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Blade Optimization Studies using Novel Low-Cost Carbon Fiber Composites

Wind Energy Science Conference

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Optimized Carbon Fiber for Wind Energy Project

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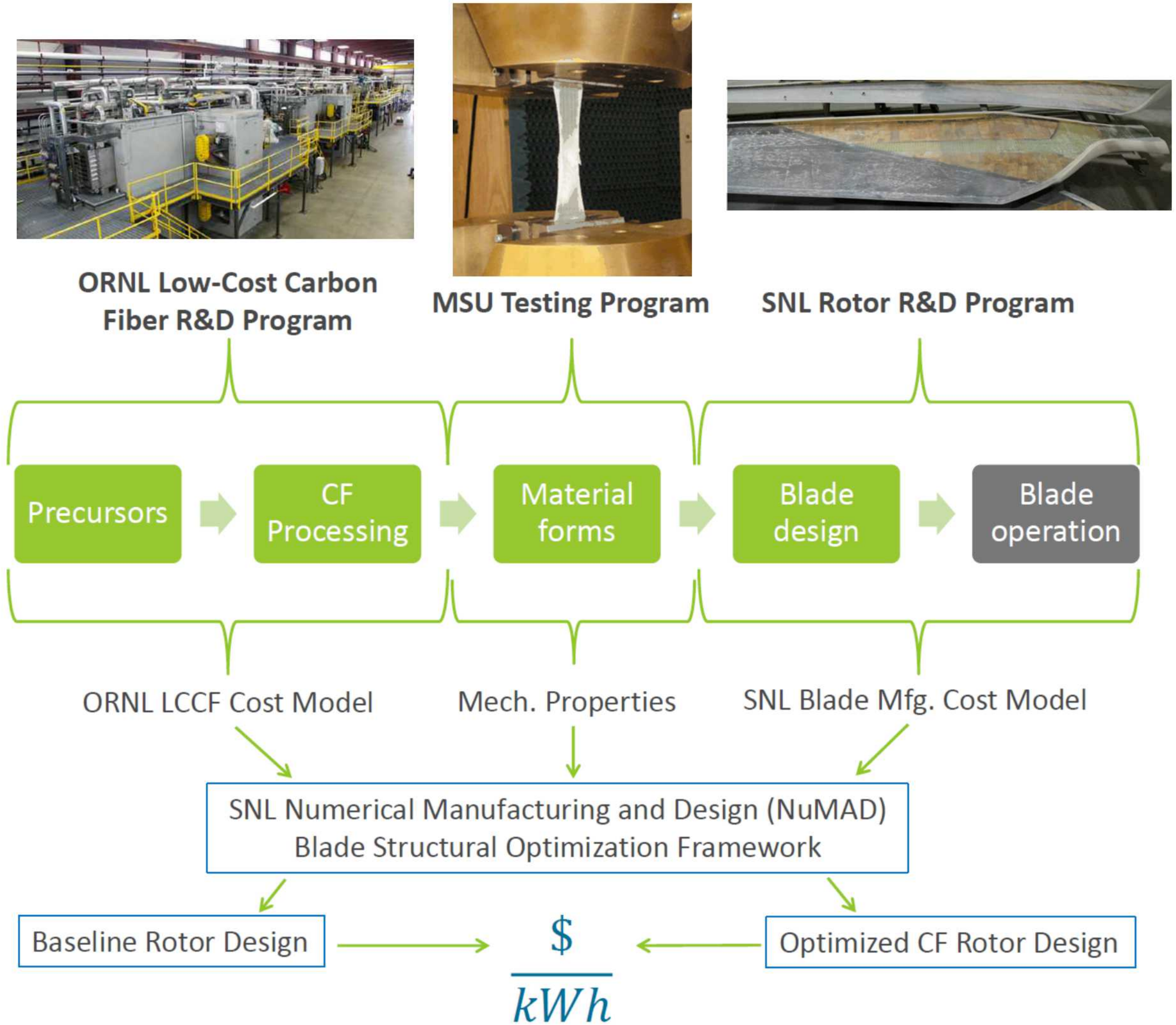
The objective of this project is to assess the commercial viability of cost-competitive, tailored carbon fiber composites for use in wind turbine blades.

- 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

- Carbon fiber materials are characterized through cost modeling and mechanical testing
- These materials are compared through structural optimization and cost minimization for representative blade designs
- The impact of novel carbon fiber materials on blade spar caps is assessed through comparison to industry baseline carbon fiber and fiberglass materials



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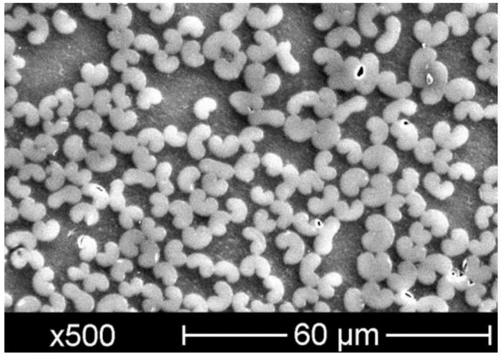
Evaluating Potential for Lower Cost Carbon Fiber

- **Textile Carbon Fiber (TCF)**
  - Acrylic fibers produced for textiles are similar chemically to those produced specifically as carbon fiber precursors, but significantly less expensive
  - Much of the cost difference is attributable to tow counts or number of filaments in each "bundle"
    - Traditional carbon fiber precursor – 0.5K to 50K (500 to 50,000 filaments)
    - Textile fiber is typically 300K and above
- **ORNL has demonstrated various TCF routes to lower cost**
  - Kaltex (457K, micrograph image bottom right), Taekwang (363K), and other "precursors" show much potential as development continues
  - Opportunity to influence product characteristics such as form, fiber stiffness, and other factors



