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ALTERNATIVE COMPOSITE MATERIALS FOR MEGAWATT-SCALE WIND TURBINE BLADES: DESIGN CONSIDERATIONS AND RECOMMENDED TESTING

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ABSTRACT

As part of the U.S. Department of Energy's Wind Partnerships for Advanced Component Technologies program, Global Energy Concepts LLC (GEC) is performing a study concerning blades for wind turbines in the multi-megawatt range. Earlier in this project constraints were identified to cost-effective scaling-up of the current commercial blade designs and manufacturing methods, and candidate innovations in composite materials, manufacturing processes and structural configurations were assessed. In the present work, preliminary structural designs are developed for hybrid carbon fiber / fiberglass blades at system ratings of 3.0 and 5.0 megawatts. Structural performance is evaluated for various arrangements of the carbon blade spar. Critical performance aspects of the carbon material and blade structure are discussed. To address the technical uncertainties identified, recommendations are made for new testing of composite coupons and blade sub-structure

NOMENCLATURE

c	chord length (m)
Ex	Longitudinal modulus (GPa)
Ey	Transverse modulus (GPa)
GPa	giga-Pascals (10^9 N/m^2)
Gxy	shear modulus (GPa)
kW	kilowatt
m	meters
MW	megawatt
R	rotor radius (m)
x/c	distance along chord
y/c	distance perpendicular to chord
ε	material strain (%)
ε_{design}	design value of material strain (%)
$\eta_{x,xy}$	shear strain coefficient
ν_{xy}	major Poisson's ratio of laminate
υ_f	laminate fiber volume fraction

BACKGROUND

In recent years both the size of wind turbine blades and the volume of commercial production has been steadily increasing. Rotors of up to 80 m diameter are in current production, and several turbine developers have prototypes in the 100 to 120 m diameter range. It is estimated that over 50 million kilograms of finished fiberglass laminate were used for the production of wind turbine blades in the year 2001, and that worldwide production volume will increase for the next several years (calculations based on the global wind energy market predictions of Reference 1). As a result of these growth trends, research programs in both the United States and Europe have been investigating alternative blade design and materials technologies.

In Europe, jointed blade designs are being evaluated for their potential benefits in transportation and erection costs, and carbon fiber composites are being investigated for potential improvements in blade weight and cost.[2-6] In the United States, the U.S. Department of Energy is conducting the Wind Partnerships for Advanced Component Technologies (WindPACT) program. The purpose of the WindPACT program is to explore the most advanced technologies available for improving wind turbine reliability and decreasing the cost of energy (COE).

Figure 1 illustrates the relationship among the WindPACT studies that concern the design and manufacture of wind turbine blades. In the initial phase of the program, scaling studies were performed in the areas of turbine blades[7], transportation and erection logistics[8], and self-erecting tower concepts.[9] The purpose of the scaling studies is to determine optimum sizes for future turbines, identify sizing limits for critical components and technologies, and to investigate the potential benefits from advanced concepts. Under the NREL-sponsored Turbine Rotor Design Study, extensive aeroelastic simulations are being performed for a wide range of rotor sizes and configurations, and the resulting loads are being used to quantify the impact on turbine cost and COE.[10,11]

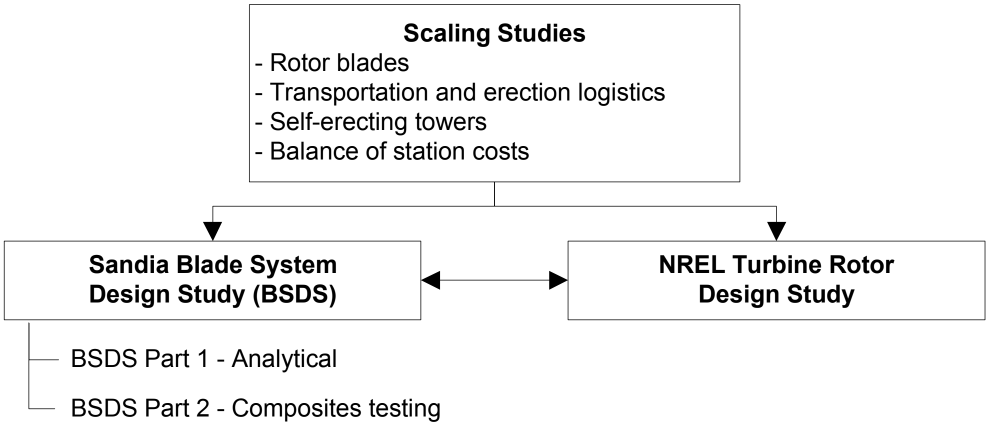


Figure 1 WindPACT studies concerning composite blade design and manufacture

Under the Sandia-sponsored Blade System Design Studies (BSDS), alternative composite materials, manufacturing processes and structural designs are being evaluated for potential benefits for MW-scale blades.[12] As indicted by Figure 1, the BSDS has two parts. Part 1 is analytical, and involves trade-off studies, selection of the most promising technologies, development of design specifications and preliminary design for MW-scale blades, identification of technical issues for alternative materials and manufacturing approaches, and development of recommendations for materials testing. The Part 2 BSDS involves testing of coupons and blade substructure with the objectives of evaluating composite materials and resolving technical issues identified in the Part 1 study. The content in this paper focuses primarily on the latter stages of the Part 1 BSDS. Earlier work under this project is reported in detail in Reference 12.

