SAND REPORT

SAND2002-1879
Unlimited Release
Printed July 2002

Blade System Design Studies Volume I: Composite Technologies for Large Wind Turbine Blades

Dayton Griffin
Global Energy Concepts, LLC
Kirkland, Washington 98109

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

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Dayton A. Griffin
Global Energy Concepts, LLC
5729 Lakeview Drive NE, #100
Kirkland, Washington 98109

Abstract

As part of the U.S. Department of Energy's Wind Partnerships for Advanced Component Technologies (WindPACT) program, Global Energy Concepts LLC (GEC) is performing a study concerning innovations in materials, processes and structural configurations for application to wind turbine blades in the multi-megawatt range. The project team for this work includes experts in all areas of wind turbine blade design, analysis, manufacture, and testing. Constraints to cost-effective scaling-up of the current commercial blade designs and manufacturing methods are identified, including self-gravity loads, transportation, and environmental considerations. A trade-off study is performed to evaluate the incremental changes in blade cost, weight, and stiffness for a wide range of composite materials, fabric types, and manufacturing processes. Fiberglass / carbon fiber hybrid blades are identified as having a promising combination of cost, weight, stiffness and fatigue resistance. Vacuum-assisted resin transfer molding, resin film infusion, and pre-impregnated materials are identified as having benefits in reduced volatile emissions, higher fiber content, and improved laminate quality relative to the baseline wet lay-up process. Alternative structural designs are identified, including jointed configurations to facilitate transportation. Based on the results to date, recommendations are made for further evaluation and testing under this study to verify the predicted material and structural performance.

Acknowledgements

This work was completed for Sandia National Laboratories as part of the U.S. Department of Energy's WindPACT program, under Sandia Purchase Order No. 13473. The author wishes to acknowledge the contributions of Sandia Technical Monitor Tom Ashwill, Paul Veers, and other Sandia personnel to this project. This project has benefited from extensive collaboration with manufacturers of composite materials, wind turbine blades, and other composite structures. Jim Sommer of MFG Fiberglass provided valuable insight on blade manufacturing and costs. Mark Elliott of Hexcel Composites and Moto Ashizawa of Toray Industries consulted throughout the project on material properties, processing and costs. Other manufacturers that contributed to this work include: Enron Wind and TPI Composites (blade manufacturing and design issues), Fortafil and Zoltek (carbon fibers), SAERTEX and Hexcel Schwebel (hybrid fabrics), Composite Engineering Incorporated (braided structure fabrication), Techniweave (3-D weaving), the National Composite Center (oriented sprayed-fiber preforms), and Rickard B. Heslehurst (composite joining technologies). Mike Zuteck consulted on all phases of this project, and John Mandell of Montana State University made significant technical contributions in material selection and development of laminate properties.

Executive Summary

As part of the U.S. Department of Energy's (DOE) WindPACT program, Global Energy Concepts LLC (GEC) is performing a Blade System Design Study. The purpose of the WindPACT program is to explore the most advanced technologies available for improving wind turbine reliability and decreasing cost of energy. The Blade System Design Study concerns composite wind turbine blades for rotors of 80 to 120 meters in diameter. The specific objectives of this study are to identify issues and constraints for the design, manufacture and use of large wind turbine blades, and to identify and evaluate alternative materials, manufacturing processes, and structural designs that may overcome those constraints.

Background

To conduct this study, GEC has assembled a project team that includes experts in all areas of wind turbine blade design, analysis, manufacture, and testing. Consistent with the overall objectives of the WindPACT Program, the Blade System Design Study has provided a mechanism for a substantial two-way flow of information between the wind energy and composites manufacturing industries. In the process of identifying candidate innovations in materials, processes, and structural designs, GEC has established a dialogue with numerous manufacturers of composites fibers, fabrics and structures. Evaluation of candidate technologies has required that GEC educate each manufacturer about design considerations that are particular to large wind turbine blades, and in turn, the manufacturers have supplied information on the potential benefits, constraints, trade-offs and technical issues for their material or manufacturing technology in this application.

This Blade System Design Study and the resulting technical exchange have proven to be well-timed with respect to the steady growth of the wind energy industry worldwide and the perceived market opportunities for manufacturers. In several cases, when GEC contacted manufacturers to determine their interest in having their technology considered under this program, the response was that not only are they interested, but they had already identified wind energy as an emerging market for which to target their capabilities.

Constraints to Scaling-Up of Current Commercial 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 layup that has been the wind industry norm.

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. However, 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.

Project Approach

Over the course of this project, alternative materials, manufacturing processes, and structural configurations were identified and evaluated for their potential benefit for large wind turbine blades. In assessing each candidate technology, the primary figures of merit were reduced weight (efficiency and mechanical properties of laminate, use of lower-density materials, efficiency of structural design), reduced cost (efficiency of material use, processing and manufacturing methods that minimize labor), and improved structural properties (fatigue properties of structural laminate, ply drops and other details, processes that increase reliability of fiber placement, orientation, and laminate composition).

An extensive trade-off study was performed to evaluate alternate materials and manufacturing processes. Material stiffness and strength properties were estimated for each of the material / process combinations considered. Structural calculations were then performed to determine the blade spar cap thickness required to withstand the peak static loads. Cost functions were developed for each material and process modeled, and the blade structural designs evaluated on the basis of cost, weight, and stiffness. Based on the trade-off study results, the most promising material and process combinations have been identified for near-term coupon testing at Montana State University, further evaluation in Part 1 of the Blade System Design Study, and potential testing under Part 2 of the Blade System Design Study. In terms of manufacturing processes, emphasis was placed on methods with low volatile emissions. Jointed and multi-piece blade designs were evaluated primarily for their potential to reduce transportation costs.

Results and Conclusions

Based on the evaluations of these options, general issues and technical concerns have been identified and discussed concerning the application to large wind turbine blades. A number of alternative materials and manufacturing processes have been identified as showing substantial promise for cost-effective application to megawatt-scale wind turbine blades and are recommended for further evaluation under the current Blade System Design Study. In summary, these are:

- Processes with low volatile emissions:
  - Prepreg materials
  - Infusion processes (vacuum assisted resign transfer molding, resin film infusion)
- Decreased weight, cost, and improved structural properties:
  - Carbon / fiberglass hybrid blades
  - "Next-generation" large-tow carbon fiber
  - Stitched triaxial carbon / fiberglass hybrid fabric
  - Automated preforming technologies for use with infusion processes

For the purposes of overcoming cost barriers to shipping of large blades, the least-risk and lowest-cost method is expected to be either on-site manufacturing or the inclusion of a limited number of major structural joints. A bonded finger joint has been identified as showing potential for field-joining of blade sections. However, it is unclear whether this option shows sufficient promise to merit further evaluation under this project.

In addition to the options identified above, several other materials, processes, and design options were evaluated in this project. Where technologies have been identified as non-competitive for application to large wind turbine blades, these conclusions are not intended to be taken as absolute. Rather, in some cases, an understanding of the constraints for a particular technology's application to large turbine blades may be useful in guiding further innovations within the composites materials and manufacturing industry.

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Nomenclature

c	chord length (m)
C_{ia}	partial safety factors for laminate materials
cm	centimeters
c_{max}	maximum blade chord (% R)
EI_{Edge}	edgewise bending stiffness ($N \cdot m^2$)
EI_{Flap}	flapwise bending stiffness ($N \cdot m^2$)
E_x	elastic modulus of laminate in longitudinal direction
E_y	elastic modulus of laminate in transverse direction
ft	feet
G_{xy}	in-plane shear modulus of laminate
kW	kilowatt
m	meters
mm	millimeters
N	number of loading cycles for fatigue analysis
MW	megawatt
P_{rated}	Rated power output of turbine (kW)
R	rotor radius (m)
R_f	fatigue bending load ratio (minimum/maximum bending moment)
r/R	spanwise blade station (%)
S	blade surface area
t	physical thickness of a blade section (m)
t/c	airfoil thickness-to-chord (%)
TSR	tip-speed ratio
TSR_{Design}	design tip-speed ratio
v_f	volume fraction of fiber in composite laminate
w_f	weight fraction of fiber in composite laminate
x/c	distance along airfoil chord
y/c	distance perpendicular to airfoil chord
ε-N	strain-cycle curve for fatigue analysis
ν_{xy}	major poison's ratio for laminate
ρ	material density (g/cm^3)

1. Summary

1.1 Introduction

As part of the U.S. Department of Energy's (DOE) WindPACT program, Global Energy Concepts LLC (GEC) is performing a Blade System Design Study. The purpose of the WindPACT program is to explore the most advanced technologies available for improving wind turbine reliability and decreasing cost of energy. The Blade System Design Study concerns composite wind turbine blades for rotors in the size range of 80 to 120 m diameter.

1.2 Project Summary

1.2.1 Overview

This project focuses on innovations in design, materials and processes that address potential barriers to the cost-effective manufacture of wind turbine blades in the multi-megawatt range. The specific objectives of the Blade System Design Study are to:

1. Identify issues and constraints for the design, manufacture and use of large wind turbine blades
2. Identify and evaluate alternative materials, manufacturing processes, and structural configurations that may overcome those constraints
3. Develop design specifications for large blades (1.5 MW and 5.0 MW)
4. Perform preliminary designs for a megawatt-scale blade, and identify areas of risk that merit testing before proceeding to detailed design
5. Develop recommendations for testing of materials, sub-component and/or sub-scale blades to resolve knowledge gaps
6. Document the project's progress and results in a manner that makes the information readily available to the U.S. wind industry, composite manufacturers, and other interested parties.

The current report addresses the first two items listed above and is intended to document the project progress to date, to provide a formal opportunity for review of this work, and solicit feedback that may be used as guidance for the follow-on project activities. In terms of the program structure, items #1 through #6 listed above fall under the Phase 1, Part1 portion of the Blade System Design Study. Subsequent manufacturing and testing of composite materials and components is planned under Phase 1, Part 2 of this program.

Consistent with the overall objectives of the WindPACT Program, this Blade System Design Study has provided a mechanism for a substantial two-way flow of information between the wind energy and composites manufacturing industries. In the process of identifying candidate innovations in materials, processes, and structural designs, GEC has established a dialogue with numerous manufacturers of fibers, fabrics and composite structures. Evaluation of candidate technologies has required that GEC educate each manufacturer about design considerations that are particular to wind turbine blades, and in turn, the manufacturers have supplied information on the potential benefits, constraints, trade-offs and technical issues for their material or manufacturing technology in this application.

This Blade System Design Study and the resulting technical exchange has proven to be well-timed with respect to the steady growth of wind energy development worldwide and the perceived market opportunities for manufacturers. In several cases, when GEC contacted manufacturers to determine their interest in having their technology considered under this program, the response was that not only are they interested, but they had already identified wind energy as an emerging market for which to target their capabilities.

1.2.2 Project Team

Figure 1 shows an organizational chart of the core project team, which includes experts in all areas of wind turbine blade design, analysis, manufacture, and testing. In addition to the project participants indicated by Figure 1, GEC has consulted with several other materials and composites manufacturers in the course of this work, including: Enron Wind and TPI Composites (blade manufacturing and design issues), Fortafil and Zoltek (carbon fibers), SAERTEX and Hexcel Schwebel (hybrid fabrics), Composite Engineering Incorporated (braided structure fabrication), Techniweave (3-D weaving), the National Composite Center (oriented sprayed-fiber preforms), and Rickard B. Heslehurst (composite joining technologies). Although the Blade System Design Study is being performed under the direct supervision of Sandia National Laboratories, the project activities are also coordinated with the National Renewable Energy Laboratory (NREL), including Walt Musial at the National Wind Technology Center (NWTC) structural testing laboratory.

