Economic Competitiveness of Pultruded Fiber Composites for Wind Turbine Applications

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Abstract

Pultrusion manufacturing of fiber reinforced polymers has been shown to yield some of the highest mechanical properties for unidirectional composites, having a high degree of fiber alignment with consistent performance. Pultrusions offer a low-cost manufacturing approach for producing unidirectional composites with a constant cross-section and are used in many applications, including spar caps of wind turbine blades. However, as an intermediate processing step for wind blades, the additional cost of manufacturing pultrusions must be accompanied by sufficient increases in mechanical performance and system benefits. Wind turbine blades are manufactured using vacuum-assisted resin transfer molding with infused unidirectional fiberglass or carbon pultrusions for the spar cap. Infused fiberglass composites are among the most cost-effective structural materials available and replacing this material in the cost-driven wind industry has proven challenging, where infused fiberglass spar caps are still the predominant material system in use. To evaluate alternative material systems in a pultruded composite form, it is necessary to understand the costs for this additional manufacturing step which are shown to add 33%-55% on top of the material costs. A pultrusion cost model has been developed and used to quantify cost sensitivities to various processing parameters. The mechanical performance for pultruded composites is improved versus resin-infusion manufacturing with a 17% increase in design strength at a constant fiber volume fraction, but also enables higher achievable fiber volume fractions. The cost-specific mechanical performance is compared as a function of processing parameters for pultruded composites to identify the opportunities for alternative material and manufacturing approaches for wind turbine spar caps. Four materials are compared in a representative wind turbine blade model to assess the performance of pultruded carbon fiber systems and pultruded fiberglass relative to infused fiberglass, where the pultruded systems produce lower weight blades with various cost distinctions.

1. Introduction

Global development of wind energy has grown rapidly over the last several decades as a result of technology improvement and cost reductions. The technology has matured significantly such that wind energy is among the three lowest cost options of new energy generation in the US, based on the local wind resource [1]. In efforts to further enhance cost competitiveness in areas with and without optimal wind resources, wind turbines are becoming larger in both physical size and energy generation capabilities. This trend results in longer blade lengths with exponentially higher blade mass and increased structural loading demands. Wind turbine blades are typically manufactured with an outer aerodynamic shell largely constructed from fiberglass and core materials, where the majority of the structural rigidity is provided by spanwise members composed of continuous length unidirectional composites, analogous to internal beam structures along the blade span. The spar caps resist the

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downwind thrust loads while the edgewise reinforcements carry the torque and gravitational loads from blade rotation. A typical wind blade cross-section is depicted in Figure 1.

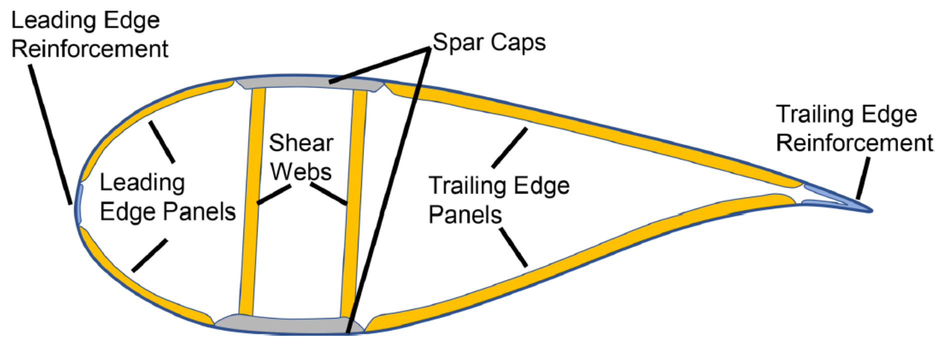


Figure 1. Traditional wind turbine blade structural components [2].

Wind turbine blade spar caps have traditionally been manufactured using resin-infused fiberglass reinforcement in a vacuum-assisted resin transfer molding (VARTM) process. This design approach capitalizes on low-cost material forms and a simple manufacturing technique with minimal capital equipment required, other than mold forms, but with higher labor than automated processes. As the blade mass and operational loading has increased for modern wind turbine blades exceeding 100 m in length, alternative materials and manufacturing methods for the spar caps that can reduce mass and cost are of increasing importance. Carbon fiber has been used as an alternate reinforcement fiber based on the approximately 3-4 times higher stiffness and 30% lower density compared to E-type fiberglass, although the fiber tensile strength for industrial grades of carbon fiber is relatively comparable. Early utilization of carbon fiber in wind turbine spar caps was accomplished by using the traditional VARTM infusion with prepreg carbon fiber sheets, which resulted in wind turbine blade failures due to the high sensitivity of carbon fiber to wrinkling with this manufacturing process [3]. Modern wind turbine blades using carbon fiber composite spar caps are exclusively comprised of pultruded carbon fiber composite planks to build up the spar cap component. This intermediate manufacturing step adds costs, but also increases the level of manufacturing control for this critical component, introducing other advantages [4]. Despite the superior mechanical performance of carbon fiber composites, wind turbine designs predominantly do not use carbon fiber due to the high relative costs. Carbon fiber is typically an order of magnitude more expensive per mass than E-type fiberglass. The higher mass-specific stiffness and strength of carbon fiber does enable lower weight structures, and to realize these performance benefits alternative manufacturing techniques are typically used to enable the most optimal cost-performance for carbon composites.

The pultrusion process as depicted in Figure 2 offers opportunity to provide greater alignment of the reinforcing fiber in the direction of the dominantly longitudinal loading of the spar caps compared to VARTM infusion. There are some notable distinctions for pultrusions for spar cap manufacturing, including utilization of a rotary take up system as opposed to the traveling cut-off saw, the surfacing veil being replaced with peel-ply application, and the removal of continuous filament mat. The pultrusion process is relatively automated requiring small amounts of labor with respect to its higher continuous throughput [5]. Unidirectional fiber rovings, or tows, are input to the pultrusion process and are among the lowest cost forms for carbon fiber and fiberglass. Production quality is highly consistent and the capital requirements for pultrusion equipment are somewhat modest with respect to the material throughput as compared to other high performance composite production approaches, such as with prepreg fabrics or filament winding. The Department of Energy (DOE) is supporting work at Oak Ridge National Laboratory and other organizations in the Institute of Advanced Composite Manufacturing Innovation to demonstrate approaches for manufacturing low-cost carbon fiber (LCCF) by utilizing alternative precursors and manufacturing techniques such as pultrusion [6]. As alternative forms of lower cost carbon fibers with various cost-performance relationships are becoming available, it becomes critical to have tools to evaluate and optimize the many processing options available to identify those materials with the greatest opportunity to reduce the levelized cost of energy. There is need for an enhanced pultrusion cost model to accurately compare material and manufacturing choices through incorporating the cost of this intermediate manufacturing step for wind blades.

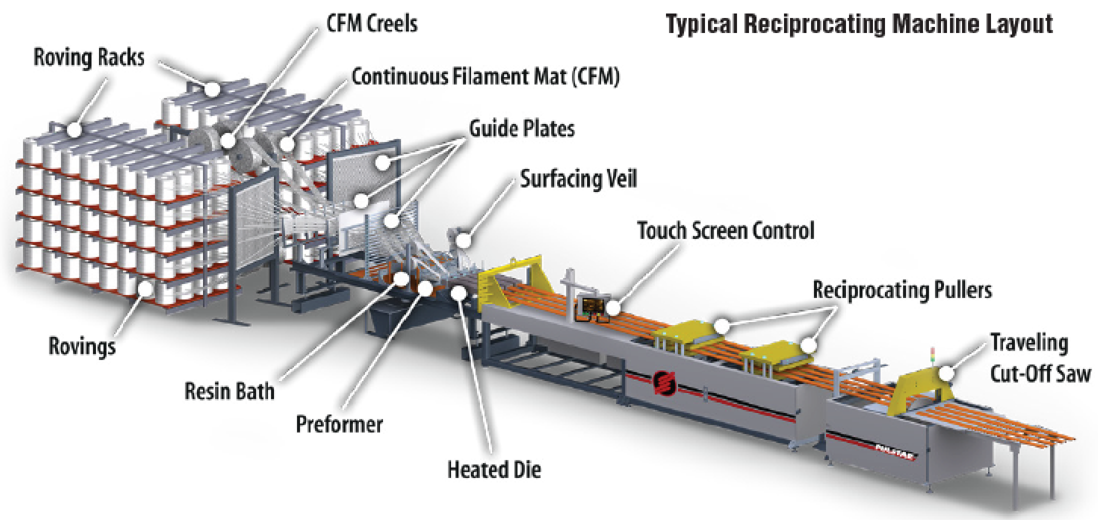


Figure 2. Example pultrusion equipment approach being modeled [7] (with distinctions for spar cap pultrusions).

This paper documents the development of a pultrusion manufacturing cost model and a techno-economic comparison of the design and production tradeoffs of pultruding various forms of fiber-reinforced polymers, using carbon fiber and E-type fiberglass. Glass fiber is by far the most common reinforcement utilized in pultrusions, but pultruded fiberglass has not been utilized at a commercial scale in wind blades. Companies such as Strongwell and Creative Pultrusions are industry leaders in fiberglass pultrusions, manufacturing standardized structural shapes such as angles, channels, and I-beams. The share of the European glass fiber composites market for glass pultrusions was estimated at only about 5% of the total 996,000 tonnes in 2020 [8], but various industry applications are projected to be major markets in the future, including the construction and infrastructure sectors. Infused fiberglass or pultruded carbon fiber are the current material options in wind blade spar caps, and in this study pultruded fiberglass will be compared from a cost-performance perspective to these traditional materials to understand the opportunity space for this material system. The implementation of pultruded carbon fiber spar caps has been successful for use in the wind industry. As a result, the largest supplier of carbon fiber to the wind industry, Zoltek, will increase its production capacity in its Mexico plant to 12,000 tonnes annually and increase the annual global production capacity of its PX35 carbon fiber (used for large-scale industrial applications such as wind energy and automotive) to a total of 35,000 tonnes [9].