APPROACH

The material in this paper was developed from a large number of sources. Throughout this project GEC consulted with manufacturers of composites materials, wind turbine blades, and turbine systems. The BSDS has also benefited from extensive synergy with other DOE-funded wind energy research efforts. The Montana State University (MSU) Composites Research Group collaborated substantially in the areas of material properties and test development. Results from the WindPACT Rotor Study were used to develop the baseline blade structural configurations and loads for the BSDS blade designs. GEC performed the majority of the design calculations using the ANSYS finite element analysis (FEA) code with the Sandia-developed NuMAD interface.[13] The results, conclusions and recommendations in this report reflect an integration of all these diverse technical elements.

GENERAL ISSUES FOR MW-SCALE BLADES

This section reviews some of the major conclusions from earlier work under the BSDS, and discusses general issues concerning large blades. Specific technical issues concerning blade composite materials will be discussed following the development of the preliminary 3.0 MW blade design.

Scaling of Conventional Blade Designs

Very few fundamental barriers have been identified for the cost-effective scaling of the current commercial blade designs and manufacturing methods over the size range of 80 to 120 m diameter. The most substantial constraint is transportation costs which rise sharply for lengths above 46 m (150 ft) and become prohibitive for long-haul of blades in excess of 61 m (200 ft).

In terms of manufacturing, it is expected that environmental considerations will prohibit the continued use of processes with high emissions of volatile gasses, such as the open-mold wet lay-up that has been the wind industry norm. Another manufacturing concern for large blade is bonding compounds. As blade sizes increase it is natural for the gaps between fitted and bonded parts to grow as well. However, the bonding materials used for smaller blades do not scale well to increasing gap sizes, and blade tooling and production costs for large blades increase rapidly as dimensional tolerances are decreased.

Gravity loading is a design consideration but not an absolute constraint to scaling-up of the current conventional materials and blade designs over the size range considered. Nonetheless, materials and designs that reduce blade weight may be of benefit for megawatt-scale blades, as this would reduce the need for reinforcements in the regions of the trailing edge and blade root transition to accommodate the gravity-induced edgewise fatigue loads.

Another issue for turbine design is the use of larger rotors at a given turbine system rating. A trend toward decreasing power output per unit rotor swept area (specific rating) has been observed in turbines designed for low-to-moderate annual average wind speeds. A Class 2 EW 1.5 has a rotor diameter of 70 m and a specific rating of 0.39 kW/m^2. Micon has recently commissioned a 1.5 MW with an 82 m rotor (specific rating of 0.28 kW/m^2). It is expected that turbine designs with low specific rating will be of continued interest for deployment in the low wind speed sites of the Midwest United States. As specific rating is decreased (i.e. blade lengths increase at a given rating), blade stiffness and the associated tip deflections becomes increasingly critical for cost-effective blade design.

Current Trends in Blade Manufacturing

A large number of turbine system manufacturers are currently moving toward in-house production of their own blades, and in doing so are using diverse materials and manufacturing methods. Nordex and GE Wind have both built blades in the 40-50 m length range using hand lay-up of primarily fiberglass structure in open-mold, wet processes. NEG Micon is building 40 m blades with carbon augmented wood-epoxy. Vestas has a long history of manufacturing with prepreg fiberglass. TPI Composites is manufacturing 30 m blades using their SCRIMP^{TM} vacuum-assisted resin transfer molding (VARTM) process. Among the more novel approaches in current use for large blades is by Bonus, where blades 30 m and greater are being produced from a dry preform with a single-shot infusion, eliminating the need for secondary bonding.

Manufacturing Alternatives

Although several manufacturers are still using open-mold, wet lay-up processes, increasingly stringent environmental restrictions will likely result in a move toward processes with lower emissions. In current production, two methods are emerging as the most common replacement for traditional methods. These are the use of preimpregnated materials and resin infusion, with VARTM being the most common infusion method. Both VARTM and prepreg materials have particular design challenges for manufacturing the relatively thick laminate typical of large wind turbine blades. For VARTM processes, the permeability of the dry preform determines the rate of resin penetration through the material thickness. For prepreg material, sufficient bleeding is required to avoid resin-rich areas and eliminate voids from trapped gasses.

Another promising alternative is partially preimpregnated fabric, marketed by SP Systems under the name SPRINT, and by Hexcel Composites as HexFIT. When layed-up, the dry fabric regions provide paths for air to flow, and vacuum can be used to evacuate the part prior to heating. Under heat and pressure, the resin flows into the dry fabric regions to complete the impregnation.

An elevated temperature post-cure is desirable for both prepreg and VARTM processes. Current commercial prepreg materials generally require higher cure temperatures (90° - 110° C) than epoxies used in VARTM processes (60° - 65° C). Heating and temperature control / monitoring becomes increasingly difficult as laminate thickness is increased. Mold and tooling costs are also strongly affected by the heat requirements of the cure cycle. In all cases, achieving the desired laminate quality requires a trade-off between the extent of fiber compaction, fabric / preform architecture, resin viscosity, and the time / temperature profile of the infusion and cure cycles.

The use of automated preforming and automated lay-up technologies are also potential alternatives to hand lay-up in the blade molds. Benefits could include improved quality control in fiber / fabric placement and a decrease in both hand labor and production cycle times.

Alternative Materials

In several recent studies, the use of carbon fiber in the load-bearing spar structure of the blade has been identified as showing substantial promise for cost-effective weight reductions and increased stiffness. In particular, new low-cost, large-tow carbon fibers could result in improved blade structural properties at a reduced cost relative to an all-fiberglass blade.