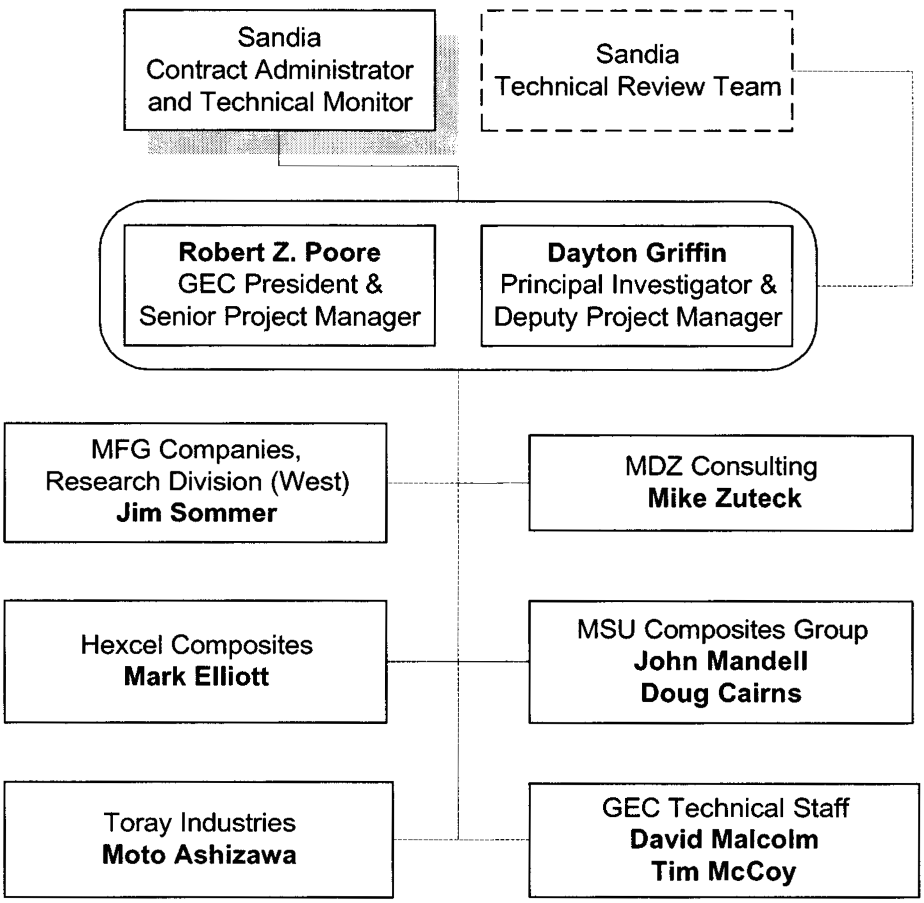

Figure 1 Organization Chart for the WindPACT Blade System Design Study

1.2.3 Relationship of WindPACT Blade-Related Projects

There are several studies under the DOE WindPACT program that concern the design and manufacture of large wind turbine blades. GEC has recently performed WindPACT scaling studies in the areas of composite blades,[1] blade and turbine transportation logistics,[2] and self erecting tower structures.[3] In addition, GEC is currently conducting a WindPACT Rotor System Design Study.[4] Under the Rotor Study, extensive aeroelastic simulations are being performed for a wide range of rotor configurations and the resulting loads used to quantify the impact on turbine system cost and cost of energy.

As indicated in Figure 2, the results from the Scaling Studies have been used as input to both the Turbine Rotor Design Study and the Blade System Design Study. GEC is integrating the activities of the Rotor (NREL) and Blade (Sandia) Design Studies. For example, properties for alternate materials (i.e. glass/carbon hybrids) developed under the Blade Design Study have been used as input to the structural models used in the Rotor Design Study. In turn, results from the aeroelastic simulations performed under the Rotor Study have been used to further evaluate material and process innovations identified under the Blade Study.

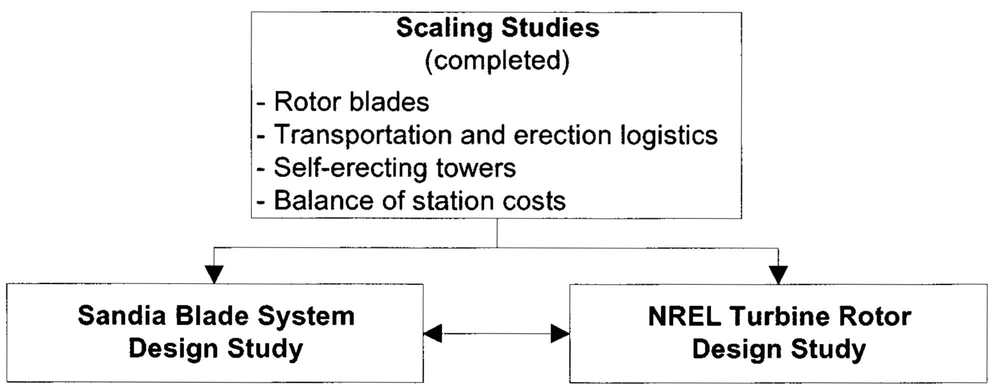

Figure 2 WindPACT studies concerning composite blade design and manufacture

1.3 Report Scope and Organization

This report addresses the first two items listed in Section 1.2.1: identification of issues and constraints for the design, manufacture and use of large wind turbine blades and evaluation of alternative materials, manufacturing processes, and structural designs that may overcome those constraints. The overall structure of this report is as follows:

- Definition of baseline blade
  - geometry and structural configuration
  - load cases and design criteria
  - manufacturing approach, cost and weight
- Identification of constraints / issues to scaling-up baseline blade
  - transportation and erection
  - manufacturing
  - weight and cost
- Trade-off study on alternative material and manufacturing processes
  - Fabric architecture

  - Fiber types (fiberglass, carbon and carbon / fiberglass hybrid)
  - Laminate properties from infusion processes and prepreg materials
- Evaluation of alternative manufacturing processes
  - Resin infusion
  - Automated preform manufacturing
  - Oriented sprayed fibers
  - Thermoplastic resins
  - Fully-integrated structures
  - Separately-cured spars
- Evaluation of alternative structural configurations
  - Jointed designs
  - Multi-piece blade assemblies
  - "decoupled skin" designs

Based on evaluations of these options, general issues are discussed concerning the application to large wind turbine blades. A number of alternative materials, manufacturing processes, and structural designs are identified that show substantial promise for cost-effective application to megawatt-scale wind turbine blades. Recommendations are made for further evaluation under the current Blade System Design Study, and the potential benefits and technical uncertainties associated with each technology are identified.

2. Baseline Blade Configuration

The following sections present the structural configuration and manufacturing approach used in the baseline blade design for this study. This configuration provides the baseline against which alternative structural designs, material combinations, and manufacturing processes are evaluated for rotors in the size range of 80 to 120 m diameter.

2.1 Blade Geometry

The baseline turbine configuration assumed for this study is a three-bladed, upwind rotor with a rigid hub, full-span pitch control, and full variable-speed operation. Figure 3 is a graph of a typical planform, with a linear taper from the maximum chord location (25% r/R) to the blade tip. A circular blade root is located at 5% r/R. The blade shape is assumed to remain circular to 7% r/R, before transitioning to a pure airfoil shape located at 25% r/R. The blade planform for the current study is the same as is being used for the WindPACT Rotor Design Study baseline. The maximum chord dimension is 8% R, and the chord dimensions decrease linearly to a value of 2.6% R at the blade tip. The baseline design was developed for a system power rating of 1.5 MW, with a radius of R = 35 meters.

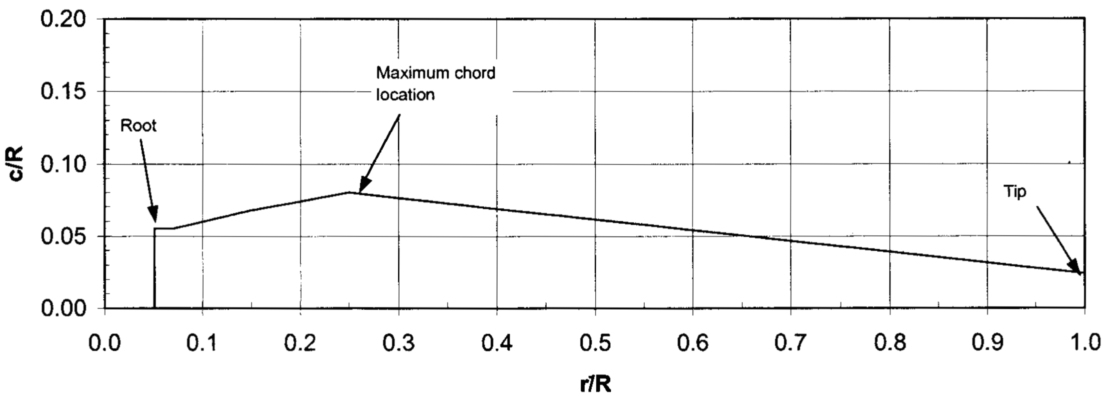

Figure 3. Typical blade planform

The NREL S-series airfoils are used for the blade structural designs of this study. During the work of Reference 1, the S818/S825/S826 family was identified as having desirable aerodynamic properties. However, the airfoils were deemed to be too thin for efficient application to large blades (assuming current commercial materials are used). A more structurally suitable set of airfoil shapes was derived by scaling the S818/S825/S826 foils and by the addition of a finite-thickness trailing edge. The shape modifications, and locations of airfoils along the blade are summarized in Table 1; the resulting airfoil shapes are shown in Figure 4.

Table 1. Airfoil Shape Modifications (baseline blade)

Airfoil	R (%)	Orig. t/c (%)	Scaled t/c (%)	Trailing-edge thickness (% c)
S818	25	24	30	1.3
S825	75	17	21	1.0
S826	95	14	16	0.75

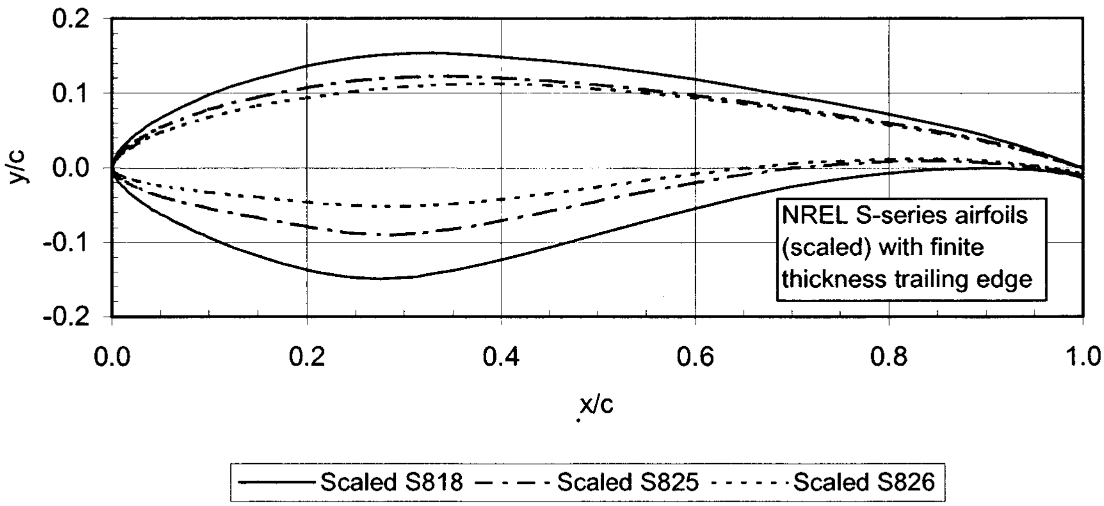

Figure 4. Airfoils used for baseline blade model

2.2 Baseline Structural Model

A baseline structural architecture was selected as being representative of current commercial blade designs. The primary structural member is a box-spar, with webs at 15% and 50% chord and a substantial build-up of spar cap material between the webs. The exterior skins and internal shear webs are both sandwich construction with triaxial fiberglass laminate separated by balsa core. This arrangement is depicted in Figure 5, where the thickest airfoil section (25% span station) is shown.