For commercial composite systems, a large portion of formulation, mechanical performance, manufacturing details, and certainly the constituent cost elements are considered trade secrets and are not shared publicly. While these manufacturers will frequently comment informally on general assumptions, it is up to the research community to develop their own cost-performance tradeoffs to assess alternative material approaches. This work outlines the steps involved in establishing such tools and provides much of the background that has been incorporated in a cost model that is useful for comparing various pultruded forms of unidirectional carbon and glass-reinforced polymers, with assumptions that are common for blade spar cap pultrusion elements.

2. Pultrusion Cost Model Formulation

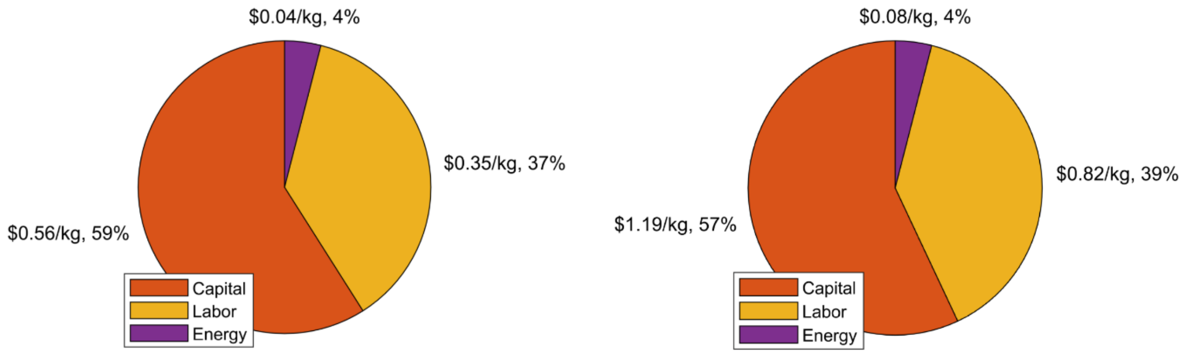
A pultrusion manufacturing cost model for fiber-reinforced polymers has been developed to examine the cost-competitiveness of this composite form for glass and carbon fiber in wind turbine applications. The cost modeling framework assumes a continuous manufacturing operation of a uniform rectangular plank with continuous length reinforcing fibers, which can be of various material forms. The process assumes a conventional approach where fiber tows are initially guided through a resin basin and pulled through a heated 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 handled and spooled onto winders. The final product cost (in terms of $/m or $/kg) is determined at the level of four major cost categories of materials, capital, labor, and energy based on the assumptions of underlying economic and technical processing parameters. A discounted process cost model is used with a 7% cost of capital and direct labor rates of $28/hour with 15% additional cost for indirect labor. Capital and building costs have been amortized over 15 years and 30 years of life, respectively. The manufacturing facility is assumed to be a 30,000 ft^2 greenfield facility at a construction cost of \$150/ft^2. The estimated product cost is not necessarily the selling price, which varies based on market dynamics.

Table 1 shows the baseline assumptions of major cost estimation parameters for carbon and glass fiber pultruded composites with a 68% fiber volume and epoxy resin. Two carbon fiber systems are shown with equivalent processing assumptions, representing a commercial-grade 50K baseline carbon fiber (based on the Zoltek PX-35 material) and a 457K heavy-tow textile carbon fiber produced by ORNL from a Kaltex precursor and characterized in earlier work [10]. Material cost estimates were developed for both carbon fiber systems representing additional manufacturing capacity using new equipment. Several fiber dependent processing parameters such as plank thickness, fiber cost, pulling speed, and total capital investment are defined independently to reflect differences in the current state of manufacturing technology between the two fiber composite types. A higher plank thickness of 5 mm for glass compared to 4 mm for carbon is representative of the commercial challenges with spooling the stiffer carbon fiber composite. Glass pultrusions reportedly can operate at higher pulling speeds than when using carbon fiber, and the reference pulling speeds are based on typical values for both. The challenges with pultruding carbon fiber require a maximum of two parallel pultrusion operation streams to ensure the quality of the pultruded product. Pultruding glass fiber is somewhat simpler, and a three-stream operation is expected to be more likely for commercial applications with a simple geometry. Total capital investment cost for a single pultrusion line (running 2 or 3 parallel planks simultaneously, referred to as 2-stream or 3-stream) is approximated at $815K for glass fiber and $835K for carbon fiber composites, quoted from one of the major equipment suppliers. Of the total capital investment cost, the pultrusion equipment has more than a 90% share and the higher cost in the case of carbon pultrusions is due to additional creel tensioning requirements. Energy consumption is estimated to be 44kW continuous for a single pultrusion machine based on commercial input. For wind turbine spar cap applications, where the pultrusion must be bonded within the final composite structure, peel-ply is frequently used on the top and bottom surfaces to prepare the surface for adequate bonding between adjacent stacked pultrusion planks during infusion in the shell mold. Peel-ply costs are estimated using a volume discount of $0.11/m which is included in the material cost component of the pultrusion cost estimates.

Table 1. Baseline assumptions for major parameters of pultruded fiber composites modeling.

Parameter	**E-Glass**	**Industry Baseline Carbon Fiber** [10]	**Heavy-Tow Textile Carbon Fiber** [10]
Plank Size (Width x Thickness)	0.005m x 0.15m	0.004m x 0.15m	0.004m x 0.15m
Plank Weight [kg/m]	1.595	0.974	0.949
Fiber volume fraction	0.68	0.68	0.68
Fiber weight fraction	0.816	0.758	0.752
Composite Density [kg/m^3]	2125	1620	1580
Fiber Cost [/kg]	$1.30	$17.98	$7.82
Epoxy Resin Cost [/kg]	$4.00	$4.00	$4.00
Peel-Ply Cost [$/m]	$0.11	$0.11	$0.11
Line Speed [m/min]	1.27	0.90	0.90
Material/Process Yield	99.7%/97%	99.7%/97%	99.7%/97%
Operating Lines Per Machine	2 or 3	2	2
Annual Production Volume [MT / Million m]	1,703 / 1.07	738 / 0.757	719 / 0.757
Capital Investment / Life	$815K / 15 years	$835K / 15 years	$835K / 15 years
Tooling Cost / Life	$75K / 300 km	$75K / 300 km	$75K / 300 km
Energy Consumption	220V x 200A = 44kW	220V x 200A = 44kW	220V x 200A = 44kW
Annual Downtime	20%	20%	20%
Labor (#)	2 per shift for a 24-hr. continuous operation	2 per shift for a 24-hr. continuous operation	2 per shift for a 24-hr. continuous operation
Floor Space (Direct)	30,000 ft2	30,000 ft2	30,000 ft2

Figure 3 shows the processing costs of pultruding fiberglass and carbon fiber (baseline of heavy-tow textile) in a two-stream operation based on the model inputs in Table 1. The total carbon fiber pultrusion processing cost-per-mass is more than double the processing costs using fiberglass. The higher processing cost results from the lower processing speed and thinner planks for carbon pultrusions, with increases in each processing cost component. The pulling speed reduction for carbon fiber pultrusions is a result of the need for more attention in creel management to assure uniform tension management as well as more fiber spool/package changeout due to typically smaller length spools utilized for carbon fiber versus fiberglass. The processing costs are dominated by capital and labor costs, comprising 96% of the total processing cost on a mass basis, while the energy costs have a nearly negligible impact on the total cost.



(a) Glass reinforcement fibers (b) Baseline carbon reinforcement fibers

Figure 3. Estimated pultrusion processing cost breakdown using a two-stream operation.

Figure 4 shows the comparative pultruded fiber composite plank costs using conventional E-glass, the industry baseline carbon fiber, and heavy-tow textile carbon fiber materials for two-stream pultrusion operations. The high relative material costs for carbon fiber, in combination with increased processing costs, results in carbon pultrusion plank costs that are greater than three to five times that of glass pultrusions (on a mass basis). The cost benefits of the heavy-tow textile carbon fiber are illustrated with a pultruded part cost that is over 40% less than the baseline carbon fiber. The materials represent 75% of the pultruded composite cost for the heavy-tow textile carbon pultrusions, compared with 64% for glass pultrusions. The high relative costs of commercial carbon fiber materials compared to fiberglass has been one of the major challenges for its broader use by the wind industry, motivating the study and development of the heavy-tow textile carbon fiber. Commercial carbon fiber pultrusions have been stated to cost in the range of $10-$15/kg using materials common to the wind industry. The carbon fiber production is thought to be mostly using fully depreciated capital equipment, meaning increased carbon fiber production capacity will come at a higher relative cost. The textile carbon fiber material from the DOE LCCF program assessed in earlier work [10] is prioritized in the following analysis to represent future innovations in carbon material systems for use in cost-driven industries.

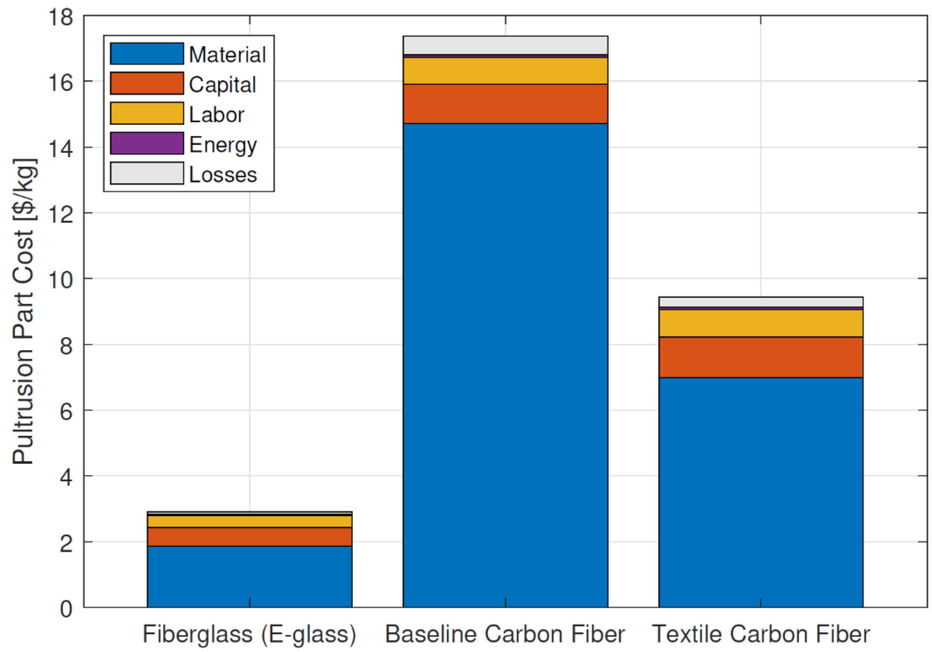


Figure 4. Estimated pultruded composite cost using a two-stream operation.