Further economies may be realized if the carbon fibers can be processed into a form that favors both structural performance and manufacturing efficiency. Stitched hybrid fabrics and other automated preforming technologies have potential benefit in this area. Maintaining fiber straightness is crucial to achieving desirable compressive strength properties from composite materials. While carbon fibers tend to have excellent stiffness and tensile strength properties, realizing the full benefits from carbon fibers will require fabric / preform architectures that also result in good compressive strength.

Carbon Fiber Price Stability

The general trend in the past decades has been one of increasing usage and decreasing cost for carbon fiber materials. This has made carbon viable alternative for wide-spread usage in wind turbine blades. In the BSDS trade-off studies, carbon fiber prices of $19.80/kg and $12.10/kg were assumed, respectively, for "currently-available" and "next-generation" large-tow carbon fibers. Although these price estimates were based on consultation with several carbon fiber manufacturers, the long-term price and price stability of carbon fibers remains questionable.

At a 2001 international carbon industry meeting several speakers and panel discussions focused on the question of whether carbon producers could profitably sustain current carbon fiber prices. A detailed analysis was presented showing the current manufacturing cost (before profit) of 12k tow carbon to be approximately $19/kg and 50k tow production cost to be about $14/kg.[14] It has been speculated that increased demand for commercial carbon fiber (i.e. through applications such as wind turbine blades, fuel cell, infrastructure, automotive and other transportation) could result in economies of scale to further reduce carbon fiber production costs. However, to date the carbon fiber industry remains dominated by aerospace applications that can pay a high premium for materials with low weight and desirable structural and thermal properties.

Blade and Laminate Size Effects

Large blades are likely to use the heaviest possible reinforcing fabrics or prepreg ply thickness to achieve manufacturing efficiency. Increases in fabric weight may affect both basic in-plane properties, delamination, and problems associated with ply drops where the thickness is tapered.

Thick composite materials may have an increased likelihood of multiple flaws being grouped in the same local area, or an increased chance of larger areas of porosity. However, there may also be offsetting improvements due to larger size, such as the likely arrest of damage as it spreads from local stress concentration areas, which is not present in test coupons due to their small size and cut edges.

A number of production-related variations may occur in larger structures which are more easily avoided in smaller structures, and rarely appear in test coupons. Typical of these are fabric joints and overlaps where individual rolls of fabric terminate, and flaws in fabric where individual strands terminate during production of the fabric. Other factors which are more likely in larger blades include fiber waviness, large scale porosity, large resin rich areas, and resin cure variations through the thickness.

PRELIMINARY DESIGN OF 3.0 MW BLADE

The following sections present the preliminary design of a 3.0 MW blade. A similar design was also developed for a 5.0 MW rating. However, the general trends and design sensitivities observed were identical to those for the 3.0 MW blade and as such are not reported here.

Design Specifications

Specifications were written to guide the development of preliminary designs for megawatt-scale blades. The specifications were developed from several sources, and include turbine design and operation, blade architecture, design loads, and criteria for determining structural integrity. The aerodynamic designs and loads are based on work performed in the WindPACT Blade Scaling and Rotor System Design Studies. Design criteria are based on regulations from the International Electrotechnical Commission (IEC 61400-1)[15] and Germanischer Lloyd (GL).[16] Materials data are based on earlier work performed under the BSDS, and on extensive research carried out at MSU.[17]

Specifications were developed for three rotor sizes with system ratings of 1.5, 3.0 and 5.0 MW. For these three configurations the blade dimensions and loads are representative of turbines with specific rating of 0.39 kW/m^2. An additional set of blade dimensions and loads was developed for a 1.5 MW rotor with a specific rating of 0.31 kW/m^2.

The specified design criteria are based on recognized international standards and are generally applicable to turbine blades spanning a wide range of design parameters. However, the design loads were derived from aeroelastic simulations that were carried out for specific aerodynamic and structural designs. While the loads in the design specifications may not be generalized to other turbine and rotor configurations, the specifications do contain approximate methods for scaling the edgewise fatigue loads for blades with mass distributions differing from the baseline designs.

The blade designs were developed per the IEC 61400-1 code to withstand the specified operational and non-operational loads and environment for a period of 20 years. The IEC 61400-1 requires different partial safety factors to be applied according to the type of analysis (ultimate versus fatigue), the type of component (fail-safe versus non fail-safe), and the type of load (aerodynamic, gravity, etc.). In all cases, the IEC specified safety factors were used for developing design loads. For composite materials, the default GL partial safety factors were applied according to the type of fabric, resin system, and cure process.

Blade bending loads were developed for selected spanwise stations, including 20-year peaks and fatigue spectra in both flapwise and edgewise directions. The criteria to be met by each blade design included static strength, fatigue strength, and allowable tip deflections.

Materials Selected

Table 1 lists static properties developed for candidate spar cap materials to be used in the preliminary blade designs. Design strain values (ε_{design}) were derived from characteristic values by applying partial safety factors per the GL regulations. In the following 3.0 MW blade design, material #2 was used for the baseline fiberglass spar cap laminate, and material #4 was used for carbon / fiberglass hybrid blade sections.

Design Process

The preliminary blade designs were developed iteratively, beginning with an initial design of the blade structure at selected spanwise stations and assuming the structural architecture indicated in Figure 2. Each station was evaluated to determine the governing flapwise strength requirement (static or fatigue) and the blade spar was sized using the ANSYS / NuMAD codes so that the flapwise strength criteria were met. Once all blade sections were sized for flapwise strength, the resulting blade was evaluated for allowable tip deflections. If the tip deflection criterion was met, then the mass distribution was calculated and compared with the baseline blade design. These data were used to adjust the baseline edgewise bending fatigue spectra as appropriate for the new blade design, and to evaluate the edgewise bending strength of the blade sections. Once the design of the blade sections was converged, an ANSYS model was developed in which the sections are connected in a three-dimensional blade.