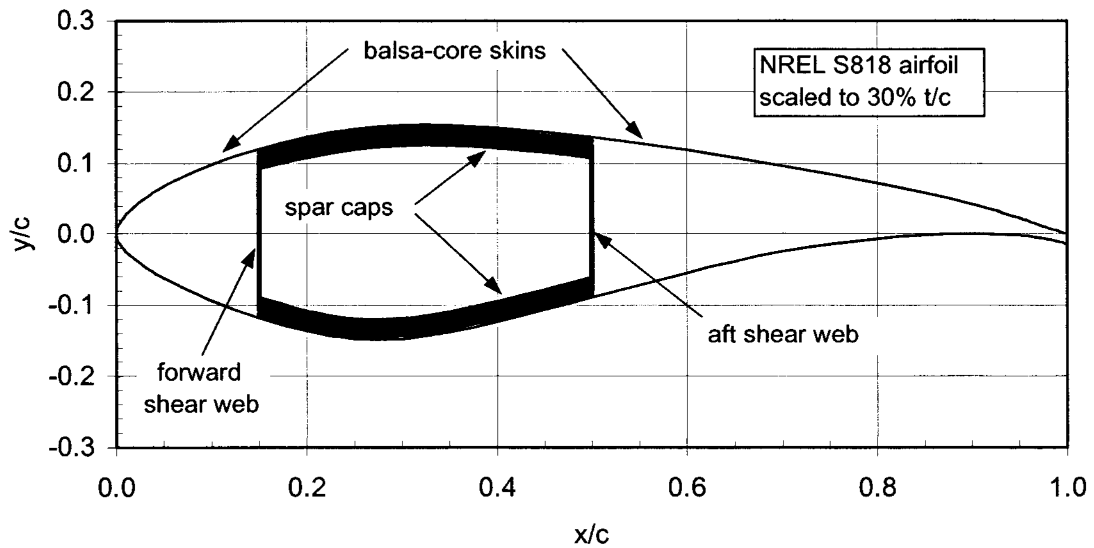

Figure 5. Architecture of baseline structural model

Table 2 lists the layers in the baseline structural shell, and describes the material contained in each. The shear web cores (balsa) were assumed to be 1% of airfoil chord (c) thick, with triaxial skins of 1.27 mm.

Table 2. Baseline Structural-Shell Definition

Layer #	Material	Thickness
1	gel coat	0.51 mm
2	random mat	0.38 mm
3	triaxial fabric	1.27 mm
4		
0%-15% c	balsa	0.5% c
15%-50% c	spar cap mixture	specified % t/c
50%-85% c	balsa	1.0% c
5	triaxial fabric	1.27 mm

The skins and spar cap are E-glass/epoxy laminate. The triaxial fabric is designated CDB340, and has a 25%, 25%, and 50% distribution of +45°, -45°, and 0° fibers, respectively. The spar cap is composed of alternating layers of triaxial and uniaxial (A260) fabric. This stacking sequence results in spar cap laminate with 70% uniaxial and 30% off-axis fibers by weight.

Characteristic material properties for the baseline blade lamina were determined at Montana State University (MSU) based on a combination of test data and laminate theory calculations. Table 3 summarizes the mass and stiffness properties for each material. Strength properties are addressed in Section 2.3.3.

Table 3. Summary of Baseline Blade Material Properties

Property	A260	CDB340	Spar Cap Mixture	Random Mat	Balsa	Gel Coat	Fill Epoxy
E_x (GPa)	31.0	24.2	25.0	9.65	2.07	3.44	2.76
E_y (GPa)	7.59	8.97	9.23	9.65	2.07	3.44	2.76
G_{xy} (GPa)	3.52	4.97	5.00	3.86	0.14	1.38	1.10
v_{xy}	0.31	0.39	0.35	0.30	0.22	0.3	0.3
v_f	0.40	0.40	0.40	-	N/A	N/A	N/A
w_f	0.61	0.61	0.61	-	N/A	N/A	N/A
ρ (g/cm^3)	1.75	1.75	1.75	1.67	0.144	1.23	1.15

In performing the blade structural calculations, it was not required that the spar cap dimensions be integer multiples of the selected material lamina thickness. This was done to avoid the need for step-jumps in the model definition and results. It was assumed that a suitable fabric (or combination of fabrics) could be identified that would be a near-match to the dimensions and fiber content modeled for each blade.

2.3 Blade Structural Calculations

The blade structural calculations were performed using two computational tools. The first is a set of spreadsheet-based blade design codes that were developed during the course of the WindPACT Blade Scaling Study and refined during the WindPACT Rotor Design study. The second is a finite-element

(FEA) calculation using the ANSYS code with the Sandia-developed NuMAD interface.[5] In both cases, the methodology described in the following sections was applied.

2.3.1 Load Cases

The primary load case used for developing structural designs was a peak flapwise bending load derived from a 50-year extreme gust of 70 m/s (IEC Class 1).[6] The gust was assumed to occur with the blades in a fully feathered position, with a ± 15° variation in wind direction. It was assumed that this load case resulted in each blade section simultaneously reaching its local maximum-lift coefficient and that the bending loads were entirely in the flapwise direction. The resulting loads were summed over the blade, to define characteristic peak bending moments at each blade station.

Although the primary blade design criteria was the IEC Class 1 extreme gust, results from the WindPACT Rotor Design Study (loads based on extensive aeroelastic simulations) were used to evaluate the effects of:

- Flapwise fatigue loading
- Edgewise fatigue loading, including gravity loads
- Design wind speed class (Class 1 versus Class 2)
- Tip deflections

2.3.2 Partial Safety Factors

In accordance with the IEC 61400-1 standard, a series of partial safety factors must be used to make adjustments from "characteristic" to "design" values of material properties and loads. The IEC 61400-1 requires a "general" material factor of 1.1. The IEC standard further states that material factors will be applied to account for "...scale effects, tolerances degradation due to external actions, i.e., ultraviolet radiation, humidity and defects that would not normally be detected"; however, the IEC document provides no specific guidance on appropriate values for these factors. Conversely, the Germanischer Lloyd (GL) regulations provide an explicit list of partial safety factors for composite materials.[7] For a static-strength evaluation of fiberglass and carbon reinforced plastics, the GL factors are:

γ_{M0}	=	1.35	general material factor
C_{2a}	=	1.50	influence of aging
C_{3a}	=	1.10	temperature effect
C_{4a}	=	1.10	laminates made from prepreg or semi-automated manufacturing
		1.20	hand lay-up laminate
C_{5a}	=	1.00	post-cured laminate
		1.10	non post-cured laminate

The GL regulations state that γ_{M0} is to be used in all cases, but that the C_{ia} may be adjusted if demonstrated by experimental verification.

For fatigue verification, the GL regulations state that γ_{M0} is to be used as described above. Default values for S-N curves are also given, but alternate forms are acceptable with experimental verification. In addition to γ_{M0}, the default partial material factors for fatigue analysis are:

C_{3b}	=	1.10	temperature effect
C_{4b}	=	1.00	for unidirectional reinforcement (UD) products
		1.10	for non-woven fabrics and UD woven rovings
		1.20	for all other reinforcement products
C_{5b}	=	1.00	post-cured laminate
		1.10	non post-cured laminate

2.3.3 Material Design Strength

Strain-based values for characteristic strength were derived at MSU for the baseline E-glass/epoxy laminate using a combination of test data and laminate theory.[8] As described in the previous section, partial material factors were developed based on the values specified by GL. For the baseline blade laminate, combined material factors of 2.67 (static strength) and 1.63 (fatigue strength) were used. These values presume a hand lay-up of A260 and CDB340 materials, with heated molds used for a post-cure. Table 4 summarizes the values for characteristic and design laminate strength that were used to develop the baseline blade designs.

Table 4. Design Values for Laminate Strain (baseline blade design)

		Design Strain (%)	
Loading	**Characteristic Strain (%)**	**Static**	**Single-Cycle Fatigue (ε_o)**
Tension	2.7	1.0	1.6
Compression	1.2	0.45	0.74

Fatigue curves were developed of the form:

$$\frac{\varepsilon}{\varepsilon_o} = A \cdot N^{-1/m} \qquad (1)$$

where

ε_o ≡ single-cycle design fatigue strain
A ≡ coefficient of the ε-N curve
N ≡ number of loading cycles
m ≡ inverse slope of the ε-N curve.

Values of A and m were derived for each of three different fatigue loading conditions, $R_f = 0.1$ (tension-tension), $R_f = 10$ (compression-compression), and $R_f = -1$ (fully reversed), where the loading ratio, R_f, is equal to the minimum load divided by the maximum load occurring in each loading cycle. In the present work, ε-N curves were normalized to the tensile static strength for $R_f = 0.1$, and to the compressive static strength for $R_f = 10$ and –1. A complete set of ε-N curve parameters is provided for the baseline materials in Section 4.2.1.

2.4 Full-Blade Design Calculation

Table 5 shows the output from a full-blade design calculation for the baseline blade. The calculation was performed using the spreadsheet-based codes developed for use in the WindPACT Blade Scaling Study, with the input parameters as described in the previous paragraphs. The blade described by Table 5 serves as the baseline structural design for comparison with blades constructed using alternative materials and manufacturing processes.

As part of the WindPACT Blade Scaling Study, cost functions based on current industry experience were developed for blade masters, mold sets, tooling, and production blades. These cost functions, described in detail in Reference 1, were used to estimate the manufacturing costs for the baseline blade design. Recurring costs (materials and labor including root connection) were estimated as $50,750 per blade. When fixed costs (blade master, molds, and tooling) are amortized over an assumed 1-year production run, the total blade cost is estimated at $53,250. The baseline blade costs, and all of the subsequent cost analyses in this report, are based on an assumed production level of 200 MW per year installed capacity, which corresponds to 400 blades per year at a turbine rating of 1.5 MW.

Table 5. Design Calculation Output for Baseline Blade
(1.5-MW Rotor at TSR_{Design} = 7, c_{max} = 8% R, Class 1 peak bending loads)

Blade Station		Spar Cap Thickness		Section EI (N-m^2)		Mass
r/R (%)	(m)	(% t)	(mm)	Flap	Edge	(kg/m)
5	1.75	N/A	N/A	7.68E+09	7.68E+09	1171
7	2.45	N/A	N/A	1.25E+09	1.25E+09	193
25	8.75	4.93	41.4	3.24E+08	6.65E+08	215
50	17.50	6.92	35.6	7.69E+07	2.58E+08	141
75	26.25	4.98	15.6	9.28E+06	6.20E+07	54
100	35.00	0.0	0.0	2.31E+05	7.87E+06	11
					Blade structure =	4463 kg
					Root connection =	253 kg
					Total blade =	**4716 kg**

3. Issues Concerning Scaling-Up of Baseline Blade

The following sections identify feasibility issues and potential barriers to the scaling of the baseline blade to the size range of 80- to 120-meter diameter. As detailed in the following paragraphs, very few fundamental barriers have been identified for cost-effective scaling of the current commercial blade designs and manufacturing methods over this size range. 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 layup that has been the wind industry norm.

Table 6 provides an approximate relationship between blade dimension and ratings over the size-range considered in this study. These data were derived using a specific power rating of 0.39 kW/m^2 of rotor area, and assuming that the hub diameter is 5% of the rotor diameter. Current commercial turbines in the megawatt-scale have specific power ratings that range between 0.36 and 0.50 kW/m^2. Therefore, the data of Table 6 are not absolute, but are representative of turbines in the size range under consideration and may be useful for providing context within this report.

Table 6. Representative Dimensions for Rotors between 750 kW and 5 MW

Rating (kW)	Diameter (m)	Blade Length (m)	Maximum Chord (m)
750	49.6	23.6	2.0
1500	70.0	33.2	2.8
2000	81.0	38.5	3.2
3000	99.2	47.1	4.0
4000	114.5	54.4	4.6
5000	128.0	60.8	5.1

3.1 Transportation and Erection

As part of the WindPACT Scaling Studies, logistics and transportation costs associated with installation of multi-megawatt-scale wind turbines were investigated.[2] The studies focus on using currently available equipment, assembly techniques, and transportation system capabilities and limitations to transport and install turbines at a hypothetical facility in South Dakota. Costs were developed for a short-haul (originating Grand Forks, ND) and a long-haul (originating Gainesville TX) scenario.

