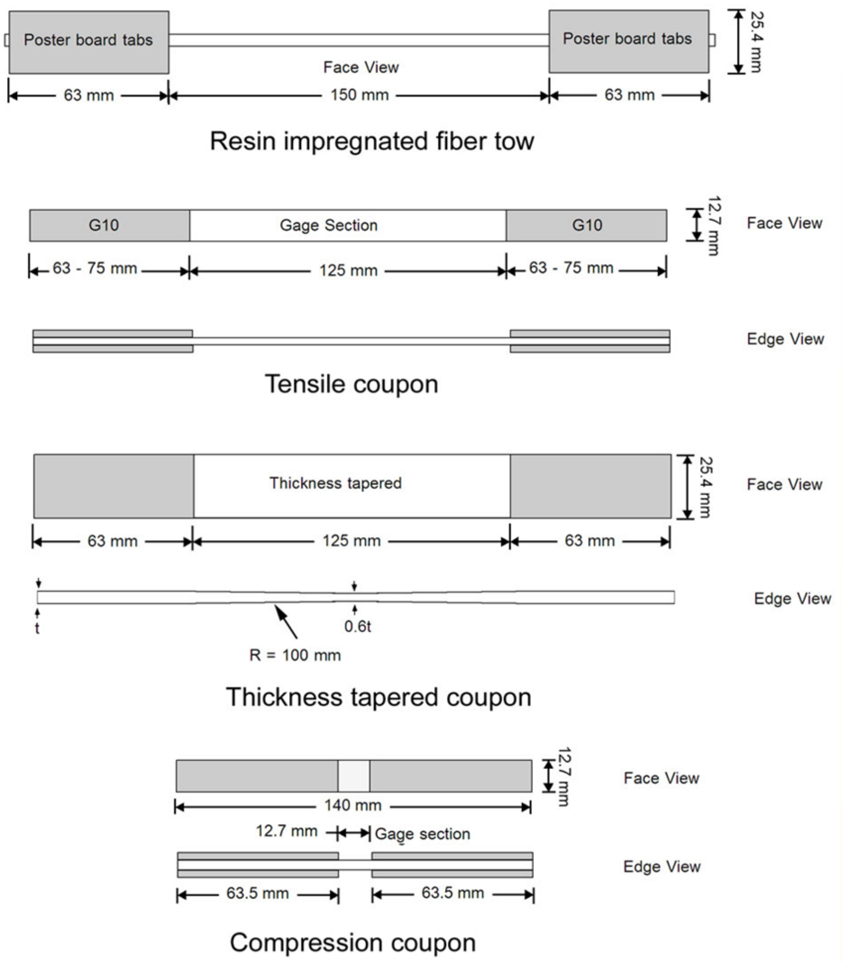


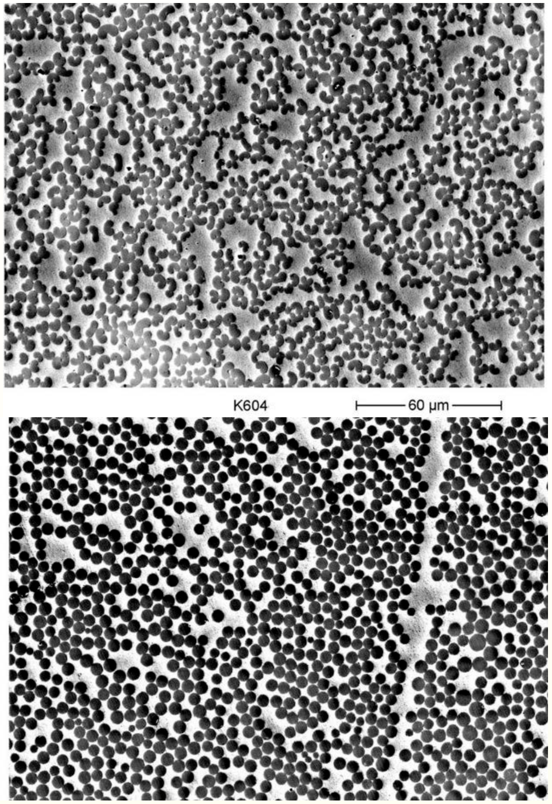






Coupons and Microstructure

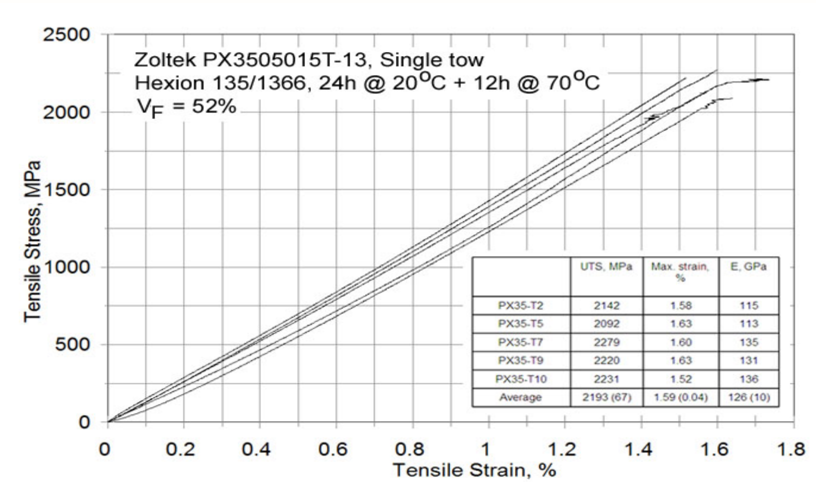




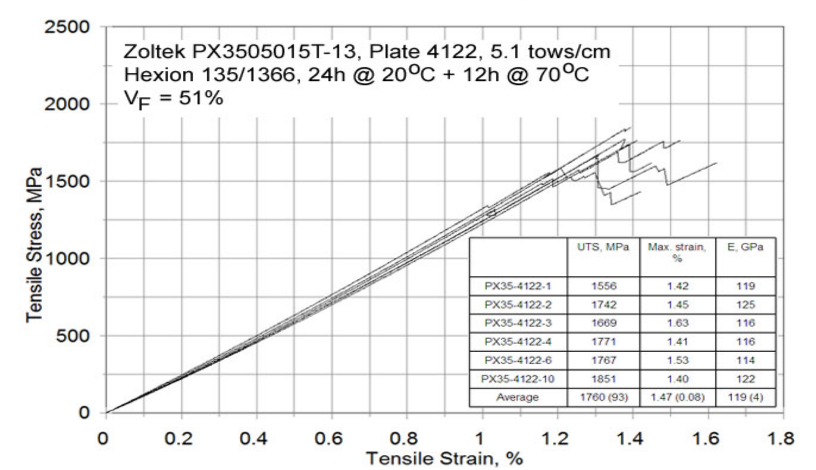
Kaltex fiber coupon (Coupon K20-604, Upper] and the Taekwang fiber coupon (Coupon T20-456, lower] detailing the fiber distributions in the MSU infused laminates.