The value of a composite material in a structural application is a function of not only the cost, but also the mechanical performance. The mechanical properties and cost-specific performance of common materials in use by the wind industry are assessed in Section 4. The pultrusion processing costs are also affected by the number of parallel pultrusion streams assumed for the reinforcement fiber. Figures Figure 3 and Figure 4 have shown the cost comparisons assuming two-stream processing for both fiberglass and carbon fiber pultrusions for consistency in the comparison, but a three-stream processing for fiberglass pultrusions is considered slightly more likely and will be used exclusively in the following sections. Where three-stream processing can be effectively deployed, material throughput is increased by 50% with negligible increase in capital equipment, labor, and energy. Three-stream production reduces the relative cost-per-mass of all cost components except for the material costs. The suitability of a three-stream processing depends on the ability to accomplish it without requiring additional labor or sacrificing pultrusion quality, which is a function of the reinforcement fiber and resin system.

3. Pultrusion Manufacturing Cost Sensitivities

This section explores relationships of several processing parameters or physical characteristics to part costs on a mass or volumetric basis, as indicated. This analysis is independent of amount of materials required to meet performance requirements, which is discussed in Section 4. The final pultrusion part cost (C_{part}) is a combination of material ($C_{material}$) and processing costs (C_{proc}). There are two primary yields considered which control the final amount of usable pultruded composite from the input material volumes, based on the material yield ($\eta_{material}$) and the process yield ($\eta_{process}$) values. The material yield is defined as the amount of input material that is processed into a pultrusion which accounts for unprocessed materials, such as at the end of fiber spools, materials that must be removed periodically, etc. The process yield is the final output of pultruded composite that can be sold, which results from the loss of startup and shutdown planks, rejected materials from quality control inspections, etc. Calculation of the pultrusion part cost is defined relative to the baseline yields in Equation (1). In this equation, the material cost is per unit of input materials (treated equivalently for reinforcement fiber and resin in their relative composite ratio in this formulation) and the processing cost is per unit of pultruded composite prior to accounting for process yields.

$$C_{part} = \frac{1}{\eta_{process}} \left(C_{proc} + \frac{1}{\eta_{material}} C_{material} \right) \tag{1}$$

The processing costs (C_{proc}) for pultruding a fiber reinforced polymer are determined from the developed pultrusion cost model with defined inputs from Table 1. In this model, the processing costs on a length basis are a direct function of the pulling speed and number of parallel pultrusion streams. Despite the minor capital cost differences for pultruding carbon fiber and glass fiber shown in Table 1, the pultrusion model results in Figure 5 are representative for either material system with only a minor reduction in accuracy due to the 2.5% difference in capital equipment costs. The results in Figure 5 were obtained for the baseline 68% fiber volume fraction composites with a 150mm width but are independent of fiber volume fraction and part width, although these two parameters could affect the processing speed or pultrusion yields.

The pultrusion model uses an energy cost that is purely a function of processing time. In practice, energy requirements would change slightly with various processing parameters but the pultrusion cost model does not currently include a physical energy model to account for these relationships [11]. However, given that energy costs are shown to represent a very minor share of the processing costs in Figure 3, the resulting energy changes with pulling speed, part width, and fiber volume fraction are considered insignificant. Clamping and pulling loads would vary interdependently as a function of part width and thickness, fiber fraction, and pulling speed [12]. In related work pultruding textile carbon fiber materials, it has been observed that once the process starts the pulling force is minimally influenced by pulling speed changes, depending on a variety of factors [6]. Tool heating loads would be expected to increase somewhat as a function of higher pulling speeds, but the heating load would decrease somewhat by higher exothermic heat generation rates at higher widths and lower fiber fractions.

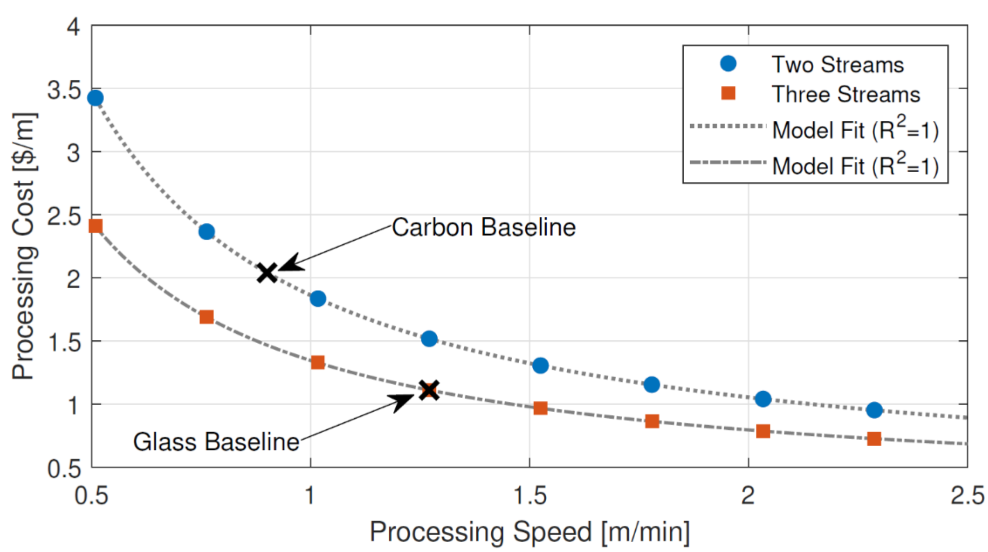


Figure 5. Processing cost versus processing speed for two and three parallel pultrusion streams.

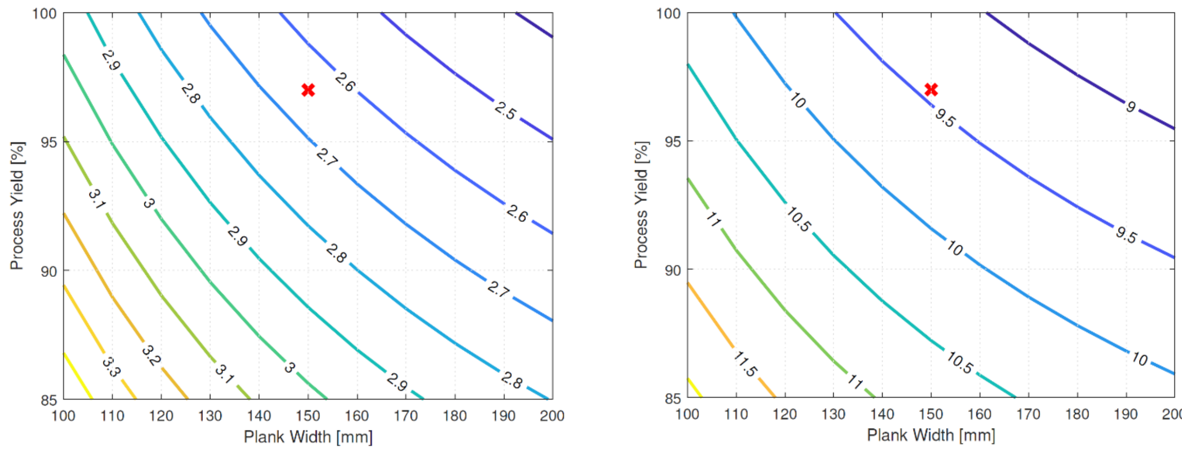
The pultrusion processing cost estimate can be defined by fitting the simulation results for the two-stream and three-stream model results. Power law fits to the simulation results are used to define the relationship between processing cost on a length basis and the curve fits are provided in Equations (2) - (3), which are plotted as the dashed grey lines in Figure 5.

$$C_{proc}^{Two\ Streams}\left[\frac{\$}{m}\right] = \frac{1.616}{{V_{proc}}^{0.9987}} + 0.244 \quad (2)$$

$$C_{proc}^{Three\ Streams}\left[\frac{\$}{m}\right] = \frac{1.10}{{V_{proc}}^{0.9987}} + 0.244 \quad (3)$$

An increase in glass operating lines from two-stream to three-stream for a pulling speed of 1.27 m/min results in a 27% decrease in processing cost-per-length with a 9% total decrease in the pultruded part cost-per-length for the baseline 68% fiber volume fraction pultrusion. Tooling costs and energy costs are functions of amount of processed material and vary little with pulling speed. In addition to pulling speed, increasing the number of streams or other means of increasing the pultruded cross-sectional area would also increase material mass throughput and reduce processing costs on a mass basis.