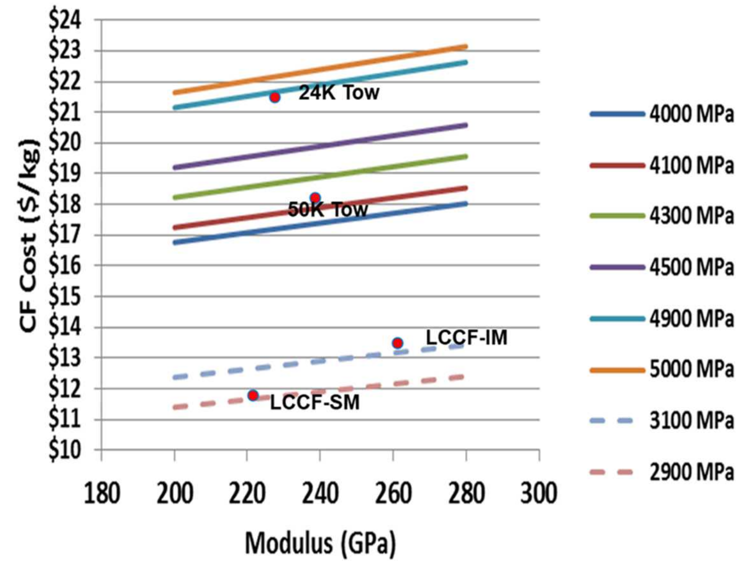
Carbon Fiber Cost Modeling

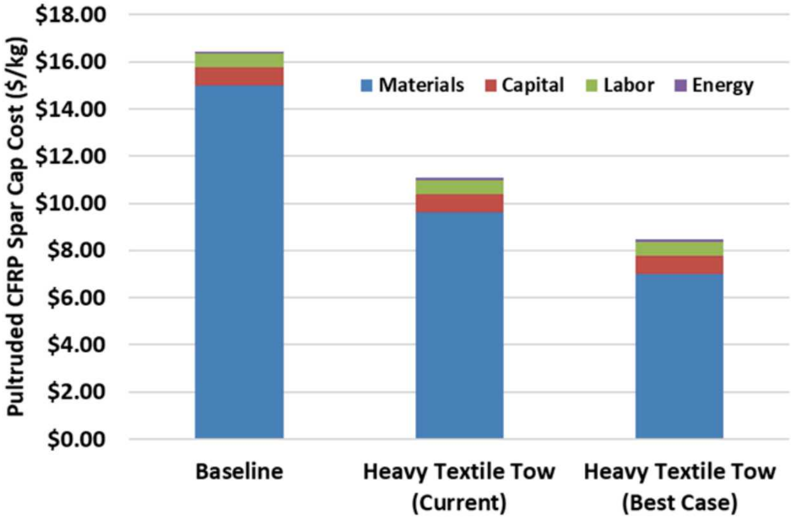
Parameter	Baseline $/kg (%)	Heavy Textile Tow (full-utilization) $/kg (%)	Reduction %
Materials	$8.09 (44.7%)	$5.05 (64.6%)	38%
Capital	$6.74 (37.2%)	$1.91 (24.4%)	72%
Labor	$2.06 (11.4%)	$0.47 (6.0%)	77%
Energy	$1.21 (6.7%)	$0.39 (4.9%)	68%
TOTAL	**$18.11 (100%)**	**$7.82 (100%)**	**57%**

- ✓ Lower precursor cost -- High output textile grade acrylic fiber used for clothing application today vs. specialty acrylic fiber
- ✓ Lower capital cost – Higher production capacity (similar conversion speed and tow spacing in addition to reduced oxidation time) using similar sized capital equipment (largest share of total cost reduction)
- ✓ Lower energy and labor cost – Economies of scale from an increased throughput

Optimized Carbon Fiber Composites Cost Modeling

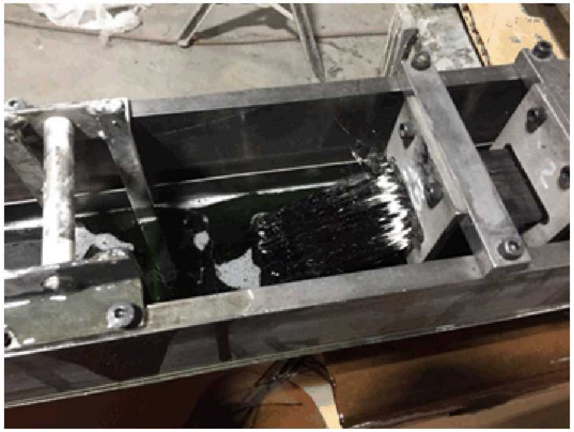
- Material (45%) and capital (37%) cost shares dominate the baseline (50K tow) carbon fiber cost of $18.11/kg
- Lower precursor cost and economies of scale from a higher throughput lowers the heavy textile tow (457K tow) LCCF (current) cost of $11.19/kg
- With an increased throughput due to reduced tow spacing, and lower oxidation time from an utilization of exothermic heat, LCCF (Best Case) cost is $7.82/kg
- A linear carbon fiber cost sensitivity to fiber modulus and strength
- A significant reduction of ~49% pultruded CFRP spar cap cost is projected using LCCF (Best Case)





Mechanical Testing of Low-Cost Carbon Fiber

- Spar caps are the first logical application of carbon fiber in blades
- Tested unidirectional coupons; pultruded composite forms are the use case in spars



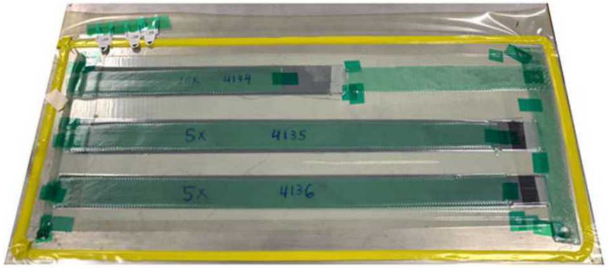
Pultrusions can produce spar caps very cost-effectively and with repeatable performance

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	-0.63
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	-1.16

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)	956 (63)	0.74 (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)	-863 (108)	-0.77 (0.44)
Zoltek PX35	Aligned strand	5.1 tows/cm	51	119 (4)	1726 (93)	1.4 (0.08)	-906 (44)	-0.74 (0.04)



MSU Aligned Strand infusions are useful for comparing fiber properties while minimizing manufacturing effects

Blade Optimization – Pultruded Model Input CFRP

- Pultruded carbon fiber properties show advantage over fiberglass, but cost more

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	0.57	42.8	1180	-750	$2.06

- The heavy textile 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

Wind Turbine Blade Optimization

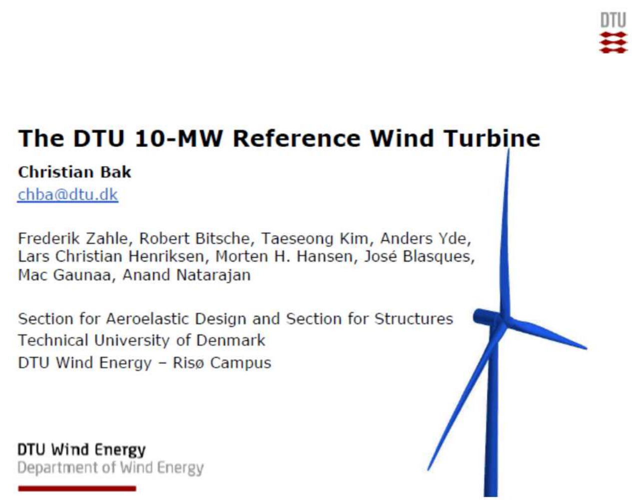
Structural and material optimizations are being performed using **two reference blade models**, representative of industry trends:

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

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

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

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


DTU

The DTU 10-MW Reference Wind Turbine

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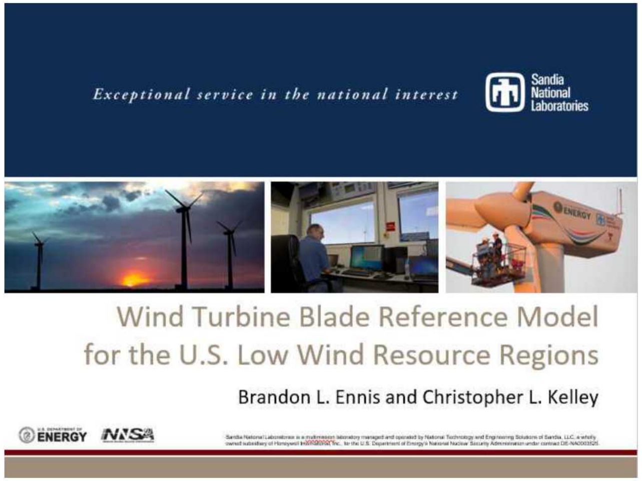
Department of Wind Energy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Wind Turbine Blade Reference Model for the U.S. Low Wind Resource Regions