Zoltek PX-35 Control Results

Aligned Strand

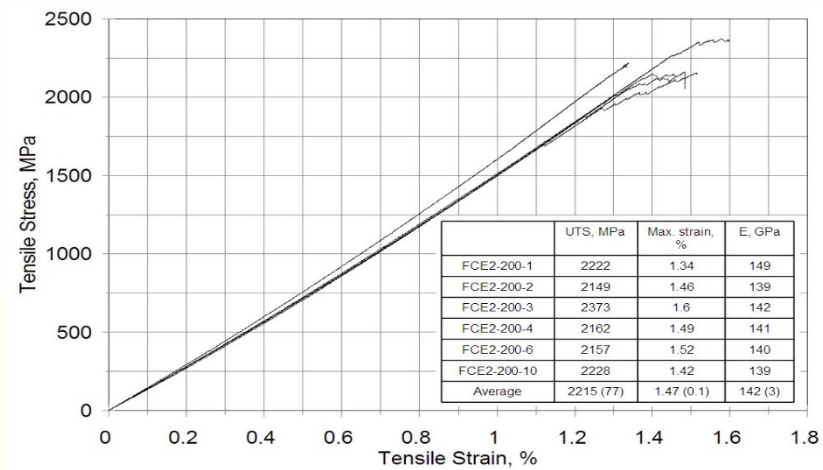


	UTS, MPa	Max. strain, %	E, GPa
PX35-T2	2142	1.58	115
PX35-T5	2092	1.63	113
PX35-T7	2279	1.60	135
PX35-T9	2220	1.63	131
PX35-T10	2231	1.52	136
Average	2193 (67)	1.59 (0.04)	126 (10)

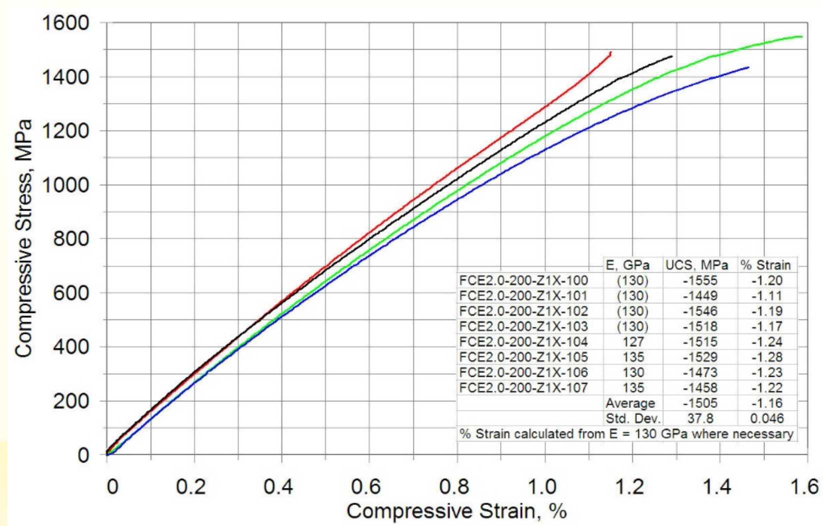


	UTS, MPa	Max. strain, %	E, GPa
PX35-4122-1	1556	1.42	119
PX35-4122-2	1742	1.45	125
PX35-4122-3	1669	1.63	116
PX35-4122-4	1771	1.41	116
PX35-4122-6	1767	1.53	114
PX35-4122-10	1851	1.40	122
Average	1760 (93)	1.47 (0.08)	119 (4)

Control Pultrusion



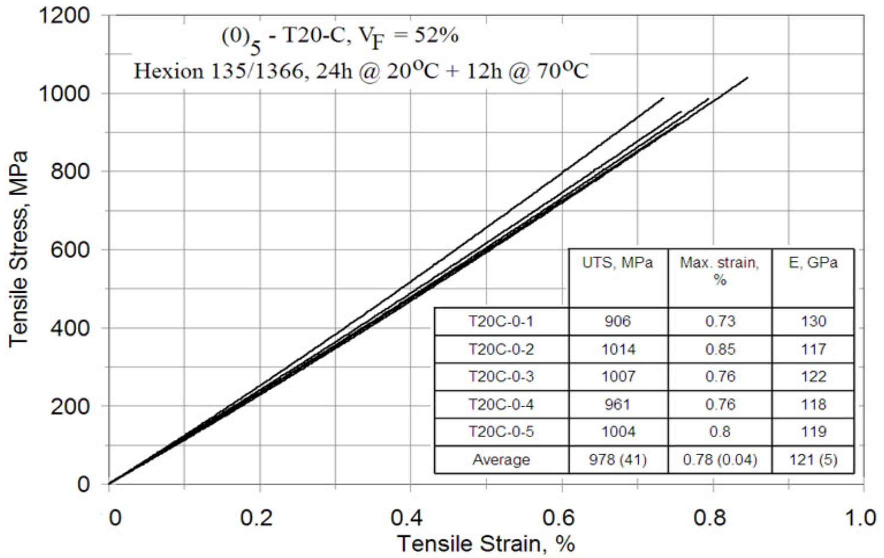
	UTS, MPa	Max. strain, %	E, GPa
FCE2-200-1	2222	1.34	149
FCE2-200-2	2149	1.46	139
FCE2-200-3	2373	1.6	142
FCE2-200-4	2162	1.49	141
FCE2-200-6	2157	1.52	140
FCE2-200-10	2228	1.42	139
Average	2215 (77)	1.47 (0.1)	142 (3)



