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Optimized Carbon Fiber Composites in Wind Turbine Blade Design

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ABSTRACT

The objective of this study is to assess the commercial viability to develop cost-competitive carbon fiber composites specifically suited for the unique loading experienced by wind turbine blades. The wind industry is a cost-driven market, while carbon fiber materials have been developed for the performance-driven aerospace industry. Carbon fiber has known benefits for reducing wind turbine blade mass due to the significantly improved stiffness, strength, and fatigue resistance per unit mass compared to fiberglass; however, the high relative cost has prohibited broad adoption within the wind industry. Novel carbon fiber materials derived from the textile industry are studied as a potentially more optimal material for the wind industry and are characterized using a validated material cost model and through mechanical testing. The novel heavy tow textile carbon fiber is compared with commercial carbon fiber and fiberglass materials in representative land-based and offshore reference wind turbine models. Some of the advantages of carbon fiber spar caps are observed in reduced blade mass and improved fatigue life. The heavy tow textile carbon fiber is found to have improved cost performance over the baseline carbon fiber and performed similarly to the commercial carbon fiber in wind turbine blade design, but at a significantly reduced cost. This novel carbon fiber was observed to even outperform fiberglass when comparing material cost estimates for spar caps optimized to satisfy the design constraints. This study reveals a route to enable broader carbon fiber usage by the wind industry to enable larger rotors that capture more energy at a lower cost.

ACKNOWLEDGEMENTS

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The authors also recognize the contributions by members of the Industry Advisory Panel which supported this project. The combined experience of these distinguished staff from turbine OEMs, carbon fiber manufacturers, blade manufacturers, and wind turbine design consultants has been very beneficial to guiding project decisions and providing critical feedback.

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EXECUTIVE SUMMARY

Trends within the wind industry correlate increasing blade length and turbine rating with reduction in the levelized cost of energy (LCOE) of modern wind plants, with blade length increasing at a faster rate than turbine rating. Blade mass scales with blade length to a power greater than two, which means that as wind turbine blades are getting longer they are becoming much more massive. Longer, heavier blades are not only more expensive, but they produce higher loads which must be carried by the turbine drive components and support structures, increasing the installed capital cost of the system. Controlling blade mass is critical to allowing further growth in rotor size and reductions in LCOE. One approach that some turbine manufacturers have taken is to utilize carbon fiber in the most critical structural portions of the blade design. Carbon fiber reinforced polymers offer a significant advantage over traditional fiberglass due to improved mass-specific strength and stiffness. However, the wind industry has been reluctant to use carbon fiber in blade design due to the high material cost, which stems from development for the aerospace industry. This project has studied the effect of novel carbon fiber materials derived from the textile industry to determine the impact these lower-cost carbon fiber materials could have on blade design.

This project characterizes a heavy-tow carbon fiber material manufactured from textile acrylic precursor to understand and relate mechanical performance and cost, which is compared to a baseline carbon fiber material common to the wind industry. The heavy-tow carbon fiber material cost estimates reveal a 57% reduction compared to similarly derived cost estimates for the baseline carbon fiber. This reduction results primarily from the lower material cost of the textile precursor and from an effective reduction in capital costs due to the increased throughput in the carbon fiber processing. Cost is only part of the evaluation of material performance, and material testing was performed to determine the mechanical properties of the study carbon fiber materials, including static strength and fatigue. In static tests, the heavy-tow textile carbon fiber was shown to perform with a similar stiffness (modulus), but at a reduced strength compared to the industry baseline material. The tensile strength was most reduced compared to the baseline, revealing nearly a 40% reduction in tensile strength for the heavy tow textile carbon fiber. However, wind turbine blades experience nearly equivalent compressive and tensile loads, so it is compressive strength that drives material demand and tensile strength exceeds design requirements. The heavy tow textile carbon fiber compressive strength is more similar to the baseline material with only a 20% reduction for this important property. When compared on a cost-specific basis (modeling a 68% volume fraction pultrusion based on the test data and cost estimates), the heavy tow textile carbon fiber has 100% more modulus per cost and 56% more compressive strength per cost than the industry baseline.

The performance of the study carbon fiber materials was assessed through structural optimization studies for representative 3 MW and 10 MW reference wind turbine blade models, and additionally compared to fiberglass. The high energy capture 3 MW blade optimizations revealed a 16% reduced cost for the heavy tow textile carbon fiber spar cap material compared to the fiberglass spar cap material to meet the design criteria. This resulted from the improved fatigue characteristics of the heavy tow textile carbon fiber compared to fiberglass, revealing one distinct advantage of carbon fiber over fiberglass. The optimization of a high wind resource 10 MW blade, more typical of an offshore machine, favored fiberglass when considering only spar cap material cost; however, the heavy tow carbon fiber material resulted in a 25% blade mass reduction which would have system cost reduction benefits that may cause this novel material to be ideal from a systems perspective. The heavy tow textile carbon fiber revealed benefits over the commercial baseline carbon fiber and met the blade design criterion at a 43% and 39% reduction in spar cap material cost for the 3 MW and 10 MW turbines, respectively. The baseline carbon fiber slightly outperformed the heavy tow

textile carbon by 1-3% in the resulting blade mass, but the novel carbon fiber resulted in blade mass values that were 25-27% lower than the fiberglass spar design.

ACRONYMS AND DEFINITIONS

Abbreviation	Definition
AEP	Annual energy production
AMER	North, Central, and South America
APAC	Asia Pacific
CAGR	Compound Annual Growth Rate
CFRP	Carbon fiber reinforced polymer
CFTF	Carbon Fiber Technology Facility
C_p	Power coefficient
CSIC	Haizhuang Windpower
CY	Calendar year
DEC	Dongfang Electric
DOE	U.S. Department of Energy
E	Young’s modulus of elasticity
EMEA	Europe, Middle East, and Africa
f	Fiber
GFRP	Glass fiber reinforced polymer
GE	General Electric
LCCF	Low-cost carbon fiber
LCOE	Levelized cost of energy
m	Matrix
MM	Million
MSU	Montana State University
NDAC	Nordex Acciona
OEM	Original equipment manufacturer
ORNL	Oak Ridge National Laboratory
SGRE	Siemens Gamesa Renewable Energy
SNL	Sandia National Laboratories
T_f	Fiber strength translation factor
UCS / S_{uc}	Ultimate compressive strength
UTS / S_{ut}	Ultimate tensile strength
VARTM	Vacuum-assisted resin transfer molding
VF	Fiber volume fraction
WTG	Wind turbine generator
XEMC	Xiangtang Electrical Manufacturing Corportation

1. INTRODUCTION

Carbon fiber reinforced polymers (carbon fiber composites) offer significantly enhanced mechanical properties compared to the more widely used glass fiber reinforced polymers, enabling the design and manufacture of larger, higher energy capture wind turbine rotors. However, carbon fiber materials are much costlier than glass fiber, hindering their broader adoption in the wind industry. Carbon fiber composites were originally designed and applied to military and aerospace applications where strength is paramount and cost was not a primary factor. Thus, significant opportunities exist to reduce the overall cost of incorporating carbon fiber materials into a wind turbine blade where cost is a primary factor. These opportunities range from changing the raw material inputs, fiber conversion processes, and formats of the carbon fiber itself, through the composite material forms (e.g. pultrusion, prepreg) used in the blade manufacturing process. The magnitude of this cost reduction opportunity needs to be quantified using a blade design tool to perform optimization studies across the blade system for representative wind turbine systems. To accomplish this, characteristic carbon fiber material properties must be determined from mechanical testing and with accurate cost modeling.

This work enables the continued reduction in the levelized cost of energy (LCOE) for wind turbines installed in the United States supporting the U.S. Department of Energy's Wind Energy Technologies Office goal of enabling wind nationwide, including low wind resource sites and offshore. This report summarizes work performed to assess the commercial and novel carbon fiber materials including material mechanical testing, material cost modeling, and blade structural optimizations. Blade spar cap material optimization studies are performed for a low wind resource 3 MW and a high wind resource 10 MW wind turbine, which are reference models representative of industry trends for land-based and offshore wind turbines in the United States, respectively.

1.1. Background and Motivation

The reduction in levelized cost of energy and broad adoption of wind energy throughout the United States is strongly correlated to increasing nameplate capacity (i.e. rated power) and rotor diameter. These trends are expected to continue, resulting in larger wind turbines and increasingly longer blades. New markets for wind turbines are opening as land area and wind resource restrictions are faced across the world. Land-based wind turbines are being designed for lower wind resource sites as many of the higher wind speed sites have already been developed. Wind turbine blades are getting longer for the same power rating to access these low-wind resource sites and for higher energy capture. The offshore wind energy industry is growing globally, enabling very large wind turbines by removing the transportation barriers experienced on land.

Historical and predicted trends for growth in turbine capacity and rotor diameter are shown for land-based and offshore installations in Figure 1-1. The global offshore industry has a large increase in turbine capacity rating predicted, where the diameter is increased only enough to accomplish the power rating at the same specific power. Land-based turbines are growing in diameter at a higher rate than needed for the power rating increase (where power is proportional to diameter squared), particularly for the U.S. market which has a lower growth rate in power rating than the other markets.

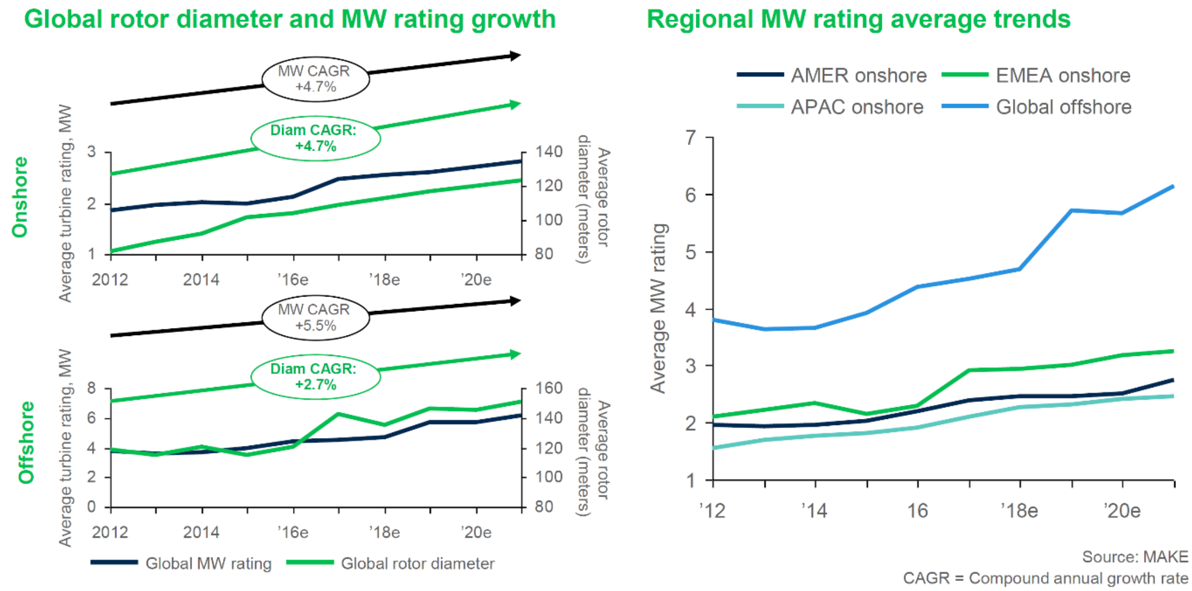


Figure 1-1. Global trends for wind turbine power rating and diameter increase.

These trends suggest that wind turbine designs will continue to utilize longer blades for land-based machines, while the offshore wind energy market will demand very large blades to meet power ratings greater than 10 MW. Despite industry growth in blade length, carbon fiber usage in wind turbine spar caps is not predicted to grow in market share with respect to fiberglass utilization, as shown in Figure 1-2. Stated reasons by turbine manufacturers for avoiding carbon fiber in blade designs include high prices, price volatility concerns, manufacturing sensitivities, and supply chain limitations or concerns. The improved system performance of carbon fiber blade designs must result in a reduced cost of energy for OEMs to heavily utilize carbon fiber blade designs.

Typical filament diameters used for commercial carbon fiber are smaller than standard glass filaments (about half of the diameter) which reduces the effectiveness of the traditional resin-infusion blade manufacturing processes for carbon fiber materials. Additionally, carbon fiber is more sensitive to wrinkling during an infusion manufacturing, significantly degrading its as-built performance. These differences from glass fiber have resulted in blade failures where carbon fiber was integrated into designs utilizing traditional blade manufacturing techniques during the earlier part of this decade (2010-2015). As an alternative to carbon fiber, and to maintain the traditional blade manufacturing methods, high-modulus glass fiber has been pursued by some turbine manufacturers.

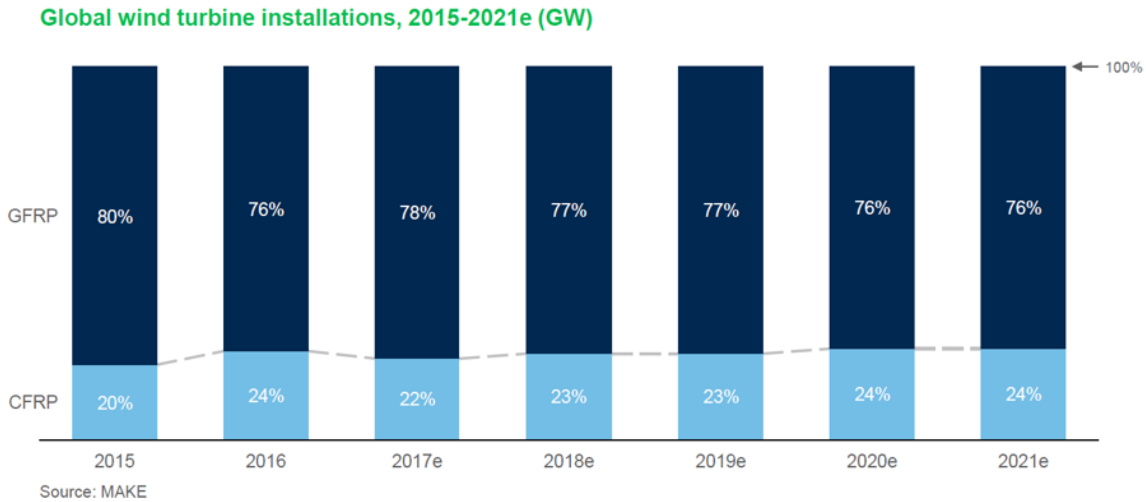


Figure 1-2. Global market share of installed wind turbines with spar caps using glass fiber reinforced polymers (GFRP) versus carbon fiber reinforced polymers (CFRP).

Carbon fiber blade designs produce value by increasing blade stiffness, addressing tower clearance constraints, and reducing the blade and tower-top weight – providing overall system cost benefits. Due to these benefits, the use of carbon fiber in blade designs is expected to increase for large, land-based and offshore wind turbines. The percentage of existing and prototype turbine platforms with carbon fiber spar caps is shown in Figure 1-3. As blade length increases, traditional carbon fiber materials used by the wind industry become increasingly beneficial, and the economics begin to favor carbon fiber in this main structural element. However, turbine manufacturers have identified ways to design blades at all available lengths using only glass fiber, where 45% of the current turbine platforms with blade lengths greater than 70 m do not utilize carbon fiber.

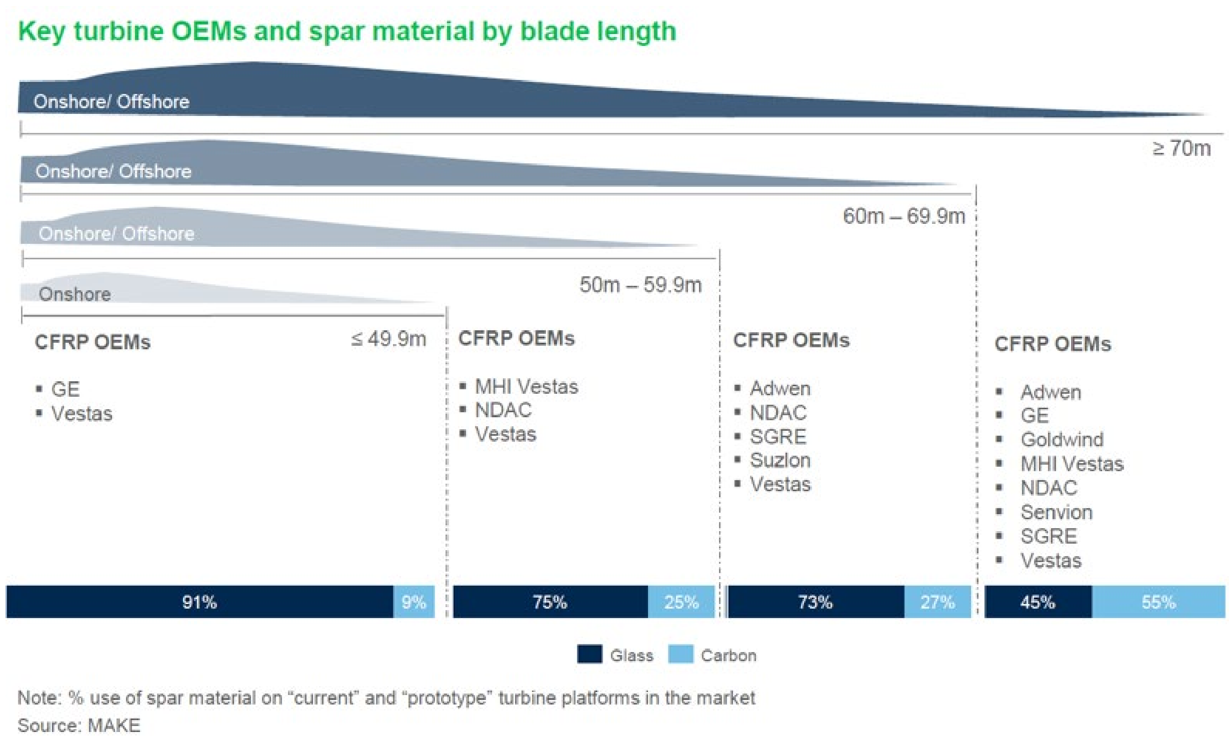


Figure 1-3. Percentage of turbine platforms with carbon fiber spar caps versus blade length.

Figure 1-4 shows the share of annual global installations for wind turbine blades with carbon fiber spar caps in 2015 and estimated for 2021. In 2015, none of the installed largest (4-8 MW) wind turbines utilized carbon fiber, highlighting the ability to design turbines using only glass fiber. As the relative blade length for land-based machines continues to grow and as higher rated offshore turbines become available the predicted share of turbine installations with carbon fiber is expected to grow in the 3-5 MW and 8-10 MW sectors. The highest rated capacity turbines are seen to favor carbon fiber in the 2021 market estimates, although still absent in the 5-8 MW range. The projected increase in carbon fiber market share is partly due to a better understanding of manufacturing sensitivities and the improved performance when utilizing pultruded carbon fiber spar caps. Adding this intermediate processing step for spar caps improves the cost relationship for carbon fiber through reduction in material variability, improved reliability, and by enabling higher fiber volume fractions compared to resin infusion of carbon fiber materials.

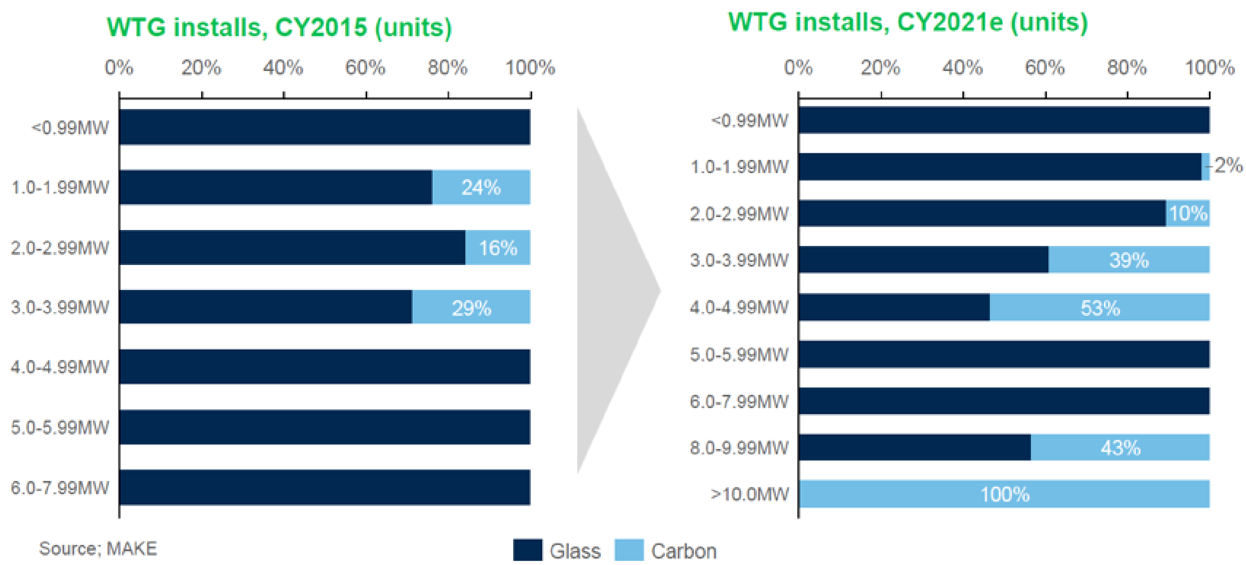


Figure 1-4. Percentage of installed turbines with carbon fiber spar caps versus power rating.