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ENERGY NNSA

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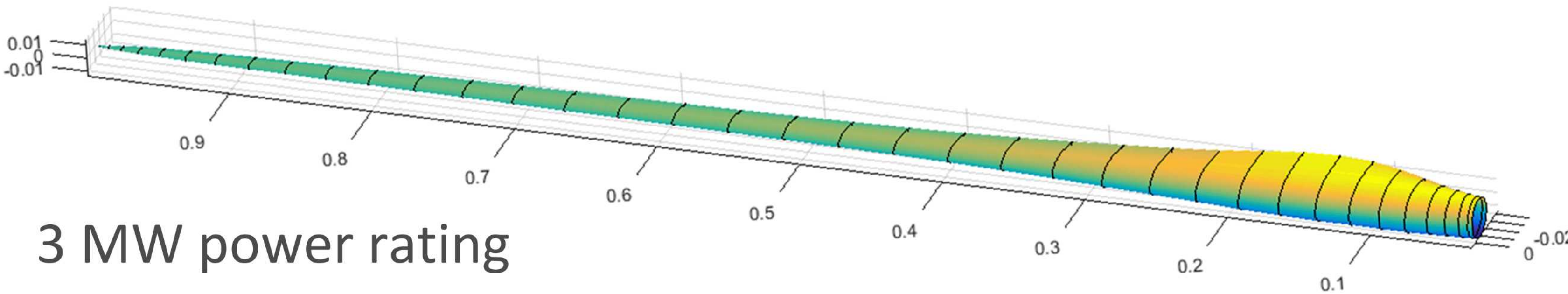
SNL3.0-148 Reference Blade Model

Publicly available reference model that is representative of the industry shift towards low specific power wind turbines for land-based sites, developed within this project.



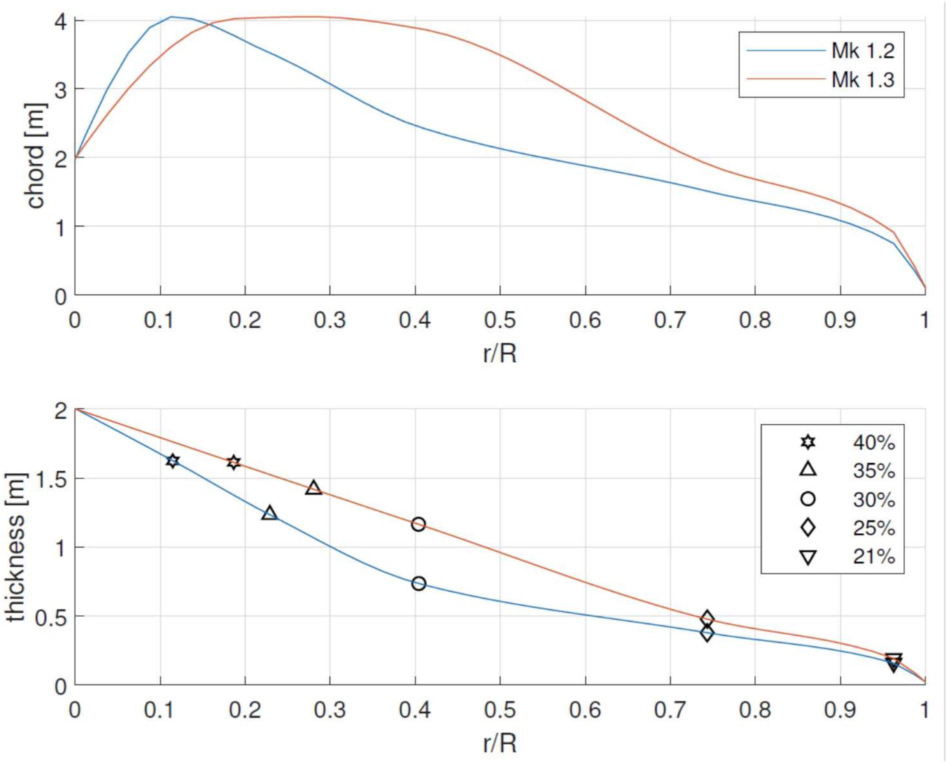
- 3 MW power rating
- 148 m turbine diameter
- 72 m blade length
- 175 W/m^2 specific power
- Class III-A site
- TSR = 9
- Blade solidity
  - Mk 1.2 = 2.85%
  - Mk 1.3 = 3.55%

- Lightly loaded tip
  - Matches the root bending moment of the "optimal" induction design (a=1/3) while increasing energy capture through a longer blade
- Tower and turbine reference models from IEA Task 37 will be used with the blade model

SNL3.0-148 Reference Blade Model

Aerodynamic Iterations:

- Mk 1.2 has the lower solidity of 2.85%, compared to 3.55% for Mk 1.3
- The Mk 1.3 was designed to have a larger thickness profile by moving the thickest airfoils outboard from the Mk 1.2 and by operating at a lower lift coefficient
- Both blades have the same induction profile and produce nearly equivalent power coefficients



SNL3.0-148 Reference Blade Model

<u>To reduce material strain:</u>

- Reduce moment (low induction rotor)
- Choose material with high Modulus
- Increase the area moment of inertia
- Decrease distance to neutral axis (c)
  - Would also decrease moment of inertia (which increases strain)

$$\epsilon = \frac{Mc}{EI}$$

<u>To reduce deflection:</u>

- Reduce moment (low induction rotor)
- Choose material with high Modulus
- Increase the area moment of inertia

$$v'' = \frac{M(x)}{E(x)I(x)}$$

SNL3.0-148 Reference Blade Model

$$\epsilon = \frac{Mc}{EI}$$

To reduce material strain:

- Increase the area moment of inertia

$$I_{spar} = I_{HP} + I_{LP}$$

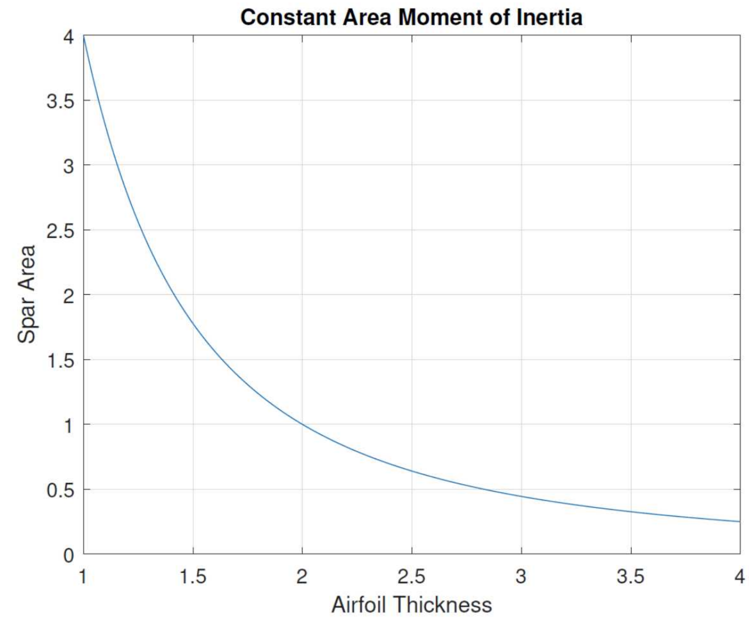
$$I_{spar} \approx 2\left({}^{1}/_{12}\, bh^3 + bh\left({}^{t}/_{2} - {}^{h}/_{2}\right)^2\right)$$