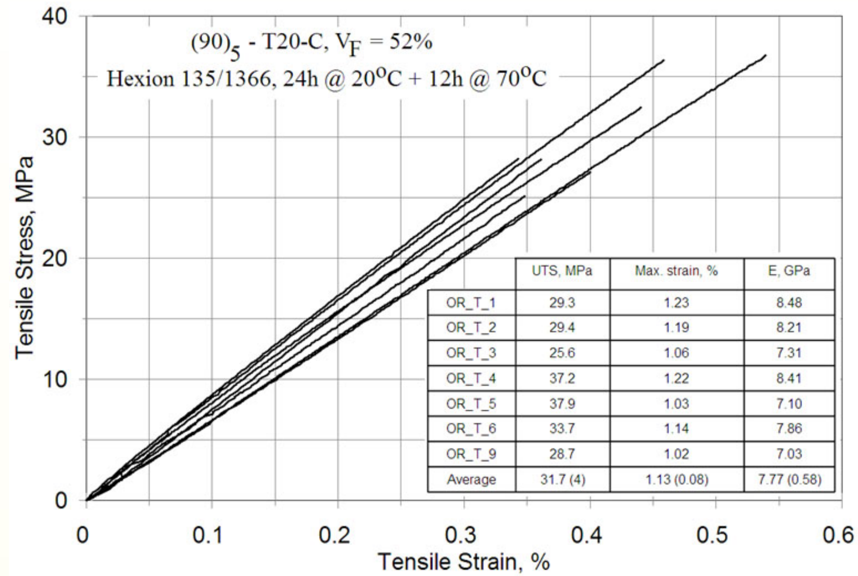
	E, GPa	UCS, MPa	% Strain
FCE2.0-200-Z1X-100	(130)	-1555	-1.20
FCE2.0-200-Z1X-101	(130)	-1449	-1.11
FCE2.0-200-Z1X-102	(130)	-1546	-1.19
FCE2.0-200-Z1X-103	(130)	-1518	-1.17
FCE2.0-200-Z1X-104	127	-1515	-1.24
FCE2.0-200-Z1X-105	135	-1529	-1.28
FCE2.0-200-Z1X-106	130	-1473	-1.23
FCE2.0-200-Z1X-107	135	-1458	-1.22
	Average	-1505	-1.16
	Std. Dev.	37.8	0.046

% Strain calculated from E = 130 GPa where necessary

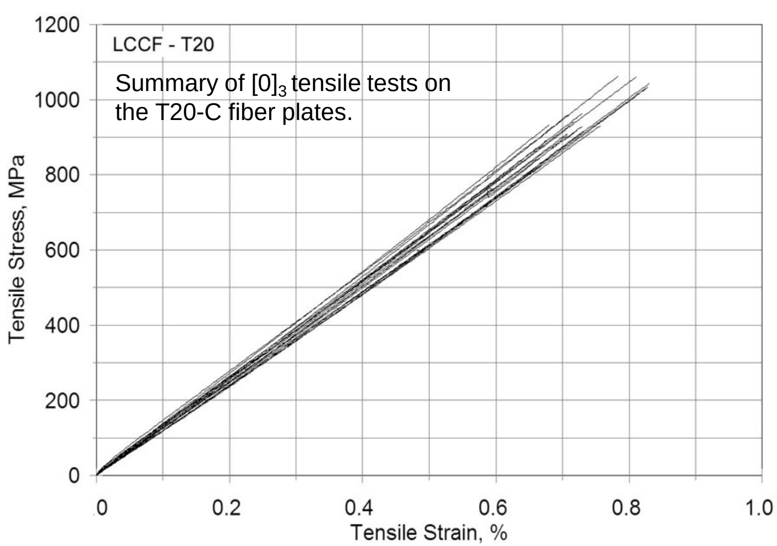
Taekwang Precursor



	UTS, MPa	Max. strain, %	E, GPa
T20C-0-1	906	0.73	130
T20C-0-2	1014	0.85	117
T20C-0-3	1007	0.76	122
T20C-0-4	961	0.76	118
T20C-0-5	1004	0.8	119
Average	978 (41)	0.78 (0.04)	121 (5)

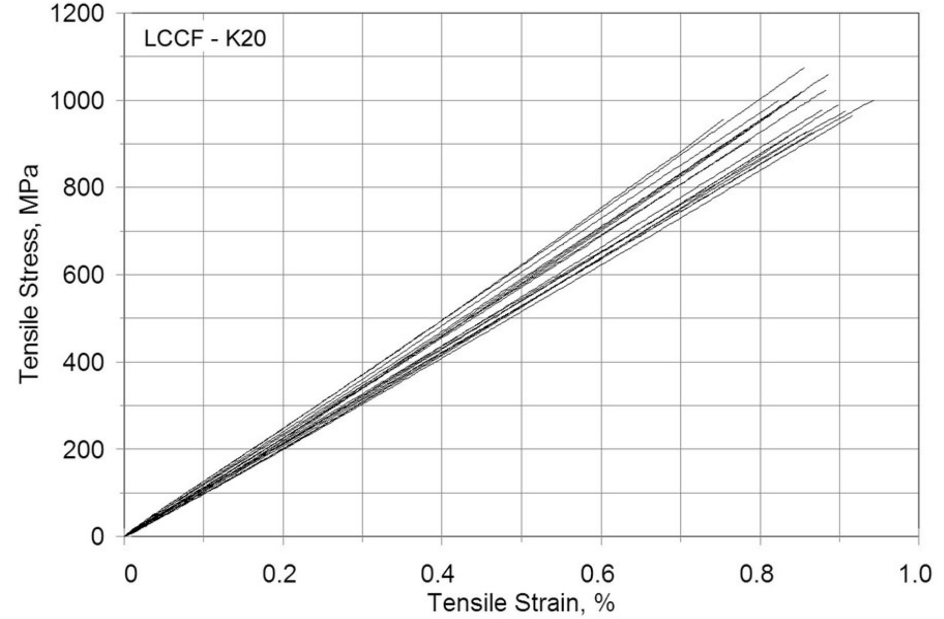


	UTS, MPa	Max. strain, %	E, GPa
OR_T_1	29.3	1.23	8.48
OR_T_2	29.4	1.19	8.21
OR_T_3	25.6	1.06	7.31
OR_T_4	37.2	1.22	8.41
OR_T_5	37.9	1.03	7.10
OR_T_6	33.7	1.14	7.86
OR_T_9	28.7	1.02	7.03
Average	31.7 (4)	1.13 (0.08)	7.77 (0.58)