The estimates for wind turbine installations with carbon fiber spar caps are based on predictions of turbine manufacturer market share. Most manufacturers avoid using carbon fiber, offering none or only a few models with carbon spar caps for their largest machines. The exception to the standard approach is Vestas, which uses pultruded carbon fiber spar caps across all their designs. Part of the justification is that it provides them with more buying power due to their high demand of pultruded carbon fiber, which likely lowers the purchase price. The breakdown of turbine model spar cap material usage by turbine manufacturer is shown in Figure 1-5.

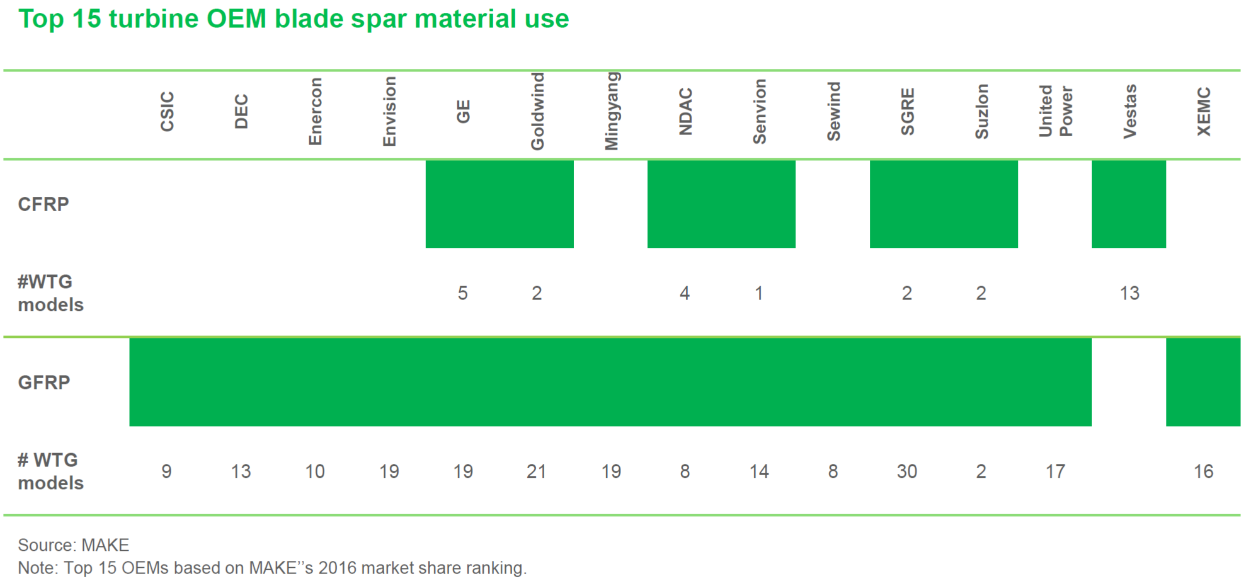


Figure 1-5. Breakdown of turbine models with carbon fiber spar caps for the top 15 OEMs.

It is clear from turbine design trends that existing, commercial carbon fiber materials have properties which are important for enabling the longer wind turbine blades being designed and the continued reductions in LCOE expected. However, the economics do not appear to work out as favorably for the lower power rating machines to justify the improved mechanical properties of existing carbon fiber materials in these blade designs. Market trends towards longer blades and larger machines will drive demand for carbon fiber blade designs, but without further innovation carbon fiber will continue to be utilized only in certain wind turbine designs. Turbine manufacturers continue to meet the load requirements of even the largest blades using pure fiberglass designs, motivated by the high cost of carbon fiber reinforced polymers. The low number of commercial material options across the cost-performance spectrum may hinder the development of wind turbines for low wind resource sites or of certain sizes.

1.2. Purpose of Study

The objective of this study is to assess the commercial viability of developing cost-competitive carbon fiber composites specifically suited for the unique loading experienced by wind turbine blades. Through analysis of commercial carbon fiber and novel low-cost carbon fiber materials, the results are useful to identify important steps in development of more optimal carbon fiber materials for wind turbine spar caps, considering cost and relevant material property relationships. Although glass fiber reinforcement is the primary structural material in wind blade manufacturing, utilization of carbon fiber has been identified as a key enabler for achieving larger rotors because of its higher specific stiffness (stiffness per unit mass) and specific strength (strength per unit mass) in comparison to fiberglass. Some carbon fiber is currently being used in wind blades, however, more wide-spread utilization of carbon fiber is highly dependent on demonstrating a compelling business case.

This project has included identification and comparison of specific materials approaches, considering fiber selection and composite processing. Material comparison is achieved through test article fabrication, mechanical testing, material cost modeling, and blade structural optimization and cost analysis. The impact of this work will be to lower the levelized cost of wind energy (which directly impacts deployment across the United States) while increasing U.S. manufacturing competitiveness. Improved and unique materials could provide domestic manufacturers a competitive advantage, leading to more U.S. jobs to supply the domestic and export markets. The results of this project are broadly applicable to the wind industry, ranging from turbine OEMs to material suppliers. This work has additional benefits to other industries, particularly transportation, where lower cost carbon fiber composites could enable broad application of carbon fiber composites in design.

The material assessment within this project has been performed looking at the blade spar cap as the primary application for carbon fiber composites, depicted in Figure 1-6. The spar cap is the most critical structural element in wind turbine blade designs, resisting the primary loading direction and ensuring the deflected blade does not strike the tower. As a result, material stiffness and strength have the greatest impact in the blade spar cap and carbon fiber composites potentially offer the greatest benefit in this section.

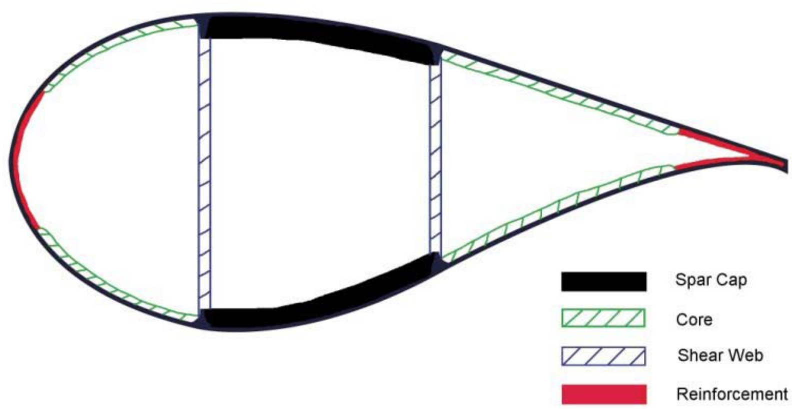


Figure 1-6. Wind turbine blade sectional drawing with region identification.

2. CARBON FIBER STUDY MATERIAL DEFINITION

The United States Department of Energy (DOE) has supported initiatives to reduce the cost of carbon fiber at Oak Ridge National Laboratory (ORNL) for well over a decade. This Low-Cost Carbon Fiber (LCCF) program has demonstrated a variety of approaches including making radical changes to precursor chemistry (such as fibers made from lignin and polyolefins) or analyzing more cost-effective forms of acrylic fibers (such as textile fiber formats). The program has also studied processing steps to increase fiber throughput by employing advanced conversion techniques using plasma and/or microwave heating. While several of these approaches have been shown to be technically viable and offer potential to be economically attractive, manufacturing carbon fiber from textile acrylic precursor is currently viewed as being closest to market based on development at ORNL and existing industry infrastructure. Textile carbon fiber processing takes advantage of existing capital investment in acrylic fiber production, which is on the order of $100MM.

As part of the DOE LCCF Program, DOE and ORNL built the Carbon Fiber Technology Facility (CFTF) which was opened in 2013. The CFTF is a carbon fiber manufacturing facility that is nominally sized to produce up to approximately 25 tonnes of carbon fiber per year. This facility is intended to fill the gap between pure research and commercial development of carbon fiber and is used for demonstration and application development of various processing approaches as previously described. Work at CFTF has mostly focused on demonstrating the technical and economic characteristics of a variety of textile precursor-based carbon fiber (TCF).

A key focus of this project is to consider existing and future forms of carbon fiber materials that could reduce the LCOE of future wind energy systems. The reduction in costs from the TCF precursor approach has been largely achieved by utilizing high filament count (heavy tow) precursor material from the textile industry which offers increased throughput capacity in precursor manufacturing (spinning) and carbon fiber conversion. Heavy tow textile-based acrylic fibers that may be utilized as precursor materials are more readily available in low cost forms for non-traditional carbon fiber producers than traditional precursor material developed exclusively for the carbon fiber industry. The details of the cost reduction have been estimated as part of this project and are further described in Section 2.3.

Moving to heavy tow, textile carbon fiber materials also affects the mechanical performance of the composites. As part of this project the material mechanical properties relevant to wind turbine spar caps are compared through mechanical testing. The materials are compared in various composite forms through coupon tests which are summarized in Section 2.2 and fully detailed in [1].

The mechanical testing and cost model results detailed within this chapter are used as model inputs in the blade structural optimization analysis described later in the report. The test results and cost estimates are used to approximate model properties and cost of a pultruded composite form relevant for wind turbine blade spar caps. The model input material properties are developed in Section 2.4 for a representative industry baseline carbon fiber and heavy-tow, textile carbon fiber material.

In this project, carbon fiber materials for use in wind turbine blade spar caps are only being considered in intermediate pultruded composite forms. In the pultrusion process (example machine shown in Figure 2-1), the reinforcing fiber strands or tows are guided through a resin bath and then through a heated die (in some cases the resin is injected directly into the die) that forms the desired cross-sectional shape and cures the resin. The continuous product form is pulled by reciprocating pullers located downstream of the die where the cured form can be easily handled. A small amount of mat or fabric may be incorporated into the spar cap, but pultrusion typically employs a high percentage of aligned fibers to maximize fiber fraction and minimize fiber undulation. Pultrusions are a promising composite form for lowering the cost of carbon fiber based wind turbine blade spar caps due to their insensitivity to blade manufacturing processes, improved structural efficiency, and high fiber volume fractions compared to resin infusions (as was utilized initially in the industry for carbon fiber spar caps).

It has been previously mentioned that carbon fiber is attractive for use in the wind turbine blade spar cap due to the material's high specific stiffness and strength (stiffness and strength per unit mass). These properties are best exploited by pultrusions where the structural efficiency is enhanced by a higher degree of fiber orientation and fiber volume fractions in the composite than resin infusions. While resin infusion and pre-impregnated (prepreg) tape or fabric processes have been utilized in making spar caps, pultrusion is a very cost-effective process for making long parts with relatively constant cross-sectional shapes such as a spar cap configuration. The pultrusion process inherently utilizes low cost material forms and minimizes materials handling by operators, maximizing automation and precision. The project team determined that pultrusions offered the most cost-effective process of incorporating carbon fiber into blade spar caps and thus chose pultrusion as the sole approach for assessing carbon fiber materials in this project. The industry advisory committee which supported this project agreed with this approach.

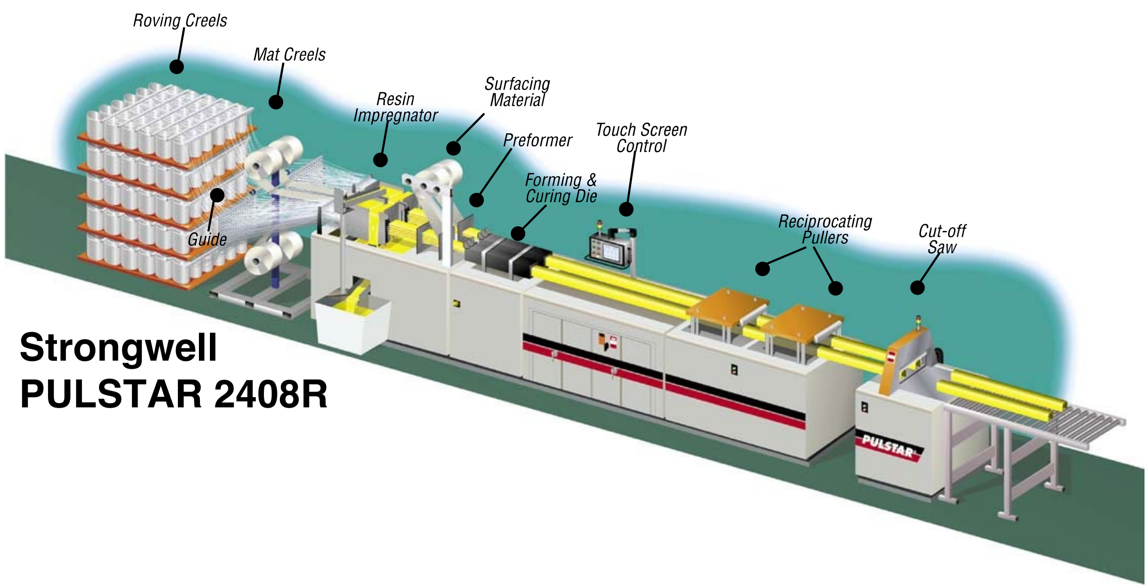


Figure 2-1. Example pultrusion manufacturing process.

2.1. Material Description

The carbon fiber currently used in wind turbine wind turbine spar caps is predominantly in 50,000 filament (50K) tow sizes. It is manufactured from polyacrylonitrile (PAN) precursor fiber manufactured specifically for conversion into carbon fiber. For the purposes of this study, the team chose an example industry baseline carbon fiber and a couple of developmental products from the CFTF for comparison. From trade publications it appears that Zoltek PX35 is the most prevalent carbon fiber product currently in use for wind turbine blades. This product was chosen as the study baseline material. Other common carbon fiber producers who supply the wind industry include SGL, Dow/Aksa, and Teijin. Zoltek and SGL also supply spar cap components in pultruded form.

There is currently no true textile-based carbon fiber material being produced commercially. The CFTF has been evaluating several standard and slightly modified variants of TCF produced from various precursor sources. The objective of the low-cost reference material selection was to identify and choose a candidate or candidates for project evaluation ideally having (1) long-term availability, (2) some capacity for customization, and, if practical, (3) some capability for comparing baseline data from other related work, such as testing being performed in the Institute for Advanced Composite Manufacturing Innovation (IACMI). During this project, the two products identified as best meeting these criteria were from textile precursor fiber tows from Kaltex and Taekwang. While the precursor characteristics and resultant developmental carbon fiber properties have varied somewhat over time based on a range of objectives established by the CFTF and fiber producers, the lot analyses shown in later sections are relatively representative of what has been demonstrated over the last few years.

It should be noted that a key factor in cost reduction is that the TCF is produced in what is considered very large tow sizes by carbon fiber standards. While tow sizes of 6K (6,000 filaments), 12K, 24K, and 50K individual filaments are common in carbon fiber production, the tow sizes for the TCF study materials are greater than 300K. However, due to the smaller fiber diameter of the TCF materials, the linear density for some of the lots under evaluation are closer to only three times that of the PX35 material.

It is also worth noting that although PAN fibers are commonly utilized in textile applications world-wide, all acrylic fiber produced for carbon fiber conversion and the majority of PAN fibers produced for textiles are solution spun. PAN is a thermoplastic material that has the relatively unique characteristic that it begins to cross-link at a temperature lower than the point at which it melts. So, while most thermoplastic fibers can be melt spun from melting and extruding chips of the polymer that are transported and stored in solid form, the PAN material must be dissolved in a solvent to be wet spun, spun into a largely solvated coagulation bath, and then washed in multiple steps of progressively smaller concentrations of solvent to remove the solvent from the fiber. The wet or solution spinning process is therefore more time and energy intensive than melt spinning and is therefore less attractive environmentally. For those reasons, there is no longer any acrylic fiber manufacturing in the US other than the PAN fiber precursor production captive to carbon fiber manufacturers.

The three carbon fiber study materials are described in the following sub-sections.

2.1.1. Zoltek PX-35 (industry baseline)

As mentioned previously, Zoltek Carbon Fiber is the largest carbon fiber supplier to the Wind Industry. Zoltek operates as an independent subsidiary of Toray Carbon Fiber, the world's largest manufacturer of carbon fiber. As with the Toray parent and many other carbon fiber manufacturers, Zoltek produces their own precursor specifically for their carbon fiber conversion. As opposed to other Toray business units, Zoltek focuses on production of large tow carbon fiber (50K) whereas the largest tows produced in other Toray operations is 24K. Zoltek targets lower cost industrial-type applications such as wind energy and sale of oxidized PAN fibers versus the traditionally higher performance markets where Toray is the major player. In separate affiliates, Zoltek also makes certain product forms from processes such as pultrusion utilizing their carbon fiber. Although fiber production costs and pricing points are considered business sensitive and highly dependent on order sizes and delivery contract negotiations, the PX35 product is frequently referred to as a $10/lb ($22/kg) product.

The marketing data for the Zoltek PX35 product is shown in Figure 2-2.

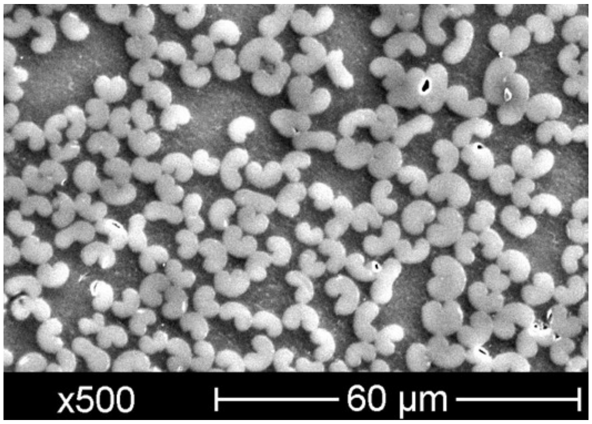
Technical Datasheet
ZOLTEK™ PX35 Continuous Tow

MATERIAL OVERVIEW	SI	US
Tensile Strength	4,137 MPa	600 ksi
Tensile Modulus	242 GPa	35 msi
Elongation	1.7%	1.7%
Electrical Resistivity	0.00155 ohm-cm	0.00061 ohm-in
Density	1.81 g/cc	0.065 lb/in^3
Fiber Diameter	7.2 microns	0.283 mils
Carbon Content	95%	95%
Yield	267 m/kg	397 ft/lb
Textile Units	267 m/kg	33700 denier
Spool Weight	5.5 kg, 11 kg	12 lb, 24 lb
Spool Length	1,500 m , 3,000 m	1,640 yd, 3,280 yd

Figure 2-2. Published technical data for Zoltek PX35 carbon fiber [2].

2.1.2. ORNL CFTF Kaltex

Kaltex is a large Mexican manufacturer of PAN-based fiber tows for textile consumption such as carpeting, hosiery, apparel, etc. where acrylic fiber is attractive. Traditional PAN chemistry for carbon fiber precursor is largely centered around acrylonitrile (AN) co-monomered with methyl acrylate (MA). The ratio of these base chemicals for textiles is typically shifted to slightly lower AN content and the molecular weight of the polymerized form is typically somewhat lower. These choices are made for overall economic reasons as well as for specific targeted characteristics in textile applications such as dye uptake. (Specific precursor comparisons are difficult due to the highly sensitive availability of the precursor itself and level of testing data control maintained by manufacturers.) The larger tow size typical of Kaltex textile tows (457K) maximizes economies of tow production and subsequent textile process handling, while other observed characteristics such as tow cross-overs have benefit in these downstream processes as well. It is also notable that the Kaltex fiber cross-section resembles that of a kidney bean as shown in Figure 2-3 (a) versus the round shape of most commercially available carbon fibers. All other characteristics being considered as equal, this shape could potentially offer advantages in conversion of the precursor into carbon fiber since the effective surface area for the fiber is larger than that of its round competitors. In theory, the greater surface area offers shorter pathway for the diffusion-limited oxidative stabilization process in conversion as well as greater area for interfacial bonding and possibly greater bending resistance in the final composite. These potential advantages have yet to be conclusively evaluated. While it is possible to modify some of these characteristics for carbon fiber production, it is preferable for the textile PAN tow producers to see their material utilized as much as possible as it is currently produced. Therefore, the CFTF demonstration of these materials in carbon fiber conversion has focused on making smaller changes in areas such as filament diameters which can be influenced by spinning/winding speeds and pre-conversion stretching, and not on making any chemical changes. The fiber provided by CFTF to this project for mechanical testing has production test properties as shown in the lot analysis data sheet from CFTF in Figure 2-3 (b).