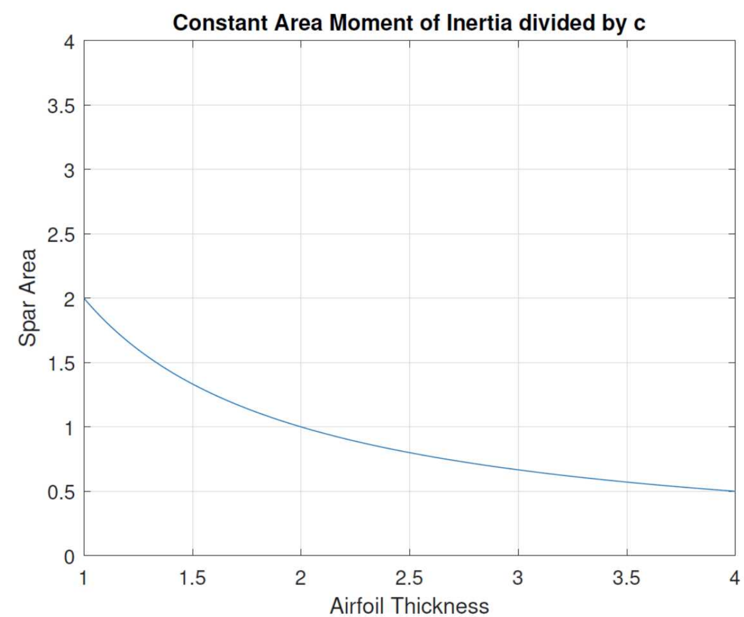
$$I_{spar} \approx 2bht^2\left({}^{1}/_{12}\left({}^{h}/_{t}\right)^2 + {}^{1}/_{4}\left(1 - {}^{h}/_{t}\right)^2\right)$$

$$I_{spar} \approx {}^{bht^2}/_{2} \qquad \text{where } t \gg h$$

- But c is ~ t/2

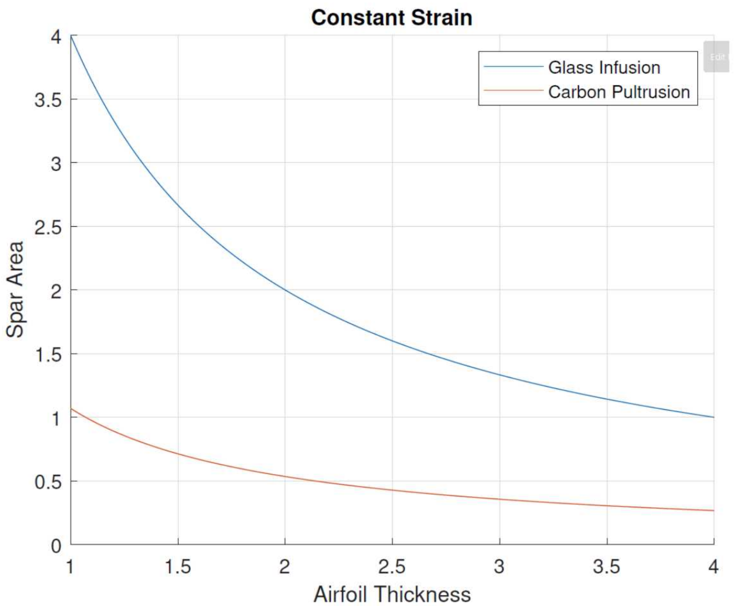
$$ {}^{I_{spar}}/_{c} \approx bht \qquad \text{where } t \gg h$$





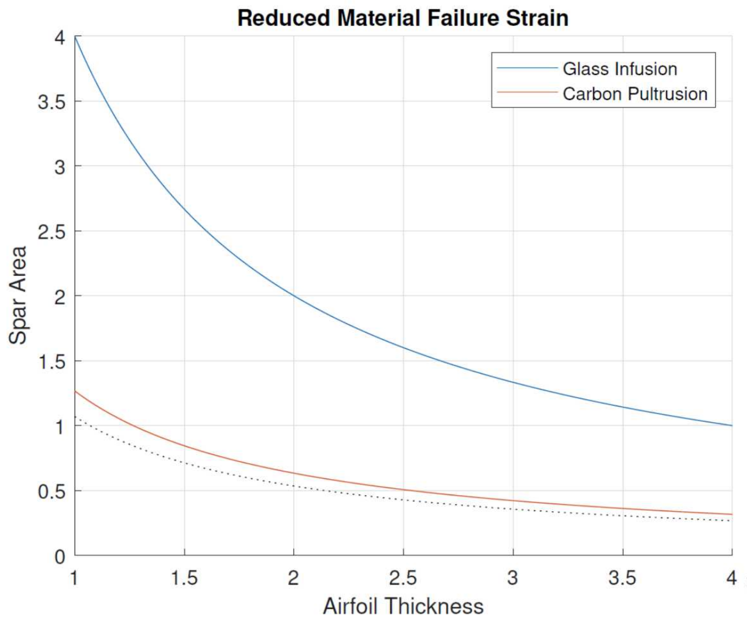
SNL3.0-148 Reference Blade Model

$$\epsilon = \frac{Mc}{EI}$$



To reduce material strain:

- Choose material with high Modulus
  - But, failure strain will likely be decreased as well



Initial Blade Optimization Results

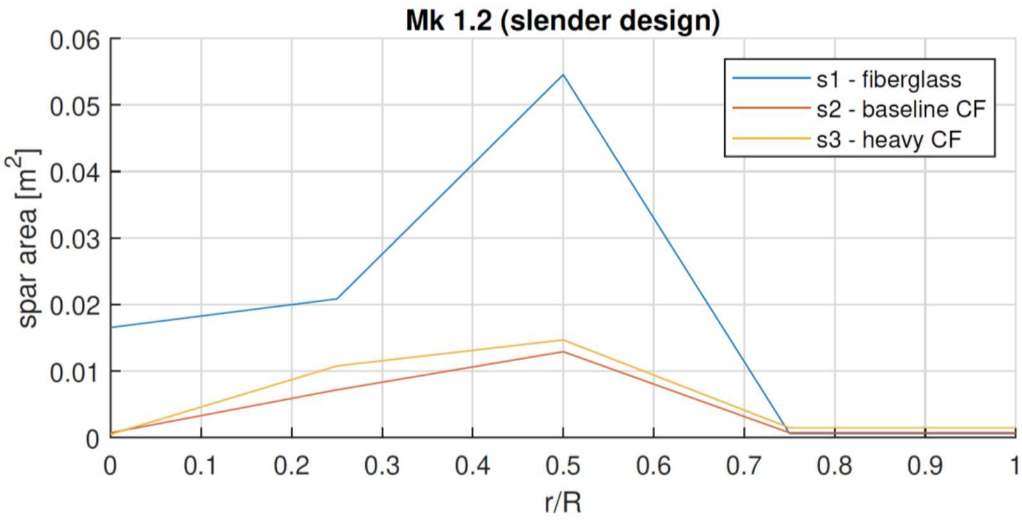
- IEC DLC 1.4: extreme coherent gust with wind direction change
- IEC DLC 6.1: 50-year parked extreme wind model
- Solve for spar material layup (width, and thickness along 5 points of the blade span)
- Minimize mass subject to spar cap strain and a 15% deflection (characteristic)