The initial 3.0 MW blade design was an all-fiberglass baseline configuration. Next, selected stations were replaced with carbon / fiberglass hybrid spar caps and the effect on blade weight and tip deflections quantified. Finally, an example design was developed assuming a fiberglass-to-carbon transition in the spar cap at mid-span (50% R).

Table 1 Static Properties for Candidate Spar Cap Materials

Material # and Description		v_f	Moduli (GPa)			ν_{xy}	Density	ε_{design} (%)	
			E_x	E_y	G_{xy}		(kg/m^3)	Tens.	Comp.
1	Woven glass uni + stitched glass triax, 70% 0°	0.4	25.0	9.2	5.0	0.35	1750	1.01	0.45
2	Woven glass uni + stitched glass triax, 70% 0°	0.5	29.0	10.2	6.0	0.31	1880	1.01	0.39
3	Prepreg glass uni + triax, 70% 0°	0.5	29.0	10.2	6.0	0.31	1880	1.01	0.63
4	Stitched hybrid carbon / fiberglass triax, 70% 0°	0.5	74.3	10.0	4.8	0.35	1621	0.50	0.34
5	Prepreg hybrid carbon / fiberglass triax, 70% 0°	0.5	74.3	10.0	4.8	0.35	1621	0.55	0.37
6	"P4A" oriented discontinuous carbon preform	0.55	94.3	20.0	6.1	0.55	1540	0.50	0.41

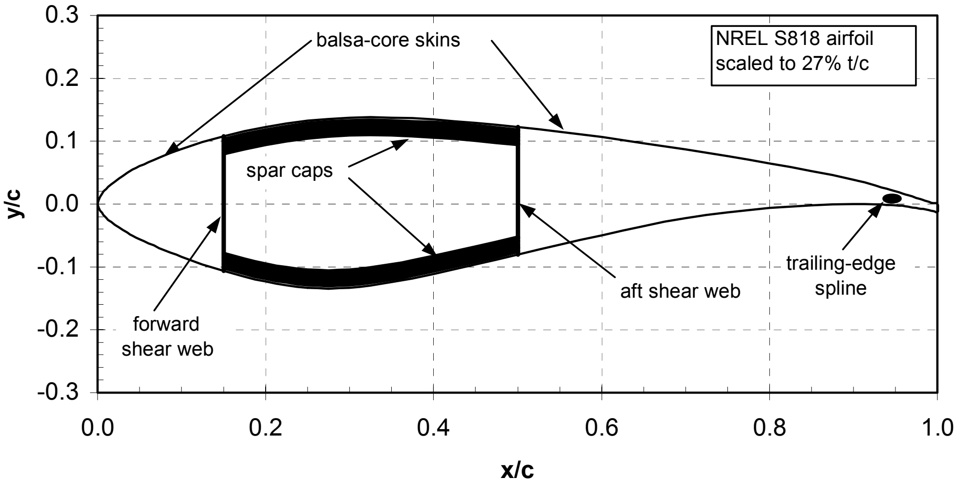


Figure 2 Architecture of baseline structural model

Spanwise Extent of Carbon Spar

A parametric assessment was performed to evaluate the sensitivity of design parameters to the spanwise extent of the carbon spar. Figures 3 through 5 illustrate the results. The x-axis of each plot indicates the extent of the "spar modification" modeled. Zero percent modification represents the baseline blade with an all-fiberglass spar cap. The spar modifications were assumed to occur from the blade tip inward, so a 25% spar modification implies that the outer quarter of the blade spar is carbon / fiberglass hybrid, 50% modification implies the outer half of the blade is carbon hybrid, and so on.

Figure 3 shows the mass of carbon fiber used and the value of the gravity-induced root bending moment, both as functions of the carbon spar extent. Note that the gravity-induced component of root bending is primarily oriented in the edgewise direction of the blade structure. As would be expected, the carbon fiber mass used increases, and the gravity-induced bending loads decrease as the carbon spar is extended inward along the blade span.

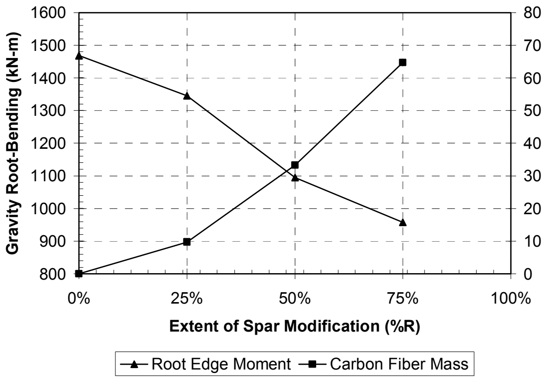


Figure 3 Gravity moments and carbon usage

Figure 4 shows the percentage change in gravity-induced root bending moment (Δ root moment), and also the "normalized" Δ root moment, where the normalization represents the percentage change per 100 kg of carbon fiber used. The figure shows that the greatest reduction in gravity-induced bending loads is realized for a carbon spar extending from the tip to mid-span. If the spar were carried further inboard, the reductions in total blade mass would be large, but because the distance to the root section is also decreasing the mass reductions have a diminishing effect on the gravity-induced moments.

Figure 5 shows a similar trend for changes in tip deflection as a function of carbon spar extent. Again, the greatest reductions in deflection are shown for a carbon spar cap that spans the outer half of the blade.