(a) Scanning electron microscope image

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	

(b) Lot data from fiber tow tests

Figure 2-3. Example tow test results for CFTF carbon fiber using Kaltex precursor.

While the samples provided for initial evaluation have a linear density of about 14.7 g/m, when material was chosen for the initial pultrusion trials using the most recently produced material, CFTF was working with a smaller effective diameter fiber form from Kaltex. Although the resulting fiber mechanical properties were very similar as shown in the lot analysis data sheet in Figure 2-4, the linear density of spools from this form was in the range of 9-10 g/m. This smaller filament size may at least partially account for higher levels of fuzz observed in pultrusion as compared to the CFTF fiber sample utilized in later pultrusion trials, described later in Section 2.2.1.2.

Lot Analysis for K15-HTU

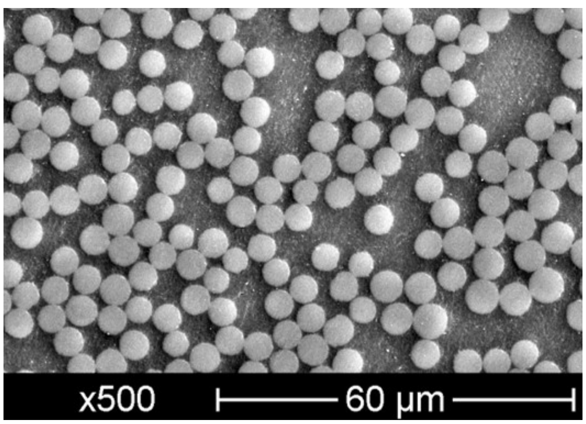
Lot Number: TE4571171004

	Average	Standard Deviation
Tensile Strength (Ksi):	391.9	12.9
Tensile Modulus (Msi):	38.0	0.5
Elongation (%):	1.05	0.05
Size (%)	1.23	0.24
Linear Density (g/m):	9.56	0.50
Density (g/cc)	1.746	0.005
Date of Manufacture:	October 2017	

Figure 2-4. Example tow test results for CFTF carbon fiber using Kaltex precursor used in pultrusion manufacturing.

2.1.3. ORNL CFTF Taekwang

Taekwang is a large South Korean textile and chemical company. Taekwang produces low cost acrylic fiber for textile applications as well as separately producing acrylic fiber specifically for internal conversion into carbon fiber. CFTF has been evaluating the textile variant specifically as an alternative route to the lower cost carbon fiber. Similar to Kaltex, the textile PAN from Taekwang has a large tow size with a 363K filament count. As shown in Figure 2-5 (a) the cross-sectional shape for Taekwang textile fiber is much more round than that of the Kaltex fiber. Interestingly, mechanical data CFTF has produced from the Taekwang material is very similar to that from the Kaltex fiber as shown in the CFTF lot analysis data sheet in Figure 2-5 (b). As opposed to the larger variation of linear density evaluated by CFTF with Kaltex fiber, CFTF work with Taekwang fiber has been largely with similar diameter fiber resulting in linear densities closer to the 11.5 g/m yields as reported in this data sheet.



OAK RIDGE National Laboratory

CARBON FIBER TECHNOLOGY FACILITY

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	

(a) Scanning electron microscope image **(b) Lot data from fiber tow tests**

Figure 2-5. Example tow test results for CFTF carbon fiber using Taekwang precursor.

2.1.4. Tow Cross-Section Area Comparisons

It is worth noting that although the number of filaments in industrial carbon fiber are much lower than the TCF variants most often produced by the CFTF, the actual tow area of TCF variants is closer in comparison as evidenced by linear density in Table 2-1. (The fiber tow area is essentially the linear density divided by the fiber volumetric density, which is close to the same value for the fibers being compared.) Fiber tow area is more important to composite fabricators than the filament count as it better delimits the fiber handling characteristics. For example, the lower linear density Kaltex samples described above (Figure 2-4) are comparable to that of the Taekwang fiber, meaning the overall tow area would also be similar. But, since there are substantially more filaments in the Kaltex tow, the Kaltex fiber at lower linear density would have substantially smaller “effective” diameter. However, since the filament is not round, an effective diameter is not reported to avoid confusion.

Perhaps a more important factor in the handling of the larger, lower cost textile tows is consideration of the cost of creeling equipment and setting up those creels for operation. It is not unusual in large processing operations for creels of over a hundred individual spools to be required. In going from a Zoltek 50K product to the larger Kaltex or Taekwang tows, the number of individual spool positions could be reduced by a factor of 3-4X to achieve the same composite cross-sectional area. Other handling tradeoffs must still be considered.

Table 2-1. Carbon fiber material tow property comparison.

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

The CFTF facility was developed with conventional winding equipment designed to helically wind fiber of up to the area in standard 50K filament tows, so an alternative winding process had to be employed for early work with larger tows. As shown in Figure 2-6, TCF is currently supplied on spools from CFTF having circumferentially wrapped layers with paper interleaving to prevent layer entanglement. While this presents handling issues for some composite manufacturers, it does allow for fiber evaluations in situations such as this study while better long-term solutions are actively being developed.

Figure 2-6. Example of initial heavy-tow CFTF material winding.

2.2. Mechanical Testing Results

Mechanical testing of the carbon fiber materials has been performed within this project to enable an accurate comparison of the materials in a wind turbine blade spar cap. Some initial testing of the developmental materials produced at the CFTF has been performed previously, but this testing focused on obtaining representative material values for properties of most importance to the wind industry (such as compressive strength and fatigue). Testing approaches were iterated upon and varied from the ASTM standards (e.g., coupon size and load introduction) to ensure compressive strength values were representative of the fundamental material strength and reduced the artifacts of coupon buckling and test fixture induced failures. The test program was performed by Montana State University (MSU) leveraging their decades of experience at testing composite materials for use in the wind industry and enabling a more direct comparison to previous tests performed and cataloged in the SNL/MSU/DOE Composite Materials Database. A detailed description of the test program for this project and a complete summary of the testing results is provided in a separate mechanical testing summary report [1]. This section provides a summary of the most pertinent testing results to the modeling needs of the project.

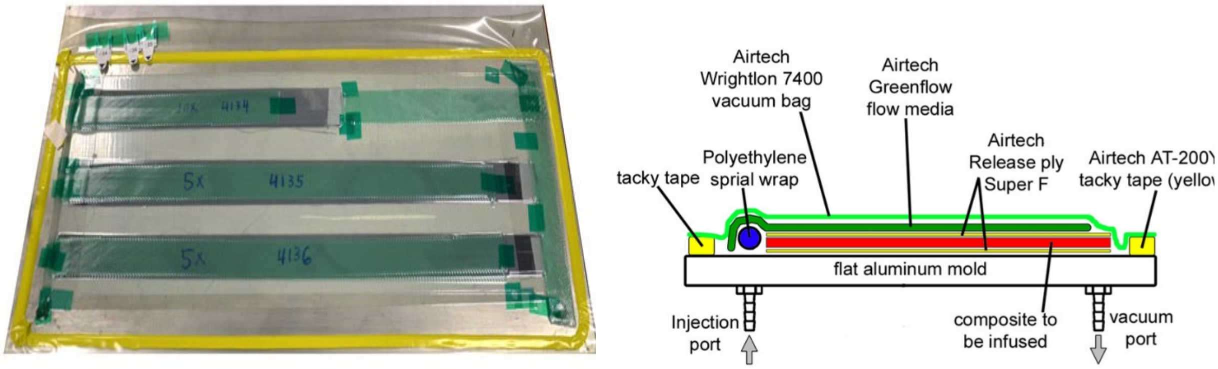
The test program studied the three study materials described previously in three composite forms. Unidirectional fiber composites are studied to represent the spar cap element with totally or largely aligned fibers along the length of the part to take maximum advantage of the fiber properties to resist the primary loading direction. As mentioned earlier, pultrusions are considered the only composite form for carbon fiber usage in wind turbine blade spar caps. The pultrusion process is favorable from the viewpoints of automation and repeatably yielding the highest composite properties from carbon fiber, but it is a process that requires substantial optimization for a given material to realize the benefits. The optimization of the pultrusion process for each of the study materials was outside of the scope of this project so direct comparison of the fundamental material properties is enabled through an aligned strand infusion manufacturing process performed at MSU. Commercially optimized pultrusions manufactured by Zoltek were also tested to assess the manufacturing improvements from a pultrusion process and to compare with the aligned strand infusion test results. The project team also worked with a third-party pultruder to process each of the study materials into a pultruded composite form. These third-party pultrusions were observed to have a significant percentage of voids and dry spots due to not achieving a sufficiently high fiber volume fraction, and the testing results were suboptimal. The process was used to identify if there are any additional issues with the heavy tow textile carbon fiber relevant to the pultrusion process, and no fundamental difference was observed in the difficulty of specifically handling larger tows compared to the industry baseline material. Further studies and improved packaging formats are merited, but these initial pultrusion runs did not reveal an increased challenge for the heavy tow carbon fiber materials compared to the industry baseline carbon fiber that would not be overcome in planned production engineering.

The three composite forms and a summary of select testing results from the test program are described in the following subsections.

2.2.1. Composite Form Manufacturing Description

2.2.1.1. Aligned Strand Infusion

The aligned strand composite manufacturing process has been developed at MSU to reduce manufacturing sensitivities in tested composite properties. This is similar to the traditional vacuum-assisted resin transfer molding (VARTM) infusion process used for wind turbine blade manufacturing with the addition of applying a slight tension to the dry fabric prior to infusion to align the fibers. Carbon fiber materials and their composite properties have been found to be more prone to fiber waviness and manufacturing defects than glass fiber composites. This method reduces the number of those defects in the composite, yielding more representative material properties in the composite tests. This process has the greatest level of control within the testing program and is useful for direct material comparison of the heavy tow and industry baseline materials and enables comparison with the commercial pultrusion process for the Zoltek PX35 material. An example of the aligned strand infusion manufacturing process is shown in Figure 2-7 and additional details of this process are provided in the testing summary report [1].



(a) Example infusion of $(0)_5$ laminates **(b) Typical vacuum infusion plate details**

Figure 2-7. Sample aligned strand infusion processing [1].

2.2.1.2. Commercial Pultrusion

Zoltek produces pultruded composites of their PX35 material in various shapes and sizes. Coupons were tested using 1.87 mm thick pultruded plate composites produced by Zoltek. This composite form of the PX35 material is used in wind turbine blades and is useful for obtaining representative mechanical properties of the industry baseline material in an optimized composite form. These composites have a high fiber volume fraction and facilitate consistent manufacturing processing via automation, thereby yielding attractive performance versus manufacturing costs. These samples also enable comparison with the aligned strand test results from the PX35 material with this optimized manufacturing process to estimate a manufacturing improvement factor, which is used in Section 2.4 to estimate the improvement in manufacturing processing/optimization for the heavy tow material.

2.2.1.3. Third-Party Pultrusion

Martin Pultrusions in Cleveland, Ohio was contracted to produce some of the samples for testing in this project. Martin has a long history of equipment and process development for pultrusion, in addition to manufacturing a wide variety of shapes from a wide variety of materials, including both carbon and fiberglass reinforcements. For the initial pultrusion trials, CFTF supplied spools from Kaltex 457K precursor. The spools came from different runs at the CFTF but had fairly consistent mechanical properties with strengths ranging from 2439-2702 MPa (353.7-391.9 ksi), moduli from 257-262 GPa (37.3-38.0 Msi), and elongation from 0.94-1.05%. The highest coefficient of variation of about 7.4% was with the elongation of one of the lots from which samples were drawn. Tow area as calculated from linear density divided by density would be estimated to vary from 0.0513 to 0.0548 cm^2. Tow area and targeted fiber fraction are used to select the number of packages to be employed in the run. Large variations in tow area would affect resulting fiber volume fraction and might be expected to alter processability.

As shown in Figure 2-8 and Figure 2-9, the spools were suspended on independent spindles without applied tension. The tows were guided over a varying number of circular steel rods (spools furthest from the die crossed over more of the guides). At the end of the creel, the tows went through a series of circular eyelets to be collected and guided into the resin dip tank before going into the die.

All of the fiber/equipment contact points were stationary (no rollers), which likely resulted in excess wear of the fibers.

Figure 2-8. CFTF tows mounted to spindles and traversing guides for pultrusion.

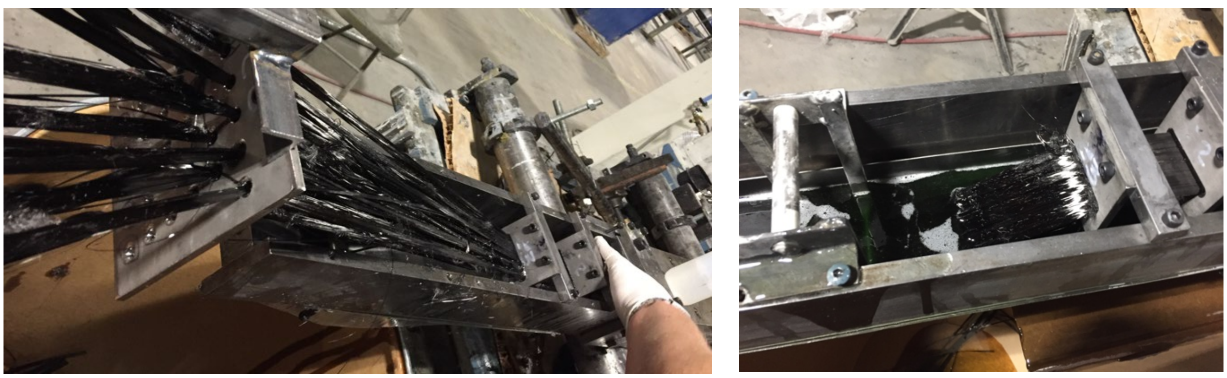


Figure 2-9. CFTF material being dipped through resin and pulled through the pultrusion die.

As expected, some fuzz was observed as the tows were unspooled, additional fuzz was generated in crossing over the steel rods, and significant fuzz was generated and collected in going through the eyelets. The eyelets seemed to collect fuzz but did not seem to cause much restriction until fuzz began to build up. Tows were not significantly separated in progressing through the creel so there was some fuzz generated in tow-to-tow contact which would at times begin to connect across multiple eyelets. For the most part, it was not very difficult to extract the fuzz in the tow itself and at the eyelets, but at times the ease in extraction appeared to actually be destroying tow integrity as much as just removing damaged elements.

Trials were run with varying die temperature conditions, numbers of tows, and changes to resin in an attempt to develop the most stable process possible. The die was selected to yield a section approximately 2 inch by 0.127 inch. Baseline resin system was DER 383 epoxy and Lindride LS81K hardener with some internal mold release. In the initial trials, the number of packages and processing temperatures were varied on working to achieve a stable processing envelope. In later trials, clay filler was added to better balance the die filling along with the modified fiber fraction. Several sample sections were produced for evaluation. Having achieved stable processing with the CFTF-produced TCF, a final run was conducted with similar conditions and Zoltek PX35 for direct comparison with the CFTF fiber. Although it was also fuzzy and with broken fiber, the Zoltek fiber did run somewhat improved over the CFTF fiber.

As expected, the CFTF fiber was somewhat difficult to process with the paper to be handled, fiber non-co-linearity or cross-overs, and excess fuzz. Fuzz levels were higher for the CFTF fiber than with Zoltek, but within the same ballpark. It is expected that while some aspects of product performance would be improved with fiber tensioning for both the CFTF and Zoltek fibers, processing would likely become more difficult for both.

2.2.2. Tested Results

A summary of the mechanical testing results from within this project are shown in Table 2-2 and Table 2-3 below for the aligned strand infusion and pultrusion composites, respectively. The data in these tables are averages of between 5 to 18 samples for each test, and the standard deviation of the set is shown in the tables in parentheses. The standard deviation is useful to understand trends in material variability, but the objective of the testing was not to produce characteristic values and further testing and refinement of the manufacturing process should be performed to yield absolute values for the composite variance. A complete list of the mechanical testing results and discussion is provided separately [1]. The summarized testing results are used to produce model input values in Section 2.4 which provides an additional direct comparison of the materials with volume fractions all extrapolated to the same value of 68%.

Results from the three study materials in aligned strand infusion composites reveals the difference in mechanical performance of the baseline and heavy tow carbon fiber materials. Accounting for variations in the composite fiber volume fraction, the modulus/stiffness is seen to be very similar across the materials while the strength differs more substantially. Due to the heavier tow and lower quality textile precursor (with more fiber interleaving), the tensile strength is noticeably degraded for the two CFTF materials compared to the baseline. However, due to fairly symmetric loading demands in wind turbine blades and universally lower compressive strength than tensile strength in fiber reinforced polymers, the compressive strength for spar cap materials is more important than the tensile strength. The fiber interleaving is less disadvantageous for compressive strength (and possibly even beneficial for the textile precursor) and compressive strength in this comparison is seen to be more similar across the three study materials. The similarity of compressive strength and modulus for the heavy tow carbon fiber materials compared to the baseline material is a very promising result for these novel carbon fiber materials, particularly when considering their relative cost which is estimated in Section 2.3.

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)		

The tested Zoltek PX35 compressive strength in aligned strand composite form shown in Table 2-2 is useful for comparison but lower than expected, based on the fiber translation factor calculations in Table 2-10. The aligned strand compressive tests were iterated upon for the PX35 material but produced similar results for each set of manufactured coupons and testing. The degraded performance in the aligned strand composite is likely due to compatibility issues with the resin system or challenges with the aligned strand manufacturing process for this material. Ultimately for the mechanical property estimation used in the modeling portion of this project, the compressive strength of the aligned strand PX35 test results were not needed to extrapolate to the model input properties as described in Section 2.4. The compressive strength of the Zoltek commercially pultruded composite is used for model input estimation, as tested and shown in Table 2-3. The tested third-party pultrusion samples are also shown in this table to reveal what was described previously that this process did not reveal any significant additional challenges between the two materials, and that the pultrusion process requires substantial optimization to produce representative material properties.

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)

Fatigue tests were also performed using the study materials to reveal any differences in mechanical performance between the heavy tow and baseline carbon fiber materials in fatigue properties. A tension-tension fatigue test was performed using a stress ratio of R=0.1 to compare the materials ($R = \sigma_{min}/\sigma_{max}$). This stress ratio would typically be expected for the high-pressure surface of the blade, which is typically loaded in tension. The results from these tests are shown in Figure 2-10 below, plotting the first-cycle maximum strain versus the number of cycles to failure. The first-cycle strain (as opposed to stress) is used in the plot to account for differences in fiber distribution and content in each coupon. The two heavy tow textile carbon fiber materials have favorable fatigue slopes that reveal a high level of insensitivity to fatigue, even compared to the baseline Zoltek carbon fiber material, which is a beneficial quality for the wind turbine blade application. The tests are comparing the commercial pultruded Zoltek material with the MSU aligned strand infusions for the heavy tow materials. Due to the higher fiber volume fraction and more optimal processing for the Zoltek pultrusions the baseline curve is shifted upwards compared to the heavy tow materials, but despite these differences an intersection between the curves is expected around 10^7 cycles. Compression-compression fatigue tests would be expected to favor the heavy tow materials when considering the more similar compressive properties of these materials to the baseline. A more detailed fatigue testing study would be needed to verify the performance at additional fatigue stress ratios, but the initial testing results remove concern for degraded fatigue properties of the heavy tow carbon fiber materials.