Figure 6 shows the estimated transportation costs for the two scenarios studied. When normalized by installed capacity, the long-haul costs remain near-constant at \$6 to \$7 per kW for rotors in the 750 kW to 2.5 MW size range. To provide context for these costs, a typical commercial wind turbine at 1.5 MW rating has an initial capital cost of about \$1000 per kW with the production cost of a three-blade set approximately \$110 per kW. For the WindPACT long-haul scenario, transportation costs for the 1.5 MW blades, tower and nacelle totaled to approximately \$35 per kW.

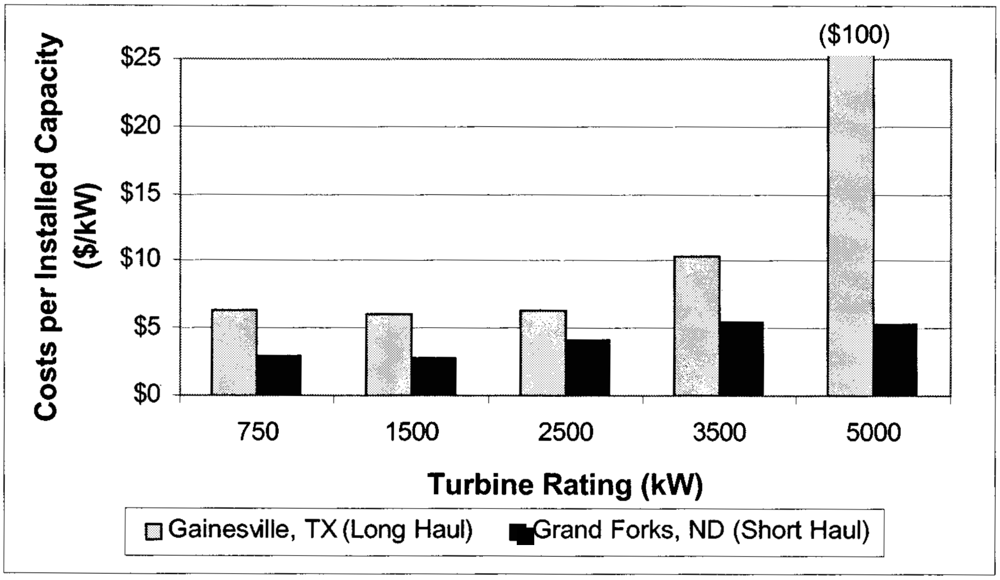

Figure 6 Estimated Blade Transportation Costs

At 3.5 MW, both the long-haul and short-haul scenarios exhibit a near-doubling of per-kilowatt costs. This is the result of the blade lengths exceeding 46 m (150 ft), which requires the use of rear-steering equipment for road transportation.

At 5.0 MW, the short-haul costs are unchanged from the 3.5 MW case, whereas the long-haul costs jump to $100 per kW. This result is highly route-dependent. For the long-haul route under consideration, barge transport was assumed between the Port of Houston and Sioux City, Iowa, and the barge-related costs are the primary cost component for the $100 per kW at 5.0 MW rating. Conversely, the assumed short-haul route was sufficiently simple so that the transportation cost per kW remained relatively low. Other short-haul routes of equal distance could have significantly higher cost per kW, as a result of local constraints or permitting considerations.

Table 7 provides a summary of the major dimensional breakpoints identified for component transportation costs (dimensions at which costs increase rapidly). For blades, length was identified as the most critical dimension in determining transportation costs. For the range of blade sizes considered, the root diameter and maximum chord dimensions could be accommodated by changing the orientation of the blade on the truck bed. In arriving at this conclusion, it is assumed that the blade loads will require permits for both length and width. Although these permits may carry restriction on routes and time of travel, the data of Figure 6 indicate that the costs can be kept acceptably low for blade lengths up to 46 m. For blade lengths over 46 m, the length may cause a significant increase in transportation costs. Although some specific short-haul routes may be identified for which transportation remains feasible, it is expected that costs will be prohibitive for long-haul transportation of blades in excess of 61 m (200 ft) in length.

The work of Reference 2 identified tower transportation factors that have the greatest influence on logistics costs, with significant cost breakpoints resulting from tower diameter dimensions at the 2.5 MW turbine size and 80-meter hub height. Although alternative tower configurations may offer the best opportunity to reduce the overall logistical costs, it is worth noting that the constraints to cost-effective transportation of blades also occur near this turbine size range.

Table 7 Dimensional Breakpoints in Transportation Costs

Object	Height	Width	Length	Mass
Blades	4.4 m (14.5 ft)	7.6 m (25 ft)	45.7-48.8 m (150-160 ft) (transport distance and route dependant)	Not Problematic
Hubs (w/o permits)	3.7 m (12 ft)	Not Problematic	Not Problematic	17,200-19,100 kg (38,000-42,000 lbs)
Nacelles	3.7 m (12 ft)	Not Problematic	Not Problematic	79,400-83,900 kg (175,000-185,000 lbs)
Towers (w/o permits)	3.7 m (12 ft)	Not Problematic	16.2 m (53 ft)	17,200-19,100 kg (38,000-42,000 lbs)
Towers (w/ permits)	4.4 m (14.5 ft)	Not Problematic	Not Problematic	79,400-83,900 kg (175,000-185,000 lbs)

3.2 Manufacturing

Based on consultation with manufacturers of turbine blades and other large composite structures it was determined that there are no fundamental limits to scaling up the baseline manufacturing process. As indicated above, the baseline process assumes the use of heated molds so that large quantities of epoxy may be applied with the ability to control the cure kick-off.

Perhaps the greatest potential constraint to continued use of the baseline open-mold, wet layup processes is the emission of volatile gasses, both for the health risks to the production workers and to the larger atmospheric environment (i.e. plant emissions). This consideration is of importance for manufacturing of blades over the entire size range under consideration. The extent and timing of regulatory restrictions on these processes is uncertain. However, it appears that health and environmental concerns will continue to shift manufacturing economics toward low-emission manufacturing such as the use of prepreg materials or closed-mold infusion processes.

3.3 Weight and Cost

In the WindPACT Blade Scaling Study (Reference 1), the scaling of current commercial blade materials and manufacturing technologies for rotor sizes of 80 to 120 m diameter was investigated. The results of that study quantified the mass and cost savings possible for specific modifications to the baseline blade design, demonstrated the aerodynamic and structural trade-offs involved, and identified the constraints and practical limits to each modification.

The blade scaling study results were compared with mass data for current commercial blades. For a given blade design, the study indicated that blade mass and costs will scale as a near-cubic of rotor diameter. In contrast, existing commercial blade designs were shown to maintain a scaling exponent closer to 2.4 for rotor diameters ranging between 40 and 80 m. Results from the scaling study indicated that:

- To realize this lower scaling exponent on cost and mass has required significant evolution of the aerodynamic and structural designs.

- Commercial blades at the upper end of the current size range are pushing the limits of what can be achieved (in terms of constrained weight and cost) using conventional manufacturing methods and materials.
- For rotors in the 80 to 120 m diameter range, avoiding a near-cubic mass increase will require basic changes in:
  - Materials, such as carbon or glass/carbon hybrids.
  - Material forms and manufacturing processes that can yield better mean properties and/or reduced property scatter through improvements in fiber alignment, compaction, and void reduction. The extent to which such improvements would result in lower blade masses may be constrained by blade stiffness requirements.
  - Load-mitigating rotor designs.

For large blades, gravity-induced edgewise fatigue loads may govern the structural design of the inboard span and root-region. Under the WindPACT Rotor Design Study, aeroelastic simulations have predicted that the baseline blade design will require additional reinforcement to resist edgewise gravity loads at the 1.5 MW size. The extent to which this effect will increase blade costs is difficult to determine without a detailed design and analysis of the blade structure, including the load paths through which the edge loads are carried into the root. However, it is clear that the relative importance of gravity loads and the associated edgewise fatigue loading will increase as blade designs are scaled-up.

As part of the cost analyses in Reference 1, it was also shown that a "learning curve" required to achieve a mature production process has a substantial effect on blade costs for the range of rotor sizes considered. A production rate of 200 MW installed capacity per year implies 800 blades at a turbine rating of 750 kW, but only 120 blades at 5 MW rating. Therefore, the cost penalty incurred for initial production cycles has an increasing impact on the first-year production costs as rotor sizes increase, and a complete cost assessment depends on both annual production rates and the extent (number of years) of sustained production.

4. Trade-Off Study on Material / Process Combinations

4.1 Overview

The 1.5 MW blade design described in the previous section was used as a baseline for performing an extensive trade-off study on alternate materials and manufacturing processes. Figure 7 shows a flow-chart of the overall approach taken for the trade-off study. Based on the cost and weight results calculated in this study, the most promising material and process combinations have been identified for near-term coupon testing at MSU as part of the ongoing materials database program[8], further evaluation in Part 1 of the Blade System Design Study, or potential testing under Part 2 of the Blade System Design Study.

Table 8 gives a summary of the material and process parameters considered in this trade-off study. Material stiffness and strength properties were estimated for each of the combinations shown. Structural calculations were then performed to determine the spar cap thickness required to withstand the peak static loads. Cost functions were developed for each material and process modeled, and the blade structural designs evaluated on the basis of cost, weight, and stiffness.

In total, the matrix of Table 8 represents 72 possible combinations of material / process parameters. Of these, 21 combinations were modeled in the present study. The baseline configuration assumes heated molds with an elevated temperature post-cure, and only one of the other configurations modeled assumes unheated molds. For blades constructed of dry fabric, a laminate volume fraction of $v_f = 0.4$ is considered to be representative of a wet lay-up (compaction with rollers), and a $v_f = 0.5$ representative of a process such as vacuum-assisted resin transfer molding (VARTM). For the remainder of the analyses and discussion in the present section, the VARTM process will be used generically to represent low-cost resin infusion processes that result in low volatile emissions and relatively high compaction. A more detailed discussion of resin infusion processes is presented in Section 5.1.