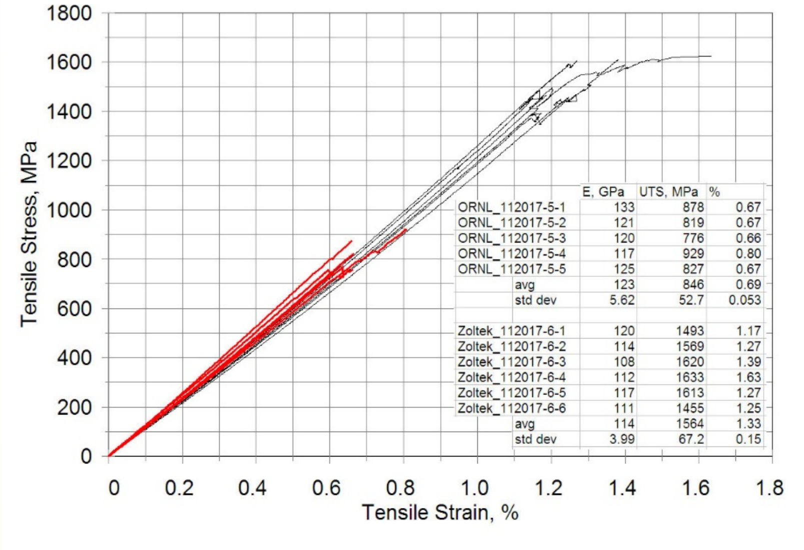


Kaltex K20 Precursor

Aligned Strand

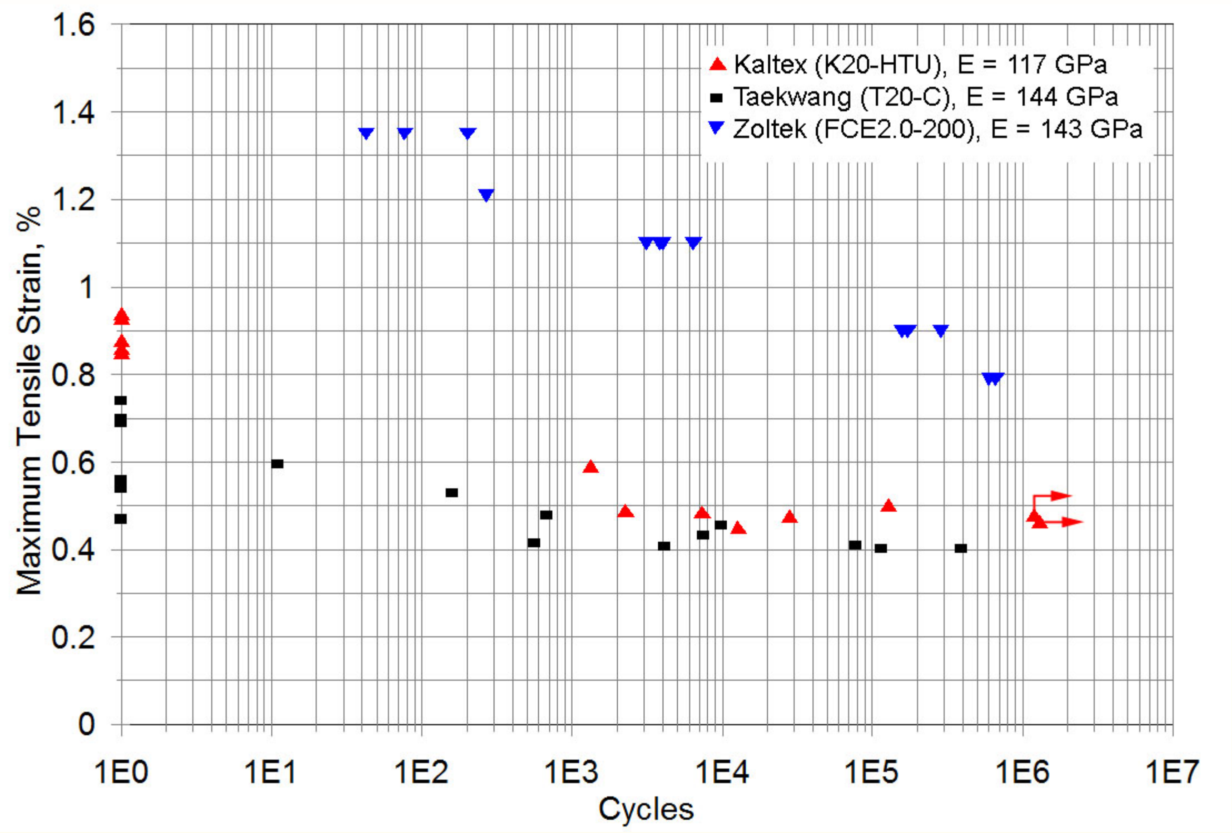


3rd Party Pultrusion



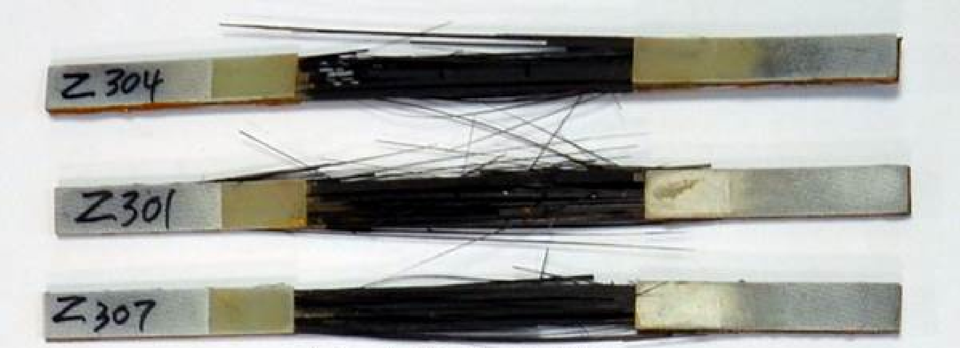
	E, GPa	UTS, MPa	%
ORNL_112017-5-1	133	878	0.67
ORNL_112017-5-2	121	819	0.67
ORNL_112017-5-3	120	776	0.66
ORNL_112017-5-4	117	929	0.80
ORNL_112017-5-5	125	827	0.67
avg	123	846	0.69
std dev	5.62	52.7	0.053
Zoltek_112017-6-1	120	1493	1.17
Zoltek_112017-6-2	114	1569	1.27
Zoltek_112017-6-3	108	1620	1.39
Zoltek_112017-6-4	112	1633	1.63
Zoltek_112017-6-5	117	1613	1.27
Zoltek_112017-6-6	111	1455	1.25
avg	114	1564	1.33
std dev	3.99	67.2	0.15