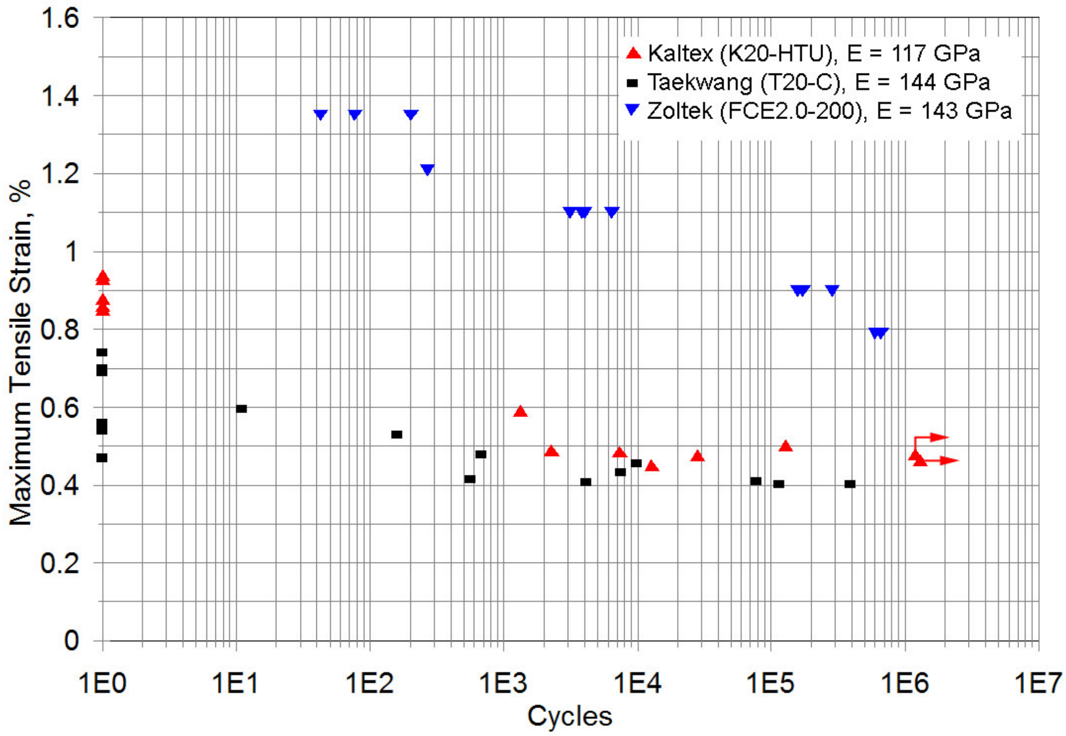


Figure 2-10. Fatigue test comparison of the study materials, R=0.1 (Zoltek in commercial pultrusion (V_F=62%), CFTF materials in aligned strand infusion (V_F~50%)).

2.3. Carbon Fiber Cost Modeling

A process-based cost modeling approach carbon fiber cost model was developed for the cost estimation at specific stages of final carbon fiber part manufacturing, i.e., fiber and pultrusion. The cost estimates are made at the level of major sequential steps of a specific form of part manufacturing, and the focus is on the cost instead of the alternative indicator price. Carbon fiber material price is dependent on changing market supply/demand dynamics and it doesn't provide any further details of the major cost drivers and competitiveness of a specific manufacturing technology. Cost is estimated at each major process step based on major input economic and technical processing parameters. The cost is further separated into four major cost categories of materials, capital, labor, and energy. Cost estimation at each process level allows identification of the major cost drivers at the specific process level and how each process cost contributes to the final fiber cost. It is noted that cost and not price is compared in the material assessment due to the commercial variability for price. A common relationship between the two is shown in Equation (2-1) based on margins applicable to composite material manufacturing [4].

$$Price = Cost \times 1.45 \quad \textbf{(2-1)}$$

Figure 2-11 shows the sequential major processing steps of carbon fiber manufacturing, starting with the input precursor cost at the Pretreatment process step to the final fiber winding, inspection, and shipping step. In conversion to carbon fiber, the precursor undergoes the seven major process steps identified in the figure. Outputs at each process step are inputs to the next sequential process step, determined by the product of process yields (both mechanical and chemical) at the process step and the product of process yields of all follow-on sequential process steps to the final output process step.

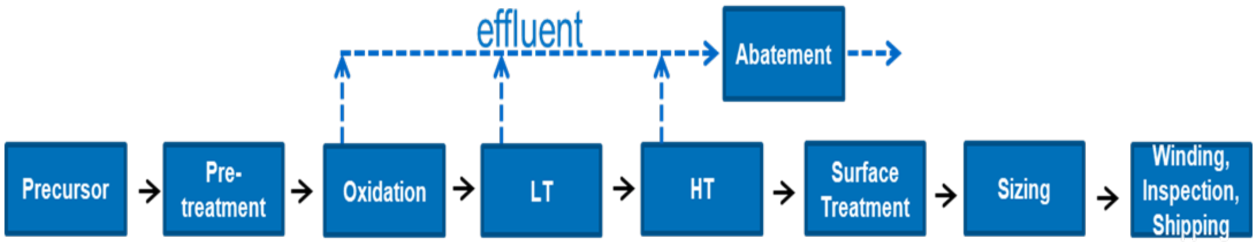


Figure 2-11. Sequential major processing steps of carbon fiber manufacturing.

Table 2-1 shows assumptions for four major input carbon fiber processing parameters, i.e., yield, total labor, total capital equipment investment, and furnace temperature and time, which are assumed to be the same in all three cases of carbon fiber cost estimation. And about 2.2 units of precursor per unit of final carbon fiber is necessary, mostly driven by the chemical yield of 48%, representative of the carbon fiber industry today. After the initial precursor pretreatment process step, which mainly includes stretching in tension, the material is heated in an oxidation oven at 250C for 90 minutes. The oxidation step is the longest processing step which limits the overall output and the line speed. Two subsequent heating operations occur in low temperature (LT) and high temperature (HT) carbonization furnaces at 700C for 1.5 min and 1400C for 1.5 min, respectively, in an inert nitrogen atmosphere (these generic parameters are assumed for estimating purposes which may or may not represent the actual process conditions utilized in making specific materials). The total installed capital investment is estimated to be $58MM, of which 22.6% is the oxidation heating furnace. Carbon fiber manufacturing is capital intensive and total labor is estimated to be 9 FTE/shift for a highly automated continuous operation.

Table 2-4. Carbon fiber processing assumptions for the study materials.

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-tow as discussed later)	Oxidation: 250C for 90 min. in air; Low Temp.: 700C for 1.5 min; and High Temp.: 1400C for 1.5 min in inert atmosphere.

Appendix A shows the detailed cost modeling framework including brief estimation processes of major cost categories by specific processing steps based on technical and economic input parameters. A listing of high-level assumptions of economic parameters, which generally drive the manufacturing cost at each specific processing step, are also included in the appendix. The approach underlying the fiber cost sensitivity to annual production volume is also discussed. The current industry practice to replicate production lines in parallel to meet the demand increase with limited discounts on capital investment and raw materials is assumed for the fiber cost sensitivity to annual production volume.

2.3.1. *Industry Baseline Carbon Fiber Cost*

The industry baseline carbon fiber cost is based on the material and processing assumptions applicable to Zoltek PX35, which is relevant for other similar commercially available materials. Table 3-2 lists the major input parameters for the baseline 50K tow carbon fiber cost estimation at a typical annual commercial fiber production line capacity of 1,500 tonnes/year. The model applies to other 50K tow carbon fiber materials with similar filament linear density, where the assumption of 0.740 dTex (g/10km per carbon fiber filament) holds (equivalent to 3.7 g/m). Baseline precursor cost is assumed to be $3.63/kg based on the recent market trend (its price highly driven by the oil market). Total electricity consumption is estimated to be 41 kWh/kg, respectively, of which the oxidation process step share is ~55%. Baseline line parameters used in this analysis are representative of existing domestic carbon fiber manufacturing facilities, providing validation to the results.

Table 2-5. Baseline major input parameters of 1500 tonnes/year 50K tow carbon fiber manufacturing.

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

The resulting baseline 50K tow carbon fiber cost with an annual production volume of 1500 tonnes/year is estimated to be $17.98/kg. Figure 2-12 and Figure 2-13 show the baseline carbon fiber cost distribution by major cost categories and major processing steps, respectively. Material has the largest share representing 45% of the total fiber cost, which is driven primarily by the low chemical yield of the final fiber conversion process. Due to the capital intensive highly automated fiber manufacturing process, capital has the next largest cost share followed by labor and energy cost categories. Energy cost share is significant, and the final fiber cost is sensitive to fluctuations in electricity price which has driven carbon fiber manufacturers to states with low electricity costs such as Washington, Wyoming, South Carolina, Alabama, Texas, and Tennessee. The estimated baseline 50K tow carbon fiber cost of $17.98/kg is within a reported industry cost range of $17.60/kg - $22.00/kg, which does not include the selling, general, and administrative (SG&A) expenses and profit margin which are influenced by the market supply/demand dynamics. Depending on the availability of low-cost precursor material, volume of orders and depreciation of equipment or equipment life, etc., a carbon fiber supplier could have a lower cost than the above industry cost range.

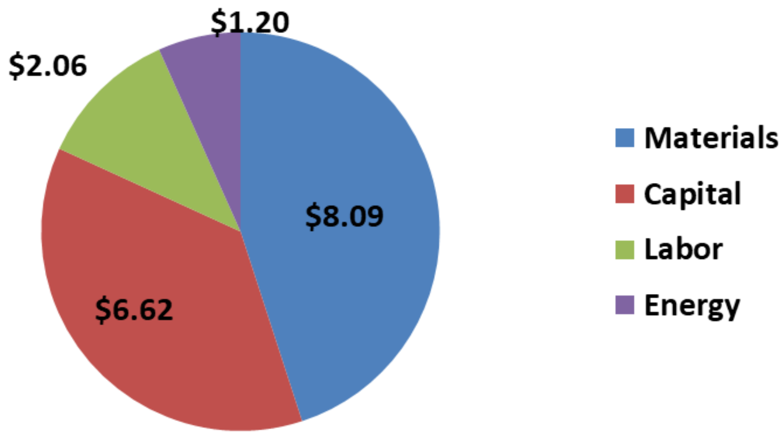


Figure 2-12. Total baseline 50k tow carbon fiber cost distribution by four major cost categories.

Precursor cost contributes to 44% of the total carbon fiber cost as shown in Figure 2-13. Among the major processing steps, oxidation is the most expensive step that contributes to 18% of final material cost. As indicated earlier, the oxidation step is also the final output limiting conversion step due to the processing time requirement. Oxidation is additionally the most capital and energy intensive processing step. Several alternative low-cost, alternative precursors (e.g., heavy tow textile acrylics, lignin, and coal tar pitch) and processing technologies (e.g., plasma oxidation and microwave assisted plasma carbonization) are being considered for improvements in carbon fiber material cost.

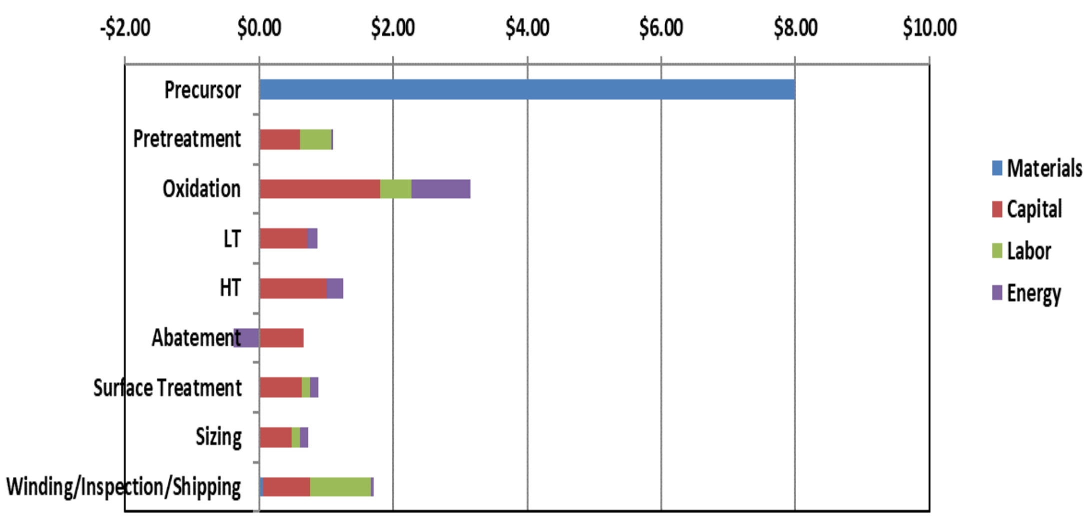


Figure 2-13. Baseline 50k tow carbon fiber cost ($/kg) distribution by major processing steps.

2.3.2. Heavy-Tow Textile Carbon Fiber Cost

Oak Ridge National Laboratory has developed the low-cost, heavy-tow carbon fiber materials using low-cost textile grade acrylic fibers used today (150K to 460K) in staple yarn form for clothing applications. Textile fibers usually have lower molecular weights and more impurities than the specialty acrylic precursor fibers for making carbon fiber. The material properties are likely still sufficient for cost-driven applications such as wind turbine blades, automotive, and certain pressure vessels. The cost of textile acrylic fiber is expected to be roughly 60% that of commercial acrylic precursor specifically for making carbon fiber. This difference alone yields a reduction in the cost of carbon fiber of at least 25% after conversion without consideration of other conversion benefits due to economies of scale.

Two cases are estimated for the heavy-tow textile carbon fiber material cost, representing current and full-utilization processing parameters. The "current" cost estimate represents the processing parameters used at the CFTF to produce the material which has been mechanically tested as a part of this project. The "full-utilization" cost is a realistic set of parameters that would be used (such as tow spacing) in commercial production of the carbon fiber material, but which comes with some uncertainty due to the resulting materials not having been manufactured at the CFTF or mechanically tested.

The cost for heavy-tow textile precursor has been estimated for 457K textile fiber precursor representative of the Kaltex material described previously at a cost of $2.24/kg. This precursor cost is compared to $3.63/kg for the baseline 50K tow carbon fiber as shown in Table 2-6. The differences in major input parameters between the baseline and heavy-tow textile materials (for both cases) are listed in this table. The higher linear density of the heavy-tow material (15 g/m vs. 3.7 g/m) increases annual output by 1.6X using the same $58MM baseline conventional 3m-wide production facility under the heavy-tow textile carbon fiber "current" case. To allow sufficient processing of heavy tow precursor, total line speed is maintained at ~ 7 m/min, lower than the baseline line 50K tow carbon fiber of 9 m/min. Heavy-tow textile carbon fiber cost is estimated to be $11.19/kg for an annual production volume of 2,400 tonnes/year, and $7.82/kg for an annual production volume of 6,000 tonnes/year. The heavy tow textile carbon fiber material cost using the current processing steps is estimated to be 38% cheaper than the industry baseline material.

Table 2-6. Major input parameter assumption differences between baseline 50K tow and heavy-textile tow carbon fibers.

PARAMETER	BASELINE	HEAVY TEXTILE TOW (current[1])	HEAVY TEXTILE TOW (full-utilization[2])
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

[1] Processing steps as manufactured at the CFTF and tested at MSU, but not capturing likely commercial processing specifications and resulting cost

[2] Mechanical properties have not been validated at the "full-utilization" line speed and processing values

A cost reduction potential of 38% estimated here for the current case is conservative, based on the experimental results obtained to date at the CFTF. It is projected that a higher carbon fiber cost reduction is viable for the heavy-tow manufacturing technology with a significantly higher throughput than 1.6X utilized to date. Based on recent experimental work at CFTF, an additional heavy textile tow (full-utilization) scenario has been considered assuming the different major input processing parameter values as listed in Table 2-6 above. Under this fiber cost scenario, it is assumed that tow spacing could be significantly reduced and due to the exothermic nature of the fiber conversion process, oxidation processing time could be significantly reduced. The reduction of oxidation processing time with changes in other processing steps will then enable a line speed increase which increases the annual production volume. The assumptions for the full-utilization scenario are as follows:

- The same tow spacing of 24 mm as the baseline 50K tow carbon fiber (vs. 50 mm originally assumed for heavy-tow textile fiber)
- A 33% reduction (60 min. vs. 90 min. original) in oxidation processing time due to exothermic reaction
- Additional precursor stretching (sensitive to the precursor type) in the pretreatment processing step increases line speed from 7 m/min to 8.45 m/min (9 m/min for baseline 50K tow)
- As a result, the annual production volume increases by 2.5 times (2,400 tonnes/year to 6,000 tonnes/year)

Heavy tow textile carbon fiber cost for the full equipment utilization is then estimated to be $7.82/kg for an annual production volume of 6,000 tonnes/year. This increase in annual production is considering the higher tow spacing for current production (50 mm), which is relaxed for the full-utilization processing. The annual production volume increases from 1.6 to 4 times for the heavy-tow textile carbon fiber compared to the baseline. The full-utilization cost estimate represents a 57% carbon fiber cost reduction compared to baseline 50K tow commercial grade carbon fiber.

Table 2-7 shows the detailed cost comparison between baseline 50K tow vs. the full-utilization heavy-tow textile carbon fiber materials by major cost categories. Cost reduction is estimated to be similar across all major cost categories, i.e., in the range 68%-77%, with an exception for the materials cost category. Lower precursor cost contributes to materials cost reduction, whereas a higher annual production volume using similar sized capital investment results in a lower capital cost. Economies of scale from an increased throughput results in a similar level of cost reductions in energy and labor cost.

Table 2-7. Carbon fiber cost comparison between Baseline 50K tow vs. Low-Cost Heavy-Tow (full-utilization).

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%**

2.3.3. Material Property Cost Relationships

A relationship between carbon fiber material cost and mechanical properties is desired for this project to assess small changes in the study materials in addition to materials beyond the specific study materials. The sensitivity of cost to tensile strength and modulus is developed within this section. It is likely these two major fiber properties are dependent, but they have been assumed independent in this analysis for simplification. Fiber tensile strength depends to a large extent on the precursor quality and therefore its cost. Higher precursor quality depends on several factors such as improved polymer filtration, use of higher molecular weight polymers, precursor porosity, lower residual solvent content, and smoother surface fibers through alternative dry jet spinning processes. In addition, the final fiber strength also depends on the extent the precursor can be stretched in tension at the fiber pretreatment step prior to precursor conversion. Fiber cost relationship sensitivity to tensile strength has been estimated based on earlier ORNL cost estimates developed for the 24K tow (similar to T700S by Toray) and 50K tow (similar to PX35 by Zoltek) carbon fibers. These two carbon fibers have similar moduli (in the range of 230 GPa to 242 GPa) but with tensile strengths of 4900 MPa and 4137 MPa, for the T700S and PX35. The T700S has a higher tensile strength due to the superior precursor quality and higher associated estimated cost ($5.04/kg for T700S compared to $3.63/kg for PX35). In addition to a lower cost precursor, the PX35 also has a higher fiber conversion throughput than the T700S, resulting in a lower PX35 fiber conversion cost of $11.20/kg vs. for $14.96/kg T700S. Based on these two fiber cost vs. tensile strength estimates at a nearly constant fiber modulus, the fiber cost sensitivity to a range of fiber tensile strengths, i.e., 4000 MPa – 5000 MPa was initially estimated.

Fiber cost sensitivity to its modulus is relatively low compared to tensile strength in this model, however, major variables such as the effect of fiber tension in conversion furnaces were not considered in this analysis. A more detailed model is being developed as part of follow-on work which better capture the combined effects of processing parameters on modulus. For example, fiber modulus depends to a large extent on the fiber tension applied and the temperature increase in the low temperature (LT) furnace and residence time during the fiber conversion process. From empirical experience at the CFTF, it is assumed that per unit GPa fiber modulus increase the LT furnace operating temperature increases by 8ºC [3]. Fiber modulus is also influenced by residence time duration and fiber stretch in the high temperature (HT) conversion furnace. It is assumed that per unit GPa fiber modulus increase the HT furnace residence time duration increases by ~2 secs [3].

Figure 2-14 shows the developed relationship of carbon fiber cost to its mechanical properties of tensile strength and modulus. For a given fiber strength, fiber cost is assumed to vary linearly with modulus, and the sensitivity is assumed to be the same across various fiber strength values. Carbon fiber materials with tow sizes of 50K and 24K have been estimated to cost $17.98/kg and $21.50/kg, respectively. Fiber tensile strength is related to cost using these two commercial tow sizes from commercial product tow test data. A derived cost sensitivity relationship from these two points is extrapolated to two material scenarios using heavy textile fibers with different mechanical properties developed at CFTF. The two textile carbon fiber materials represent a standard modulus, LCCF-SM (modulus=224 GPa, tensile strength=2913 MPa), and an intermediate modulus, LCCF-IM (modulus=265 GPa, tensile strength=3140 MPa). Carbon fiber cost in these two cases is estimated to be $11.75/kg and $13.25/kg, respectively, as shown in the figure. The estimated heavy textile tow in the “current” processing scenario has a modulus of 258 GPa and tensile strength of 2657 MPa as calculated from the tow test data in Figure 2-3 (b). Despite the significant extrapolation from the 50K tow strength to the 457K tow strength, the cost estimate of $11.19/kg for the heavy textile tow study material is very similar to the prediction in this model for the tow strength and modulus pair.