Table 8 Matrix of Material / Process Combinations Considered in Trade-Off Study

Parameter	Combinations / Values Considered
Fiber material	• Fiberglass 0° and ± 45° fibers • Carbon 0° fibers with fiberglass ± 45° • Carbon 0° and ± 45° fibers
Fabrics used in spar cap construction	• Woven unidirectional fabric combined with stitched biaxial fabric (dry) • Stitched unidirectional and biaxial fabrics (dry) • Prepreg unidirectional and biaxial fabrics
Laminate fiber volume fraction	• 0.4 • 0.5
Percentage of unidirectional laminate in spar cap (by volume)	• 70% • 80%
Cure temperature	• Unheated molds with room temp. cure • Heated molds with elevated temp. post-cure

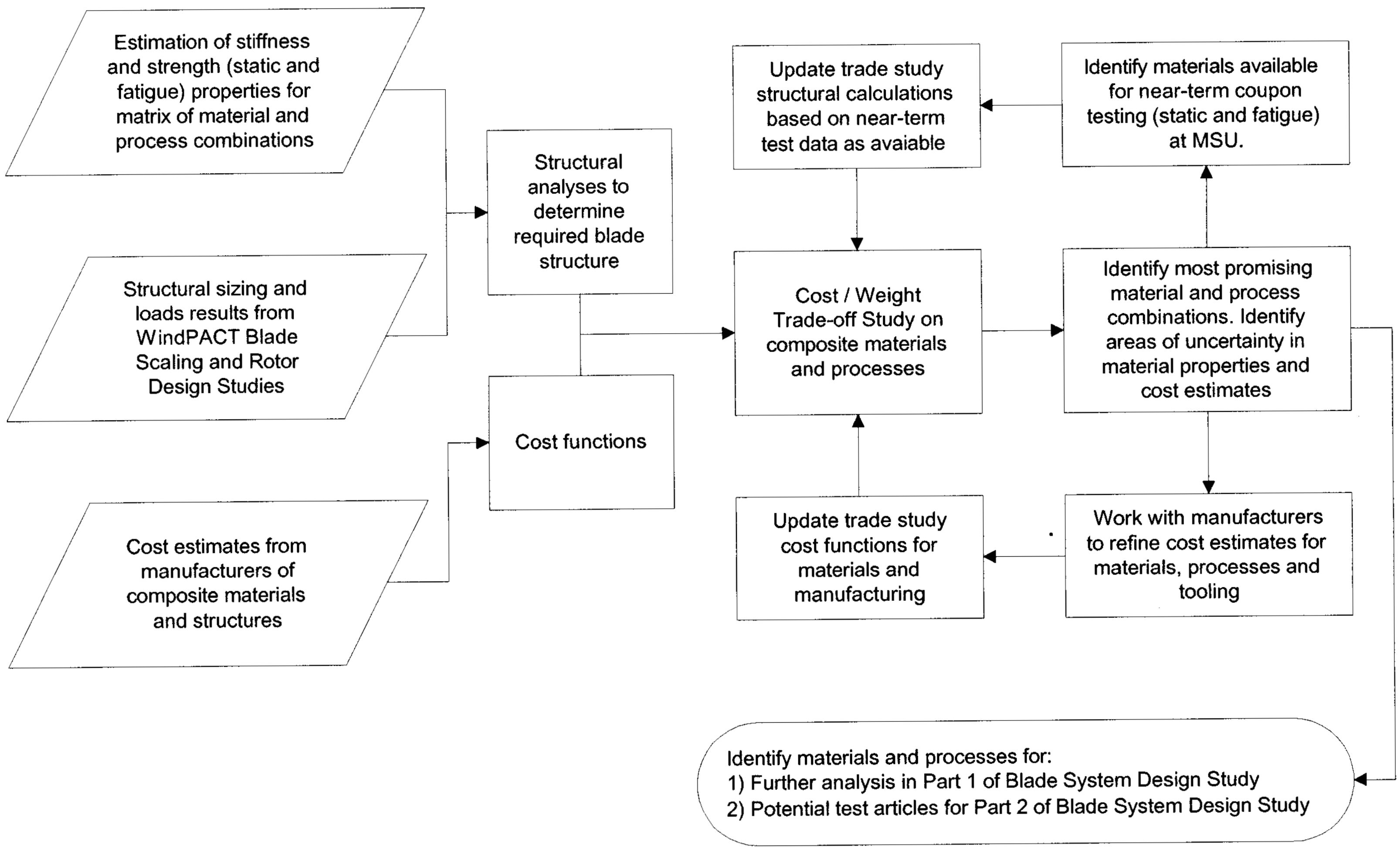

Figure 7 Trade-off Study on Alternative Composite Materials and Processes

4.2 Trade-Off Study Input

The following sections describe the initial input used for material properties and manufacturing costs. As indicated by Figure 7, the most promising configurations will be assessed further under this project, with material and cost estimates refined through testing and ongoing discussions with fiber, fabric, and composites manufacturers.

4.2.1 Material Properties

Material properties were derived using a combination of micromechanics and test data from the MSU/DOE database[8] for the spar cap laminate combinations implied by the matrix of Table 8. Tables 10 through 14 summarize the material properties used in the trade-off study. The tables also list the partial material factors that were used in determining the design strength for each laminate considered (refer to Section 2.3.2 for listing and explanation of partial safety factors). In all of the work reported herein, laminate compaction is characterized by the fiber volume fraction, v_f. However, cost calculations are most easily done for laminate that is characterized by fiber weight fraction, w_f. For convenience, Table 15 provides a conversion between v_f and w_f for both fiberglass and carbon fiber laminate.

4.2.2 Material Cost Estimates

Material cost estimates have been developed using combined information obtained from numerous material and composites manufacturers. These material costs are indicated in Table 9 and were used as input for estimation of production blade costs. Hybrid spar cap structures were assumed to be constructed of layered unidirectional carbon and biaxial glass fabrics.

Table 9 lists both currently-available and "next-generation" large-tow carbon fibers. The cost data for the next-generation carbon tow is representative of the target production price point as indicated by two potential suppliers of such fiber. For the purposes of this initial trade-off study, the same mechanical properties were used for all of the carbon materials. It remains to be seen if carbon suppliers are able to reach this target cost, and if so, how the mechanical properties and processability might differ from the currently available tow. As part of the current study, GEC is working with one supplier toward near-term testing of a next-generation large tow carbon for inclusion in the DOE/MSU database.

Table 9 Estimated Material Costs

Material	Cost ($/kg)
Epoxy	$4.60
E-glass woven unidirectional fabric	$3.60
E-glass stitched biaxial or triaxial fabric	$4.50
Carbon stitched unidirectional fabric (current large-tow)	$22.90
Carbon stitched biaxial or triaxial fabric (current large-tow)	$23.30
Carbon stitched unidirectional fabric ("next-generation" large-tow)	$15.20
E-glass prepreg unidirectional	$4.10
E-glass prepreg biaxial or triaxial	$4.35
Carbon prepreg unidirectional (current large-tow)	$15.00
Carbon prepreg biaxial or triaxial (current large-tow)	$15.25
Carbon prepreg unidirectional ("next-generation" large-tow)	$10.50

Table 10 Static Properties for 100% E-Glass Spar Cap Materials

Description	v_f	Moduli (GPa) E_x	E_y	G_{xy}	ν_{xy}	Density (kg/m^3)	$\varepsilon_{char.}$ (%) Tens.	Comp.	Static Partial Material Factors γ_{mo}	C_{2a}	C_{3a}	C_{4a}	C_{5a}	Total	ε_{design} (%) Tens.	Comp.
*Woven uni + stitched triax, 70% 0°	0.4	25.0	9.2	5.0	0.35	1750	2.70	1.20	1.35	1.5	1.1	1.2	1.1	2.94	0.92	0.41
Woven uni + stitched triax, 70% 0°	0.4	25.0	9.2	5.0	0.35	1750	2.70	1.20	1.35	1.5	1.1	1.2	1.0	2.67	1.01	0.45
"	0.5	29.0	10.2	6.0	0.31	1880	2.70	1.05	1.35	1.5	1.1	1.2	1.0	2.67	1.01	0.39
Woven uni + stitched triax, 80% 0°	0.4	27.1	9.0	4.7	0.35	1750	2.70	1.20	1.35	1.5	1.1	1.2	1.0	2.67	1.01	0.45
"	0.5	31.3	9.7	5.7	0.31	1880	2.70	1.05	1.35	1.5	1.1	1.2	1.0	2.67	1.01	0.39
Stitched uni + triax, 70% 0°	0.4	25.0	9.2	5.0	0.35	1750	2.70	1.80	1.35	1.5	1.1	1.2	1.0	2.67	1.01	0.67
"	0.5	29.0	10.2	6.0	0.31	1880	2.70	1.55	1.35	1.5	1.1	1.2	1.0	2.67	1.01	0.58
Prepreg uni + triax, 70% 0°	0.5	29.0	10.2	6.0	0.31	1880	2.70	1.55	1.35	1.5	1.1	1.1	1.0	2.45	1.01	0.63

* Assumes unheated molds with no post-cure

Table 11 Static Properties for Hybrid Carbon \ E-Glass Spar Cap Materials

Description	v_f	Moduli (GPa) E_x	E_y	G_{xy}	ν_{xy}	Density (kg/m^3)	$\varepsilon_{char.}$ (%) Tens.	Comp.	Static Partial Material Factors γ_{mo}	C_{2a}	C_{3a}	C_{4a}	C_{5a}	Total	ε_{design} (%) Tens.	Comp.
Woven carbon + glass biax, 70% 0°	0.4	59.2	8.3	3.7	0.33	1547	1.35	0.60	1.35	1.5	1.1	1.2	1.0	2.67	0.50	0.22
"	0.5	74.3	10.0	4.8	0.35	1621	1.35	0.60	1.35	1.5	1.1	1.2	1.0	2.67	0.50	0.22
Woven carbon + glass biax, 80% 0°	0.4	66.2	7.8	3.2	0.32	1518	1.35	0.60	1.35	1.5	1.1	1.2	1.0	2.67	0.50	0.22
"	0.5	82.9	9.0	4.1	0.33	1584	1.35	0.60	1.35	1.5	1.1	1.2	1.0	2.67	0.50	0.22
Stitched carbon + glass biax, 70% 0°	0.4	59.2	8.3	3.7	0.33	1547	1.35	0.90	1.35	1.5	1.1	1.2	1.0	2.67	0.50	0.34
"	0.5	74.3	10.0	4.8	0.35	1621	1.35	0.90	1.35	1.5	1.1	1.2	1.0	2.67	0.50	0.34
Stitched carbon + glass biax, 80% 0°	0.4	66.2	7.8	3.2	0.32	1518	1.35	0.90	1.35	1.5	1.1	1.2	1.0	2.67	0.50	0.34
"	0.5	82.9	9.0	4.1	0.33	1584	1.35	0.90	1.35	1.5	1.1	1.2	1.0	2.67	0.50	0.34
Prepreg carbon + glass biax, 70% 0°	0.5	74.3	10.0	4.8	0.35	1621	1.35	0.90	1.35	1.5	1.1	1.1	1.0	2.45	0.55	0.38

Table 12 Static Properties for 100% Carbon Spar Cap Materials

Description	V_f	Moduli (GPa) E_x	E_y	G_{xy}	ν_{xy}	Density (kg/m^3)	$\varepsilon_{char.}$ (%) Tens.	Comp.	Static Partial Material Factors γ_{mo}	C_{2a}	C_{3a}	C_{4a}	C_{5a}	Total	ε_{design} (%) Tens.	Comp.
Stitched carbon + biax, 70% 0°	0.5	73.9	13.1	9.6	.63	1510	1.35	0.90	1.35	1.5	1.1	1.2	1.1	2.94	0.50	0.34
Stitched carbon + biax, 80% 0°	0.5	82.8	11.2	11.2	.56	1510	1.35	0.90	1.35	1.5	1.1	1.2	1.0	2.67	0.50	0.34
Prepreg carbon + biax, 70% 0°	0.5	73.9	13.1	9.6	.63	1510	1.35	0.90	1.35	1.5	1.1	1.1	1.0	2.45	0.55	0.37
Prepreg carbon + biax, 80% 0°	0.5	82.8	11.2	11.2	.56	1510	1.35	0.90	1.35	1.5	1.1	1.1	1.0	2.45	0.55	0.37

Table 13 Fatigue Properties for 100% E-Glass Spar Cap Materials

Description	V_f	$\varepsilon_{char.}$ (%) Tens.	Comp.	Fatigue Partial Material Factors γ_{mo}	C_{3b}	C_{4b}	C_{5b}	Total	Single-Cycle ε (%) Tens.	Comp.	ε-N Curve Coefficients R = 0.1 A	m	R = 10 A	m	R = -1 A	m
*Woven uni + stitched triax, 70% 0°	0.4	2.70	1.20	1.35	1.1	1.1	1.1	1.80	1.50	0.688	1.24	9.5	1.10	15.0	1.06	13.5
Woven uni + stitched triax, 70% 0°	0.4	2.70	1.20	1.35	1.1	1.1	1.0	1.63	1.65	0.735	1.24	9.5	1.10	15.0	1.06	13.5
"	0.5	2.70	1.05	1.35	1.1	1.1	1.0	1.63	1.65	0.643	1.30	7.4	1.10	15.0	1.06	13.5
Woven uni + stitched triax, 80% 0°	0.4	2.70	1.20	1.35	1.1	1.1	1.0	1.63	1.65	0.735	1.24	9.5	1.10	15.0	1.06	13.5
"	0.5	2.70	1.05	1.35	1.1	1.1	1.0	1.63	1.65	0.643	1.30	7.4	1.10	15.0	1.06	13.5
Stitched uni + triax, 70% 0°	0.4	2.70	1.80	1.35	1.1	1.1	1.0	1.63	1.65	1.102	1.20	8.0	1.07	18.4	1.02	16.9
"	0.5	2.70	1.55	1.35	1.1	1.1	1.0	1.63	1.65	0.949	1.20	8.0	1.07	18.4	1.02	16.9
Prepreg uni + triax, 70% 0°	0.5	2.70	1.55	1.35	1.1	1.1	1.0	1.63	1.65	0.949	1.15	12	1.07	18.4	1.02	16.9