Fatigue

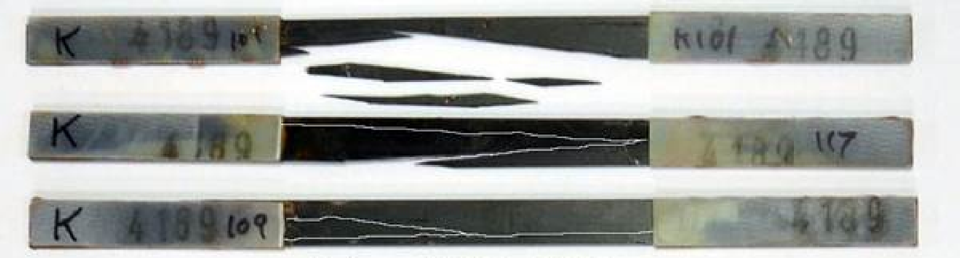


Kaltex (K20-HTU), E = 117 GPa
Taekwang (T20-C), E = 144 GPa
Zoltek (FCE2.0-200), E = 143 GPa
Maximum Tensile Strain, %
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1E0
1E1
1E2
1E3
1E4
1E5
1E6
1E7
Cycles

Failed Coupons



Zoltek FCE2.0-200



Kaltex (K20-HTU)

Taekwang (T20-C)