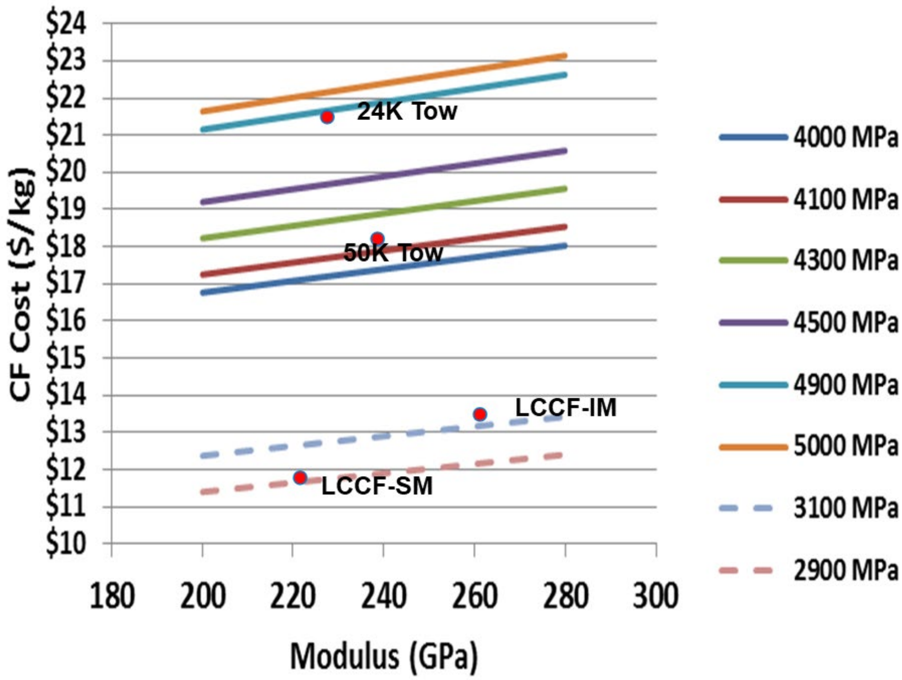


Figure 2-14. Carbon fiber cost sensitivity to its mechanical properties.

A carbon fiber cost relationship as a function of fiber tensile strength (UTS in MPa) and stiffness (E in GPa) has been developed. This model uses linear property assumptions and strength cost sensitivity data previously described, in addition to independent modulus relationships. The derived linear carbon fiber cost relationship using a regression analysis is as follows:

$$Carbon\ Fiber\ Cost\left(\frac{\$}{kg}\right) = -6.45 + 0.005 * UTS + 0.016 * E \qquad \textbf{(2-2)}$$

The total number of observations used for the regression analysis was 40, and R2 obtained for the above relationship was greater than 0.99. The derived cost relationship is appropriate for a given fiber mechanical property fiber cost sensitivity, while maintaining the other property constant. It is likely that both of these major properties are interrelated, particularly in the case of heavy-tow textile carbon fibers. The cost model does not currently take into account the impacts of one modulus on tensile strength, and vice versa.

2.3.4. Pultrusion Manufacturing Cost

Pultrusion is arguably one of the most stable, repeatable and cost-competitive composite manufacturing processes of continuous fiber composites. It is a manufacturing (pulling) process for producing continuous lengths of fiber reinforced composite structural shapes with constant cross-sections, yielding high unidirectional loading reinforcement properties. Reinforcing fibers are saturated in a resin bath, shaped by a preformer, and pulled through a heated die which initiates resin cure by setting off a catalytic reaction. This results in a rigid, cured profile corresponding to the die cavity shape. Pultruded carbon fiber reinforced spar caps incorporated as the structural member of wind turbine blades are a result of the evolution and increasing technological sophistication of the global wind energy industry. Zoltek Carbon Fiber is one of the largest producers of carbon fiber-reinforced pultruded plate that can be used for wind turbine blade spar caps in the world today. In addition to being about 30% lighter than glass by volume, carbon fiber has roughly three times the tensile modulus and one-and-a-half times the compressive strength of glass (dependent upon the specific carbon and glass fibers considered). These improved mechanical properties are most efficiently capitalized upon in a pultruded composite form.

As in the case of the carbon fiber cost estimation, pultruded spar cap cost and not price is estimated. This assumption is valid when the fiber manufacturer is also the pultruder (eliminates intermediate profit if the fiber is supplied by an outside fiber manufacturer). Table 2-8 shows the same major input parameter assumptions for carbon fiber-reinforced pultruded spar cap manufacturing for all three cases considered here. A material composition of 68% volume fraction carbon fiber with epoxy resin is assumed for the pultruded composite, which is representative of industry trends. Standard high production commercially available epoxy resin at $3.63/kg is assumed, which is generally less than half the cost of low volume and high temperature performance epoxy resin used for pre-impregnated (prepreg) carbon fiber tapes. Pultruding is a low capital, highly automated, and high yield operation as noted below in underlying parameter values assumptions in Table 2-8.

Table 2-8. Major input parameter assumptions for carbon fiber-reinforced pultruded spar cap of a 61.5m turbine blade manufacturing cost estimation.

Parameter	Value
Annual Production Volume	1.5 million tonnes
Material Composition	Carbon Fiber (68 vol.%, 75 wt.%); Epoxy Resin (32 vol. %, 25 wt.%)
Resin price (*includes profit)	$3.63/kg
Total Capital Investment	$1.5M
Labor (#)	2 per shift for a 24-hr continuous operation
Yield	99.7% (Material); 97% (Pultrusion Process)

Total spar cap cost breakdown under three carbon fiber cost scenarios (baseline 50K tow commercial grade carbon fiber, heavy textile tow (current), and heavy textile tow (full-utilization)) is shown in Figure 2-15. The baseline spar cap is estimated to be $16.44/kg. The spar cap cost (per kg) is lower than the $17.98/kg carbon fiber as 25 wt.% is from the significantly lower cost epoxy resin. Materials have the largest cost share of 91% of total spar cost under the baseline scenario. Due to the highly automated, large volume pultrusion manufacturing operation assumed here, a relatively small cost share for other cost categories is determined, i.e., 5% and 4% for capital and labor, respectively. Tooling and facility costs are also included in the capital cost category in addition to the pultrusion equipment.

With lower carbon fiber cost estimates, the heavy-tow textile pultruded spar cap cost is estimated to be ~33% and ~49% cheaper compared to the Baseline spar cap under the current and full-utilization material scenarios, respectively. Although capital cost might possibly be lower due to a significantly smaller number of creel positions being required for the much larger TCF tow sizes, the only difference assumed between the baseline and two heavy textile tow scenarios is the carbon fiber cost, so the total non-materials cost remains the same, i.e., $1.46/kg under all three spar cost scenarios considered. Total non-materials cost share is thereby higher under the two heavy textile tow spar cost scenarios than the baseline spar cost estimated share of 9%. Thus, materials cost shares are estimated to be lower, i.e., ~87%, and 83% under the heavy textile tow current and full-utilization scenarios, respectively.

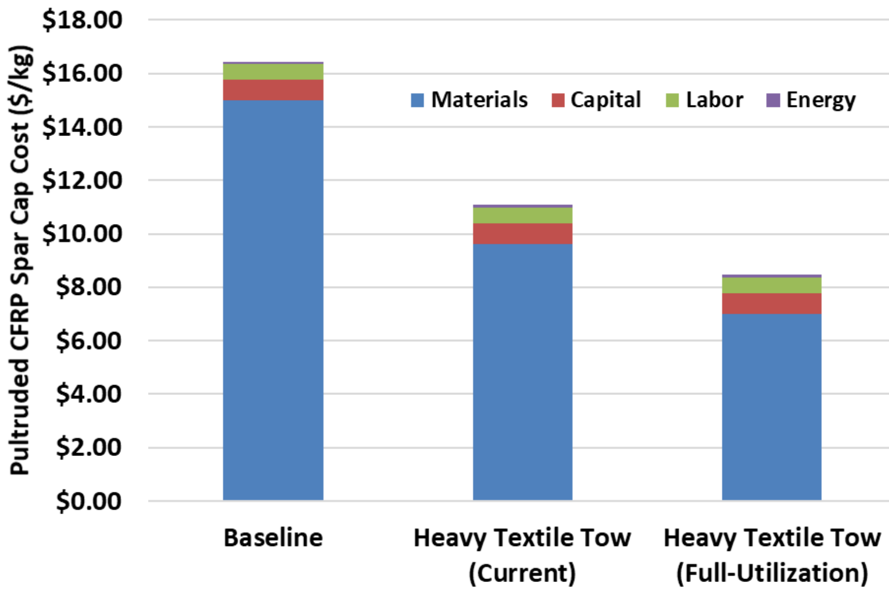


Figure 2-15. Carbon fiber-reinforced spar cap cost breakdown of three different carbon fiber cost scenarios.

Pultruded plates for spar caps are generally 3-5 mm thick. It is unlikely that the pultrusion line speed is dependent on the plate surface area for these standard thicknesses. Any change in the plate thickness for a given width will affect the pultrusion line speed and its cost due to a change in the plate cross-sectional area.

2.4. Model Material Inputs

The results from mechanical testing and cost modeling of the study materials are used to generate property estimates relevant for wind turbine spar caps to be used in the blade structural optimization studies in the next chapter. The unidirectional composites tested within this project are used to estimate mechanical properties for the likely use case of carbon fiber spar caps in intermediate pultruded composite forms. A 68% fiber volume fraction pultrusion is assumed based on industry trends, which is already being achieved by commercial pultruders who distribute to wind turbine OEMs.

The longitudinal Young's Modulus is estimated from known fiber (f) and matrix (m) properties based on the classic rule of mixtures formulation in Equation (2-3). For modulus extrapolation to the composite properties of the 68% pultrusion, the aligned strand infusion data are used for consistency amongst the materials. As a check of this approach for the Zoltek material, the formulation was used to extrapolate from the aligned strand infusion and commercial pultrusion data and the difference was less than 2% for extrapolations from the 51% and 62% fiber volume fraction composites. The modulus is assumed to be the same in tension as compression in the design tools, and this is replicated by the model material inputs which use the tensile modulus. The testing results confirmed this approach where small differences are seen between the tensile and compressive static test values for modulus.

$$E = V_f E_f + (1 - V_f) E_m \quad \textbf{(2-3)}$$

Strength values for composite materials are more complicated to estimate from constituent fiber and matrix properties, and the adjustment to the classical rule of mixtures for ultimate tensile strength is shown in Equation (2-4). This equation assumes failure at fiber strain levels and makes a correction to the tested tensile fiber strength (S_{ft}) using the calculated fiber translation factor (T_f). This factor accounts for effects such as manufacturing flaws, fiber matrix interface, and interleaving of the fibers in the composite. The fiber translation factor is calculated using the tested fiber and composite properties for each test case. Fiber properties were shown previously in Figure 2-2 through Figure 2-5. The calculated fiber translation factors are shown in Table 2-9 for each of the tested materials and composite forms. The composites manufactured using the heavy tow textile carbon fiber materials have lower fiber translation factors for the tensile tests, which could be caused by the lack of optimization of fiber surface treatment for compatibility with the resin system used, or due to the higher level of interleaving and fiber angle distribution compared to the baseline case. There is an observed improvement in the fiber translation for the commercial, optimized pultrusions performed by Zoltek compared to the aligned strand infusion process. This manufacturing improvement factor (85.9/81.0) is used to extrapolate the Kaltex aligned strand testing results to the model input values, resulting in a fiber translation factor of 82.9% for a model representation of the optimized 68% fiber volume heavy tow pultrusion. The fiber translation factor from the Zoltek commercial pultrusion (85.9%) is used as the value for the 68% fiber volume pultrusion to produce the industry baseline carbon fiber ultimate tensile strength.

$$S_{ut} \approx S_{ft} T_f \left[V_f + (1 - V_f) \, {}^{E_m}\!/_{E_f} \right] \quad \textbf{(2-4)}$$

Ultimate compressive strength should not be extrapolated in the same manner as tensile strength due to the increase in failure modes for compressive loads, such as fiber buckling. Instead, to estimate compressive strength the ratio of compressive and tensile strengths for a tested composite is used as a factor to multiply the estimated ultimate tensile strength for the model input. This approach maintains the relative compressive to tensile performance of materials but does not account for issues that may arise (or improvements) from the changed manufacturing process. Compressive strength is likely more affected by manufacturing processes and optimization, so the estimation approach is thought to be conservative when estimating the heavy tow 68% optimized, pultruded model input value from the aligned strand infusion test data.

$$S_{uc\,(VF2)} \approx \left({}^{S_{uc}}\!/_{S_{ut}} \right)_{VF1} S_{ut\,(VF2)} \quad \textbf{(2-5)}$$

Testing results are summarized from Section 2.2 in Table 2-9 and Table 2-10 from the tensile and compressive static tests. The tables show tested values with the predicted value for modulus and strength from the classical rule of mixtures (T_f=1) in parentheses, calculated using fiber values from tensile tow tests. The fiber translation factors are also shown in the tables which are used for extrapolating the tensile strength to model input estimates. Compressive fiber translation factors are not used in the calculations but are shown to reveal differences between the materials. The Kaltex and Zoltek aligned strand infused materials have similar fiber translation factors in tensile tests, however, the heavy-tow materials have higher compressive fiber strength translation than even the commercially optimized pultruded composite. This result reveals a benefit of the heavy-tow textile materials for wind energy applications in that less fiber strength is lost in composite compressive properties. The higher compressive fiber translation factor is likely caused by the heavy-tow material having greater fiber interleaving resisting compressive failure and fiber buckling. The tradeoff is lower tensile strength for the heavy-tow materials. The third-party pultrusions have the lowest fiber translation factors which confirms the previous discussion about resin voids in these samples.

Table 2-9. Summary of selected tensile tests (rule of mixtures predictions in parentheses).

Material	Composite Form	V_f	E [GPa]	UTS [MPa]	T_f [%]
Zoltek	aligned strand infusion	0.51	119 (125)	1726 (2132)	81.0
	third-party pultrusion	0.53	114 (130)	1564 (2213)	70.7
	commercial pultrusion	0.62	142 (151)	2215 (2579)	85.9
Kaltex	aligned strand infusion	0.47	112 (123)	990 (1266)	78.2
	third-party pultrusion	0.51	123 (133)	846 (1371)	61.7
Taekwang	aligned strand infusion	0.50	126 (128)	956 (1360)	70.3

Table 2-10. Summary of selected compressive tests.

Material	Composite Form	V_f	E [GPa]	UCS [MPa]	T_f [%]
Zoltek	aligned strand infusion	0.51	--	-906	42.5
	third-party pultrusion	0.53	--	-897	40.5
	commercial pultrusion	0.62	138	-1505	58.3
Kaltex	aligned strand infusion	0.47	--	-863	68.1
	third-party pultrusion	0.51	--	-769	56.1
Taekwang	aligned strand infusion	0.50	--	-869	63.9

As discrete points of study, two carbon fiber materials and one fiberglass material will be analyzed in the optimization studies. The two carbon fiber materials represent a current industry baseline material and a heavy-tow textile carbon fiber material, based on the Zoltek PX35 and the Kaltex 457K materials, respectively. The estimated model material inputs for the industry baseline and heavy-tow textile carbon fiber study materials are listed in Table 2-11.

Table 2-11. Model spar cap material properties based on average test data and cost estimates.

<table>
<tr><th>Material</th><th>V_f</th><th>E [GPa]</th><th>UTS [MPa]</th><th>UCS [MPa]</th><th>Cost [/kg]</th></tr>
<tr><td>Industry Baseline CFRP pultrusion</td><td>0.68</td><td>157.6</td><td>2427.3</td><td>-1649.2</td><td>$16.44</td></tr>
<tr><td rowspan="2">Heavy-Tow CFRP pultrusion</td><td rowspan="2">0.68</td><td rowspan="2">160.6</td><td rowspan="2">1508.5</td><td rowspan="2">-1315.0</td><td>$8.38 (full-utilization)</td></tr>
<tr><td>$11.01 (current)</td></tr>
<tr><td>Fiberglass infusion</td><td>0.57</td><td>42.8</td><td>1169.7</td><td>-743.5</td><td>$2.06[3]</td></tr>
</table>

[3] The material cost for fiberglass infusions in considered conservative in comparing to the intermediate composite carbon fiber pultrusion form and does not include material preforming costs, manufacturing labor costs such as cutting and positioning, or infusion costs/time which are significant for the dry fabric infusion.

The extrapolated mechanical properties of the two carbon fiber materials in a 68% fiber volume fraction pultrusion are compared to each other on a per-cost basis in Table 2-12. This comparison is made using both heavy-tow textile carbon fiber cost estimates. These cost estimates represent the processing approach used for the tested material (current) and the cost estimate for the realistic commercial-scale carbon fiber processing (full-utilization). For reference, the fiberglass infusion properties are also provided in this basis. The cost-specific mechanical properties are also shown as a percentage of the baseline in the table to reveal the relative change from the industry baseline carbon fiber. This analysis highlights the benefit of the heavy-tow textile carbon fiber material, which has a lower cost for modulus/stiffness and compressive strength using either cost estimate. The heavy-tow fiber has a nearly equivalent modulus compared to the baseline carbon fiber at a lower cost, which produces up to 100% more modulus per-cost. This means that if stiffness drove the blade spar cap design, and material strength was not exceeded, the spar cap would cost half as much with the heavy-tow material compared to the industry baseline. The heavy-tow, full-utilization material has 56% more compressive strength and 22% more tensile strength for the same cost as the industry baseline. This direct comparison of the cost-specific mechanical properties does not however capture the effect of the absolute difference in material strengths. In certain blade designs, more material will be needed for the lower strength heavy-tow spar caps which increases the blade mass and some of the resulting loads. The increase in heavy-tow material required for these strength-driven blade designs will also increase the blade stiffness which then reduces the strength/strain requirements placed on the material. Due to the non-linearity of these effects, the materials are best compared in blade structural optimization studies such as performed in Chapter 4.

Table 2-12. Cost-specific mechanical properties of the model spar cap materials.

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

The cost-specific mechanical properties of a traditional fiberglass infusion are also provided in Table 2-12. Comparing fiberglass with the baseline carbon fiber material reveals very clearly why most turbine OEMs have resisted using carbon fiber in blade designs. The fiberglass infusion has a 117% improvement in cost-specific modulus and a 211% improvement in cost-specific compressive strength, due to the significantly lower cost of fiberglass. Fiberglass does have a higher density than carbon fiber, so comparison on a volumetric cost basis is done in Table 2-13 which is a fairer representation of material cost differences. From this comparison the novel heavy-tow textile carbon fiber material actually outperforms fiberglass in the cost-specific modulus, but the fiberglass material is significantly better in cost-specific strength. The cost-specific basis of comparing materials is useful in comparing similar materials but does not account for absolute differences in the mechanical properties. Fiberglass is much cheaper, but also has much lower properties than carbon fiber which means significantly more material would be needed. This difference results in a heavier blade which has system cost implications, and likely with increased blade manufacturing costs. The cost-specific approach provides insight into material differences and targets for material selection, but a more complete comparison of the study materials requires detailed blade structural optimizations and understanding of system costs (drive components, transportation, installation, etc.) related to blade mass and blade manufacturing.

Table 2-13. Volumetric cost-specific mechanical properties of the model spar cap materials.

Material	UTS(MPa)/($/m^3)	%	UCS(MPa)/($/m^3)	%	E(GPa)/($/m^3)	%
Industry Baseline	9.2e-2	100	-6.3e-2	100	6.0e-3	100
Heavy-Tow (full-utilization)	11.3e-2	122	-9.8e-2	156	12.0e-3	200
Fiberglass infusion	22.2e-2	241	-15.8e-2	252	10.6e-3	176

2.4.1. Model Input Design Strength Calculation

The material property averages listed in Table 2-11 must be factored prior to their use in design to account for statistical variation in test data and to include safety factors related to how those properties get translated into the final blade structure. Wind turbine design standards require the use of statistical values for 95% exceedance with 95% confidence from the test data samples [5], calculated as shown in Equation (2-6) which converts the testing average to a statistical 95/95 characteristic value. The confidence factor, k, is a function of the number of test samples and differs by a factor of over 2 for test data with 5 samples compared to 50 samples, as defined by the student t-distribution.

$$|S_k| = |\bar{S}_{test}| - k\sigma_{test} \quad \textbf{(2-6)}$$

The material strength values used in design are further reduced by a series of partial safety factors which account for more global considerations such as failure criticality, lifetime considerations, manufacturing effects, and analysis methods used. The characteristic strength values are reduced by the product of partial safety factors, γ_m, into the design strength as shown in Equation (2-7).

$$S_d = {}^{S_k}/_{\gamma_m} \quad \textbf{(2-7)}$$

Table 2-14 shows the safety factors for static and fatigue analyses used for the infusion and pultrusion spar caps in this analysis. The difference between the two comes from the fact that pultrusions are an intermediate composite form which do not suffer from unknown manufacturing defects in the way that infused dry fabric spar caps inherently do. The uncertainty in fiber wrinkles, dry spots, or other spar cap manufacturing defects for the infusion process show up as an additional partial safety factor related to manufacturing effects of 1.1 for the infusion process compared to 1.0 for pultrusions. The safety factor for fatigue strength is used in the analysis as prescribed by the DNV-GL design standard in conjunction with the Shifted Goodman failure criterion [5].

Table 2-14. Material safety factors for static and fatigue failure in infused and pultruded spar caps.