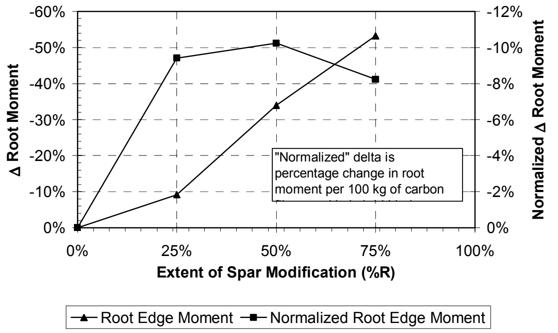


Figure 4 Effect of carbon spar spanwise extent on root bending moments

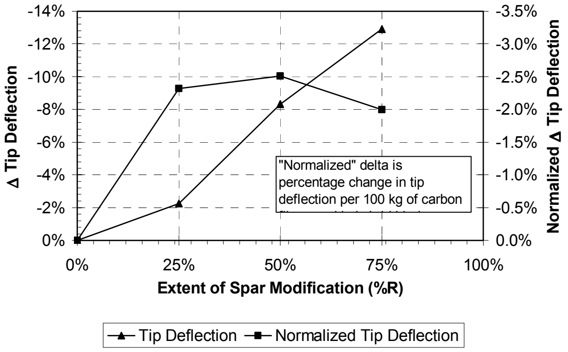


Figure 5 Effect of carbon spar spanwise extent on blade tip deflections

Blade Design with Mid-Span Transition

In this section, a 3.0 MW blade design is developed assuming a mid-span transition from a fiberglass to a carbon hybrid spar cap. In the following section, the technical challenges associated with such a transition are presented and discussed.

Table 2 lists the design margins for static and fatigue strength at each spanwise section for both the fiberglass and fiberglass / carbon hybrid blade designs. Shaded entries indicate that a margin is at or near a governing value. Margins for "compressive", "tensile", and "reversed" strength correlate, respectively, to the upper, lower, and trailing edge regions of the blade sections.

Static compression strength governs the inboard region of the all-fiberglass blade. In addition, the 25% span section also has a negative margin on edgewise fatigue strength. At mid-span the design is critical in static strength, but is also near-critical in compressive fatigue. At the 75% span station, the fiberglass section is governed by compressive fatigue strength. The all-

Table 2 Design Strength Margins for 3.0 MW Fiberglass / Carbon Hybrid Blade

Blade	Station	Static Margins (%)		Fatigue Margins (% Strength)		
	(% R)	Comp.	Tens.	Comp.	Tens.	Reversed
Fiberglass	Root	0.4	411	13.0	25.6	35.1
"	25% R	0.2	504	16.2	25.7	-5.3
"	50% R	0.3	332	3.5	11.7	34.7
"	75% R	10.5	289	0.1	10.6	262.3
Fiberglass / Carbon Hybrid	Root	0.4	411	13.0	25.6	50.4
"	25% R	0.2	504	16.2	25.7	7.3
"	50% R	0.6	161	43.5	139.8	50.4
"	75% R	-0.2	105	24.7	106.3	264.0

Table 3 Spar Cap Geometry for 3.0 MW Fiberglass / Carbon Hybrid Blade

Blade Section	Spanwise Location (m)	Spar Cap Dimensions		Approximate # of Plies
		Width (mm)	Thickness (mm)	
25% R, Fiberglass	12.4	1188	39.7	40
50% R, Fiberglass	24.8	912	40.8	41
50% R, Carbon Hybrid	24.8	912	18.3	18
75% R, Carbon Hybrid	37.2	633	70	7

fiberglass blade design also has a negative 5.5% margin on allowable tip deflection (not shown in Table 2). Although the negative margins on edgewise bending and tip deflection could be remedied by selective use of additional fiberglass materials, the substitution of a carbon hybrid spar in the outer blade can also be used to increase blade stiffness and decrease gravity-induced bending loads.

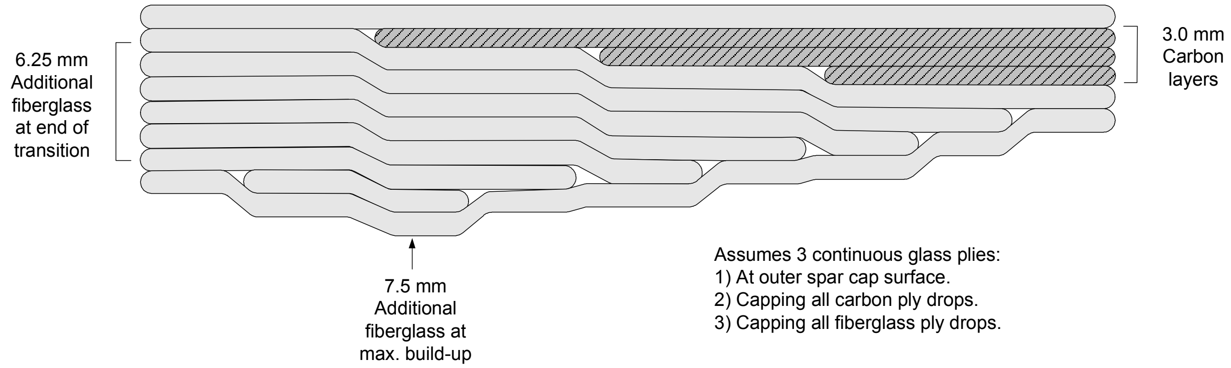
The lower half of Table 2 shows the strength margins for the 3.0 MW blade with an assumed fiberglass-to-carbon transition at mid span. The root and 25% span sections are structurally unchanged from the all-fiberglass design as reflected by the flapwise margins (compression and tension). However, due to the reduced mass in the outboard part of the blade the edgewise bending margins are improved over the entire blade span and the margin at the 25% station is increased from -5.3% to +7.3%. The margin on tip deflection (not shown in the table) is also increased from -5.5% to +2.5%. At 75% span, the governing criterion has shifted from compressive fatigue to compressive static strength.