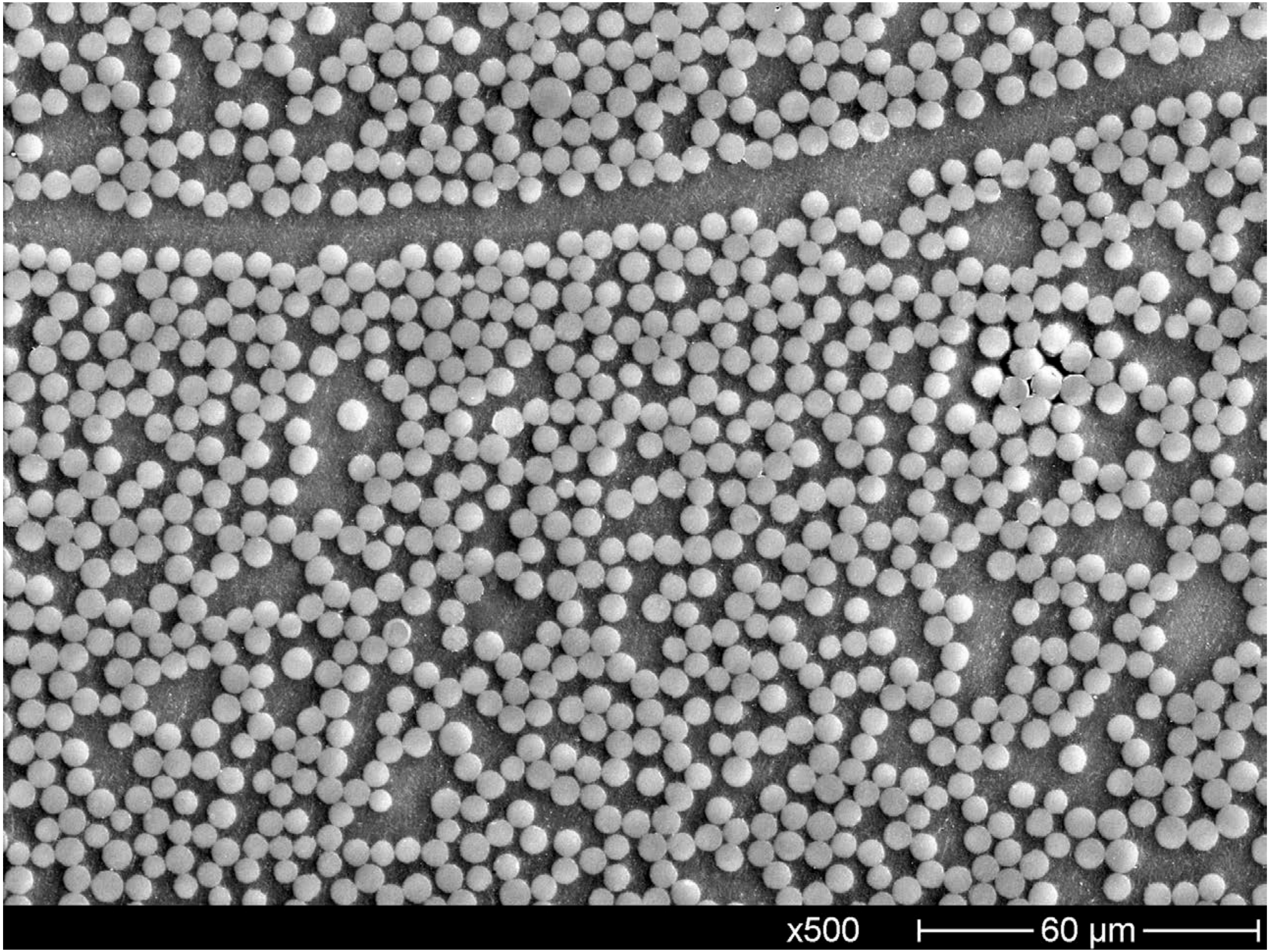
Pultrusion Kaltex

Pultrusion 3rd Party PX-35

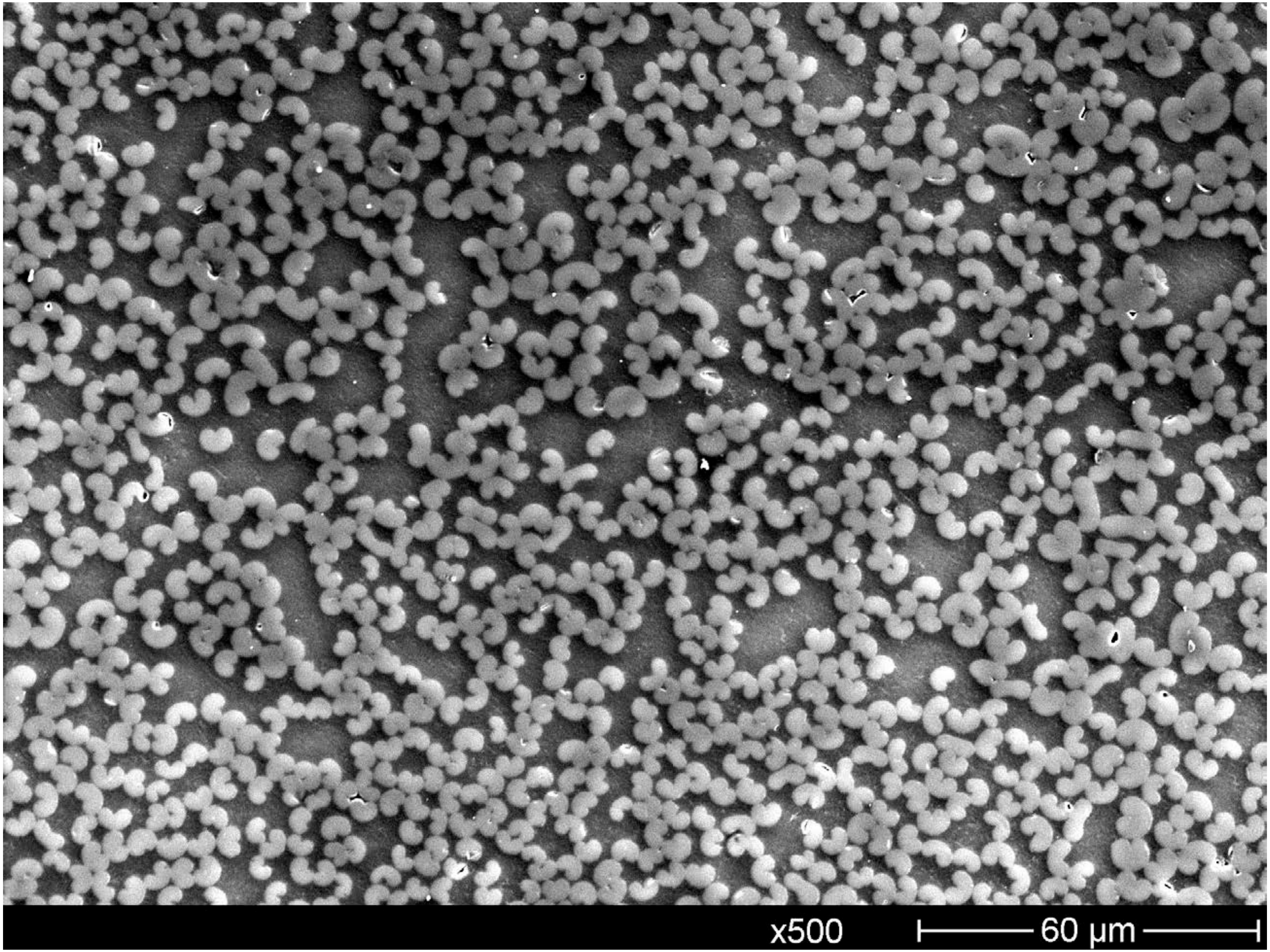
Summary Results

Material	Layup	V_F, %	E, GPa 0.1-0.3%	UTS, MPa	%, max	UCS, MPa [1]	%, min
Zoltek PX35 MSU Infused	Single tow	52	126 [10]	2193 [67]	1.59 [0.04]		
	5.1 tows/cm	51	119 [4]	1726 [93]	1.4 [0.08]		
	[0]	51				-906 [44]	-0.74 [0.04]]
Zoltek PX35 Third-party pultruded	[0], 112017-6	53	114 [4]	1564 [67]	1.33 [0.15]	-897 [67]	-0.79 [0.06]
Zoltek FCE2.0-200	[0]	62	142 [3] 138 [9]	2215 [77]	1.5 [0.10]	-1505 [38] -880 [37]	-1.21 [0.05] -0.63 [0.04]
	[90]	62	9.13 [0.12]	50.1 [8]	0.58 [0.11]		
ORNL T20-C MSU Infused	$[0]_3$	49	126 [4]	968 [54]	0.75 [0.05]		
	$[0]_5$	52	121 [5]	978 [41]	0.78 [0.04]		
	$[0]_{10}$	52	124 [13]			-573 [30]	-0.47 [0.07]
	$[90]_5$	52	7.8 [0.6]	31.7 [4]	1.13 [0.08]		
	$[0/90]_{3S}$	50	67.4 [0.8]			-475 [22] -893 [41] [A]	-0.73 [0.05]
	$[0]_5$ Tension $[0]_{20}$ Comp.	50	126 [4]	956 [63]	0.74 [0.05]	-869 [46]	-0.69 [0.04]
ORNL K20-HTU Third-party pultruded	[0], 112017-4	51				-803 [26]	-0.65 [0.02]
	[0], 112017-5	51	123 [6]	846 [53]	0.69 [0.05]	-769 [73]	-0.63 [0.06]
ORNL K20 MSU Infused	$[0]_5$ Tension $[0]_{20}$ Comp.	47	112 [6]	990 [49]	0.84 [0.06]	-863 [108]	-0.77 [0.10]