Manufacturing Method	Static failure, $\gamma_{m,s}$	Fatigue failure, $\gamma_{m,f}$
Traditional resin infusion (VARTM)	1.88	1.96
Intermediate Pultrusion	1.71	1.78

The tensile and compressive strengths are determined in each basis using the statistical test data from this project for the carbon fiber materials. The sample standard deviation data used to calculate the characteristic strength were scaled by the volume fraction ratio to represent the expected variability increase for the higher fiber volume fraction pultrusions modeled. Previous test campaign data were used for the fiberglass infusion [7]. The characteristic and design static strengths in the longitudinal direction are shown in Table 2-15 for the three spar cap materials studied. The static design strain is also calculated for the materials using the average test moduli for the three materials along with the design strength. The characteristic strength is between 85-92% of the test average for the three study materials. This value could be higher with larger test sample sizes, but that was not a direct objective of the previous and current test campaigns. It is noted that the design strength is around 50% of the average material strength as a result of the combined effects of material variability and uncertainty of properties in the final blade structure. There are additional partial safety factors used on the loads side of the analysis as well which are not included here and adjust for uncertainty in the aeroelastic loads analysis, as specified in the IEC standard [6].

Table 2-15. Static strength basis and design failure strain values.

	Industry Baseline CFRP		Heavy Tow Textile CFRP		Fiberglass Infusion	
Basis	**UTS [MPa]**	**UCS [MPa]**	**UTS [MPa]**	**UCS [MPa]**	**UTS [MPa]**	**UCS [MPa]**
Mean Strength	2427	-1649	1509	-1315	1170	-744
Characteristic Strength	2236	-1528	1345	-1172	1002	-637
Static Design Strength	1307	-893	786	-685	532	-338
Static Design Strain	0.829%	-0.567%	0.489%	-0.427%	1.244%	-0.790%

Material fatigue properties based on tests performed within this project are used in conjunction with standard fatigue failure analysis methods to estimate life of the wind turbine blades within the design optimization studies. The fatigue test data performed with a stress ratio R=0.1 are used to estimate the fatigue slope exponent of the baseline and heavy-tow carbon fiber materials. The high-cycle fatigue slope for this tension-tension test is calculated by fitting a line to the stress-cycle (SN) data on a log-log plot. Composites typically display low-cycle fatigue characteristics that differ from their high-cycle fatigue characteristics, so the data are fit above a cutoff number of cycles, N_{min}. Figure 2-16 shows the results of fitting the fatigue test data for the three materials tested in this project, using the data with a failure above 100 cycles. The DNV-GL wind turbine design standard recommends a cutoff value of 10^3 with a minimum of three test samples within each decade up to the decade between 10^6 to 10^7 [5]. The objective of the test campaign was not to certify fatigue properties, and as a result some samples are missing from the specified protocol for the tested materials. The data markers with the black outline were not used in the fit and slope calculation.

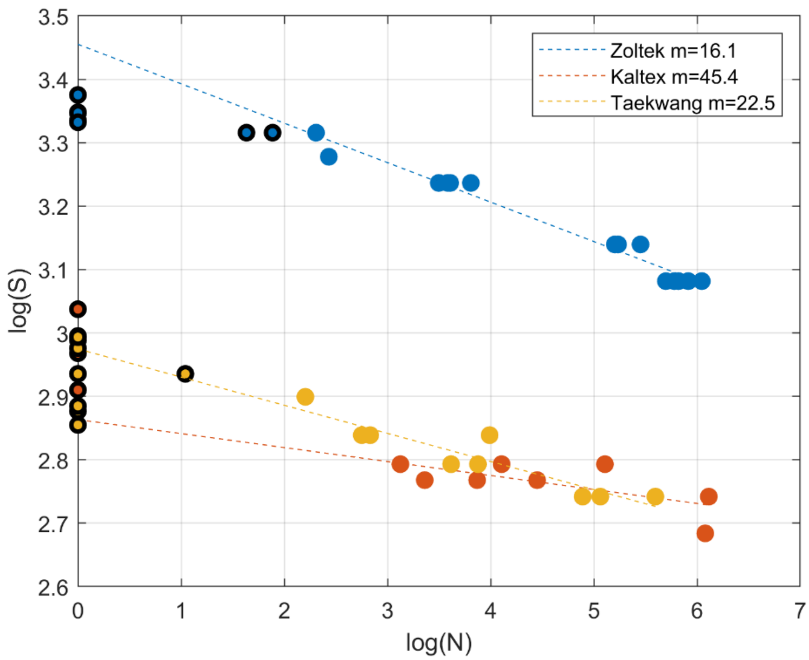


Figure 2-16. High-cycle fatigue exponent calculation from R=0.1 fatigue tests.

The sensitivity to the starting number of cycles for estimating the high-cycle fatigue exponent was analyzed by comparing slope estimates for orders of 1 up to 1000. The fit does a poor job of representing high-cycle fatigue failure when including the single-cycle static failure data, but the slope exponents do not vary significantly for low cycle limits from 10 to 1000. Table 2-16 lists the results of the fatigue slope fit for low cycle limits of 100 and 1000. For this analysis, the exponents associated with a 100 cycle lower limit are used to be conservative in comparison of heavy-tow textile carbon fiber with the baseline carbon fiber in the optimization studies. This was also chosen because of the missing failure data in the 10^4 decade for the Zoltek PX35. The fatigue exponent for the baseline Zoltek material performed as expected with a value near fifteen (m=16.1), which is commonly accepted for carbon fiber composites. The two heavier-tow textile carbon fiber materials have notably higher exponents than the baseline, which is consistent for the two similar materials. The Kaltex material, which is used in the optimization studies, has a fatigue exponent that is very high and indicative of a material that has a very low sensitivity to fatigue. This is a favorable property for materials used in wind turbine blades where the blades see on the order of 10^9 fatigue cycles over their lifetime. As further justification for the high fatigue exponent of m=45.4 for the Kaltex material, it is noted that the two highest cycle failure points were actually run-outs and did not fail at their listed 10^6 cycle value, as indicated in Figure 2-10. The fatigue exponent calculation for the Kaltex material would be even higher if these two points were run to failure. It is observed from the fit of the Kaltex data that the higher exponent (-1/m slope) would result in a better fit of the failure data between 10^2 to 10^5 cycles, as an additional validation of the high fatigue exponent. It is noted that the Zoltek material was tested in a 62% commercial pultrusion whereas the two textile carbon fiber materials were tested in ~50% fiber volume aligned strand infused composites, which shifts the Zoltek data up compared to the other materials. It is unclear how these manufacturing differences would affect the fatigue slope exponent values, however the trends would not be expected to change significantly.

Table 2-16. Fatigue exponent, m, for high-cycle fatigue versus minimum cutoff cycle, N_{min}.

Spar Cap Manufacturing Method	N_{min} = 100	N_{min} = 1000
Zoltek PX35 (Industry Baseline)	16.1	14.9
Kaltex K20 (Heavy Tow Textile)	45.4	45.4
Taekwang T20	22.5	24.3

3. WIND TURBINE BLADE DEFINITION

Structural optimization studies have been performed to assess the impact of material choices in wind turbine blade design and are described in Chapter 4. Two reference blade models are used and were selected to be representative of industry trends in the U.S. for future land-based and offshore installations. A 3 MW reference turbine was developed within this project that is indicative of development in low wind resource regions of the U.S. This is occurring in states where many of the better wind resource sites have been developed and, in part, due to limited access to electrical transmission in higher wind resource regions. This turbine has a high energy capture design with a specific power equal to the lower end of commercial turbines recently developed of 175 W/m^2. Industry trends reveal the move toward lower average specific power values closer to this design. A 10 MW reference turbine is also studied which represents the development of high wind resource, offshore sites off the U.S. coasts. This 10 MW, 198 m diameter turbine is similar to wind turbines currently being designed and certified for offshore developments.

The reference turbine design specifications and aerodynamic shapes are described in the following sections. The structural design is partially described in this chapter, except for the spar cap design which is the subject of the optimization studies in the following chapter. The materials used in the design are listed in Table B-1, including their moduli and characteristic strengths.

3.1. Land-Based Turbine in a Low Wind Resource

The SNL3.0-148 reference turbine is a 3 MW, 148m diameter wind turbine designed for low wind speed IEC class III-A sites. Additional design parameters are listed in Table 3-1. To enable the high energy capture, low specific power design a low-induction aerodynamic target was selected which unloads the blade tip compared to the aerodynamic optimum 1/3 induction profile. This design slightly sacrifices aerodynamic efficiency (C_p) in exchange for a more significant increase in annual energy production (AEP). The induction profile selected weights AEP relative to C_p such that the blade root bending moment is held constant for a 11% increase in blade length which results in a 5% increase in energy capture, as described by Kelley [8]. The low-induction aerodynamic target results in a slender blade design for this turbine, which reduces the surface area of the blade and the resulting shell material mass and cost. The turbine is designed for a 30-year life to represent modern trends in land-based turbine design and certification.

Table 3-1. Low wind resource, high energy capture 3 MW turbine specifications.

Parameter	SNL3.0-148.mk1
Power Capacity	3 MW
Turbine Diameter	148 m
Blade Length	72 m
Specific power	175 W/m^2
Rotor Solidity	2.86%
Cut-in Wind Speed	3 m/s
Cut-out Wind Speed	20 m/s
Rated Wind Speed	8.7 m/s
IEC Design Class	III-A (hub height average wind speed of 7.5 m/s; average turbulence intensity at 15 m/s of 16%)

Parameter	SNL3.0-148.mk1
Design Life	30 years
Tip Speed Ratio	9
Rated Rotational Speed	10.09 rpm

The design uses the DU-series of airfoils, with thicknesses ranging from 40% to 21% at the tip [9]. The resulting outer geometry and chord and twist profiles are shown in Figure 3-1. A maximum chord of 4 m was used for transportation considerations.

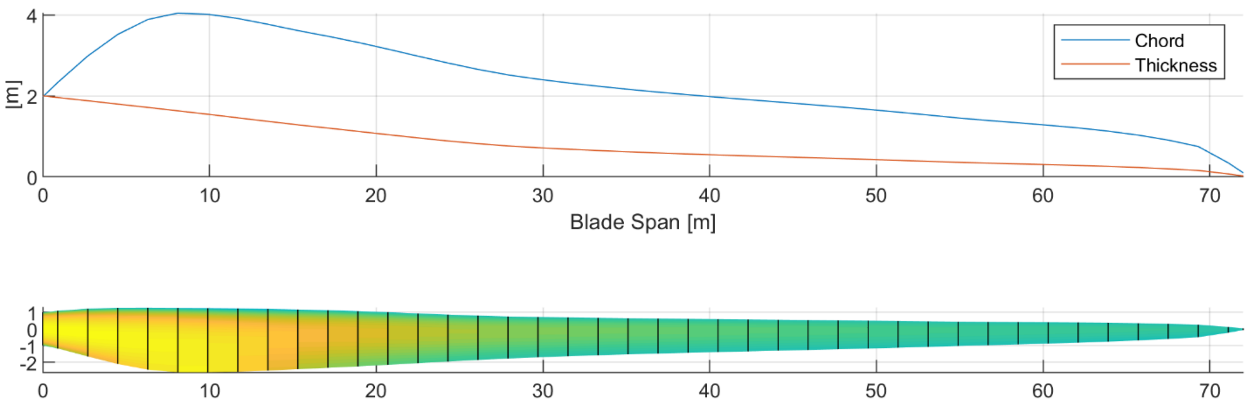


Figure 3-1. Top view and chord and thickness profiles for the SNL 3MW reference blade.

3.2. Offshore Turbine in a High Wind Resource

The offshore turbine in this study is based on the IEA 10MW reference turbine designed within Task 37 [10]. This 198 m diameter, IEC class I-B turbine was designed in an integrated aero-structural optimization with the objective to maximize AEP. The aerodynamic shape from this design is used for the blade structural optimization studies in Chapter 4. Design specifications for this turbine are listed in Table 3-2. The cut-out wind speed was changed from the original design to 30 m/s to represent current trends in offshore wind turbine certification.

Table 3-2. High wind resource, offshore 10 MW turbine specifications.

Parameter	IEA10.0-198
Power Capacity	10 MW
Turbine Diameter	198 m
Blade Length	96.7 m
Specific power	325 W/m^2
Rotor Solidity	3.61%
Cut-in Wind Speed	4 m/s
Cut-out Wind Speed	30 m/s
Rated Wind Speed	10.9 m/s

Parameter	IEA10.0-198
IEC Design Class	I-B (hub height average wind speed of 10 m/s; average turbulence intensity at 15 m/s of 14%)
Design Life	25 years
Tip Speed Ratio	10.6
Rated Rotational Speed	8.68 rpm

The IEA 10 MW reference turbine uses the FFA-W3 airfoil series which have thickness values ranging from 36% to 21% at the tip. Figure 3-2 illustrates the blade aerodynamic shape and the chord and thickness profiles for the 10 MW blade.

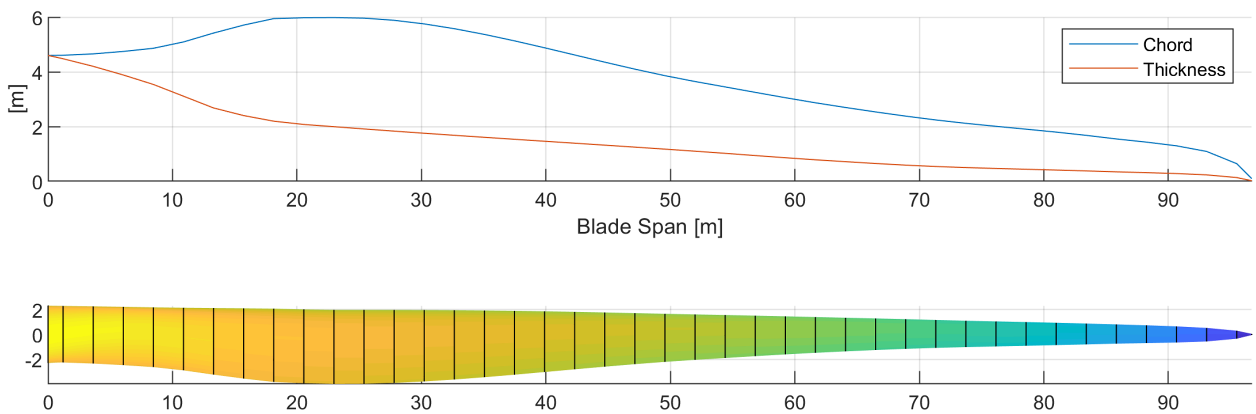


Figure 3-2. Top view and chord and thickness profiles for the IEA 10 MW reference blade.

4. WIND TURBINE BLADE SPAR CAP OPTIMIZATION STUDIES

This chapter describes the results from blade structural optimizations using the carbon fiber material properties that have been studied within this project, described in Chapter 2. These optimizations have been used to assess the performance of the novel, heavy tow textile carbon fiber material in comparison to the commercial baseline carbon fiber material and to the traditional fiberglass infusion. The optimizations and material manufacturing are focused only on the blade spar cap which is the first logical application for carbon fiber due to the structural significance of this portion of the blade. The three study materials are assessed in the 3 MW and 10 MW reference blades described in the previous chapter. The design and selection of these two reference wind turbines was done to represent industry trends in the U.S. and to ensure that the results in this chapter span the range of demands placed on materials in wind turbine blade design.

4.1. Optimization Configuration Description

The objective of the optimization is to assess the performance of the study materials in wind turbine blade spar caps. With that objective, only the design variables related to the blade spar cap are used in the optimization routine. Other blade design variables have been sized based on the performance of these material regions of the blade discretely between optimization routines. Blade buckling checks are performed outside of the optimization loop and used to size the panel shell thicknesses and dimensions along the span. Performing the buckling analysis offline mimics the standard approach, but prevents the optimization from identifying a stiffer blade that is more resistant to buckling as the optimal solution (increasing spar material to reduce shell panel materials). Trailing edge reinforcement was also sized offline for the two reference turbines based on strain and fatigue behaviors in the edgewise direction. The optimization was performed iteratively until the offline variables were converged based on the optimized spar cap profile.

The spar cap thickness profile was optimized at five evenly spaced locations along the blade span from root to tip. Spar cap width was determined through a buckling analysis and was not a variable in the final optimization configuration. The flap and edge stiffnesses are negligibly sensitive to spar cap geometry (section height, h, to width, b, ratio) due to the greater impact on the area moment of inertia from the distance to the bending axis ($h \ll t$), as shown in Equations (4-1) through (4-4). By not including both spar cap section width and thickness within the optimization the routine reaches a robust solution more quickly and repeatably, improving the ability to compare the performance of the three study materials.

$$I_{spar,flap} = I_{LP} + I_{HP} \quad \textbf{(4-1)}$$

$$I_{spar,flap} = 2\left(\frac{1}{12}bh^3 + bh\left(\frac{t}{2} - \frac{h}{2}\right)^2\right) \quad \textbf{(4-2)}$$

$$I_{spar,flap} = 2bht^2\left(\frac{1}{12}\left(\frac{h}{t}\right)^2 + \frac{1}{4}\left(1 - \frac{h}{t}\right)^2\right) \quad \textbf{(4-3)}$$

$$I_{spar,flap} \approx \frac{1}{2}At^2, h \ll t \quad \textbf{(4-4)}$$

The optimization objective is to minimize blade mass, as a proxy for spar cap material cost, subject to three constraints which were assessed through an aeroelastic loads analysis. Constraints were placed on the blade tip deflection, spar cap material strain (max./tensile, min./compressive), and spar cap material fatigue damage. Material strain limits were based on the failure strain values defined within this project. Strain was calculated on the high pressure (HP) and low pressure (LP) sides of the blade considering the combined load effect from flexural bending and centrifugal axial strain as shown in Equation (4-5). Including the axial loading from centrifugal forces acts to reduce the compressive strain and increase the tensile strain and is used in the strain and fatigue calculations.

$$\varepsilon_{spar} = \frac{F_z}{EA} + \frac{M_y c}{EI} \tag{4-5}$$

Blade tip deflection is an important constraint for wind turbine design and the design value was set as 20% of the blade length. Several design factors define the actual clearance between the blade tip and the tower such as prebend, precone, tower and nacelle geometries. For this study, the goal was to keep the results independent of these design decisions and the design deflection limit was verified by the industry advisory panel members, including wind turbine OEMs. The results are quite sensitive to the deflection limit, and, as a trend, the lower limits tend to favor the stiffer carbon materials. The third constraint is on spar cap material fatigue, to ensure survivability for the blade design life. The fatigue analysis is performed using rainflow cycle counting from the aeroelastic time series simulations and Miner's rule for damage accumulation. A shifted Goodman curve is used for the failure criterion to calculate each fatigue cycle's contribution to lifetime damage. The shifted Goodman failure criterion is shown in Equation (4-6), as described in the design standard [5].

$$N_i = \left(\frac{\frac{S_{k,t} + |S_{k,c}|}{2} - \left| \gamma_{m,s} * \sigma_{d,m} - \frac{S_{k,t} - |S_{k,c}|}{2} \right|}{\gamma_{m,f} * \sigma_{d,a}} \right)^m \tag{4-6}$$

The Numerical Manufacturing and Design (NuMAD) tool was used to manage material and structural design properties within the optimization [11]. Blade structural representations were created through NuMAD preprocessing for PreComp [12] and the commercial 3d finite element analysis software ANSYS. Aeroelastic simulations were performed using the FAST wind turbine simulator [13]. A reduced set of design load cases (DLC) from the IEC design standard was used in the optimization loop representing the fatigue analysis, an extreme coherent gust with direction change, and the parked 50-year extreme wind case. These cases were simulated using Sandia's runIEC toolset and correspond to the design standards DLC's 1.2, 1.4, and 6.1. The full load case suite was analyzed outside of the optimization loop to confirm assumptions on the driving load cases. The complete fatigue analysis specified by the design standard is computationally demanding and instead of calculating these loads within each design iteration the loads for DLC 1.2 were frozen within the optimization and were recalculated between optimization routines using the optimized spar cap properties to convergence. The loads were calculated using the partial safety factors specified in the design standard and design (factored) loads were compared to the design (factored) strength values defined within this report.