Design / Manufacturing Issues for Spar Transition

As shown in the previous section, carbon fiber spars appear be of greatest advantage for reducing gravity-induced bending loads and tip deflections when located in the outer blade span. However, there are significant challenges to designing a fiberglass-to-carbon spar transition that is structurally efficient and cost-effective to manufacture.

One issue in a spar transition is the mismatch between the carbon and fiberglass ply stiffness and strain-to-failure. The most simple ply transition coupon would be one with a single butt-joint between the dissimilar plies. However, this is not likely to be a favorable option from either a manufacturing or structural performance standpoint, and so that arrangement is not depicted herein. In any approach, maintaining straightness in the carbon plies will be desirable for preserving static compressive strength.

For reference, Figure 6 depicts a candidate spar cap design with a fiberglass-to-carbon transition. The thickness scale of these figures correctly reflects the assumption that carbon layers are 1.0 mm thick whereas the fiberglass layers are 1.25 mm thick. The horizontal scale has been compressed to show the complete transition. The transition dimensions were developed assuming materials #2 (fiberglass) and #4 (carbon hybrid) as described by Table 1. As a result of the stiffness and compressive design strain, a 2.5-to-1.0 ratio of fiberglass-to-carbon laminate thickness is required in regions where both materials are present. Because the fiberglass materials have larger design strains than the carbon, one of the fiberglass layers is shown as being dropped following the transition region. The ratios shown are only valid for specific combinations of material and design strains, and could be higher or lower for alternate materials.



Assumes 3 continuous glass plies:
1) At outer spar cap surface.
2) Capping all carbon ply drops.
3) Capping all fiberglass ply drops.

Figure 6 Example candidate fiberglass-to-carbon spar transition

As a result of some structural inefficiency and the manufacturing complexity of a mid-span fiberglass-to-carbon spar transition, the preferable option may be to extend the load-bearing carbon inboard to the blade root. However, some testing is planned under the Part 2 BSDS to quantify the structural performance aspects of such transitions.

TECHNICAL ISSUES AND RECOMMENDED TESTING FOR PART 2 BSDS

The following sections discuss some of the specific technical issues that were identified in the course of this project, and corresponding recommendations for testing under the Part 2 BSDS. The primary context for the technical issues and testing is to establish the performance of commercial (i.e. low-cost, large-tow) carbon fiber in application to large wind turbine blades.

Material Types

Numerous material types have been identified, reviewed and evaluated for application to wind turbine blades during the course of this project, many of which are currently in coupon testing as part of the DOE/MSU database program. Items that have been assigned high priority for the Part 2 BSDS include; large and moderate tow size carbon fiber, prepreg and VARTM infusion, and hybrid multi-layer multi-axial warp knit (MMWK) fabric. In addition to a hybrid MMWK fabric, dry carbon unidirectional fabric with thermoplastic bead adhesion is a material form of high interest.

It is expected that for a given fiber, laminate manufactured with prepreg resin will have the best static and fatigue strength. As a result of induced waviness and other details, dry fabrics that are then infused by VARTM are expected to have lower strength performance. However, prepreg materials have historically been more expensive and require higher cure temperatures than liquid epoxy resin systems. Currently, the majority of turbine blade manufacturers use a "wet" process, either VARTM or a open mold layup and impregnation. Dry layup of preforms and subsequent infusion therefore remains as a process of high interest for the wind industry.

To address this issue, the proposed Part 2 BSDS testing will seek to answer several questions: What is the best strength performance that can be obtained by combining commercial carbon fibers in a low-cost fabric / preform process with VARTM infusion? How do the strength and estimated production costs compare with prepreg versions of corresponding fibers? Is the performance/cost ratio better for large or moderate tow fibers? What appear to be the most cost-effective combinations?

Thick Laminate

Thick laminate tests are expected to be of value to evaluate several technical issues. The first is simply thickness scaling of basic carbon / hybrid spar cap laminate. In laminate with ideal fiber alignment, some increase in compressive strength may be expected as the thickness increases. However, the thicker laminate will also include a greater distribution of naturally-occurring material defects than the smaller coupons, and also a greater opportunity for fabrication-related irregularities. Given the relatively large strand size of commercial carbon fibers and the heavy-weight fabrics in use for large blades, some investigation of basic thickness effects is planned.

Thick laminates can also be used to investigate details that are not amenable to testing in thin coupons. Examples in the current test matrix are multiple ply drops, multiple ply transitions, and as-manufactured laminate properties (effects of defects).

Ply Drops and Transitions

It is expected that ply drops in load-bearing carbon spars will cause a greater decrease in fatigue strength than in an equivalent fiberglass structure. This is due to the fact that the carbon fibers are more highly loaded than the fiberglass and as a consequence will shear a higher load per unit area into the resin-rich region at the ply termination. An additional effect may be due to any waviness or jogs that are introduced in the remaining carbon plies as a result of the ply drop. Ply thickness is another important parameter for ply drops. The technical issue at hand is the trade-off between the increase in processing / handling efficiency of blade construction and the decrease in fatigue performance at ply drops which would be expected for the thicker carbon plies.