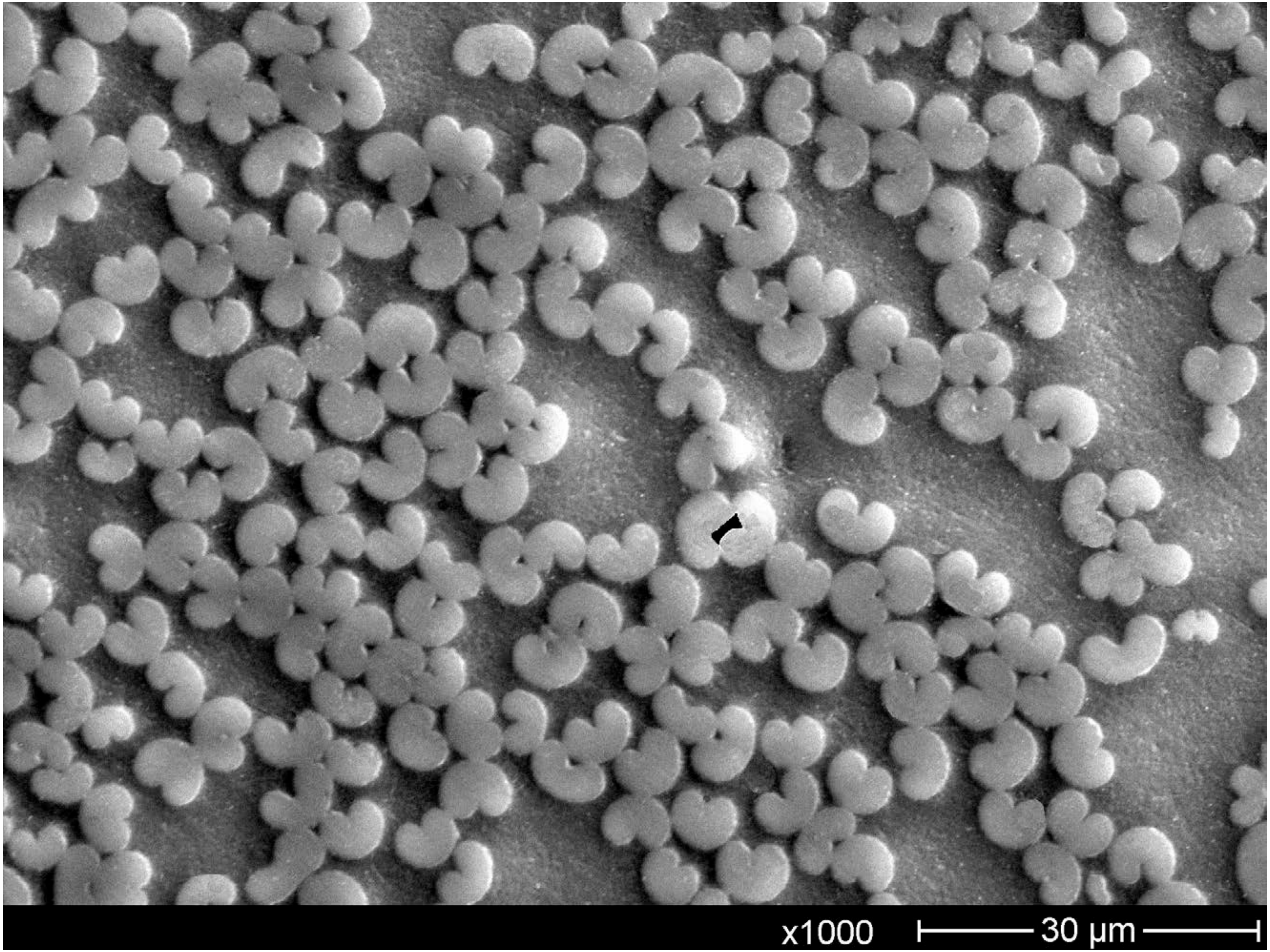
[1] Compressive testing followed a modified ASTM D6641 method. [A] UCS was calculated using a back-out factor method.



Typical T20 fiber distribution, aligned strand

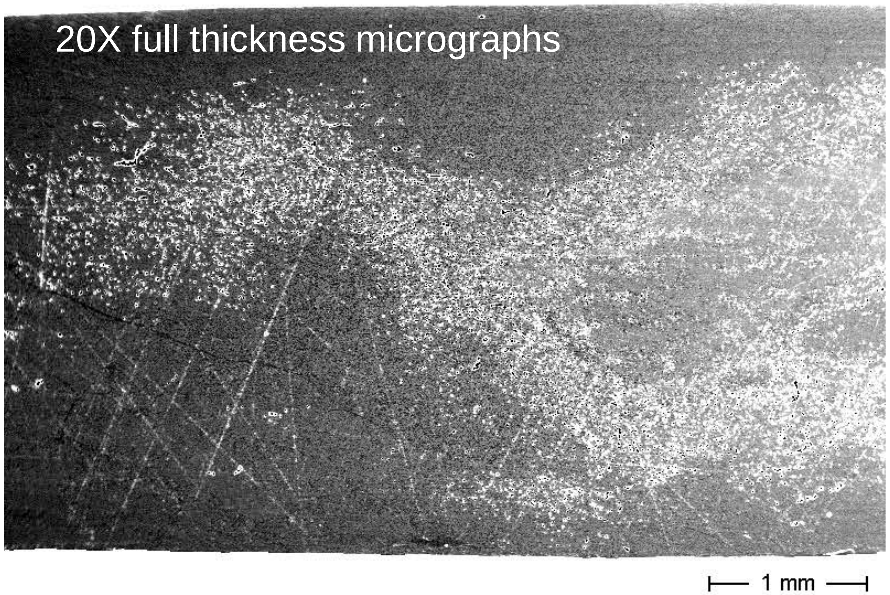


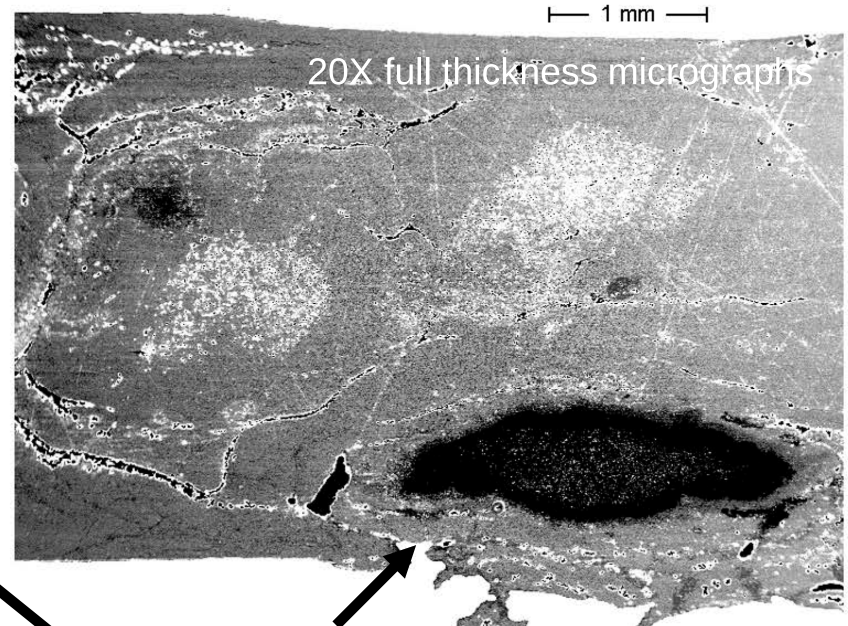
Typical K20 fiber distribution, aligned strand