* Assumes unheated molds with no post-cure

Table 14 Fatigue Properties for Hybrid Carbon \ E-Glass Spar Cap Materials

											ε-N Curve Coefficients					
		$\varepsilon_{char.}$ (%)		Fatigue Partial Material Factors					Single-Cycle ε (%)		R = 0.1		R = 10		R = -1	
Description	v_f	Tens.	Comp.	γ_{mo}	C_{3b}	C_{4b}	C_{5b}	Total	Tens.	Comp.	A	m	A	m	A	m
Woven carbon + glass biax, 70% 0°	0.4	1.35	0.60	1.35	1.1	1.1	1.0	1.63	0.826	0.367	1.01	48	1.03	28	1.02	17
"	0.5	1.35	0.60	1.35	1.1	1.1	1.0	1.63	0.826	0.367	1.01	48	1.03	28	1.02	17
Woven carbon + glass biax, 80% 0°	0.4	1.35	0.60	1.35	1.1	1.1	1.0	1.63	0.826	0.367	1.01	48	1.03	28	1.02	17
"	0.5	1.35	0.60	1.35	1.1	1.1	1.0	1.63	0.826	0.367	1.01	48	1.03	28	1.02	17
Stitched carbon + glass biax, 70% 0°	0.4	1.35	0.90	1.35	1.1	1.1	1.0	1.63	0.826	0.551	1.01	48	1.03	28	1.02	17
"	0.5	1.35	0.90	1.35	1.1	1.1	1.0	1.63	0.826	0.551	1.01	48	1.03	28	1.02	17
Stitched carbon + glass biax, 80% 0°	0.4	1.35	0.90	1.35	1.1	1.1	1.0	1.63	0.826	0.551	1.01	48	1.03	28	1.02	17
"	0.5	1.35	0.90	1.35	1.1	1.1	1.0	1.63	0.826	0.551	1.01	48	1.03	28	1.02	17
Prepreg carbon + glass biax, 70% 0°	0.5	1.35	0.90	1.35	1.1	1.1	1.0	1.63	0.826	0.551	1.01	48	1.03	28	1.02	17

Table 15 Fiber Volume Fraction / Weight Fraction Conversions

Fiber Volume Fraction, v_f	Fiber Weight Fraction, w_f	
	Fiberglass	Carbon
0.40	0.486	0.571
0.45	0.537	0.621
0.50	0.586	0.667
0.55	0.634	0.710
0.60	0.680	0.750

4.2.3 Manufacturing Cost Estimates

During the work of Reference 1, cost functions were developed based on current industry experience for blade masters, mold sets, tooling, and production blades. Because of the large number of configurations and processes considered in the current trade-off study, the cost functions of Reference 1 were updated and the sub-categories of fabric, matrix, labor, and waste were broken out. In making these cost function refinements, the following assumptions were used:

- The labor rate was assumed to be $5.50 / kg of produced laminate for a wet layup process, and $5.00 / kg for processes using VARTM or prepreg material.
- Material waste was estimated as;
  - 10% for dry fabrics and prepreg material
  - 2% of matrix for a wet layup
  - 5% of matrix for a VARTM process
- Costs for combined blade master and mold sets were originally derived from data for unheated molds. To approximate the costs of heated mold sets, these cost functions were escalated by;
  - 25% for "low temperature" heated molds (60°- 65° C)
  - 50% for "high-temperature" heated molds (90°- 110° C)

Heated molds were assumed to control kick-off of the cure process and also for post-cure of the laminate. It was further assumed that the higher temperature molds would be required for prepreg materials, whereas for the wet lay-up and VARTM processes, lower temperature molds would be adequate.

4.3 Weight and Cost Calculations

The baseline blade structure for these trade-off studies was determined using the design codes that were originally developed during the course of the WindPACT Blade Scaling Study and refined as part of the Rotor System Design Study. These spreadsheet-based codes were also used in the present work to investigate perturbations in structural design about the baseline and to quantify the relationship between the spar cap mass at the 25% span station and the total blade spar cap mass. Based on these relationships, detailed structural analyses at a single blade station (25% span) were used to characterize the incremental weight changes for the entire spar cap structure. In performing these calculations it was assumed that only the spar cap structure was altered. Both the blade skins and the region between 25% span and the blade root were assumed to remain unchanged.

Using the NuMAD interface, an ANSYS calculation was performed to determine the required spar cap thickness at the 25% span blade section for each combination of materials and process considered. For each case, a detailed FEA model was constructed, including gel coat, veil mat, sandwich-construction skins, shear webs and spar cap. To approximate a section analysis, the FEA model was built as a cantilevered beam with constant cross-section. A unit tip load applied, and the results were evaluated at the beam mid-span, on the basis of the strains at the section critical fiber locations. The spar cap structure was sized to ensure that the calculated material strains under the peak static bending load were within 0.5% of the design values (as specified in Tables 10 through 12). In addition to sizing the spar cap thickness, the ANSYS calculations were used to evaluate the blade section weight and deflection under load.

Once the spar cap weight and skin type for each configuration was established, complete cost calculations were performed. In addition to the cost functions described in Section 4.2, the following assumptions were used:

- For all blades, the root connection was assumed to remain unchanged, with a weight of 243 kg and a production cost of $4,860.
- Fixed costs were included assuming 200 MW of installed capacity (400 blades) is built over one year of production, with;
  - Combined cost of master and mold sets ranging between $266,600 and $399,875 depending on the cure temperatures required
  - Production tooling cost (other than master and mold sets) of $609,750
  - A 22% escalation of production costs (relative to the expected long-term production rate) applied to all cases to account for the process "learning curve" for the one-year production run

The analyses of this trade study are idealized, as they do not account for the weight and cost associated with structural details such as bonds, ply-drops, load paths, root connection details, and additional buckling restraint that may be necessary for sections with reduced thickness. As such, the results below should not be taken as the absolute cost and weight reductions that will be realized for each material and process combination, but rather be used to identify the most promising combinations for further evaluation under this program.

4.4 Trade-Off Study Results and Discussion

Table 16 provides a summary of the weight and cost results for this trade-off study. The incremental changes in cost are closely correlated with changes in weight. In all of the following discussion, the percentage variations are taken relative to the baseline design (Case 2). These results should be interpreted in the context of the approach and assumptions listed above, and also the discussion which follows.

Although the results of Table 16 are based entirely on the assumption that an IEC Class 1 50-year gust governs the blade design at all sections, blades must also be designed to withstand fatigue loads. The results of the WindPACT Rotor Design Study indicate that for the baseline structural configuration and materials, blades designed to Class 1 loads tend to be governed by peak static loads, consistent with the assumptions used in the present study. However, for Class 2 design loads, the baseline Rotor Design Study blades are governed by tension-tension fatigue at nearly every spanwise station. This observed shift in design loads is attributed to the fact that the peak-gust load drops substantially between Class 1 and Class 2, whereas the fatigue loading due to operation decreases in a much smaller proportion. Additionally, for some alternate materials (i.e. carbon and higher-quality fiberglass), the fatigue performance is improved relative to the baseline fiberglass. The significance of these observations is that for Class 2 blade designs, the relative reductions possible for blade spar structure by the use of alternative materials may be greater than the incremental changes indicated in Table 16.

In addition to static and fatigue strength, blades must be designed to maintain acceptable clearance from the tower. Designing to higher stain levels in the blade composite material (with other design parameters held constant) will result in higher deflection under a given bending load. This can constrain some of the weight and cost savings implied by the results in Table 16, particularly for material combinations that show an increase in tip deflection.

Table 16 Summary Trade-Off study Results (blades structure sized to IEC Class 1 50-year gust)

Case #	Description	% 0°	v_f	Mass (kg) Spar	Mass (kg) ***Blade	Total Cost	Changes Relative to Baseline (%) Spar Mass	Total Mass	Total Cost	Tip Deflection
1	*All glass, woven uni + stitched biax (wet layup)	70	0.4	2493	4770	$57,150	14.0	6.9	7.3	-8.9
2	All glass, woven uni + stitched biax (wet layup)	70	0.4	2186	4463	$53,250	-	-	-	-
3	All glass, woven uni + stitched biax (wet layup)	80	0.4	1983	4260	$51,000	-9.3	-4.5	-4.3	0.0
4	All glass, woven uni + stitched biax (VARTM)	70	0.5	2384	4661	$55,350	9.1	4.4	3.9	-12.4
5	All glass, woven uni + stitched biax (VARTM)	80	0.5	2167	4444	$51,750	-0.9	-0.4	-2.8	-12.4
6	All glass, stitched uni + stitched biax (wet layup)	70	0.4	1262	3539	$44,200	-42.3	-20.7	-17.0	48.3
7	All glass, stitched uni + stitched biax (VARTM)	70	0.5	1419	3696	$45,200	-35.1	-17.2	-15.1	28.2
8	All glass, prepreg uni + biax	70	0.5	1259	3536	$43,400	-42.4	-20.8	-18.5	38.3
9	Woven carbon + glass biax (wet layup)	70	0.4	1716	3993	$58,700	-21.5	-10.5	10.2	-48.7
10	Woven carbon + glass biax (VARTM)	70	0.5	1377	3654	$54,300	-37.0	-18.1	2.0	-48.7
11	Stitched carbon + glass biax (wet layup)	70	0.4	1034	3311	$48,300	-52.7	-25.8	-9.3	-24.3
12	Stitched carbon + glass biax (wet layup)	80	0.4	891	3168	$46,850	-59.2	-29.0	-12.1	-24.3
13	Stitched carbon + glass biax (VARTM)	70	0.5	841	3118	$45,650	-61.6	-30.1	-14.3	-24.3
14	Stitched carbon + glass biax (VARTM)	80	0.5	741	3018	$45,000	-66.1	-32.4	-15.5	-24.3
15	**Stitched NG carbon + glass biax (wet layup)	70	0.4	1034	3311	$45,500	-52.7	-25.8	-14.6	-24.3
16	**Stitched NG carbon + glass biax (VARTM)	70	0.5	841	3118	$43,100	-61.6	-30.1	-19.1	-24.3
17	Prepreg carbon + glass biax	70	0.5	768	3045	$44,400	-64.9	-31.8	-16.6	-17.8
18	**Prepreg NG carbon + glass biax	70	0.5	768	3045	$42,100	-64.9	-31.8	-21.0	-17.8
19	Stitched carbon + carbon biax (VARTM)	70	0.5	796	3073	$45,500	-63.6	-31.2	-8.9	-24.3
20	Stitched carbon + carbon biax (VARTM)	80	0.5	705	2982	$46,500	-67.8	-33.2	-12.7	-24.3
21	Prepreg carbon + carbon biax	70	0.5	713	2990	$46,700	-67.0	-33.0	-12.3	-17.8

* Initial case assumes unheated molds with no post-cure, all other cases assume heated molds with post-cure

** "NG" carbon denotes "next-generation" low-cost, large-tow fibers

*** Blade masses indicated in table do not include steel root connection, total costs shown include root connection and fixed manufacturing costs

For materials that are currently available, the lowest cost design is estimated to be the all-glass blade made from prepreg materials (Case 8), with an 18.5% cost reduction from the baseline. Although the all-glass prepreg blade is estimated as 20.8% lighter than the baseline case, these weight and cost reductions come at the expense of a 38.3% increase in tip deflection for a given bending load distribution. This illustrates a general trend concerning high strength fiberglass (high-strain) designs. However, the deflections could be reduced or the effects mitigated through some combination of pre-coning, nacelle tilt and the use of thicker airfoils.