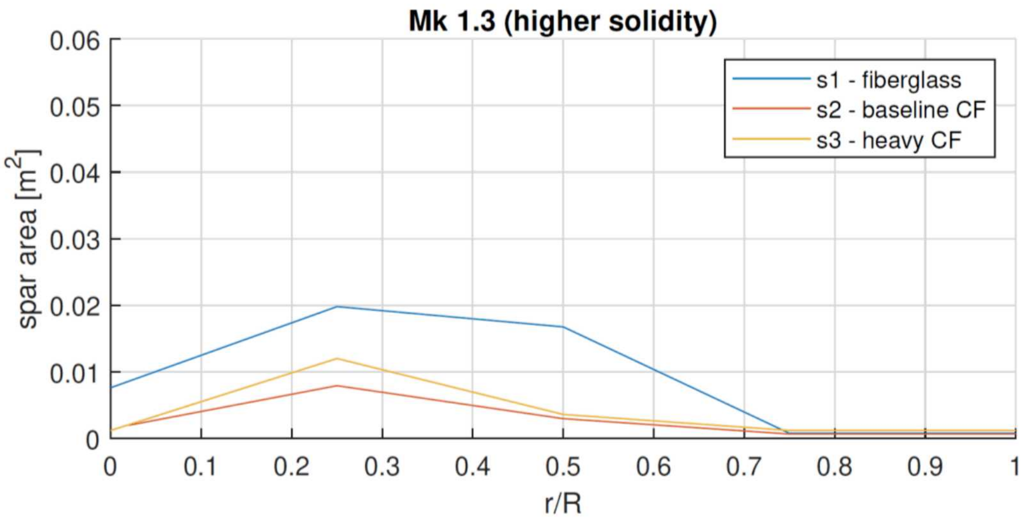
- Results are preliminary, but are useful for showing the trends with the different materials
  - Detailed material sizing beyond the spar cap is the next step
    - TE/LE reinforcement through fatigue analysis
    - Panel layup through FEA buckling analysis
  - Checks utilizing the entire set of Design Load Cases (DLC)

Initial Blade Optimization Results

- Spar caps need more material for more slender designs, due to the decreasing moment of inertia
- A factor of 2-4 times less material is needed for the stiffer carbon fiber, as explained analytically

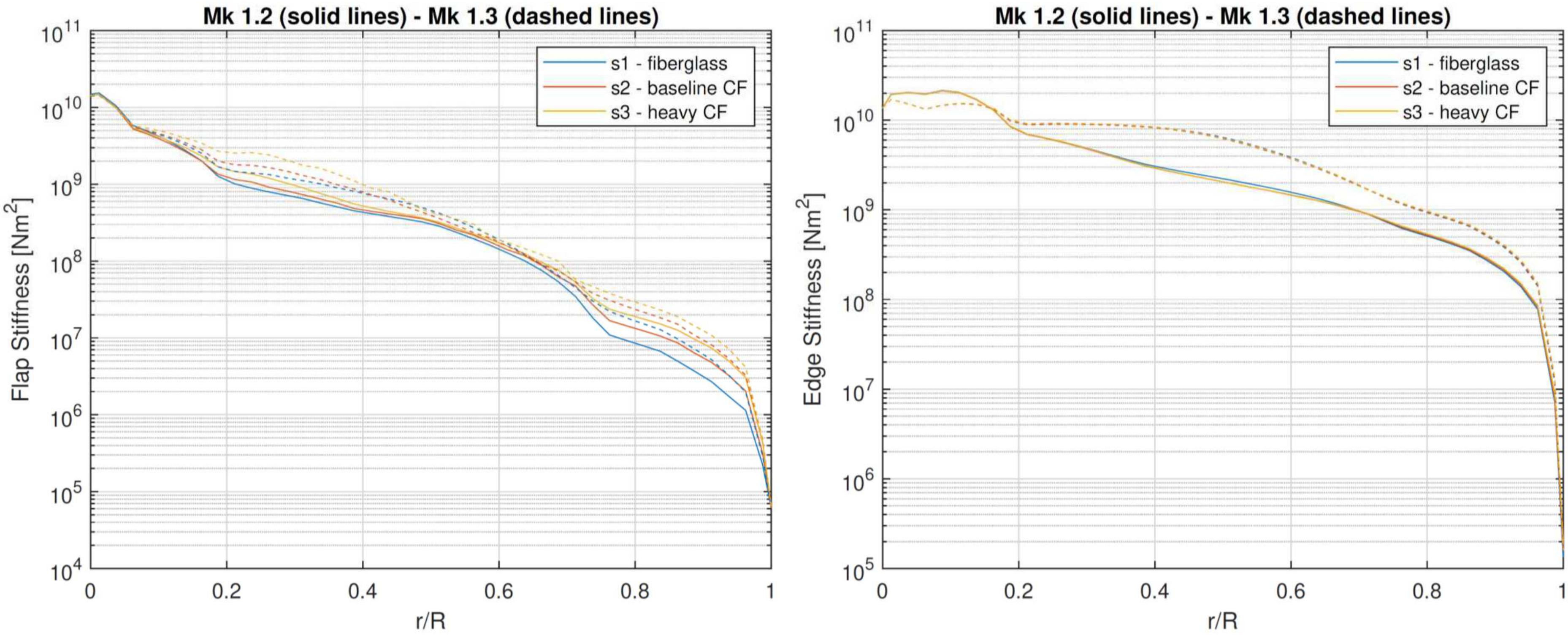
Spar Cap Width [mm]	Mk 1.2	Mk 1.3
Fiberglass	681	846
Baseline CF	239	110
Heavy CF	163	400





Initial Blade Optimization Results

- For the same aerodynamic loading, blades with the same EI along the span would have the same deflection
- Spar cap width doesn't significantly affect the edge moment of inertia
  - can use spar area instead of width + thickness as optimization variable