The pultrusion processing costs are treated as independent of plank dimensions, resulting in the relative processing cost (per mass) decreasing for wider or thicker planks. Plank thickness is considered controlling of the curing requirements [13], but thickness increases from the baseline values are unlikely to be substantial given the requirement to roll the pultrusions onto spools. The part cost sensitivities to plank width and process yield are shown in Figure 6 for the fiberglass and heavy-tow textile carbon fiber pultrusions using the baseline values in Table 1. A variability of plank width in the range of 100 to 200 mm is considered common based on industry trends for land-based and offshore wind turbines. Increases in plank width reduce the cost of the pultruded parts due to higher capital utilization and direct reductions in energy and labor components of the processing costs. The plank width does have a cost-performance tradeoff where narrower planks allow for greater position control during layup in manufacturing of blades with variable curvature along the span. For an increase from the baseline 150mm width to 200mm there is a cost reduction of 7% and 6% for fiberglass and carbon fiber, respectively, while decreasing the width to 100mm results in a 15% and 12% increase in part costs. The process yield has a direct impact on the pultrusion part cost where the percentage cost change equals the reciprocal of the process yield ratio change.



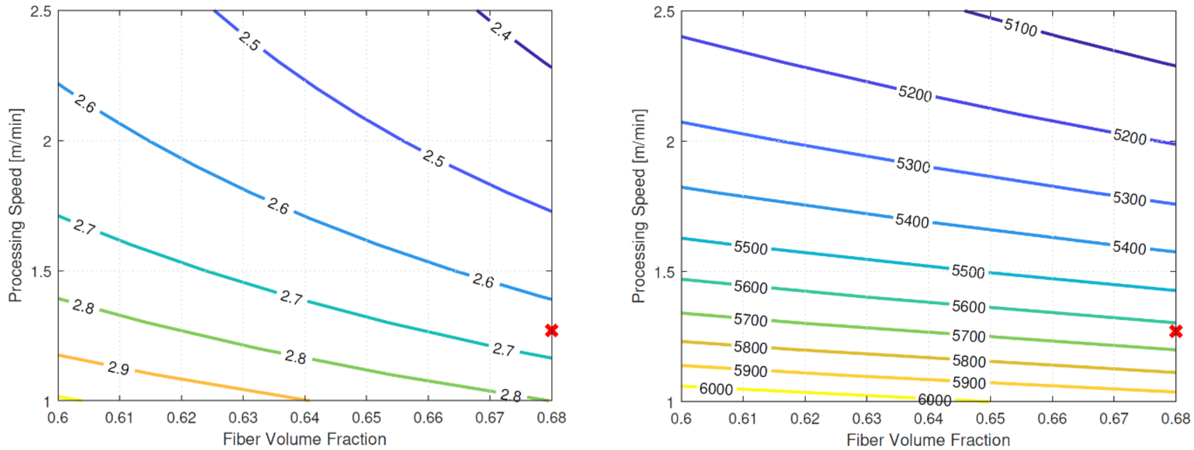
(a) Fiberglass (E-glass) pultrusion, 3 stream, 5 mm thick [$/kg]

(b) Heavy-tow textile carbon fiber pultrusion, 2 stream, 4 mm thick [$/kg]

Figure 6. Pultrusion part cost as a function of part width and process yield (68% fiber volume fraction, Red X = baseline).

The baseline 68% fiber volume fraction for the study pultrusions has been used to represent industry trends for pultruded carbon fiber by the wind industry. The high fiber volume fraction composite in the blade spar caps enables mass savings while achieving the required blade rigidity to satisfy deflection constraints. However, the overall part cost tradeoffs could favor lower fiber volume fraction pultrusions if processed with significantly higher pulling speeds, evaluated below. The pultrusion cost model has been used to determine plank costs as a function of varying fiber volume fraction within reasonable ranges from 60% to 68%. It is generally understood that as you move to lower fiber volume fractions you can achieve higher pulling speeds, but these exact relationships vary across fiber and resin systems. Instead of assuming pulling speed relationships with fiber volume fraction for both fiberglass and the textile carbon fiber systems, contour plots have been generated to identify sensitivities for the two reinforcement fibers, shown in Figures Figure 7 and Figure 8. The total part costs are shown on a mass basis and a volumetric basis, using the additional processing parameters from Table 1, but continuing to use three streams for fiberglass pultrusions. The volumetric cost is useful to show since the plank area is important for material stress and blade stiffness calculations, to represent this benefit for the thicker fiberglass pultrusions for comparison across the two material systems.

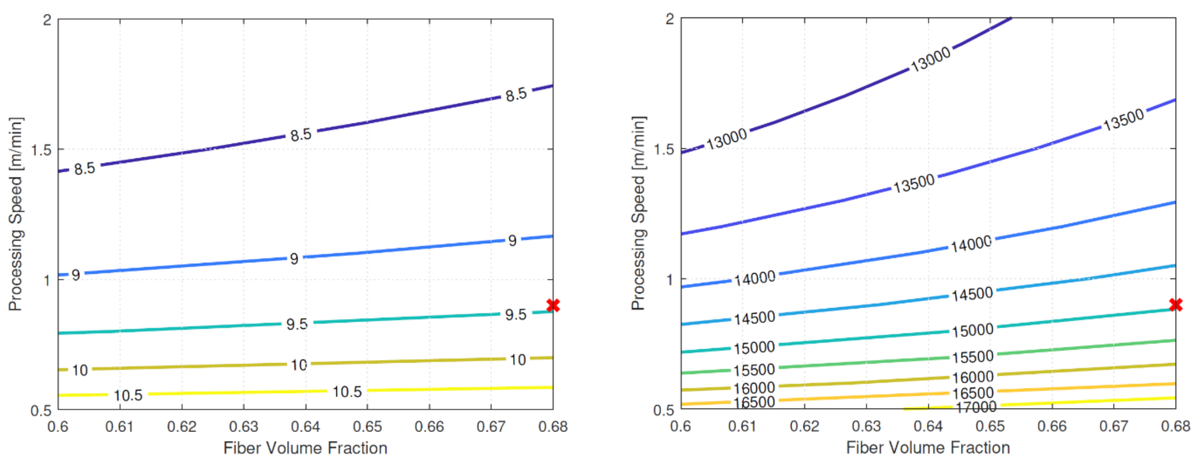
The cost of fiberglass pultrusions as a function of the related variables of fiber volume fraction and pulling speed are shown in Figure 7. These part cost isocontours reveal that decreasing the fiber volume fraction from the baseline value (red X marker) requires an increased processing speed to maintain the same cost, on a mass or volumetric basis. This result is caused by the low cost of E-glass reinforcement fibers compared to the matrix system, meaning that the composite material costs decrease for E-glass at higher fiber volume fractions.



(a) Part cost per mass [$/kg] (b) Part cost per volume [$/m^3]

Figure 7. Pultruded fiberglass part costs for three-stream pultrusion (150 mm width, 5 mm thickness, Red X = baseline).

The pultruded part cost relationships for the heavy-tow textile carbon fiber system are shown in Figure 8, revealing opposite trends from the fiberglass pultrusion with fiber volume fraction. The reinforcement fiber is more expensive than the matrix system for carbon pultrusions resulting in higher material costs with increased fiber volume fraction. For carbon pultrusions, where the reinforcement fiber is the most expensive material, cost equivalency can be achieved at lower fiber volume fractions while reducing the processing speed. This is counter to the actual processing relationship where pulling speed increases with reduced fiber fraction, meaning in practice that a lower part cost with reduced fiber volume fractions can be achieved for carbon pultrusions. As a result of this distinction, the speed increase at lower fiber volume fractions would have to be higher for glass than for carbon to achieve an equivalent cost reduction percentage at lower fiber volume fractions. An additional distinction is that the high material cost of carbon fiber relative to E-glass results in part costs that are 2-3 times higher, and the values in the contours do not overlap between the two materials.



(a) Part cost per mass [$/kg] (b) Part cost per volume [$/m^3]

Figure 8. Pultruded heavy-tow textile carbon fiber part costs for two-stream pultrusion (150 mm width, 4mm thickness, Red X = baseline).

It is apparent that the part cost of carbon fiber pultrusions decreases with lower fiber volume fraction, where there would be higher operating pulling speeds. The cost for fiberglass pultrusions may also decrease with lower fiber volume fraction, although this requires substantial increases in pulling speed.

However, part cost is only one indicator of the value of composite materials, and it is necessary to consider the mechanical properties of the composites in the comparison. The composite mechanical properties also vary with fiber fraction and control the material volumetric requirements and total resulting cost.

4. Material Property Comparison

Modern wind turbine blades use two primary composites for the spar cap component, infused E-glass or pultruded carbon fiber. Pultruded fiberglass spar caps have been considered for wind blade spar caps [14], but to date have not been incorporated at a commercial scale. Development of heavy-tow textile carbon fiber systems shows promise at outperforming the baseline 50K systems but is not currently developed at scale or in use by the industry. These four material and processing approaches are compared to understand the usefulness of pultruded fiberglass and heavy-tow textile carbon fiber for wind turbine spar caps. Baseline composite properties with epoxy resin systems are provided in Table 2 for each material and processing approach using E-glass and the two carbon fiber materials.

Table 2. Longitudinal properties for uniaxial composites (95/95 characteristic properties) [10].