For a carbon / fiberglass hybrid utilizing currently-available carbon fibers (Case 17), the cost reduction is 16.6%. This is reduction slightly less than for the all-glass prepreg case, however the carbon / fiberglass hybrid prepreg blade is estimated to be 31.8% lighter than the baseline, with a 17.8% reduction in tip deflection. In addition to the favorable fatigue properties of carbon, the lower-strain design of the hybrid blade may allow for some combination of reduced stresses in the fiberglass skins, reduced overhang requirements, and/or the use of thinner airfoil sections. Additional consideration for high-strain and low-strain blade designs are discussed in Section 7.3.

For both fiberglass and carbon / fiberglass hybrid designs, the VARTM weight and cost estimates are slightly higher than the corresponding prepreg cases. This is primarily the result of a higher partial material safety factor (C_{4a}) being applied for the VARTM cases in the trade-off study analyses. It should be noted, however, that the labor and tooling estimates for these processes were necessarily rough, and that for either process the manufacturer has substantial opportunity to reduce labor and tooling costs through innovation. In that context, the results of this trade study may be interpreted as showing substantial promise for both VARTM and prepreg materials in cost-effective application to large wind turbine blades.

A significant economy is estimated with the use of "next generation" large-tow carbon fibers (Cases 15, 16 and 18). However, as discussed above it remains to be seen whether the estimated carbon fiber price points can be reached in production volumes, while maintaining desirable physical properties and quality.

Although the absolute lowest weight blades were those using all-carbon spars (Cases 19 through 21), the results of Table 16 indicate that the overall cost / weight economics of all-carbon spars is questionable. For instance comparing prepreg cases with 70% zero degree fibers at $v_f = 0.5$, the carbon / fiberglass hybrid (Case 17) has a 31.8% weight and a 16.6% cost reduction, whereas the all-carbon design has a 33.0% weight reduction, but a cost reduction of only 12.3%.

The following sections identify specific areas of technical importance and uncertainty, and are meant both to provide context for the present trade-off study results, and to indicate possible areas of emphasis for follow-on work under this project.

4.4.1 Material Properties

In many cases, the material properties have been estimated in the absence of available test data for the fabric weight, tow sizes and hybrid laminate configurations modeled. Of greatest significance to the study results are the compressive static strength and high-cycle fatigue properties. Unfortunately, these properties are also difficult to predict from micromechanics with high accuracy, and are sensitive to fiber alignment, compaction, and fabric details. Some of the specific materials used in this trade study are currently under test at Montana State University, and others are planned to be tested in the near-term. The results of the MSU tests will be used to update the present study, and to increase the confidence of the predicted weight and cost results.

4.4.2 Partial Safety Factors

Closely related to the material properties are the material partial safety factors that are applied. In the present study, the GL partial material factors have been used, with some necessary interpretation, following the default lists given in the GL regulations. In accordance with the limit-states design approach partial material factors are intended to account for uncertainties in strength due to each specific effect.

A particular aspect of interest concerns the GL factor C_{2a}. At a value of 1.5, this is the largest of the material partial safety factors specified for static analyses. In the current version of the GL regulations, this factor is termed an "aging" effect, whereas in the previous revision of the GL standard it was specified as accounting for "creep." In either case, carbon fiber laminate will typically have lower creep and higher residual static strength than a corresponding fiberglass material. This is an additional area where testing could be performed to support lower combined factors for hybrid materials with the potential for further reductions in cost and weight.

4.4.3 Cure Temperatures

The baseline process for this study assumes some heating of the blade molds. This is a fundamental shift in approach relative to the production of smaller blades, and one that skews the apparent economics. Based on discussions with several manufacturers of composite structure, it was concluded that at the 1.5 MW and greater sizes, the ability to control the kick-off of the cure (or more appropriately the risk associated with not being able to control the kick-off) will compel the manufacturer to include some means of elevating the mold temperature, even for the baseline wet layup process. In addition to controlling the kick-off of the cure, heated molds may allow for additional control of the cycle time, the use of lower cost resins, and improved laminate quality through post-cure.

A comprehensive evaluation of the manufacturing trade-offs on heated molds is beyond the scope of the present study. However, this is directly related to the materials and processes used and is of significant importance for some further consideration. Some of the issues identified include:

- Mold heating methodology;
  - Copper tubing with heated fluid
  - Hot air flow through manifold mold shells
  - Embedded resistive heating elements in mold material
  - Modular oven structures built around molds (i.e. Styrofoam walls with injected hot air)
- Desired temperatures;
  - For hand layup and VARTM processes, 60° - 65° C is of significant benefit
  - For prepreg materials, cure temperature may range from 88° to 120° C.
  - Dimensional stability concerns increase with higher temperatures
- The optimal combination of materials, process, temperature, and mold / heating system design. This depends on;
  - Acceptable tolerances in blade dimensions
  - Number of blades produced over mold-set lifetime
  - Post-cure performed in mold sets or in secondary fixtures

5. Alternative Manufacturing Processes

The following sections address manufacturing processes that may be used as an alternative to the baseline method of hand layup in an open mold with roller-impregnation.

5.1 Resin Infusion Processes

In the trade-off study of Section 4.0, blades manufactured with resin infusion processes were generally referred to as VARTM. However, VARTM is only one of several resin infusion processes that can be used to manufacture wind turbine blades, and many vacuum-assisted infusion processes may be considered to fall under the term VARTM. The following paragraphs describe a few of the infusion processes that are likely to be cost-competitive for manufacture of large wind turbine blades, and present a summary discussion of some of the advantages, disadvantages and technical challenges presented by each.[9]

In a conventional resin-transfer molding (RTM) process, resin is injected under pressure into a dry-fiber preform. The RTM process requires a rigid closed mold, typically a matched-metal set. A vacuum-assisted resin transfer molding (VARTM) process is one in which vacuum is used to pull resin into the preform. A VARTM process will typically use a rigid tooling surface on one side of the part, with soft vacuum bagging on the other. In a VARTM process the resin may, or may not, be injected under pressure. If pressure is used, then the vacuum is pulled first, drawing the vacuum bag down toward the part. Resin can then be injected under pressure, without the need for two-sided rigid tooling as in conventional RTM.

A large number of processes have been developed that fall under the general category of VARTM. SCRIMP™ is one patented VARTM process that has been used extensively for large yacht hulls, rail cars and wind turbine blades lengths up to 26 m.[10] A key aspect of the SCRIMP™ process is a resin distribution medium, typically placed between the vacuum bag and the inside surface of the part, that facilitates flow of the resin over the part surface. Under a contract parallel to the present work (also under the DOE WindPACT Program), TPI Composites is investigating the application of SCRIMP™ to the manufacture of large wind turbine blades. TPI has also developed a method for embossing the SCRIMP™ resin distribution pattern on the inside surface of a reusable silicone vacuum bag. These reusable bags with their integral resin distribution channels significantly reduce the amount of material waste in the SCRIMP™ process.

The RTM and VARTM infusion processes discussed above involve moving low viscosity resin into molds and tooling using some combination of vacuum and pressure. An alternative approach is resin film infusion (RFI), whereby a partially-cured resin film is placed in a mold with the dry preform. A combination of heat, pressure and vacuum is then used to reduce the resin viscosity and promote the infusion of the resin through the preform thickness. RFI eliminates the need for multiple resin injection ports and intermediate resin distribution media. It also allows the use of some well-characterized prepreg resin systems without the need for low-viscosity resin as required by VARTM processes.

As with VARTM-type processes, there are a large number of processes in use that can be considered sub-sets of RFI. Hexcel is developing a derivative of the RFI method under the brand name HexFIT (Hexcel Film Infusion Technology). The HexFIT material uses prepreg resin. One side of the fabric is resin-rich, and the other side has a dry surface. When placed under temperature and pressure in a mold, the resin viscosity will initially decrease, allowing resin flow through the fabric thickness prior to curing. Potential advantages of the HexFIT materials (over conventional prepreg) are improved fabric handling, and the elimination of peel-ply from one side of the material. This material could also facilitate the infusion of sandwich skin structures, reducing the need for paths to allow resin flow past the core material.

VARTM and RFI methods are particularly well-suited to large, integrated structures that require only one high-quality surface finish. Therefore, these processes are a natural fit for the manufacture of shells for large wind turbine blades. Because of the requirement for matched tooling sets, traditional RTM is considered unlikely to be cost-competitive for very large turbine blades.

Infusion processes have the potential for low-cost, high-quality production of wind turbine blades, with the added benefit of having low volatile emissions. Additional benefits may be possible if the infusion process is combined with automated preforming technologies, as discussed in the following sections.

5.2 Automated Preform Manufacturing

Whatever the infusion process used, a preform is required. The most simple method is to build the preform in the mold, much in the same way that a wet layup part would be built. Tackifying agents are used to form temporary bonds, holding the dry materials in place until the part is ready for infusion. This manual preforming method has the disadvantages of being labor intensive and having increased cycle times due to the need to work in the part mold. Automated preform manufacturing can be used to achieve reduced hand labor, improved quality of fiber placement and orientation, and reduced production cycle times.

The following sub-sections summarize some of the candidate methods for producing preforms with varying levels of automation, and discuss some of the potential benefits, estimated costs, and limitations of each.[11] All of the processes considered fall under the category of engineered textiles and could generally be used with either a single fiber type or some hybrid combination of fibers.

5.2.1 Stitched Hybrid Fabrics

The baseline blade considered for this study incorporates a fiberglass triaxial fabric, CDB 340. This fabric has a significant amount (50%) of unidirectional fiber content. When built into the spar structure of an all-fiberglass blade, this fabric can be interspersed with unidirectional fiberglass layers with no loss in structural efficiency. However, if a hybrid spar cap is constructed by combining unidirectional carbon fibers with fiberglass triaxial fabric (with significant zero-degree fiberglass content) then the laminate would have an inefficient combination of fibers in the primary load-bearing direction. The result of this combination would be increased cost and weight of the spar cap structure.

In principle, an efficient hybrid spar structure could be built using alternating layers of unidirectional carbon and biaxial fiberglass fabrics. However, pure biaxial fabric is difficult to handle, and for manufacturing considerations would be bonded or stitched to a lightweight mat or third-axis fiber. Similarly, the unidirectional carbon fabric would be stabilized by stitching or bonding the 0° (warp) fibers to a 90° (weft) fiber or plastic bead.

A natural alternative to stacking alternating layers of unidirectional carbon and biaxial fiberglass in a spar cap laminate is to develop a hybrid triaxial stitched fabric, with carbon fibers in the warp direction and fiberglass in a ± 45° orientation. In this way, the carbon and fiberglass stabilize each other, with minimal crimping and curvature introduced in the warp fibers. A stitched multi-axial fabric represents the most simple level of automation for preform construction. A hybrid carbon / fiberglass fabric could be used in a wet layup process, used to manually construct a dry preform for infusion, or processed into a prepreg form prior to cutting. It could also be used in a secondary cut-and-sew process as discussed in the next section.

Figure 8 shows a photograph of a stitching machine (manufactured by the Liba company) installed at the SAERTEX Company in Germany.[12] The machine depicted can produce multi-axial stitch bonded non-crimp fabric with as many as 54 layers and areal weight as high as 5000 grams per square meter (gsm). Each layer contains a single fiber type and orientation angle. Fiber angles can be unidirectional or off-axis fibers in the range between ± 22° and ±90°.