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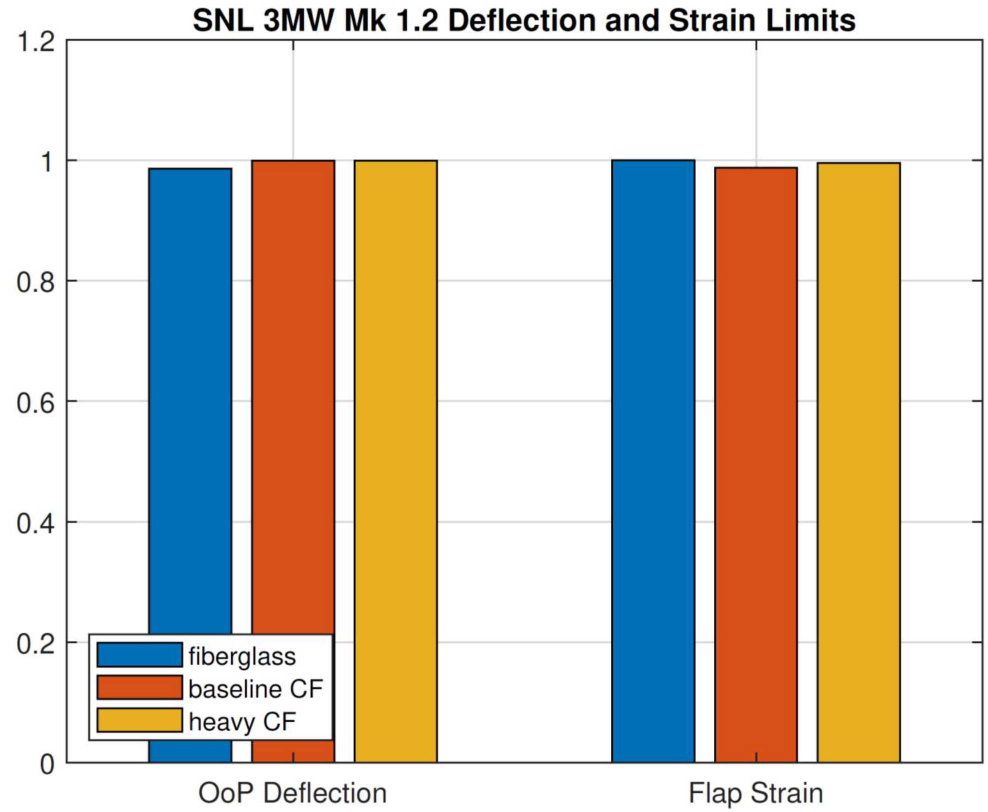
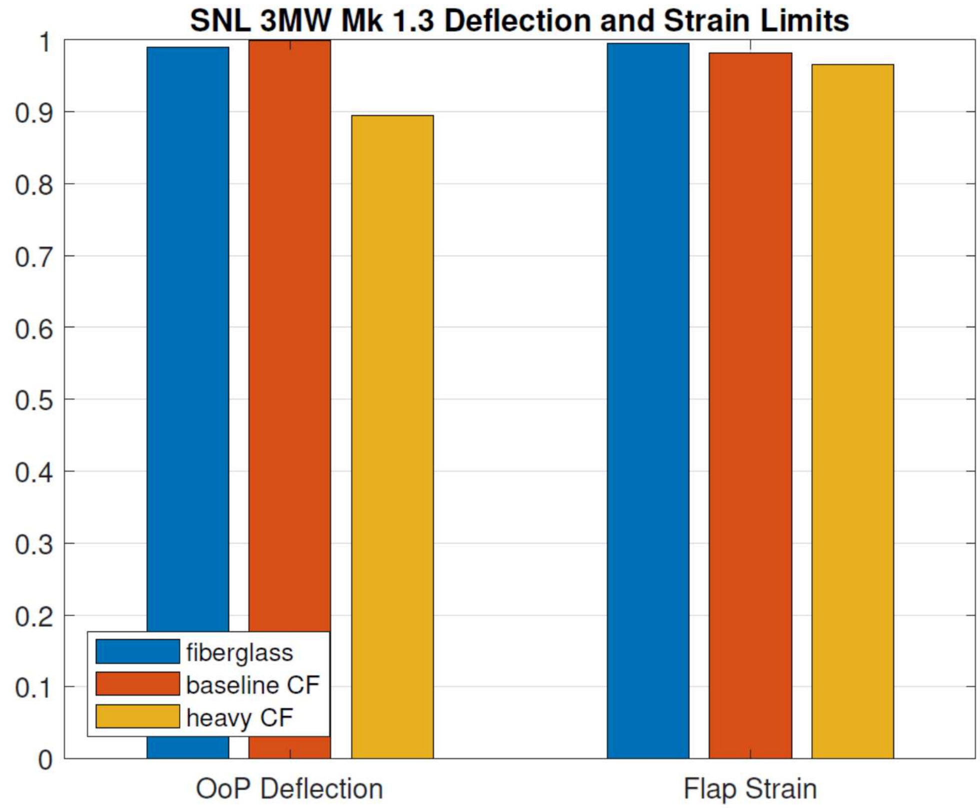
Initial Blade Optimization Results

- The slender blade achieves the limit of tip deflection (15%) almost exactly at the material's failure strain for each material
  - This is not the case for a 10% deflection, the fiberglass blade has unused strength to achieve a small deflection