	Fiberglass infusion	Fiberglass Pultrusion	Carbon Pultrusion	Carbon Pultrusion
Reinforcement Fiber	E-glass	E-glass	Industry Baseline	Heavy-Tow Textile
Fiber volume fraction (mass fraction)	0.57 (0.73)	0.68 (0.82)	0.68 (0.76)	0.68 (0.75)
Modulus [GPa]	42.8	51.1	157.6	160.6
Tensile Strength [MPa]	1002	1252	2236	1357
Compressive Strength [MPa]	-637	-796	-1528	-1183
Composite density [kg/m^3]	1980	2125	1620	1580
Composite Material cost [/kg]	$1.92	$1.80	$14.60	$6.87
Total composite part cost	$1.92/kg ($3,802/m^3)	$2.65/kg ($5,631/m^3)	$17.38/kg ($28,156/m^3)	$9.44/kg ($14,915/m^3)

The compressive strength is typically a critical mechanical property for a wind turbine blade spar cap, particularly for high wind speed sites. Compressive strength of a fiber-reinforced polymer is highly sensitive upon the alignment of the reinforcement fibers, in addition to several other factors related to the matrix and interface. Due to the nature of the pulling forces in a pultrusion, the process typically results in better alignment of reinforcement fibers compared to dry fabric infusion. Test results have revealed a 6% improvement in the compressive strength relative to infusions, using representative carbon fiber and glass fiber pultrusions [10], resulting from the improved fiber alignment and manufacturing quality [15, 16]. The strength value used in design is a factored “characteristic strength” ($S_{characteristic}$) per governing rotor design standards [17], as shown in Equation (4). The “design strength” (S_{design}) values are factored based on a series of partial safety factors ($\gamma_{combined}$) that account for different sources of uncertainty or strength reduction, one of which being manufacturing considerations. An additional benefit of pultrusions is the high level of control and repeatability in manufacturing the pultruded composites which enables a 9% reduction in the combined safety factor when using a pultruded spar cap versus a VARTM infused spar cap [10], Table 3. The combination of these two manufacturing benefits for pultrusions represents a 17% improvement in the design compressive strength for a reinforcement fiber at a consistent fiber volume fraction compared to VARTM infusion. These manufacturing improvements for pultrusions are even more pronounced in fatigue life calculations, which have highly nonlinear relationships with the improved design fatigue strength. Combining the compressive strength and cost estimates enables comparison of the three spar cap materials based on their cost-specific compressive strength, shown in Table 3. Fiberglass composites have a high failure strain which results in relatively high compressive strength values, due to the lower modulus. The cost-specific compressive strength of fiberglass composites is unrivaled for this low-cost composite. The fiberglass pultrusion does have a similar cost-specific performance to the infused glass, but with a 7% decrease resulting from the pultrusion costs from this additional manufacturing step.

$$S_{design} = S_{characteristic} / \gamma_{combined} \quad (4)$$

The stiffness is also a critical property for blade spar cap materials, which resist the downwind deflection of the blade to maintain clearance from the tower. Material stiffness is where carbon fiber pultrusions provide substantial advantages over fiberglass composites, with a three to four times higher longitudinal modulus. Higher absolute properties for the modulus (and compressive strength) can enable substantial blade mass savings, but the cost-specific performance is a useful tool for identifying material cost-performance tradeoffs. Table 3 shows that the cost-specific modulus for the heavy-tow textile carbon pultrusion is comparable to the baseline fiberglass infusion, but it also highlights the challenges with moving away from infused fiberglass for cost-driven industries. The infused fiberglass has the best cost-specific performance for both compressive strength and modulus amongst the set of materials. The pultrusion process increases the modulus due to the increased fiber volume fraction, but there is not an additional manufacturing improvement increase as is seen for compressive strength, in both the characteristic and design values. The result of this more linear relationship to modulus is that the fiberglass pultrusion has a 20% decrease in the cost-specific modulus relative to the VARTM-infused fiberglass, when using E-glass for both composite forms.

Table 3. Compressive strength and modulus comparisons and cost-specific performance.

	Fiberglass infusion	Fiberglass Pultrusion	Carbon Pultrusion	Carbon Pultrusion
Normalized Property	E-glass	E-glass	Industry Baseline	Heavy-Tow Textile
Static safety Factor [10]	1.88	1.71	1.71	1.71
Normalized design compressive strength [-]	1.0	1.37	2.49	2.04
Cost-specific design compressive strength, by volume [MPa*m³/$]	-0.0891 (100%)	-0.0827 (93%)	-0.0300 (34%)	-0.0463 (52%)
Normalized modulus [-]	1.0	1.19	3.68	3.75
Cost-specific modulus, by volume [GPa*m³/$]	0.0113 (100%)	0.0091 (80%)	0.0056 (50%)	0.0108 (95%)

The pultrusion processing cost model shows a sensitive relationship of processing cost to processing speed for the baseline processing speeds, shown in Figure 5. There is motivation to operate pultrusion machines at the highest pulling speed possible to reduce the part costs, but the pulling speed is also controlled by the composite fiber volume fraction and higher speeds can result in lower yields or increased labor requirements. There is a complicated relationship between processing speed and fiber volume fraction and how the combination affects yields and other associated parameters, which is best understood by commercial pultruders. The fiber volume fraction of a composite also affects the composite mechanical performance; therefore, the cost-specific composite properties are a function of fiber volume fraction and processing speed. Composite properties (S_{ut}, S_{uc}, E) are related to the fiber volume fraction (V_F) based on Equations (5) - (7) which use defined constitutive properties for the fiber tensile strength (S_{ft}) and modulus (E_f) and the matrix modulus (E_m) and rule of mixtures approximations, as discussed in prior work [10] using a strength translation factor (T_F) and maintaining a constant composite strength ratio (S_{uc}/S_{ut}) for variations in fiber volume fraction.

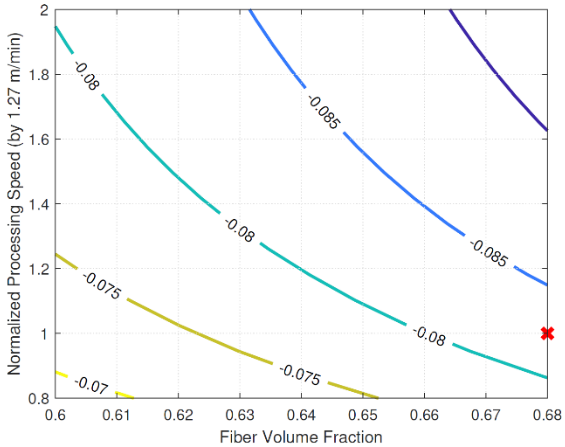
$$S_{ut} \approx S_{ft} T_F \left[V_F + (1 - V_F) {}^{E_m}\!/_{E_f} \right] \quad (5)$$

$$S_{uc\,(V_{F2})} \approx \left({}^{S_{uc}}\!/_{S_{ut}} \right)_{V_{F1}} S_{ut\,(V_{F2})} \quad (6)$$

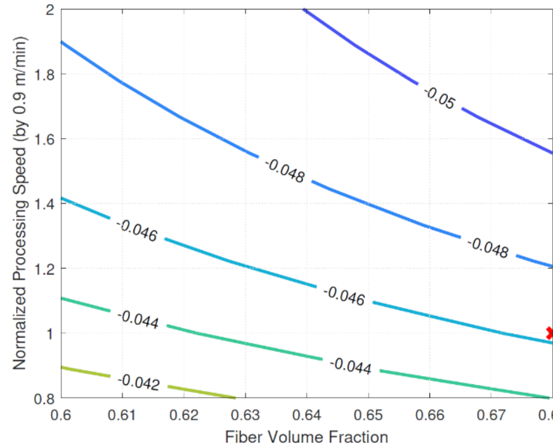
$$E \approx V_F E_f + (1 - V_F) E_m \quad (7)$$

With the defined cost and mechanical property relationships, contours of the volumetric cost-specific properties are generated for fiberglass and the heavy-tow textile carbon fiber pultrusions to reveal performance trends with fiber volume fraction and pulling speed. The maximum optimal pulling speed is a function of fiber volume fraction and depends on technology approaches and materials used, both for the reinforcement fiber and resin system (including resin formulation and curing mechanisms). The plots in Figures Figure 9 and Figure 10 reveal the sensitivities of the cost-specific mechanical performance to changes in processing speed, at a given fiber volume fraction, as well as required processing speed increases for lower fiber volume fractions to maintain constant cost-specific performance.

Figure 9 show the cost-specific compressive strength as a function of the fiber volume fraction and the normalized pulling speed. For fiberglass pultrusions to maintain a constant cost-specific compressive strength at lower fiber volume fractions will require a more substantial increase in pulling speed than carbon fiber pultrusions. The required pulling speed increase for carbon pultrusions is less sensitive to fiber volume fraction due to a combination of effects from the high relative material costs, the larger contribution of processing costs with two-stream operation and a lower baseline pulling speed, and the high relative mechanical properties compared to E-glass. These trends for the cost-specific compressive strength processing sensitivities are repeated for the cost-specific modulus, shown in Figure 10.

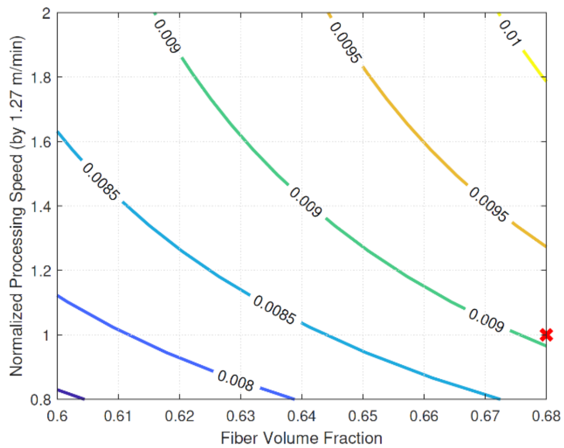


(a) Fiberglass (E-glass) pultrusion, 3 stream, 5 mm thick [MPa-m^3/$]

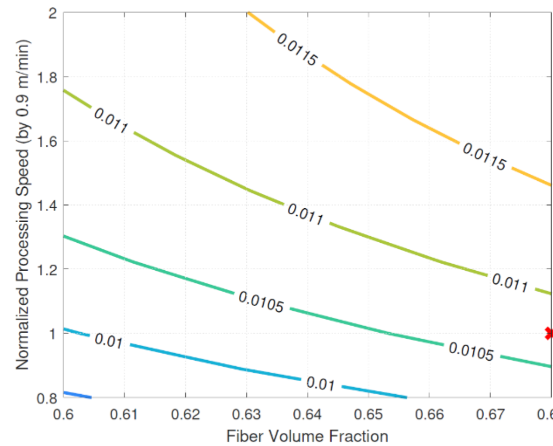


(b) Heavy-tow textile carbon fiber pultrusion, 2 stream, 4 mm thick [MPa-m^3/$]

Figure 9. Volumetric cost-specific compressive strength (design) comparison for pultruded fiberglass and textile carbon fiber planks (150 mm width, Red X = baseline).