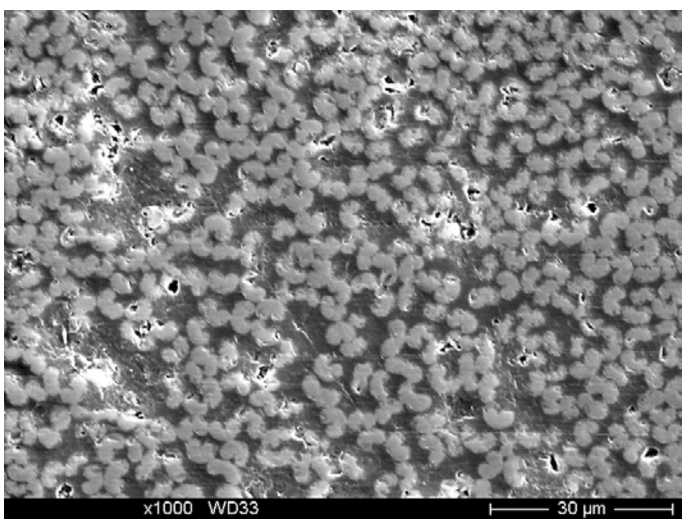
Typical K20 fiber distribution, higher magnification

- Material 112017-4 had large areas of dry carbon tows.
  - Potentially caused by fiber wrapping (rotation) boundaries / broken fibers interfering with fiber packing and fiber wet out.





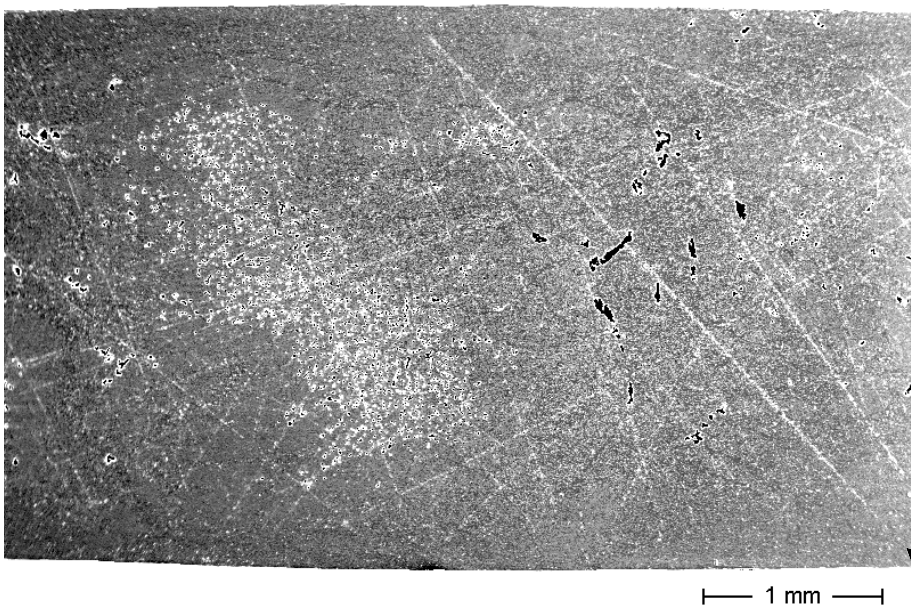
Black area = dry carbon fiber

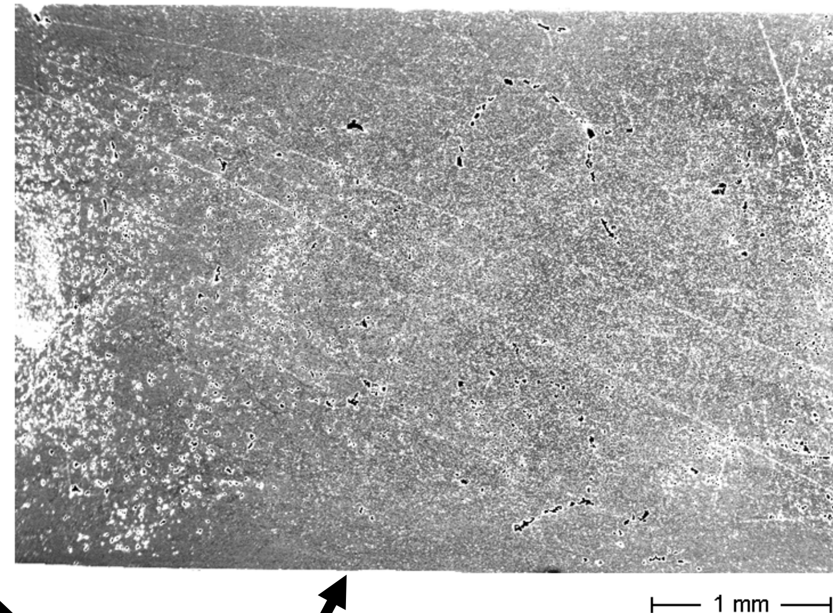


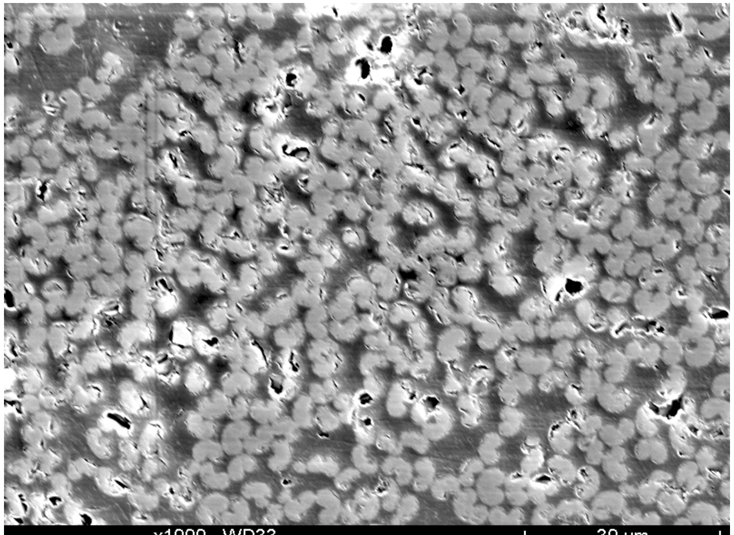
Fiber defects and straight white scratches (20X) shown are caused by polishing

1000X micrograph shows good fiber wet out

- Material 112017-5 had areas of high porosity (white and black areas).
  - Potentially caused by fiber wrapping (rotation) boundaries / broken fibers interfering with fiber packing and fiber wet out.







Fiber defects and straight white scratches (20X) shown are caused by polishing

1000X micrograph shows good fiber wet out