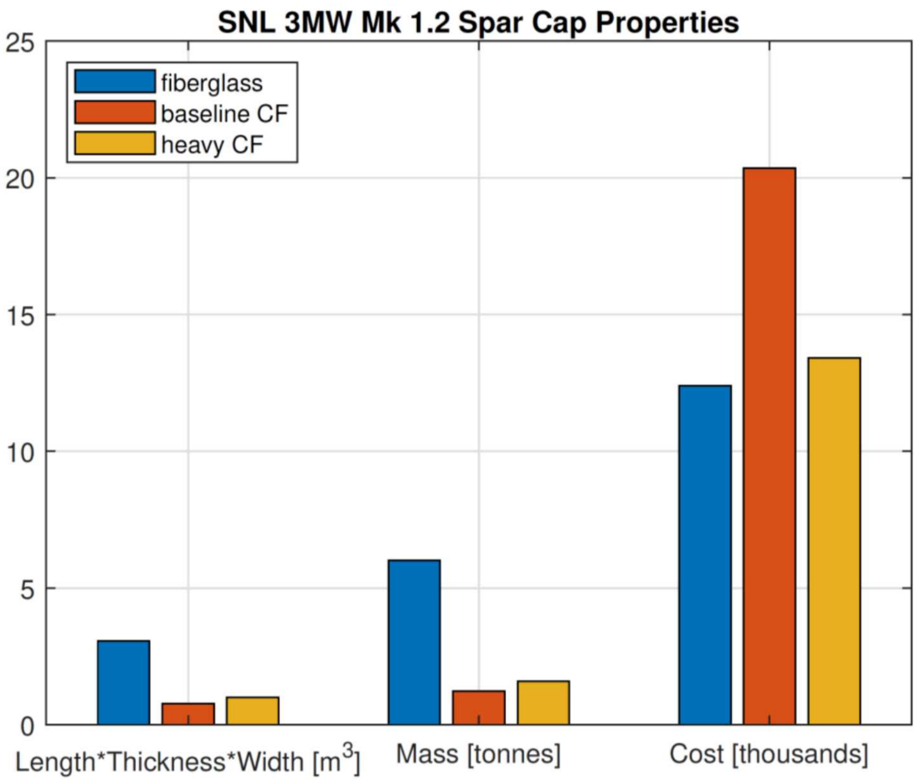
Initial Blade Optimization Results

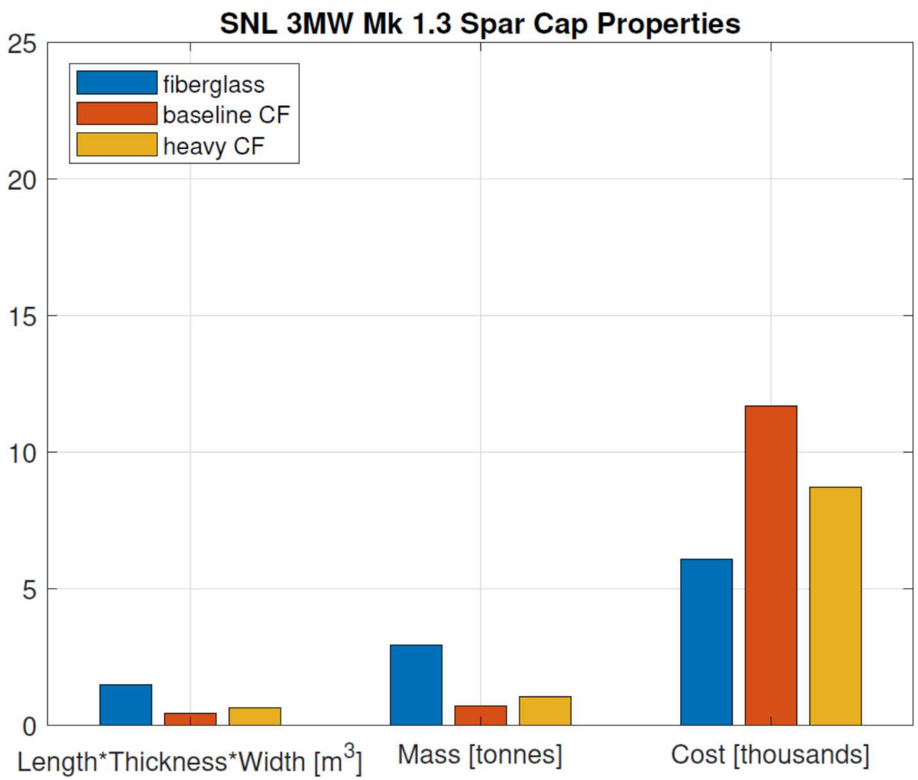
- The heavy-tow carbon fiber does not reach maximum deflection for this blade because it reaches its ultimate strain
  - A more slender blade is preferable for this material due to the lower tensile strength



Initial Blade Optimization Results

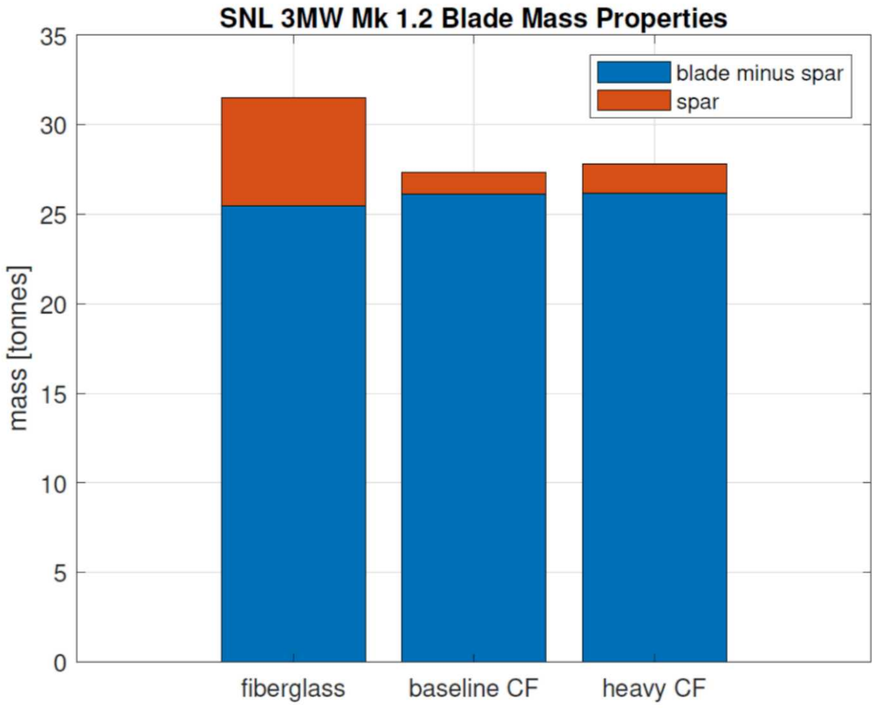
- The heavy tow carbon fiber is around 25-35% lower cost than the baseline carbon fiber material, with greater savings for more slender blades due to the comparable modulus
- The fiberglass spar cost is very similar for the slender blade, but much more massive

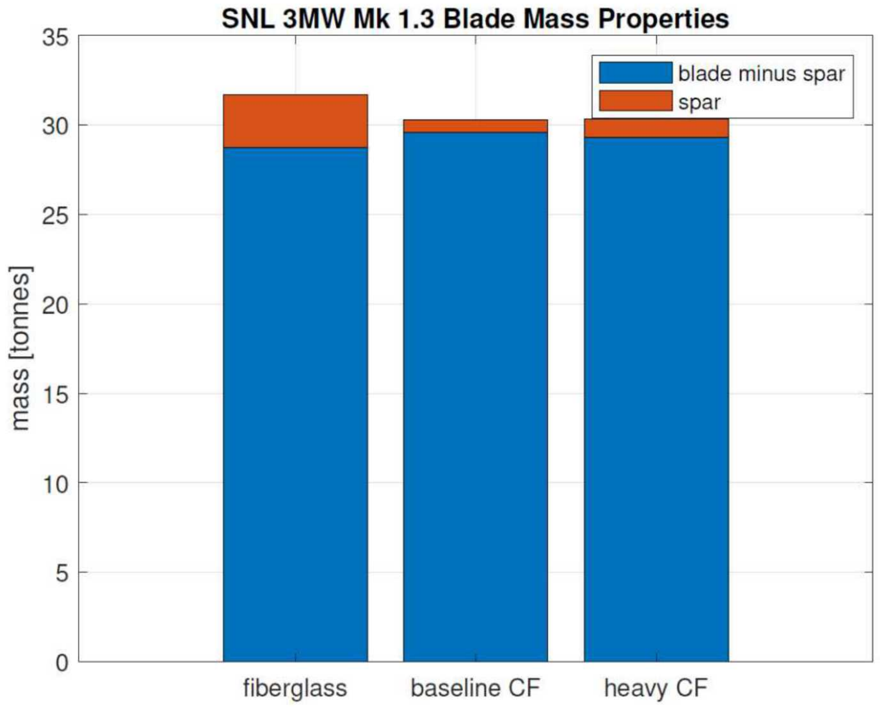




Initial Blade Optimization Results

- Carbon fiber enables slender blades to be more cost effective, system benefit of having less blade surface area
  - Lower blade material and manufacturing costs
    - 4 tonnes less blade shell material, savings of over $8k
  - Slender blades are more aerodynamically efficient (AEP gains)