(a) Fiberglass (E-glass) pultrusion, 3 stream, 5 mm thick [GPa-m^3/$]



(b) Heavy-tow textile carbon fiber pultrusion, 2 stream, 4 mm thick [GPa-m^3/$]

Figure 10. Volumetric cost-specific modulus comparison for pultruded fiberglass and textile carbon fiber planks (150 mm width, Red X = baseline).

Maintaining constant cost-specific mechanical performance is a useful metric for comparing across material systems and processing approaches but does neglect some additional important effects. The absolute mechanical performance of structural composites ensures less total mass is required which provides additional system and manufacturing cost reductions, meaning that for constant cost-specific performance the composite with higher absolute mechanical performance will typically be the more optimal choice. For the purposes of this study, this relationship means for the same cost-specific mechanical property that carbon fiber will outperform fiberglass and that higher fiber volume fractions will outperform lower values. Considering the importance of absolute mechanical performance, the isocontours in Figures Figure 9 and Figure 10 should be considered slightly more sensitive than what would be required at constant cost-specific performance for lower fiber volume fraction pultrusions to outperform the baseline 68% pultrusion. However, the constant cost-specific performance is still helpful to identify general trends with fiber volume fraction composite design decisions. Tables Table 4 and Table 5 show the required pulling speed increases for constant cost-specific compressive strength and cost-specific modulus at 60% and 64% fiber volume fractions for fiberglass and the heavy-tow textile carbon fiber pultrusions, respectively. In all cases, the required pulling speed increase is exponential when decreasing the design fiber volume fraction. Additionally, fiberglass pultrusions require a 168-200% increase in pulling speed for a 60% fiber volume fraction for constant cost-specific compressive strength or modulus, compared to only a 48%-51% required increase in pulling speed for the heavy-tow textile carbon fiber. Based on these trends it seems more challenging to justify a lower fiber volume fraction for fiberglass pultrusions than carbon fiber pultrusions, however the likely speed increases for the two materials is uncertain for these two material systems. Various resin formulations and curing technologies (such as polyurethane or UV-cured resin systems) may enable sufficiently high pulling speed increases at lower fiber volume fraction to favor lower fiber volume fractions, although this is unclear.

Table 4. Fiberglass pultrusion processing speeds required for constant cost-specific performance at representative fiber volume fractions.

	60% FVF	64% FVF	68% FVF
Constant Cost-Specific Compressive Strength [MPa*m^3/$]			
Required Line Speed [m/min]	3.40 (268%)	1.85 (146%)	1.27 (100%)
Part Cost [$/kg]	$2.48	$2.57	$2.65
Constant Cost-Specific Stiffness [GPa*m^3/$]			
Required Line Speed [m/min]	3.83 (300%)	1.91 (150%)	1.27 (100%)
Part Cost [$/kg]	$2.46	$2.55	$2.65

Table 5. Heavy-tow textile carbon fiber pultrusion processing speeds required for constant cost-specific performance at representative fiber volume fractions.

	60% FVF	64% FVF	68% FVF
Constant Cost-Specific Compressive Strength [MPa*m^3/$]			
Required Line Speed [m/min]	1.34 (148%)	1.08 (119%)	0.9 (100%)
Part Cost [$/kg]	$8.57	$9.00	$9.44
Constant Cost-Specific Stiffness [GPa*m^3/$]			
Required Line Speed [m/min]	1.37 (151%)	1.09 (120%)	0.9 (100%)
Part Cost [$/kg]	$8.55	$8.99	$9.44

5. Wind Turbine Pultruded Spar Cap Analysis

The actual performance of the study composite materials in a wind turbine blade spar cap depends on complicated, non-linear relationships between the modulus, strength, and fatigue resistance. The performance tradeoffs depend on the specific turbine design (blade length, thickness profile, allowable deflection) in addition to the design class based on maximum wind speed and statistical turbulence intensity. Based on these factors, the spar cap material can be stiffness-driven, strength-driven, and/or fatigue-driven. To assess the three study materials from Table 2, blade optimization studies are performed using a reference model that is representative of modern wind turbine designs for land-based installations in the US. The SNL3.0-148 is a 3 MW turbine with 72 m long blades with a low-induction aerodynamic design where the tip is slightly unloaded to enable greater energy capture while controlling blade root bending moments [10, 18].

The blade optimization approach follows earlier work where the blade spar cap dimensions along the span are optimized to minimize mass for the fixed reference turbine while satisfying the design requirements [10]. The additional composite layup dimensions for the blade are determined outside of the optimization loop to ensure the structure survives global buckling checks. The spar cap width is set independently for the four materials from the buckling check, to prevent buckling within the spar cap. The materials with the higher mechanical properties require a narrower spar cap width to prevent excessively thin spars in critical portions of the blade. This analysis resulted in spar cap widths of 600 mm, 500 mm, and 200 mm for infused fiberglass, pultruded fiberglass, and pultruded carbon fiber (both systems), respectively. The spar cap spanwise thickness dimensions are solved within the optimization studies where three critical design load cases (DLC) are simulated based on the governing wind turbine design standards [19]:

- Operating turbine with normal turbulence levels for probabilistic fatigue calculations (DLC 1.2)
- Operating turbine near rated speed with an extreme wind gust with direction change (DLC 1.4)
- Parked turbine with a 50-year extreme wind speed (DLC 6.1)

The spar cap optimization studies are performed with the reference blade model to quantitatively compare the material cost and performance of the four study materials, and to identify opportunities for the use of pultruded fiberglass spar caps. There are three optimization constraints which are active for the spar cap:

- Blade tip deflection less than 20% of the blade length (14.4 m)
- Spar cap material strength/strain limits, compressive and tensile
- Fatigue damage for a 30-year design life using Miner's rule and a Shifted Goodman failure model [17] with a Rayleigh wind speed distribution

The spar cap optimization routines were performed for the study materials with a low wind resource design siting of IEC class 3A, which is typical of many of the available land-based sites within the US with existing electrical transmission. The resulting constraint values for the optimal spar cap profiles are shown in Figure 11, normalized by the respective allowable design constraints of the four study materials. For this low wind resource site, the design constraints that are most active are on the material modulus (tip deflection) and the fatigue resistance due to the high turbulence intensity associated with low wind speed sites. The two fiberglass materials have excess material strength relative to the maximum stress due to the low material modulus for E-glass and tip deflection limits. As a result, the improved relative strength of the glass pultrusion does not impact the material's performance for this design class. The compressive strength of the carbon pultrusions are approximately fully utilized meaning that the combination of modulus and compressive strength drive its performance. The infused fiberglass is also fatigue-driven, while the pultruded glass and carbon fiber spar caps are predicted to survive greater than a 60-year design life. An increase of the design life would be handled for the three pultruded spar cap systems, while requiring more material for the glass infusion.

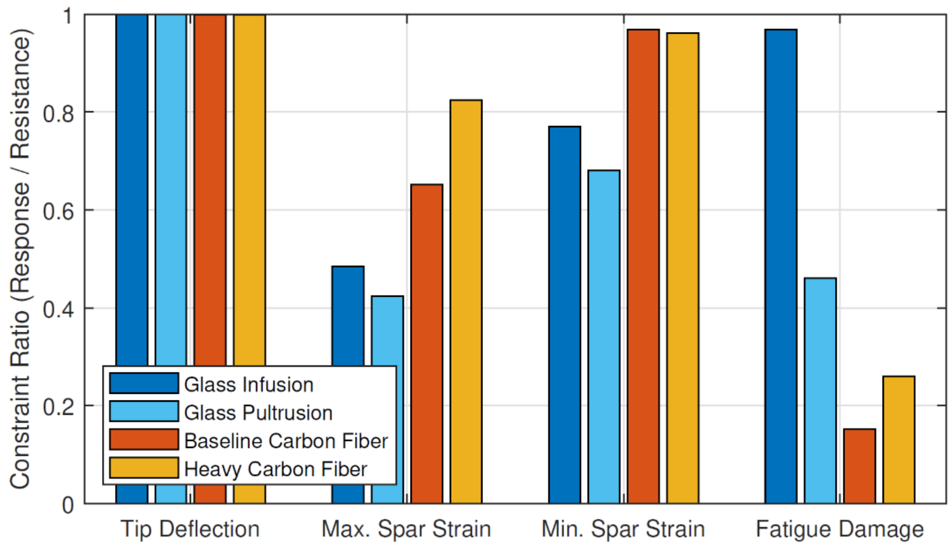


Figure 11. Optimal spar cap constraint performance for a low wind resource design (IEC class 3A).

The material cost for the optimal spar caps with the four study materials are shown in Figure 12, along with two other cost-associated parameters. The cumulative length of the spar cap composite layup is a proxy for blade manufacturing costs where labor is associated with this length. The spar cap mass (and total resulting blade mass) also affects system costs through the support structures and drivetrain which are sized in response to the weight and loads of the blade, although these associated costs are not quantified in this analysis. Despite the high costs of the heavy-tow textile carbon fiber system relative to E-glass, it is seen to have the lowest required spar cap material cost in addition to the lowest mass and build-up length. The specific heavy-tow textile carbon fiber system was chosen for this analysis due to its cost-specific performance relative to commercially available carbon fiber systems as was determined from earlier work [10], and seen here where the baseline carbon fiber has the highest spar cap material cost. The fiberglass pultrusion system requires 18% less composite mass, but costs 13% more than the infused fiberglass spar because of the additional pultrusion manufacturing step and costs. However, this comparison doesn't account for the reduced costs for the fiberglass pultrusion for blade manufacturing and associated systems costs for the reduced weight, which could offset the pultrusion manufacturing cost increase.