In general, carbon-to-fiberglass ply transitions have all of the technical considerations of carbon ply drops (i.e. load transfer though resin-rich areas, sensitivity to carbon layer straightness and ply thickness). However, as discussed above ply transitions also add the complication of mismatch between the carbon and fiberglass ply stiffness and strain-to-failure.

Margins / Safety Factors

A starting point in determining margins and safety factors is to develop a sufficient number of data points so that statistically-based characteristic (i.e. 95% exceedance with 95% confidence) properties can be derived. Another aspect is the difference between material properties as generated in coupon tests and the performance of similar material in an as-built blade. This encompasses a wide range of effects, some of which are inherent (natural variations of material properties, unavoidable variations in fiber and fabric alignment, volume and thickness effects, inherent process-related effects) and some of which can vary depending on the execution of the manufacturing approach (avoidable misalignment of fabric, irregularities due to varying quality control of fabrication and process).

The tests currently planned under the Part 2 BSDS to address this issue assume thick laminate that is constructed with designed and controlled irregularities in the fiber alignment and/or void content. Such testing is more correctly characterized as evaluating the “effects of defects” and only addresses a subset of the effects that combine in “as-manufactured properties”

Biased Fabrics

Although not formally included in the trade-off studies of the Part 1 BSDS, biased carbon-fiberglass hybrid materials are of interest for testing under the Part 2 study. The motivation for including these materials is that modeling under the WindPACT Rotor Study predicts substantial COE reductions for twist-coupled blades, and biased carbon-fiberglass laminate has been identified as a promising approach to cost-effective manufacture of such blades. There are also several other ongoing DOE-funded research efforts in the area of twist-coupled blades, but at this time property characterization data are lacking for the material combinations of interest.

Figure 7 shows a schematic representation of a candidate test that incorporates biased carbon / fiberglass laminate in a tubular specimen with combined axial and torsional loading. The dimensions and fiber orientation angles shown the figure are nominal, but were used in specifying the required test equipment and estimating costs for part fabrication and testing. It is assumed that the parts can be fabricated by wrapping a biased carbon / fiberglass fabric around a foam core, with subsequent infusion. The article would then have an extension-twist bias. When loaded axially, the laminate would respond much as biased material would on either the upper or lower surface of a turbine blade (assuming mirror symmetry of upper and lower surface laminate to achieve bend-twist coupling).

With the proposed design, the axial and torsional degrees of freedom can be loaded independently, or either can be left free. From the test measurements, the laminate properties E_x, G_{xy}, and $\eta_{x,xy}$ (measure of the amount of shear strain generated in the x-y plane per unit strain in the x-direction) can be inferred. Following an evaluation of the material stiffness properties, the article can be progressively loaded to failure. The measured stiffness and strength properties can then be compared with values predicted by micromechanics.

Summary of Recommended Tests

Table 4 provides a summary of the technical issues identified, and types of testing recommended for resolving each issue under the Part 2 BSDS. For the majority of the tests listed, both static and fatigue testing would be of practical interest.

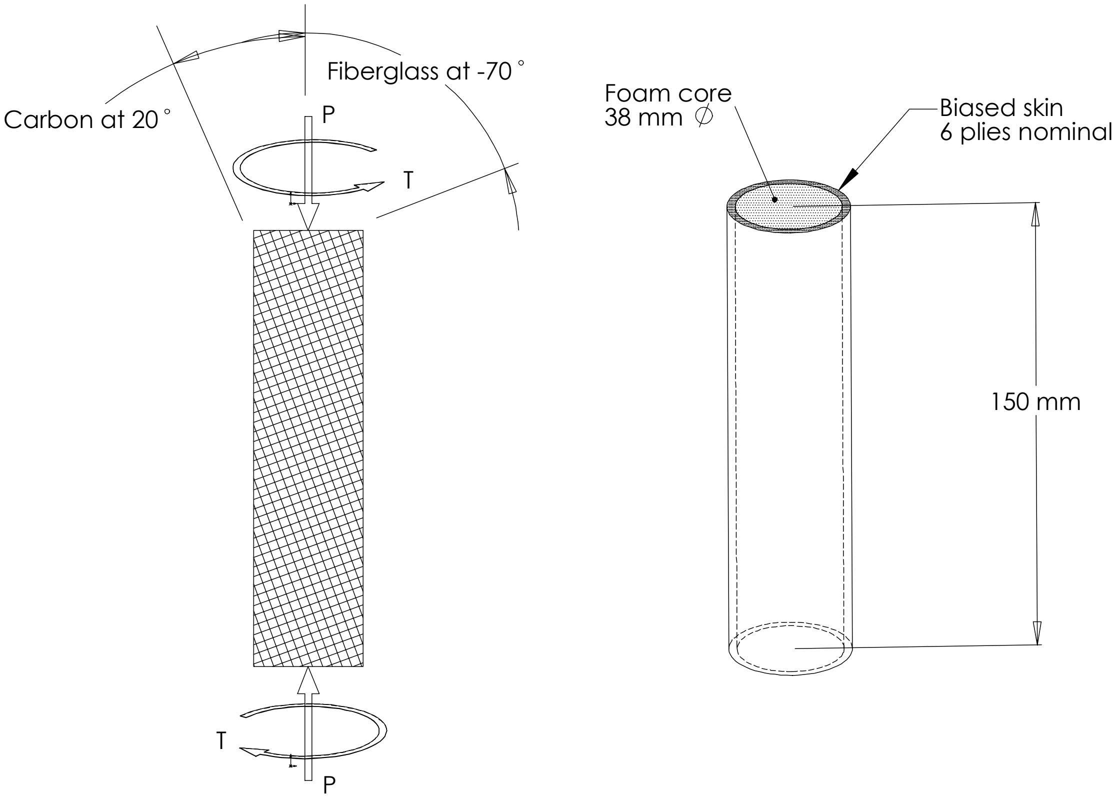


Figure 7 Schematic of candidate test for biased tube in combined axial / torsional loading