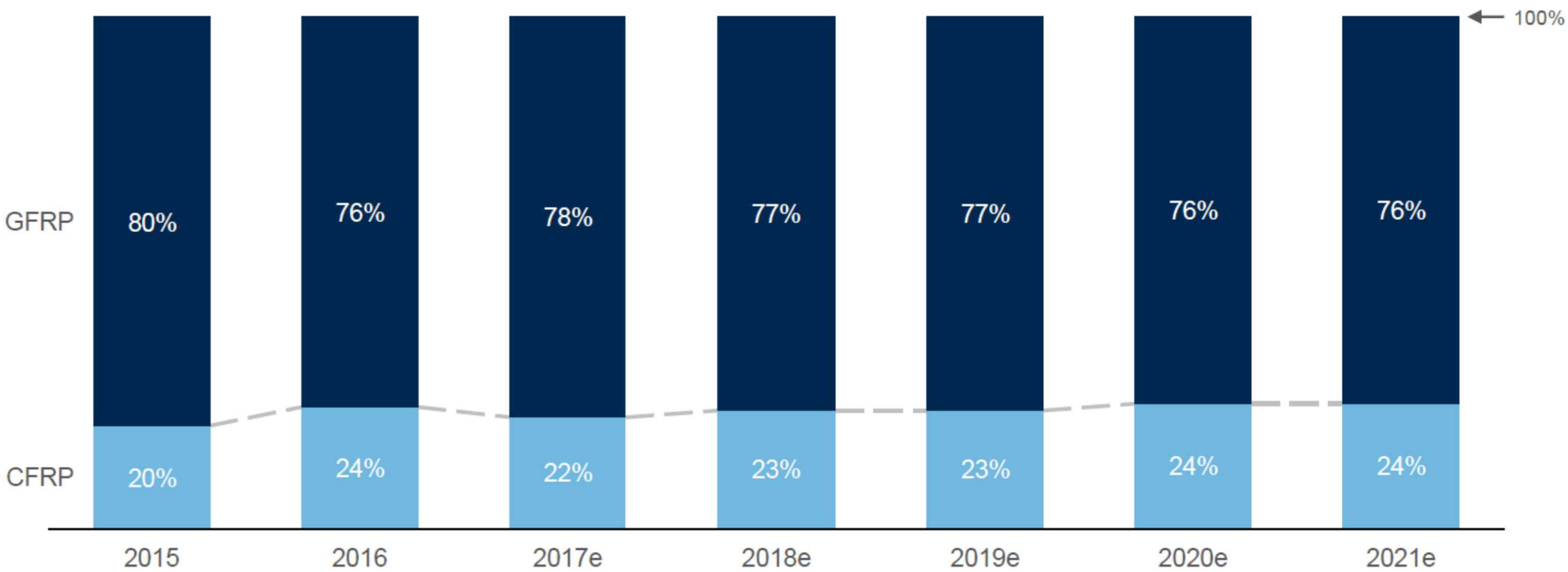
Blade Optimization Studies using Novel Low-Cost Carbon Fiber Composites

Backup Slides

Wind Turbine Blade Material Trends

- Despite industry growth in blade length, carbon fiber usage in wind turbine spar caps is not predicted to grow
- 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)

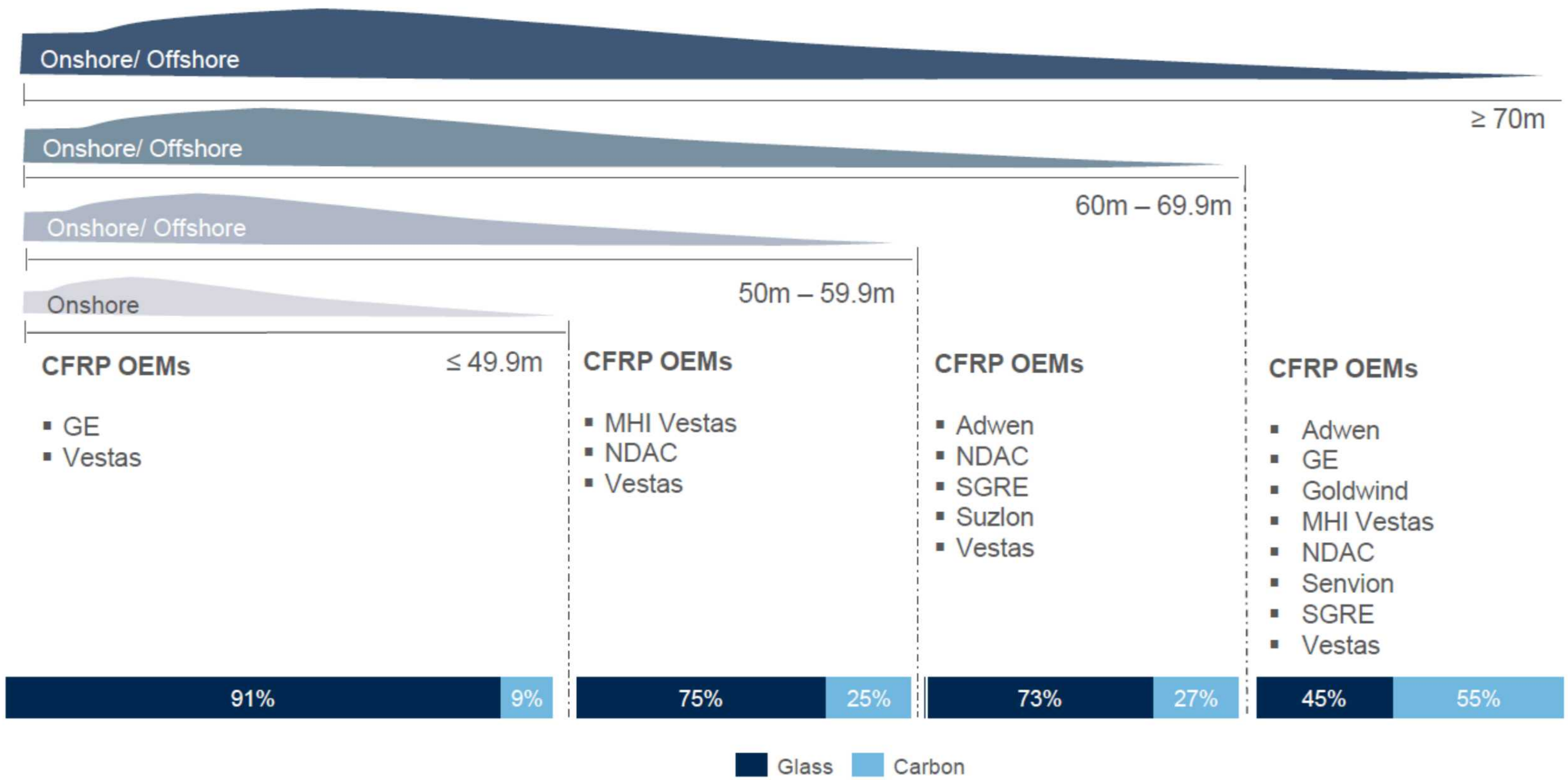


Source: MAKE

Wind Turbine Blade Material Trends

- 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

Key turbine OEMs and spar material by blade length



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

Initial Blade Optimization Results

For a 10% deflection limit:

- This low wind-resource, Class III turbine is stiffness driven for the fiberglass design
  - Fiberglass (E glass) is not optimal for this design
- The two carbon fiber materials equally meet the deflection and strain limits