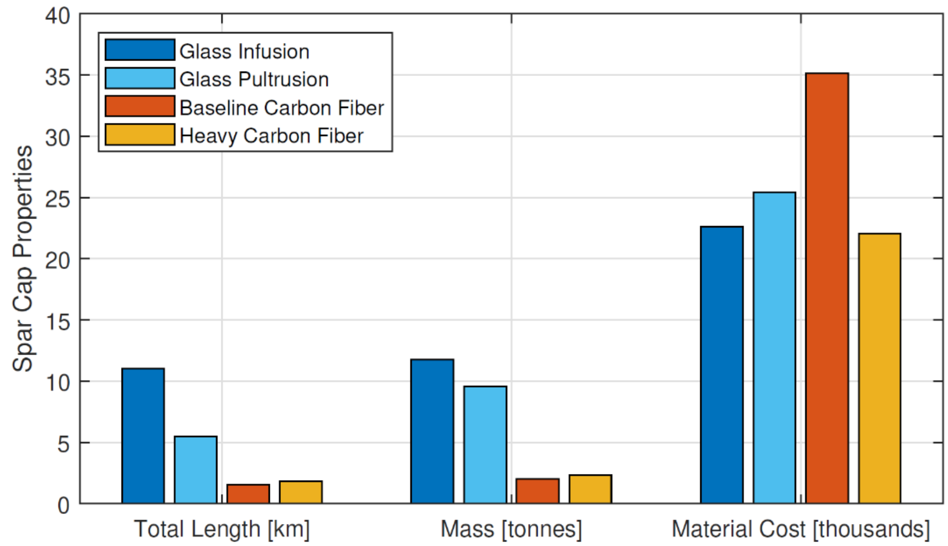
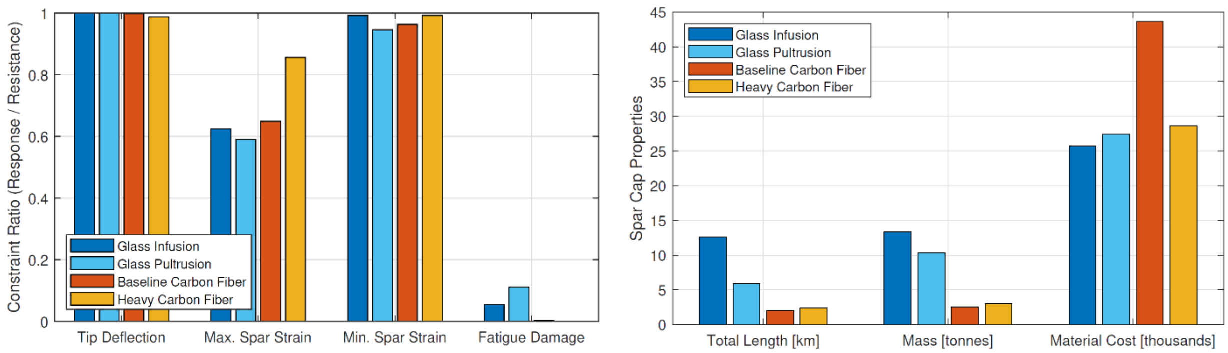


Figure 12. Optimal spar cap properties for a low wind resource design (IEC class 3A).

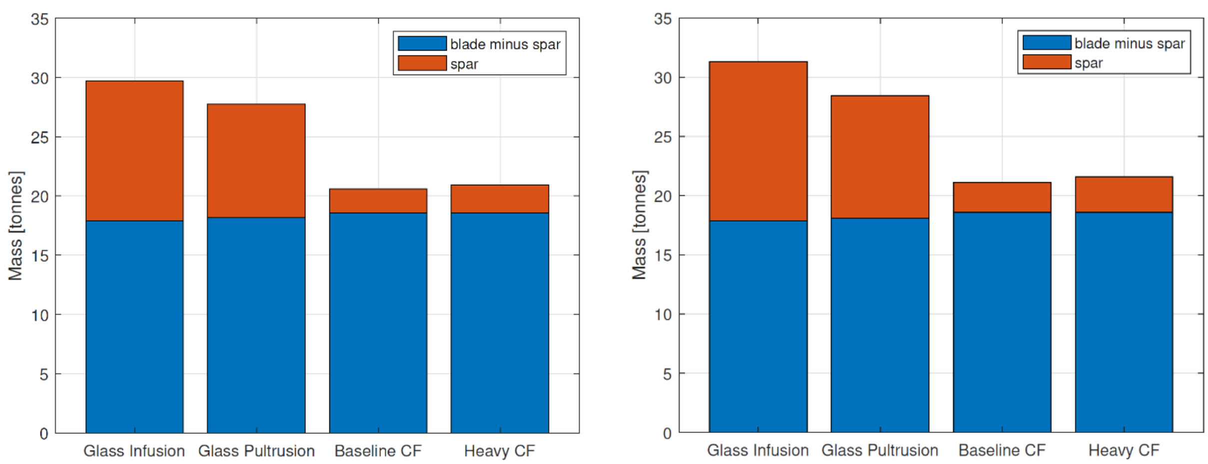
In addition to fatigue performance, one of the benefits for pultruding fiberglass compared to VARTM-infusion is the increased strength performance. The low wind resource classification design doesn't take advantage of this mechanical property for fiberglass spar caps. The spar cap material optimization was also performed for a high wind resource design siting of IEC class 1B which represents future land-based siting locations across the Great Plains in the US, which require electrical transmission upgrades for mass development. This classification is also representative of offshore sites along the east and west coasts in the US, although the design blade lengths are greater than 100 m for offshore turbines. Results for the optimal spar caps using the four study materials with a high wind resource design are shown in Figure 13. For the high wind speed class rating each of the materials operate near their design compressive strength in addition to the mass optimization resulting in the maximum allowable tip deflection. Fatigue damage is not a driver in the spar cap for this high wind resource site, where both fiberglass spar caps have a predicted design life of greater than 200 years and the carbon pultrusions have essentially no damage. The high wind resource design results in mass increases in each of the spar cap material systems to survive the higher 50-year extreme wind loads, but the fiberglass infusion requires the most additional material. The three pultrusion spar cap materials require an increase of around 680 kg of additional composite mass for this high wind resource siting, while the infused fiberglass spar cap required 1610 kg of more material. There were relative cost improvements for the glass pultrusion for the high wind resource design, but the spar cap material cost is still 7% more expensive than infused fiberglass. The heavy-tow textile carbon fiber spar cap material cost is now higher than the two glass systems, although this doesn't account for the blade manufacturing or system cost reductions.



(a) Optimal spar cap constraint performance (b) Optimal spar cap properties

Figure 13. Spar cap optimization results for a high wind resource design (IEC class 1B).

The absolute mechanical properties of the spar cap material determine the total mass of the spar cap and resulting blade mass. The blade mass has additional cost implications on the wind turbine system which are not quantified in this comparison, affecting system costs for supporting the wind turbine rotor. Heavy blades also require additional edgewise reinforcement to withstand the gravitational fatigue loads which have a cycle frequency every revolution. This effect is increasingly significant as blades get longer and more massive. The total blade mass is compared for the four study materials with the two design siting classifications in Figure 14, with differences in the non-spar weight resulting from the different spar cap widths. Compared to traditional infused fiberglass, there is a 30% to 31% reduction in blade mass with the pultruded heavy-tow textile carbon spar and a 6% to 9% mass reduction using a pultruded fiberglass spar for the low and high wind resource designs, respectively.



(a) Low wind resource design (IEC class 3A) (b) High wind resource design (IEC class 1B)

Figure 14. Blade mass comparison when using the three study materials in the spar cap component.

6. Discussion on System Benefits for Wind Turbine Blades with Pultruded Spar Caps

Pultrusions improve the composite strength per mass of unidirectional composites and in wind turbines have an added benefit of requiring lower safety factors in design, yielding additional weight savings. The benefits of pultrusion manufacturing are amplified when using higher performing reinforcement fibers, such as carbon fiber or high-modulus glass systems, where the additional pultrusion manufacturing cost represents a smaller percentage of the final composite cost. Less material is required when using pultrusions in the blade spar cap, and the resulting blade mass is decreased. Additionally, the precured planks have typical thicknesses of 3-6 mm and the total length of pultruded planks decreases compared to fabric plies for VARTM infusion. The use of infused glass spar caps challenges blade manufacturing due to the large thicknesses of this component for modern wind blades. As a result of this challenge, infused spar caps are typically cured in a separate spar mold to control the large exotherms. Even when taking these additional costly measures, it can still be a challenge to limit fiber waviness and generate defect-free spars. Pultrusions offer a significant improvement on this challenge and produce high-reliability spar caps, but the blade manufacturing processes are substantially distinct and require further quantification.

A recent study has compared manufacturing differences between infused fabric spar caps and pultruded carbon fiber spar caps for a 61.5 m long wind turbine blade [20]. Manufacturing distinctions were quantified and modeled using a virtual blade manufacturing factory model to estimate the resulting manufacturing cost for the two spar cap systems. The use of pultrusions eliminates the need for spar molds which saves on capital costs, eliminates associated spar mold labor, and frees up factory space. The use of pultrusions does require the addition of an automated pultrusion prepper which is used to decoil the pultrusion spool, remove the peel-ply, and add bevel cuts at plank transitions. A comparison of the blade manufacturing distinctions between VARTM infused and pultruded spar caps is summarized in Table 6 from the study performed by Sherwood [20]. In summary, the authors found there were reductions in the blade manufacturing costs when using carbon pultrusions for the 61.5 m study blade with an 11.5% decrease in labor costs, 3.5% decrease in overhead, and a 2.9% decrease in business costs. These combine to reduce the blade manufacturing costs (not including material costs) by a total of 5.9%. The authors noted additional opportunities for factory optimization from the studies performed where two spar preppers were modeled but had utilization rates of 38.7% and 38.1%, meaning one machine would suffice saving additional capital costs and factory floor space. Additionally, the elimination of the spar mold areas resulted in seventeen of the workers exhibiting below 40% utilization which should be optimized to bring further reductions in labor costs. The prior work clearly illustrates the advantage of the use of pultrusions to improve reliability and decrease blade manufacturing costs, but continued work is needed in this area to optimize the virtual blade manufacturing models for the use of pultruded spar caps to obtain more exact cost distinctions.