Table 4 Summary of Technical Issues and Recommended Tests for the Part 2 BSDS

Technical Issue	Type of Testing Recommended / Planned
Basic performance of candidate materials	• Thin coupon • Thick coupon
Ply drops	• Thin coupon (single ply drop) • Thick coupon (multiple ply drops) • Internal and external drops • Variations on ply thickness
Carbon / fiberglass ply transitions	• Thin coupon (single ply drop) • Thick coupon (multiple ply drops) • Variations on ply thickness
Performance of complete spar design, with ply drops and/or transitions	• 4-point beam bending
Margins and safety factors	• Thin coupons (development of statistical data for selected material / process combinations) • Thick coupons with pre-designed irregularities (effects of defects)
Biased fabrics	• Specialty cylinder in combined axial / torsional loading

CONCLUSIONS

In the Part 1 BSDS, constraints were identified to cost-effective scaling-up of the current commercial blade designs and manufacturing methods, and candidate innovations in composite materials, manufacturing processes and structural configurations were assessed. Preliminary structural designs were developed for hybrid carbon fiber / fiberglass blades at system ratings of 3.0 and 5.0 megawatts. Structural performance was evaluated for various arrangements of the carbon blade spar, and critical performance aspects of the carbon material and blade structure are discussed. To address the technical uncertainties identified, recommendations were made for new testing of composite coupons and blade sub-structure. These test efforts are currently ongoing under the Part 2 BSDS.

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REFERENCES

1. BTM Consult ApS., *A Towering Performance – Latest BTM Report on the Wind Industry*, Renewable Energy World, July-August 2001, p.p. 69-87, James & James (Science Publishers Ltd.), London UK.
2. Dutton, A.G., et. al. (March 1-5, 1999). *Design Concepts for Sectional Wind Turbine Blades*. Proceedings of the 1999 European Wind Energy Conference, Nice, France. p.p. 285-288.
3. Joosse, P.A., et al. (January 10-13, 2000). *Economic Use of Carbon Fibres in Large Wind Turbine Blades*? Proceedings of AIAA/ASME Wind Energy Symposium. Reno, NV.
4. Joosse, P.A., et al. (July 2-6, 2001). *Toward Cost Effective Large Turbine Components with Carbon Fibers.* Presented at the 2001 European Wind Energy Conference and Exhibition, Copenhagen.
5. Joosse, P.A., et al. (July 2-6, 2001). *Fatigue Properties of Low-Cost Carbon Fiber Material.* Presented at the 2001 European Wind Energy Conference and Exhibition, Copenhagen.
6. Joosse, P.A., et al. (January 14-17, 2002). *Toward Cost Effective Large Turbine Components with Carbon Fibers*. Proceedings of AIAA/ASME Wind Energy Symposium. Reno, NV.
7. Griffin, D.A. (March, 2001). *WindPACT Turbine Design Scaling Studies Technical Area 1 – Composite Blades for 80- to 120-Meter Rotor*. NREL/SR-500-29492. Golden, CO: National Renewable Energy Laboratory.
8. Smith, K. (March, 2001). *WindPACT Turbine Design Scaling Studies Technical Area 2 – Turbine, Rotor and Blade Logistics*. NREL/SR-500-29439. Golden, CO: National Renewable Energy Laboratory.
9. Vandenbosche, J. (March, 2001). *WindPACT Turbine Design Scaling Studies Technical Area 3 – Self-Erecting Tower Structures*. NREL/SR-500-29493. Golden, CO: National Renewable Energy Laboratory.
10. Malcolm, D., Hansen C. (June, 2001) *Results from the WindPACT Rotor Design Study*. Proceedings Windpower 2001, American Wind Energy Association, Washington DC.
11. Malcolm, D.J. and Hansen, A.C. (June 2002). *Lessons from the WindPACT Rotor Design Study.* Poster presentation at WindPower2002. American Wind Energy Association, Portland OR.
12. Griffin, D.A. (July, 2002). *Blade System Design Studies Volume I: Composite Technologies for Large Wind Turbine Blades*. SAND2002-1879. Albuquerque, NM: Sandia National Laboratories.
13. Laird, D.L. (January 11-14, 2001). *2001: A Numerical Manufacturing and Design Tool Odyssey*. Proceedings of AIAA/ASME Wind Energy Symposium. Reno, NV.
14. Service, D. (October 16-18, 2001). *PAN Carbon Fibre Precursor.* Proceedings of Intertech's Carbon Fiber 2001, Bordeaux, France.
15. International Electrotechnical Commission. (1999). *IEC 61400-1: Wind turbine generator systems – Part 1: Safety Requirements*, 2nd Edition. International Standard 1400-1.
16. Germanischer Lloyd (1999) Rules and Regulations IV – Non-Marine Technology, Part 1 – Wind Energy, *Regulation for the Certification of Wind Energy Conversion Systems*.
17. Mandell, J.F., Samborsky, D.D. (1997). "*DOE/MSU Composite Material Fatigue Database: Test Methods, Materials and Analysis*." SAND97-3002. Sandia National Laboratories. Albuquerque, NM.