4.2. Optimization Results for Land-Based Turbine in a Low Wind Resource

The performance of the three study materials is compared for the SNL3.0-148 reference turbine. The optimization routine used penalties on the objective fitness to ensure the constraints were satisfied in the optimal solution. A comparison of the three materials relative to the constraints is shown in Figure 4-1, normalized to the respective constraint limits for each material. The massminimization objective of the optimization would attempt to drive each of the constraints to the upper limit by removing spar cap material. Blade tip deflection has a double integral relationship with the blade sectional bending stiffness profile and is highly nonlinear. Blade material strain is determined from a sectional analysis and has a more direct relationship to the local bending stiffness (inversely proportional to the sectional EI, as a close approximation). The ratio of material modulus to material strength partially determines how optimal a material is for a given turbine design. The optimization will add material to the spar cap until the tip deflection limit is satisfied, which is related to the modulus and thickness profile of the material. The spanwise location of where the optimization adds material is based on the need to satisfy the strain (strength) limits in tension and compression along the blade span. It is clear from the results for this 3 MW blade that the tip deflection drives the spar cap design for each of the materials, where the optimized spar cap layup nearly perfectly met this limit for each material. The two carbon fiber materials met this deflection limit without much residual (unused) strength which makes them ideal materials for this blade based on their modulus and strength ratios. The material properties of greatest importance for wind turbine blade design are modulus and compressive strength. For symmetric spar caps (HP and LP) the maximum tensile and compressive strain values are nearly equivalent and due to the lower compressive strength of composites this material property is more of a driver for wind turbine blade design. Considering unused material tensile strength suboptimal (indicated by Equation (2-2)), the novel heavy tow textile carbon fiber material performs best in utilizing the material strength, while the baseline carbon fiber could have 35% lower tensile strength without affecting the amount of material used in this design. It is not directly apparent from this plot, but the fiberglass spar design is fatigue driven which increased the amount of material required for the fiberglass design. Removing the fatigue constraint and analysis produces results that are very similar to the 10 MW turbine in the following section. The optimal fiberglass design reached an accumulated damage value of 0.92 (92% of blade life used) for this low wind speed site. The discrete nature of composite layers combined with the high sensitivity of loads on cumulative fatigue damage prevented the fiberglass fatigue damage from reaching a value of exactly 1, and this is the optimal solution. The improved fatigue performance of carbon fiber materials compared to fiberglass means that the accumulated damage is much less than the design life for the blade spar cap. The heavy tow carbon fiber spar is predicted to survive 63 years at this site while the baseline carbon fiber is predicted to survive 800 years, compared to 32 years for the fiberglass spar cap.

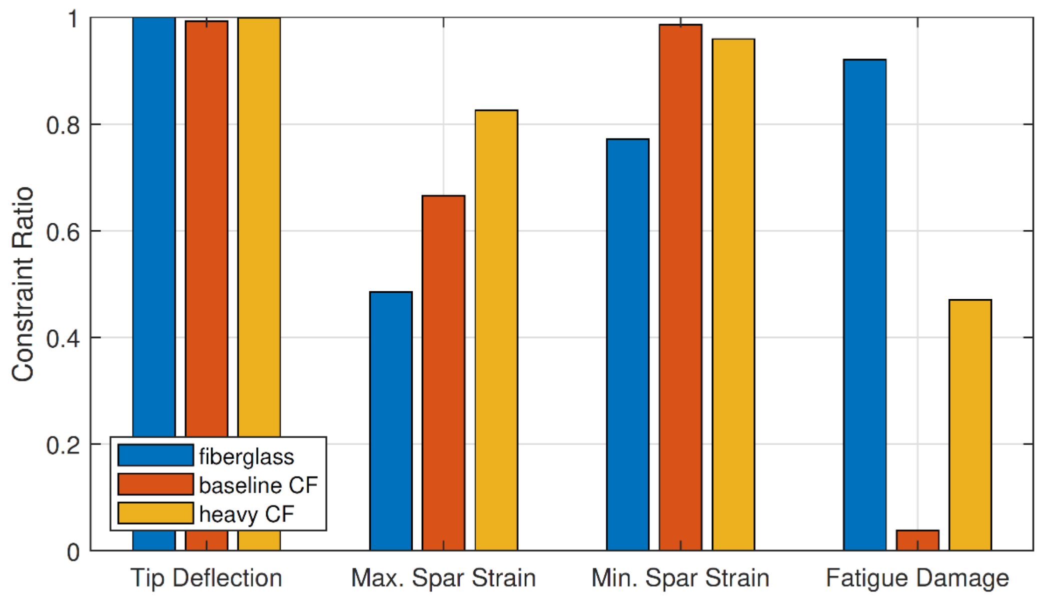
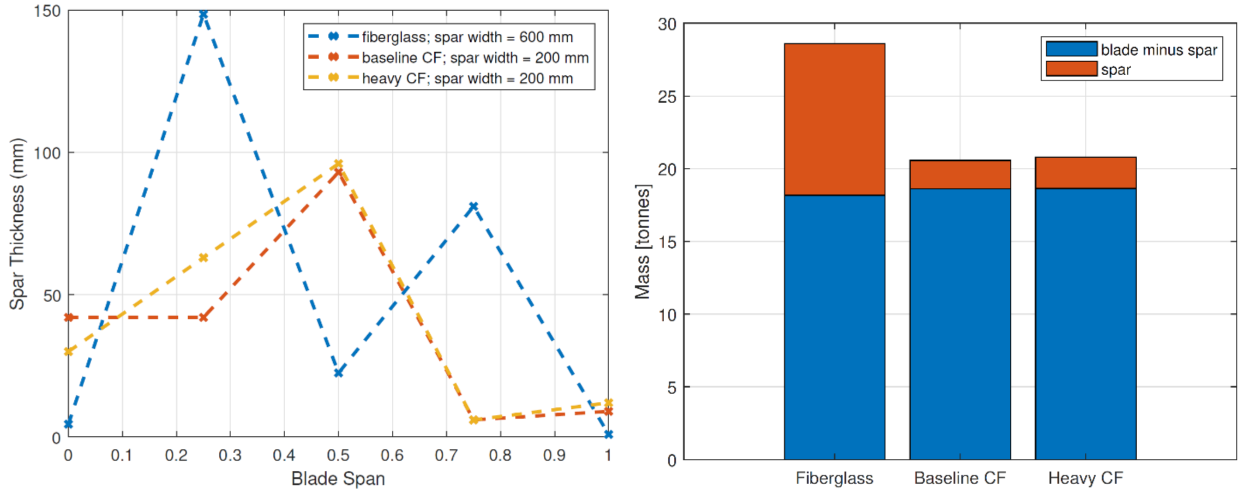


Figure 4-1. Land-based turbine optimal solution constraint values.

The optimal spar cap thickness profiles for the three study materials are shown in Figure 4-2 (a). The spar cap width is three times higher for the fiberglass design to achieve similar spar thickness values by approximating the increased modulus for the carbon fiber pultrusions. To compare the relative amount of spar cap material required, the fiberglass thickness profile should be multiplied by three. The reduced width for the carbon spar was done for spar cap buckling considerations to not falsely favor the carbon fiber materials in manufacturing cost comparisons which are related to the length of composite layers in the manufacturing process. As a verification of the optimal fiberglass design which has two peaks in the thickness profile a sampling study was performed for this blade and the optimal designs all exhibited this characteristic and were around 10% lighter than the more traditional single peak spar design. This feature is a result of the aerodynamic loading and blade thickness profile which greatly affects sectional modulus and could be removed with an aero-structural optimization. Due to the complicated relationship between sectional bending stiffness and tip deflection the effect of an aero-structural optimization is not intuitive. The 3 MW aerodynamic design was selected based on comparison of structural optimization results using three different blade geometries with the same aerodynamic target and the selected low-solidity design was optimal from this comparison [14]. The spar cap mass and total blade mass is compared when using the three different materials in Figure 4-2 (b). The spar cap thickness profiles and resulting mass is nearly identical for the baseline and heavy tow carbon fiber (CF) materials, with slightly more material required for the heavy tow carbon material. For the lower modulus fiberglass material that is fatigue driven a substantial increase in spar cap mass is observed compared to the carbon fiber materials which have better fatigue characteristics.



(a) Spar cap thickness profile comparison **(b) Spar cap and blade mass comparison**

Figure 4-2. Land-based turbine optimal solution spar cap dimensions.

A summary comparison of the cumulative spar cap layer length, mass, and material cost is shown in Figure 4-3 for the three study materials. The cost bar is the spar mass multiplied by the material cost from Table 2-11, using the commercial “full-utilization” processing estimate for the heavy tow carbon fiber. The earlier discussion on why carbon fiber is avoided in most blade designs is apparent from this plot, where the baseline carbon fiber spar cap material cost is 48% higher than for fiberglass. Despite the improved mechanical properties of carbon over glass, the significantly higher cost of the baseline carbon fiber material results in a more expensive blade spar cap compared to fiberglass. The novel heavy tow textile carbon fiber material however is approximately 49% less expensive than the baseline material, and despite the slightly lower compressive strength the resulting spar cap material cost is 43% lower than the baseline carbon fiber. The spar cap material cost using the novel carbon fiber is actually found to be 16% less expensive than the fiberglass spar cap material cost in this blade design. For this low wind speed turbine design the heavy tow textile carbon fiber is the best economic choice for spar cap material and would reduce the LCOE for this turbine. The spar cap material cost is only part of the reduction in LCOE when using the heavy tow textile carbon fiber. There is a system benefit for decreasing the rotor mass which affects the blade bearings, hub, drivetrain, and nacelle costs. This benefit is not quantified as part of this work, but it would be the same for both carbon fiber materials which have a 27-28% lower rotor mass compared to the fiberglass design. An additional cost component which is not directly quantified is the blade manufacturing cost difference between the fiberglass and carbon fiber spar caps. In previous work it was found that the spar cap manufacturing costs scale with the length of each composite layer for the infusion process [15]. This relationship may no longer be appropriate as blade manufacturers have moved towards pre-assembled spar cap layups which are added into the blade mold in one step. The number and length of layers would still affect the assembly time and cost of this intermediate step. The manufacturing costs are fundamentally different for the carbon fiber pultrusions which may have additional steps such as removing peel-ply (used in some pultrusions), kitting at ply drops, and adding a flow medium layer between the pultrusion sheets. The fiberglass costs vary with respect to weaving or other formatting, cutting and trimming, layer installation, and infusion-related steps as well. The total length of the spar cap layers is still shown in Figure 4-3 as a proxy for manufacturing costs for the different materials. These costs are expected to scale with total layer length, but at different and unknown factors for the fiberglass infusion and carbon pultrusions.

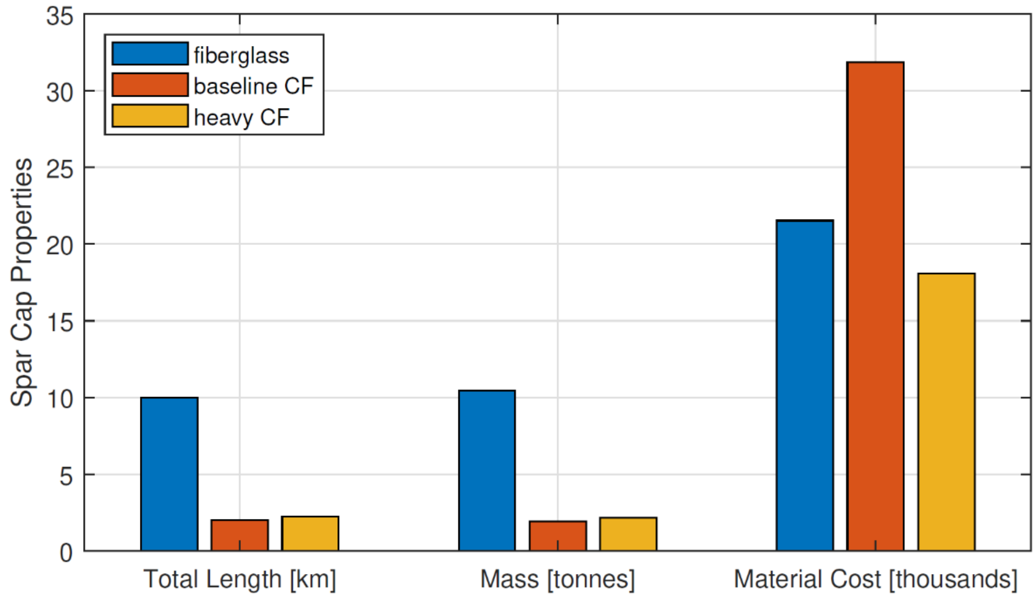


Figure 4-3. Land-based turbine optimal solution spar cap properties.

4.3. Optimization Results for Offshore Turbine in a High Wind Resource

The 10 MW reference wind turbine is studied to represent offshore wind turbine designs and to capture the material demands placed on wind turbine designs in high wind resource sites. The optimized spar cap performance of the three study materials is shown relative to the constraint values in Figure 4-4. The main difference in the 10 MW results compared to the 3 MW design results is that the 10 MW turbine is not fatigue driven for the 25 year design life common for offshore turbines. Additional spar cap material is not required for the fiberglass design to satisfy the fatigue requirement and as a result there is not excess strength as was seen in Figure 4-1. The three study materials each optimized to reach the tip deflection and compressive strain limits simultaneously. The lower compressive strain limits for the carbon fiber materials did require some additional material for this high solidity blade design, which is seen in the tip deflection limit not quite being met with the carbon fiber spar caps. A more slender blade design would be optimal for the carbon fiber designs. Although the fiberglass design is not fatigue driven in this analysis, it would be for a blade life beyond 29 years. The industry will likely push design life values for 30-35 years for the offshore sites and these results will change for those designs. The baseline carbon fiber spar cap design however is predicted to survive 63 years, and the heavy tow carbon fiber material will effectively never fail in fatigue in this design.

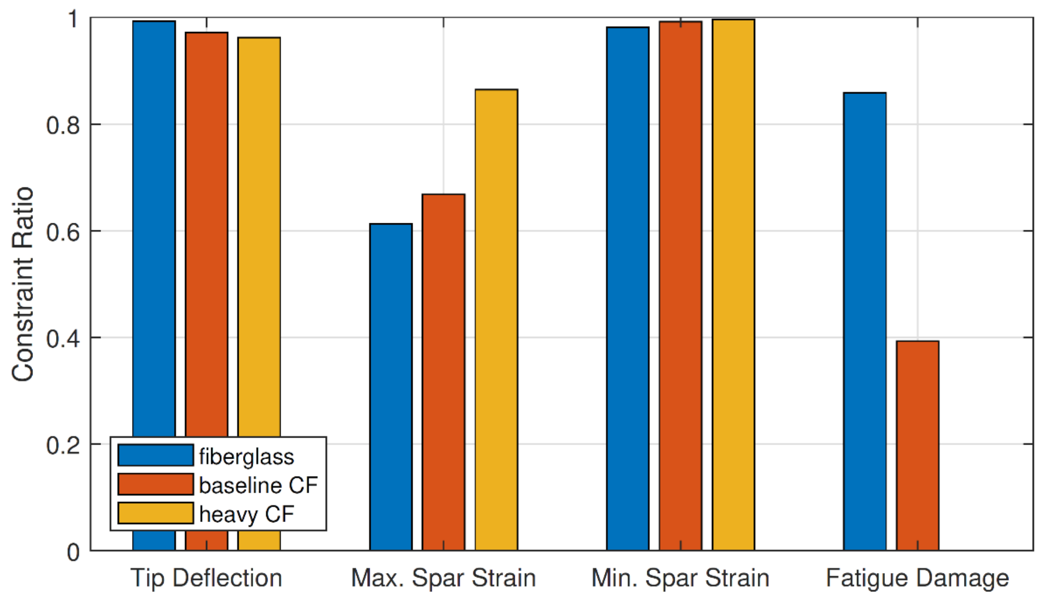
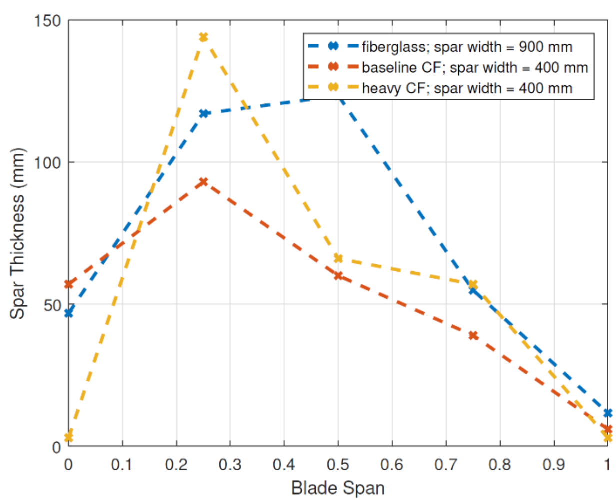
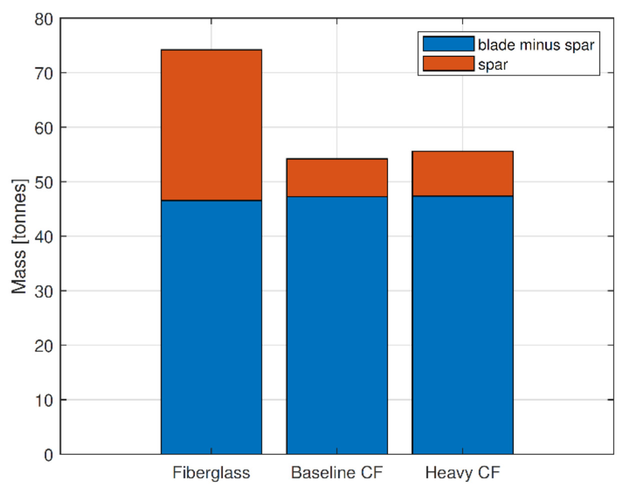


Figure 4-4. Offshore turbine optimal solution constraint values (nearly infinite fatigue life prediction for the heavy tow textile carbon fiber).

The optimized spar cap thickness profile and the resulting blade mass for the 10 MW turbine are shown in Figure 4-5. The spar cap for the carbon fiber designs represents 13-15% of the total blade mass, while the fiberglass spar cap is over 37%. This difference results in a 25-27% decrease in blade mass for the carbon fiber designs.



(a) Spar cap thickness profile comparison



(b) Spar cap and blade mass comparison

Figure 4-5. Offshore turbine optimal solution spar cap dimensions.

Although the carbon fiber spar designs reduce the spar cap mass by upwards of 20 tonnes, the resulting material cost for the carbon spar caps is greater than that for the fiberglass design as seen in Figure 4-6. The baseline carbon fiber spar cap material cost is 100% higher than the fiberglass spar, while the novel heavy tow carbon fiber is 22% higher. There are additional system-level reasons to utilize carbon fiber in this design due to the high sensitivity of platform and installation costs to turbine mass (particularly for floating offshore sites). The system benefit of lower blade mass is likely why larger, heavier blades more commonly utilize carbon fiber spar caps, as shown in Figure 1-3. When this is the case, the heavy tow carbon fiber spar cap will save 39% in material cost over the baseline carbon fiber material and will reduce the system LCOE.

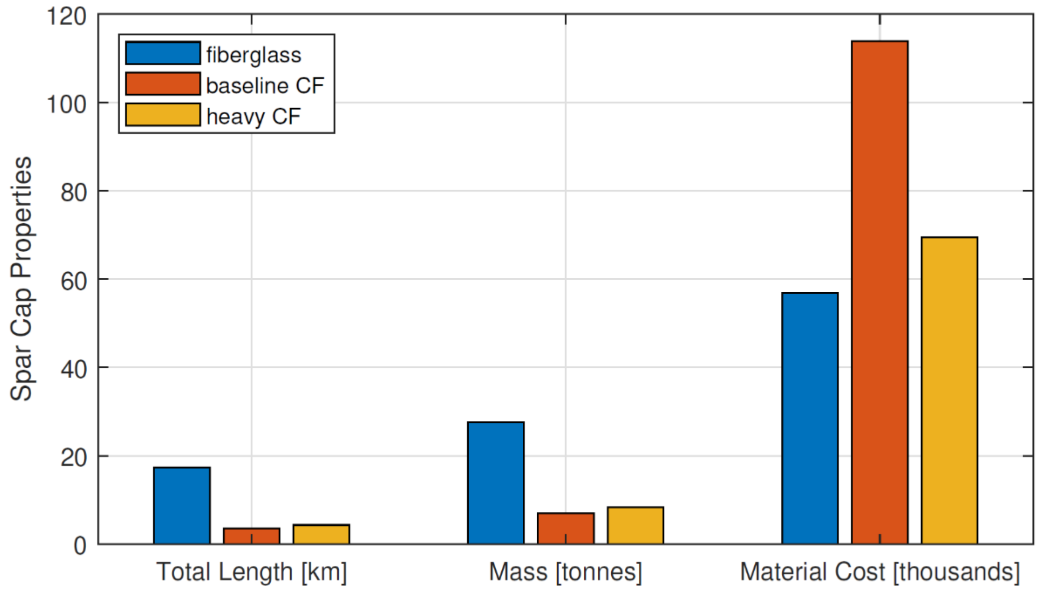


Figure 4-6. Offshore turbine optimal solution spar cap properties.