Table 6. Comparison of blade manufacturing process steps [20] for pultruded spar cap materials versus VARTM infusion for a representative 61.5 m wind turbine blade.

Process Step	VARTM Infused Spar	Pultruded Spar	Difference
Prep spar mold	4 x 1 hour	Eliminated	-4.0 man-hours per infusion
Layup glass	5 x 3 hours	Automated pultrusion cutting, beveling, and layup (2 x 2 hours)	-11.0 man-hours per infusion
Infusion prep	5 x 1.5 hours	Eliminated	-7.5 man-hours
Infuse	3 x 0.5 hours	Eliminated	-1.5 man-hours
Cure	0.5 x 8 hours	Eliminated	-4.0 man-hours
Demold & cleanup	2 x 2 hours	Eliminated	-4.0 man-hours
Spar into shell	5 x 0.25 hours	Pultrusion stack into shell (5 x 0.5 hours)	+1.25 man-hours +0.25 shell cycle
Spar mold	$575k each	Replace four spar molds with two pultrusion decoil, cutting, surface prep,	-$375k investment per spar mold

		beveling, and stacking ($400k each)	

In addition to blade manufacturing cost savings, the lower blade mass with pultruded spar caps reduces system costs related to supporting the blades. The blades are supported first by the pitch bearings, then the hub, then the drivetrain, then the nacelle, and ultimately by the tower and foundation. While each of these components can see cost reductions from reduced blade mass, a detailed design analysis of the turbine would be required to quantify the savings. Instead, a research tool is used to estimate the cost of the various components where empirical data are used to relate the cost to the blade mass. The National Renewable Energy Laboratory's Cost and Scaling Model within WISDEM [21] has related the cost of three turbine components to blade mass for the pitch system, rotor hub, and the low-speed shaft. The mass and cost of the other support structures are related to turbine diameter within WISDEM and do not include secondary relationships to blade mass. The resulting cost estimates for the IEC Class 3A blade designs with infused fiberglass, pultruded fiberglass, and pultrusions using the baseline carbon fiber and the heavy-tow textile carbon fiber are shown in Figure 15, based on blade mass values of 29,673 kg, 27,756 kg, 20,576 kg, and 20,907 kg, respectively. While these results should not be taken as exact values due to the empirical nature of the scaling model, the impact of reducing blade weight on the turbine system costs is clearly illustrated. The difference in spar cap material costs among the two fiberglass systems and the heavy-tow textile carbon fiber blade designs was less than $5k per blade ($15k per turbine) which is more than compensated by the turbine cost reductions due to the lower blade weight. In addition to the lower spar cap material costs for the heavy-tow textile carbon fiber system for this design site, these two research tools illustrate that there would be expected blade manufacturing cost reductions and turbine component cost reductions which might have the largest impact to reduce turbine costs and the system levelized cost of energy.

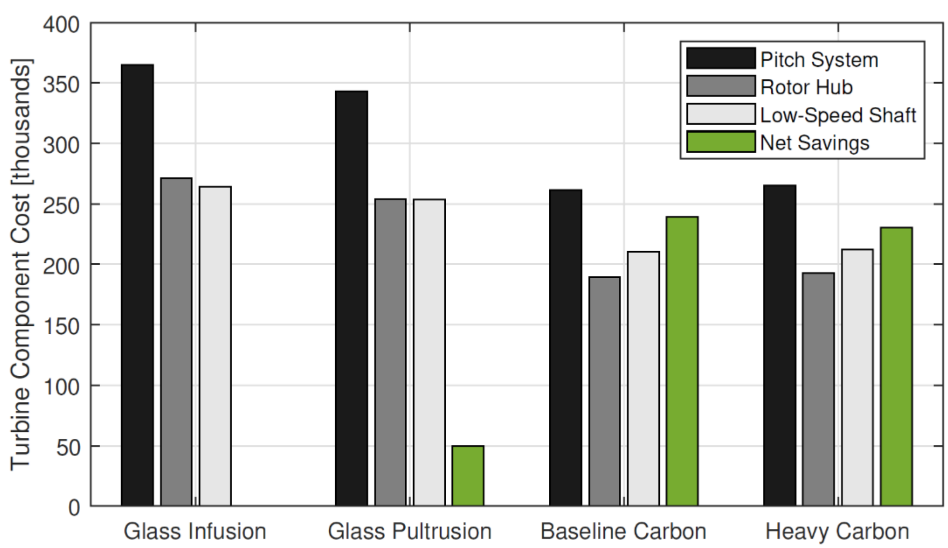


Figure 15. Turbine cost reductions for spar caps with pultruded fiberglass (E-glass) and pultruded carbon fiber material systems (net savings shown relative to infused fiberglass).

7. Conclusions

A cost model has been developed for resin-bath pultrusion manufacturing of fiber-reinforced polymers that determines the pultrusion processing costs and total part costs based on various processing parameters and efficiencies, including the fundamental categories of material, capital, labor, and energy. This model is useful for techno-economic comparison of reinforcement fibers and manufacturing processes in composite structures, including the manufacturing cost-competitiveness when also considering the mechanical performance. Baseline input parameters have been established for carbon fiber systems and fiberglass (E-glass) for a 68% fiber volume fraction, representative of pultrusions used in wind turbine blade spar caps. The pultruded composite part costs for both reinforcement fiber systems are dominated by material costs, with a 25%-36% share of processing costs for a two-stream pultrusion operation. The absolute processing costs are lower for fiberglass than carbon fiber pultrusions due to a higher optimal pulling speed, increased thickness, and where operation of a three-stream manufacturing process can be assumed. Processing cost reductions are shown for a three-stream operation for fiberglass pultrusions due to an increased material throughput, which resulted in a total part cost reduction of 9% compared to a two-stream pultrusion. The likelihood of being able to operate a three-stream pultrusion depends on various factors including handling challenges of the reinforcement fiber and is considered less likely in the near-term for carbon fiber pultrusions in this analysis.

Pultrusion manufacturing of unidirectional composites has multiple benefits relative to resin infusion manufacturing, including improved mechanical performance and lower required safety factors due to a high degree of control and repeatability in addition to enabling higher achievable fiber volume fractions. Infused unidirectional fiberglass spar caps in wind blades achieve a fiber volume fraction of 57% which is increased to 68% for pultruded spar cap members. This increase in fiber volume fraction results in an overall structural weight savings in addition to reducing the amount and cost of the resin material component. The reduction of resin volume is particularly meaningful for the fiberglass pultrusions where the resin is more expensive than the reinforcement E-glass fiber by a factor of three. The material cost reduction for pultruded glass is contrasted with increased processing costs by adding this intermediate manufacturing step. The tradeoff of these two cost relationships is explored versus the target fiber volume fraction for the study reinforcement fibers. The optimal pultrusion pulling speed is a function of the fiber volume fraction, which was also varied to identify cost trends independently from the uncertain relationship between pulling speed and fiber volume fraction.

The cost of a composite is only one consideration, and the mechanical performance also varies with fiber volume fraction. Cost and performance relationships were combined to assess the impact of fiber volume fraction on the cost-specific mechanical properties of compressive strength and modulus. The fiberglass pultrusions reveal a stronger sensitivity to pulling speed for cost-specific properties compared to carbon pultrusions, resulting from the low cost of glass fiber compared to the resin material cost. To achieve a constant cost-specific compressive strength at a 60% fiber volume fraction relative to the 68% baseline, the fiberglass pultrusion requires a pulling speed increase of 168% compared to a 48% increase in pulling speed for the carbon pultrusion. The large increase in required pulling speed for the lower fiber volume fraction glass pultrusions may require alternative technology approaches, such as UV-cured resin systems, which were not assessed directly within this study.

The pultruded carbon fiber and fiberglass composites were compared to infused fiberglass as the spar cap material using a reference 3 MW wind turbine blade model, for both a low wind resource and high wind resource siting design. The pultruded fiberglass spar cap resulted in a 6% to 9% blade weight reduction compared to infused fiberglass for the two design siting's but with a resulting spar cap cost increase of 12% to 7%, respectively, as a result of the pultrusion processing cost. The pultruded fiberglass spar cap did have a lower material cost than the pultruded heavy-tow textile carbon fiber for the high wind resource design due to the increased material strength requirements. Wind turbines with strength-driven designs in a high wind resource, such as offshore wind installations, may be the most favorable application to use pultruded fiberglass as an alternative to pultruded carbon fiber. The pultruded heavy-tow textile carbon fiber spar cap enabled a 30-31% reduction in blade mass and had the lowest associated spar cap material cost for the stiffness and fatigue-driven low wind resource design. The industry baseline carbon fiber produced a slightly larger mass savings but had the highest spar cap material cost at nearly 50% more than the heavy-tow carbon fiber. The wind turbine analysis does not quantify the full cost implications on the design. The additional cost implications favor the pultruded composites which have a lower blade mass, shorter total length of spar cap layers, and eliminate the need for spar cap molds during blade manufacturing. The lower blade mass for the pultruded composite spar caps reduces system costs on the drivetrain and support structures in addition to reduced blade manufacturing costs where fewer layers are required and the pultruded planks can be laid up directly in the blade shell mold.

This paper has identified the advantages and challenges of using pultruded composites in a wind turbine blade spar cap, based on epoxy resin systems. The paper did not assess the opportunity of using non-traditional resin systems, such as polyurethane, thermoplastics, or UV-cured epoxies, or the use of alternative high-modulus glass fibers, such as H-glass or S-glass. In addition to the use of alternative materials, there have been advancements in pultrusion manufacturing technologies and fiber architecture which may be promising for the wind industry [5] and these studies are recommended for follow-on work. The model formulation presented can be easily extended to perform alternative assessments for pultrusion systems with similar capital expenditures by using alternative model inputs.

Disclaimer

This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

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