5. SUMMARY AND LIMITATIONS OF FINDINGS

Heavy tow textile carbon fiber materials have been identified as promising candidates for use in wind turbine blade design through this project. Two novel carbon fiber materials in research and development production at ORNL's Carbon Fiber Technology Facility have been selected as points of study in this project, to compare with Zoltek PX35 carbon fiber as a representative industry baseline. Previous work has shown the merit of the textile carbon fiber materials in terms of a projected cost reduction compared to commercial carbon fiber. This work was expanded to include the actual carbon fiber processing of the Kaltex CFTF material which was tested in this project and to estimate the likely commercial-scale processing of the material. This analysis found that the heavy tow textile carbon fiber has an estimated 38-57% cost reduction in comparison to the industry baseline, for the two processing scenarios (Table 2-6). A pultrusion cost model was also developed within this project to estimate the additional cost of this intermediate manufacturing step and to enable comparison with other manufacturing approaches, such as fiberglass VARTM infusion. When adding the pultrusion manufacturing step into the cost estimate for a 68% fiber volume pultrusion, the heavy tow carbon fiber material has a 49% reduction in cost from the baseline carbon fiber, for the commercial processing assumptions. The substantially reduced cost is promising but the performance of this material is equally important and necessary to compare materials in a blade design.

Characterization of the mechanical properties has been accomplished through mechanical testing in pertinent composite forms to identify performance differences. The tested mechanical properties were used to compare performance in a 68% fiber volume pultrusion that has been used in blade optimization studies. The heavy tow textile carbon fiber material was found to have a nearly identical modulus in testing but with a 38% reduction in tensile strength from extrapolation of the testing results (Table 2-11). Wind turbine blade spar caps experience similar compressive and tensile loads however, and the lower compressive strength is what drives structural design and not the tensile strength. The heavy tow carbon fiber material was observed to be more similar to the industry baseline in compressive strength, giving up only 20% of this important property. Fatigue properties were also verified through a single load cycle ratio comparison at R=0.1 and the Kaltex heavy tow carbon fiber material was observed to have a fatigue slope of m=45, revealing a high level of fatigue insensitivity for this material – an important factor in wind turbine design (Figure 2-16). Comparing mechanical properties of the heavy tow textile carbon fiber pultrusion on a cost-specific basis with the industry baseline reveals a 100% increase in modulus per-cost, and a 22% increase in tensile strength and 56% increase in compressive strength per-cost (Table 2-12). This cost-specific comparison uses test data from material processed in a different manner, and there is some uncertainty on the mechanical properties at the commercial "full-utilization" cost scenario. This more likely commercial processing approach is not expected to greatly affect the mechanical properties, but is an unknown. The processing parameters used to produce the tested heavy tow carbon fiber material result in a cost estimate that is 31% higher than the cost used and are considered conservative.

As noted in the experimental description, the textile carbon fiber tow does present some processing challenges as the product forms are evolving. The heavy tow material utilized in this experimental work supplied from CFTF were spools having circumferentially wrapped layers with paper interleaving to prevent layer entanglement. Dealing with the paper removal and fuzz generated in unspooling and passing through contact points added additional labor. However, these issues are being addressed in ongoing initiatives to improve precursor uniformity at the textile fiber suppliers and to develop new packaging approaches with fiber packaging specialists that actually take advantage of the potential gains from utilizing the much larger tow sizes. A key factor in many intermediate fiber forming and final composite manufacturing operations is the cost of creeling equipment and setting up those creels for operation. It is not unusual for large processing operations to require creels of over a hundred individual spools. In going from a Zoltek 50K product to the larger Kaltex or Taekwang tows, the number of individual spool positions could be reduced by a factor of three to four times to achieve the same composite cross-sectional area. The textile carbon fiber study material is considered a developmental material that will likely benefit from further process refinement to yield more optimized mechanical properties for the wind turbine application. Other handling and cost/performance tradeoffs are under consideration and can take advantage of findings from this project to guide future developmental focus.

The improvements of the cost-specific mechanical properties for the novel textile carbon fiber material are expected to result in a similar reduction in spar cap material cost compared to the baseline materials. There is a complicated relationship between mechanical properties and material demand in a wind turbine blade and this was analyzed through structural optimization routines. The two carbon fiber materials were compared with traditional fiberglass in the blade spar cap with structural optimizations studies of a 3 MW and 10 MW reference turbine. These two reference turbines were used to represent industry trends and to capture the different material demands placed on wind turbine blades.

The resulting spar cap material cost is used as a comparison of the three materials. This comparison is appropriate for the two carbon fiber materials, which are both in a pultruded composite form, but there are secondary cost effects related to manufacturing costs and rotor mass not included in this comparison. The material cost comparison of the carbon spar caps versus the fiberglass spar does not account for additional system cost benefits of the carbon fiber resulting in a lower mass rotor or potential manufacturing cost reductions due to the lower number of spar cap layers for carbon pultrusions. Additional system cost reductions are present using either carbon fiber material, but these are not quantified by this study. Comparing purely the spar cap material cost, it is apparent why the industry has mostly avoided utilizing carbon fiber in their turbine models. The baseline carbon fiber spar cap material cost was seen to be 48% and 100% higher than the fiberglass spar cap material cost for the 3 MW and 10 MW turbines, respectively. The novel heavy tow textile carbon fiber material was observed to have a 43% and 39% reduction in spar cap material cost compared to the baseline carbon fiber. This reduction is a result of the 56% improvement in cost-specific compressive strength for the heavy tow carbon fiber material, which also has a lower absolute value for the compressive strength.

The spar cap material cost for the heavy tow carbon fiber design was actually 16% lower than the fiberglass design for the 3 MW turbine. This novel material is the optimal choice for this low wind speed, high energy capture turbine design which will be increasingly common for wind turbine deployment within the United States. The 3 MW turbine with a fiberglass spar cap was fatigue driven and these designs benefit greatly from the usage of carbon. An additional benefit for the heavy tow carbon fiber material from the improved fatigue properties is seen in a spar cap life of 63 years, compared to 32 years for the fiberglass design.

For the 10 MW turbine, the heavy tow carbon fiber spar cap material cost is 22% higher than the fiberglass design, which is a significant reduction from the baseline carbon fiber spar cap cost. The industry trends shown in Figure 1-3 and Figure 1-4 suggest that the baseline carbon fiber is preferred over fiberglass for these large turbines however, and this is likely a result of the system benefits from reduced blade mass. This reduction is especially significant for offshore wind turbines where the support foundation costs represent 30-40% of the system LCOE and scale with the topside mass. The blade structure is greatly affected by the aerodynamic shape and thickness profile of the turbine, and a follow-on study is recommended to perform aero-structural optimizations of this blade. This would further reduce the mass of the carbon fiber designs and potentially result in improved material costs for the heavy tow carbon fiber blade relative to the fiberglass design.

The 3 MW baseline carbon fiber spar cap had a fatigue life prediction of 800 years and the 10 MW heavy tow textile carbon fiber spar cap would effectively never fail in fatigue. The improved design life is a result of the exponential relationship between loads and fatigue damage, and the better fatigue characteristics of carbon fiber compared to fiberglass. The performance of carbon fiber could actually enable carbon spar caps to be reused in wind turbines or other structural applications, resulting in a higher end-of-life recycling value for this portion of the carbon spar blade designs.

The heavy tow carbon fiber had a comparable performance in the blade designs to the baseline carbon fiber design, but at a significantly lower cost and a slightly higher mass (1-3% for the two turbine designs). The improved mechanical properties of carbon fiber result in significantly lower spar cap material mass compared to the fiberglass design and were found to reduce the total blade mass by 27-28% for the 3 MW turbine and 25-27% for the 10 MW turbine. Blade mass reduction comes with an associated cost reduction for the drivetrain, foundation, and installation, which would be reduced for the carbon spar cap designs. Carbon fiber enables longer rotors which capture more energy through reduced mass scaling exponents with blade length, as shown in Figure 5-1.

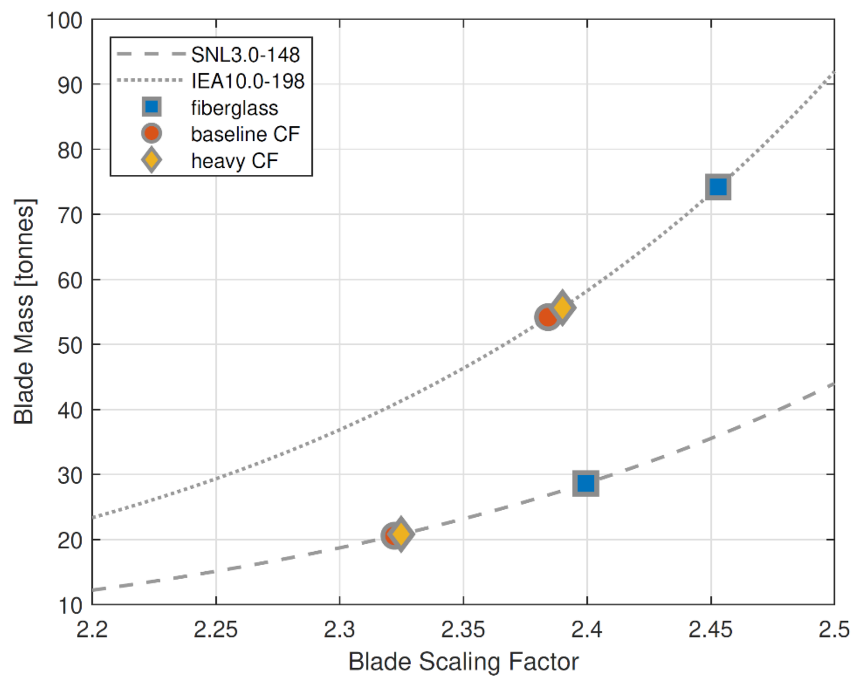


Figure 5-1. Blade mass scaling (*mass=length* $^{scaling\ factor}$) utilizing the three study materials (dashed lines show traditional blade mass scaling; markers show mass results from this study).

The novel heavy tow textile carbon fiber material was found to have a more optimal relationship between tensile and compressive strength for wind turbine blades. The improved precursor quality and processing that yields a higher tensile strength for the resulting commercial carbon fiber comes at a higher cost, as correlated in Equation (2-2). The optimization studies confirmed that tensile strength does not drive the material demand for the spar cap, and carbon fiber material design should focus on compressive strength as opposed to paying for excess tensile strength. The 3 MW and 10 MW designs with carbon fiber optimized to use up effectively all the design compressive strength for both carbon fiber materials. The baseline carbon fiber had 33% remaining tensile strength for both the 3 MW and 10 MW turbine designs. This is compared to only 17% and 14% unused tensile strength with the heavy tow textile carbon fiber. There is a complicated relationship between carbon fiber material cost and compressive strength, but the ratio of tensile to compressive strength is seen to be more ideal for the heavy tow carbon fiber in wind turbine blade design. The reduced tensile strength for the heavy tow textile carbon fiber of ~40% compared to the baseline carbon fiber material is not problematic, but actually more optimal for wind turbine blade design.

6. CONCLUSION

Novel heavy tow carbon fiber materials derived from the textile industry have been characterized and found to have improved performance-per-cost compared to baseline carbon fiber materials commonly used in the wind industry. The commercial carbon fiber does have higher strength values than the heavy tow textile carbon fiber, but it does so at a higher cost. The significantly reduced cost and similar performance for mechanical properties of greatest significance (e.g., modulus and compressive strength) of the heavy tow textile carbon fiber result in lower spar cap material costs for utilizing this novel carbon fiber in wind turbine blade design.

The heavy tow textile carbon fiber was shown to have a more optimal relationship between tensile and compressive strength for wind turbine blades. There is an associated cost with tensile strength and the blade designs using the industry baseline material cannot adequately utilize this property, as tensile strength does not drive the material demand for wind turbine spar caps. There is a complicated relationship between compressive strength and cost, but the ratio of tensile to compressive strength is more ideal for the heavy tow carbon fiber. The reduced tensile strength of ~40% compared to the baseline carbon fiber material is not problematic but rather more optimal for wind turbine blade design to reduce material precursor costs.

There are additional benefits and considerations shared by both the heavy tow textile and the commercial carbon fiber materials, relative to turbine designs with fiberglass spar caps. Carbon enables slender blade designs to be more cost effective due to the relationship between strength and stiffness. Slender blade designs are more aerodynamically efficient resulting in energy gains and reduced thrust loads, in addition to utilizing less shell material. Slender designs may also result in reducing transportation costs and constraints for larger land-based rotors. Carbon fiber blade designs have lower mass which produces system cost benefits to the drivetrain and structural components and bearings. Carbon designs also have higher modal frequencies compared to fiberglass designs, providing a simple means to avoid dwelling at resonant conditions through material selection. The carbon fiber spar cap material fatigue life was predicted to survive at least double that of the fiberglass design for both the land-based and offshore reference turbines, enabling a longer design life and/or improving the value for recycling the materials. Finally, the higher performing carbon fiber materials result in fewer layers which could reduce manufacturing costs for the spar cap compared to fiberglass designs.

Subject to the assumptions and approach taken within this project, the heavy tow textile carbon fiber material studied offers a more optimal solution for wind turbine blade spar cap material than the commercial carbon fiber materials currently available to the wind industry. This novel material could enable the benefits of carbon fiber to be realized more broadly across the wind industry and reduce the levelized cost of energy from commercial carbon and glass fiber materials presently available to turbine blade designers. This discrete comparison shows promise for the novel study material, and future studies will focus on the tradeoff of mechanical properties and cost to further optimize carbon fiber materials for wind turbine blade design.

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APPENDIX A. CARBON FIBER COST MODELING DETAILS

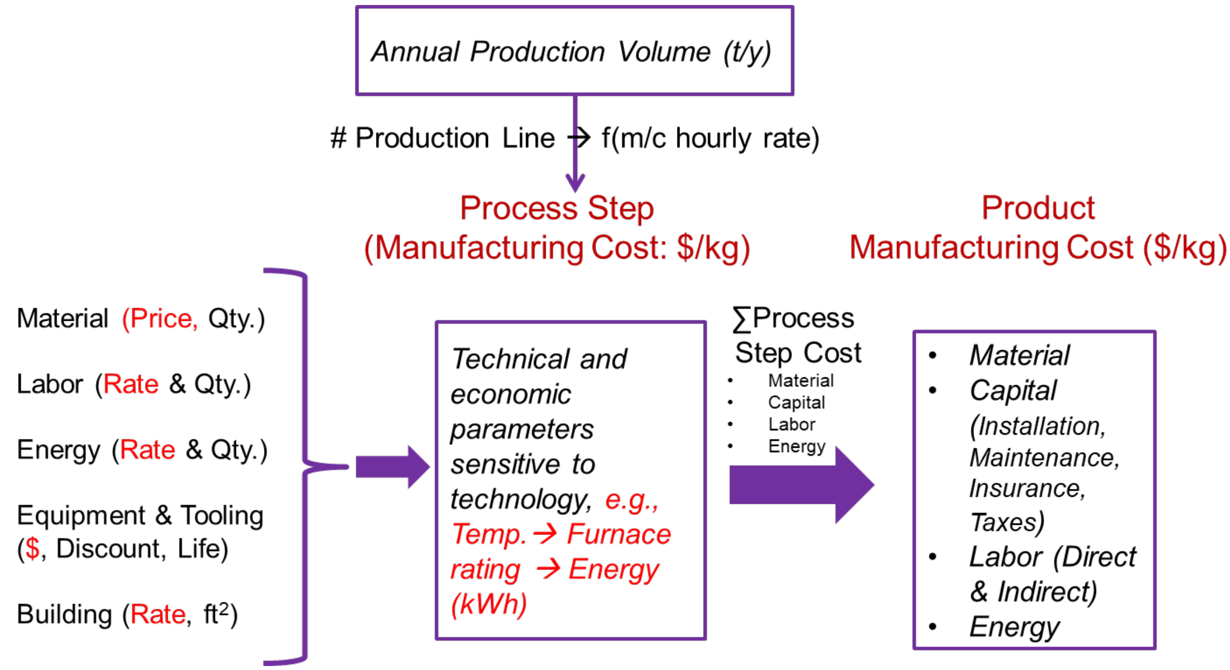

Figure A-1. Carbon fiber cost modeling framework.

- 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

Figure A-2. High level assumptions in the material cost modeling.

Product Description				
Tow size	50,000	filaments		
monofilament dtex	0.74	g/10,000m/CF filament		
yield (English) as a function of dtex	*402*	*ft/lb*		
yield (metric) as a function of dtex	*270*	*meters/kg*		
Production Volume				
Desired production volume	1,500	tonnes CF/yr		
Desired production volume	*1,500,000*	*kg CF/yr*		
Desired production volume	*3,306,900*	*lbs CF/yr*		
Plant Availability				
Total hours in one year	8760	hr		
Availability proportion	0.815	dimless		
Available hours per year	7,139	hr		
Available minutes per year	*428,364*	*min*		
Available seconds per year	*25,701,840*	*s*		
Step Yields and Annual Mass Flows				
	Proportion of original precursor mass remaining due to chemical changes	Step input (kg/yr	Chem yield	Mech yield
Pretreatment	1.000	3,303,861	1.000	0.987
Oxidation	0.960	3,260,911	0.960	0.987
LT	0.556	3,089,778	0.580	0.993
HT	0.470	1,778,110	0.846	0.993
Abatement	0.470	1,492,869	1.000	1.000
Surface Treatment	0.470	1,492,869	1.000	0.995
Sizing	0.480	1,485,405	1.020	0.995
Winding/Inspection/Shipping	0.480	1,507,538	1.000	0.995
		Yield	0.4798	0.9462
Capacity of one CF line for the assumed plant availability and Yields				
Equipment width	3000	mm		
Tow band width as proportion of equipment width	0.96	dimless		
Tow band width	2880	mm		
Tow spacing	24	mm		
Strands/line	120	strands		
Required line speed for entire plant	8.3348	m/min		
Desired cxidation residence time	90	min		
Required oxidation heated length for entire plant	750	m		
Actual oxidation heated length for single CF line	752	m		
Desired LT residence time	90	s		
Required LT heated length for entire plant	12.5	m		
Actual LT heated length for single CF line	12.6	m		
Desired HT residence time	90	s		
Required HT heated length for entire plant	12.5	m		
Actual HT heated length for single CF line	12.6	m		
Line speed imposed by oxidation equipment	8.36	m/min		
Line speed imposed by LT equipment	8.40	m/min		
Line speed imposed by HT equipment	8.40	m/min		
Overall line speed imposed by equipment (min of Oxi, LT, HT)	8.36	m/min		
Capacity of one CF line as defined by user	1,503,742	kg CF/yr		
Number of CF lines required for desired production volume	1	CF lines		
Collective utilization of all CF lines	0.9975	dimless		
Hours equipment in operation per CF line	7,122	hours/CF line		

Figure A-3. An example of the spreadsheet cost modeling framework global parameters.

- **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 might 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**

Figure A-4. Annual production volume impact approach.

APPENDIX B. REFERENCE BLADE MATE RIALS

Table B-1. Material input characteristic properties (95% value with 95% confidence) used for blade model development and structural optimization.

Material	Modulus (E1, E2, E3) [GPa]	Shear Modulus (G12, G13, G23) [GPa]	Poisson Ratio (v12, v13, v23) [-]	Tensile Strength (S1, S2, S3) [MPa]	Compressive Strength (S1, S2, S3) [MPa]	Composite Thickness [mm]	Composite Density [kg/m³]	Material Cost [$/kg]
Intermediate Pultruded Composite (68% fiber volume fraction) [4]								
Industry baseline CFRP	150.2, 9.1, 9.1	4.0, 4.0, 3.5	0.318, 0.318, -	2236, -, -	-1528, -, -	3-5	1600	$16.44
Heavy-tow textile CFRP	149.4, 9.1, 9.1	3.0, 3.0, 2.6	0.323, 0.323, -	1357, -, -	-1183, -, -	3-5	1600	$8.38
Vacuum Assisted Resin Transfer Molding (VARTM) Infusion (57% fiber volume fraction) [5]								
Unidirectional glass (0º)	41.3, 16.3, 16.3	3.3, 3.3, 3.3	0.263, 0.263, 0.35	863, 33, 33	-614, -39, -39	0.9	1970	$2.06
Vacuum Assisted Resin Transfer Molding (VARTM) Infusion (55% fiber volume fraction) [6]								
Biaxial glass (-45º/+45º)	11.1, 11.1, 11.1	12.6, 3.3, 3.3	0.263, 0.263, 0.5	-, -, -	-, -, -	0.6	1940	$2.08
Triaxial glass (-45º/0º/+45º)	21.8, 15.1, 15.1	9.5, 3.3, 3.3	0.263, 0.263, 0.5	-, -, -	-, -, -	1.5	1940	$2.08
Balsa	0.1, 0.1, 3.57	-, 0.16, 0.16	0.26, 0.26, 0.26	-, -, -	-, -, -	6-13	160	-
Gelcoat	3.4, 3.4, 3.4	-, -, -	0.3, 0.3, 0.3	74, 74, 74	-87, -87, -87	0.5	1200	-

[4] Longitudinal properties estimated in Section 2.4; transverse modulus used is from 62% fiber volume industry baseline pultrusion tests; shear properties are theoretical estimates with high uncertainty

[5] Properties derived using test data [7] and calculation of characteristic strengths [5]

[6] Biaxial and Triaxial properties estimated using unidirectional data and classical lamination theory

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