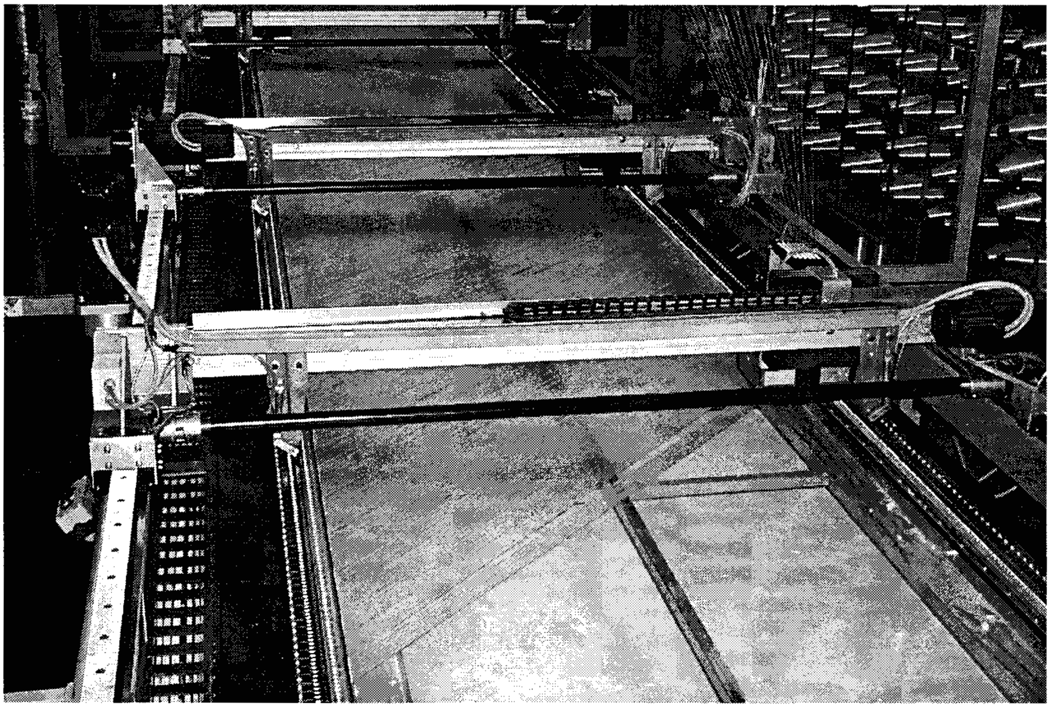

Figure 8 Photograph of Working Liba Machine at SAERTEX, Germany

GEC has consulted with both SAERTEX and Hexcel-Schwebel on issues concerning the fabrication of a stitched carbon / fiberglass hybrid fabric. An initial cost estimate of about $15 per kg was developed for a fabric with areal weight of 1000 gsm, and 75% carbon by volume (68% carbon by weight). This estimate is lower than would be estimated for stacking of standard unidirectional and biaxial fabrics ($17 per kg) using the cost estimates of Table 9. Therefore, the initial cost estimates for a stitched hybrid fabric imply a high degree of efficiency in the stitching process and significant promise for cost-effective application to wind turbine blades.

5.2.2 Cut-and-Sew Preforming

Cut-and-sew preforming is a process that adapts the techniques of the apparel industry to convert two-dimensional fabrics into three-dimensional shapes ready for placement into mold and subsequent infusion. It can be used with any combination of unidirectional or multiaxial fabrics, incorporating ply drops, cores and inserts as necessary. Preform materials are held together by sewing, stitching, or some form of tackifying agent. Cut-and-sew preforming can usually take place outside of the mold and as a result can be used to reduce production cycle times.

At the time of this report, GEC has not yet identified a manufacturer to evaluate the potential of cut-and-sew preforming for application to wind turbine blades. If a suitable manufacturer is identified, this technology may be further investigated during the course of this study.

5.2.3 3-D Woven Preforms

In contrast to 2-D weaving, a 3-D woven fabric can have true unidirectional content, with minimal waviness in the 0° fibers. In typical 3-D weaving the in-plane orientations are limited to 0° (warp) and 90° (fill). The integral inclusion of z-axis (through the thickness) yarns results in a very robust structure, with high interlaminar strength and damage tolerance. 3-D weaving can be used to create preforms that include taper in both the width and thickness. Taper of the cross-section is achieved by successive termination of the warp yarns. The interior yarns can be selected for termination, with the potential for producing a tapered structure with improved robustness relative to conventional laminate ply drops. Woven preforms can be fabricated with either a single fiber type or some combination of different fiber types and/or tow sizes.

GEC worked with Techniweave Inc. to evaluate the potential for use of this process to wind turbine blade manufacturing. 3-D weaving was considered for the fabrication of spar-cap structure that could be placed in the molds as an element of a blade shell preform for subsequent infusion. The spar cap preform would essentially be a long beam of 3-D woven material, with rectangular cross-section, tapering in both the thickness and width dimensions. Techniweave developed cost estimates for a hybrid preform containing carbon in the warp direction and fiberglass in the fill and z-axis directions. Two manufacturing options (loom styles) were considered. Use of a high-volume loom with a limited number of yarn-carrying harnesses resulted in the lowest cost per unit weight for finished structure, but the preform would have a relatively course taper (abrupt step-changes on the section as the large warp tows are dropped out). Alternately, a Jacquard-style loom would allow for very subtle taper of the structure at the expense of increased processing costs. For the lowest-cost option (18-harness loom) the preform structure was estimated as $77/kg. As this cost was considered unlikely to be cost-effective for MW scale blades, no estimates were developed for the higher-cost (Jacquard-style loom) option.

5.2.4 3-D Braided Preforms

3-D braiding can be used to create fabric "sleeves", with a wide range of flexibility on fiber types, weights, and orientations. The braided material can be of constant cross-section, or more complex preforms can be created by braiding onto a shaped mandrel.

Composite Engineering Incorporated (CEI) has significant experience with the application of 3-D braiding to the manufacture of small (50 to 100 kW) wind turbine blades and large yachting masts (up to 19 m). The typical CEI approach is to braid preimpregnated fibers, then to transfer the part for oven-curing while still on the shaped mandrel. CEI has consulted with GEC concerning the application of this method to large wind turbine blades. The dimensions of CEI's braiding equipment and oven would restrict sectional dimensions to about 0.76 m (30 in), which would prohibit the fabrication of circular root sections for megawatt-scale turbines. It may be feasible within these dimensions to fabricate a main structural spar for a turbine in range of 1.5 MW rating. Initial cost estimates for this fabrication method are approximately $33/kg for finished spar structure with 75% unidirectional carbon content by volume.

5.2.5 Oriented Sprayed-Fiber Preforms

The majority of alternative material and manufacturing approaches considered under this project have focused on methods for improving the physical properties of blade composite structure, while constraining the associated material and manufacturing costs required to realize these improvements. To this end, this study has focused on processes and fabrics that maximize compressive static strength (and hence minimize the amount of material and associated weight) through the use of continuous unidirectional fibers in fabric and preform architectures with minimal crimping and waviness.

An alternative design approach is to accept a known reduction in material properties if the materials and manufacturing process lend themselves to significant labor savings or other benefits. Chopped fiber materials, whether sprayed or used in a liquid molding operation, generally fall in this category. However, the use of chopped fibers has traditionally been directed toward rapid manufacturing (low-cost, high volume) of non-structural products. The application of commercial-style chopped fiber manufacturing, and the associated weight increase, is not considered to be a good alternative for manufacturing of large wind turbine blades.

However, the National Composite Center (NCC) has recently developed a process directed toward the use of discontinuous fibers in high performance applications.[13] In this process, carbon fiber tow is chopped into strips and sprayed to create a preform with a high degree of orientation so that good mechanical properties are maintained. The objectives of the NCC-developed process include low hand labor costs, control of fiber placement, control of fiber orientation, high level of consistency, capability to produce complex geometrical shapes, low waste of raw materials, and decreased cycle times.

NCC has built and infused a large number of test articles using this process and has also conducted an extensive evaluation to determine the optimal carbon fiber parameters (tow size, tow shape, sizing, binder and packaging) for use with this process. The favorable mechanical properties of the laminate are achieved mainly through the high degree of orientation that is maintained in the preform spray-up. For the best combination of tow size and shape (laminate designated "P4A"), NCC measured approximately 80% of fibers to be within ±5° of the nominal direction, 15.6% between ±5° and ±10°, 4% between ±10 and ±20°, and less than 1% outside of ±20°.

GEC evaluated the physical properties that were measured by NCC for the P4A laminate and found them to be promising for application to load-bearing structure of large wind turbine blades. GEC developed size estimates for a spar cap structure composed of P4A laminate with a rotor rating of 1.5 MW. NCC then developed cost estimates for fabricating such preforms, using currently-existing machinery. The initial cost estimates were $66/kg for the preforms, with $13.20/kg for the 48k tow carbon fiber materials, and $52.80 for processing costs. At this cost, the NCC process appeared prohibitive for cost-effective application to wind turbine blades. However, GEC worked with NCC to identify the capabilities of the existing machinery (such as 6-axis control of fiber orientation) that would not be needed to fabricate the relatively simple geometry and fiber architecture of a spar cap preform. NCC subsequently developed cost estimates for machinery tailored to the wind turbine application. For this case, the processing costs were reduced to $14.30/kg, with a total preform cost of $27.50/kg.

5.2.6 Summary of Cost Estimates for Automated Preforming Technologies

In the previous sections, cost estimates for materials produced by automated preforming were presented in \$/kg, with some general comments as to whether such costs were in the competitive range for application to large wind turbines. However, the preform materials under consideration have differing material content, composition, and mechanical properties. Therefore, a comparison of these options requires additional analysis to evaluate how much of each material is used and what impact the material form has on the labor costs.

Table 17 provides a comparison of cost estimates for several automated preforming technologies that were evaluated. All preforms are assumed to be of a carbon / fiberglass hybrid, and the \$/kg values shown reflect the preform materials, matrix, labor and material wastage for each process. The comparisons are made for production costs per unit span of spar structure at the 25% span location of a 1.5 MW blade. Note that if the preforms considered were used as a bulk replacement for the baseline spar cap materials, then the percentage changes in total blade weight and cost would be lower than indicated by Table 17 (due to the portions of the blade shell and root that would remain unchanged).

The baseline for the comparisons of Table 17 is a spar constructed by hand layup of alternating layers of stitched unidirectional carbon and biaxial glass fabrics with 70% zero-degree fibers by volume and a fiber volume fraction of 0.5. With the exception of the 3-D braided preform, all processes are assumed result in a dry-fiber preform for subsequent infusion. Labor saving in the construction of spar material were estimated at 10% for stitched hybrid carbon / fiberglass fabric, and 75% for 3-D woven and P4A oriented carbon preforms. The cost estimate for 3-D braided spar structure assumes that preimpregnated fibers are used in the braiding and the laminate is oven-cured on the winding mandrel.

The stitched carbon / fiberglass hybrid fabric shows a cost savings of approximately 8% from the baseline case, which is largely the result of lower processing costs for the hybrid fabric relative to the assumptions made by GEC in developing the baseline cost estimates. Cost estimates for the P4A oriented carbon preform predict a savings of approximately 33% from the baseline. This is the result of the relatively high stiffness and compressive strength measured by NCC for this material. While these results show promise, the mechanical properties and fatigue performance of this material in a turbine-blade application has yet to be demonstrated. Based on these analyses, both the 3-D weaving and braiding processes considered appear non-competitive for manufacturing large wind turbine blade spar cap structure.

Table 17 Comparison of Cost Estimates for Automated Preforming Technologies

Process	Mass of Spar Cap at 25% R (kg/m)	Spar Cap Laminate Cost	
		(\$/kg)	(\$/m span)
Baseline hybrid construction	58.1	17.00	990
Stitched carbon /fiberglass hybrid fabric	54.6	16.65	910
3-D woven preform	54.6	56.55	3,090
3-D braided preform with separate cure	54.6	33.00	1,800
NCC oriented carbon preform (P4A)	33.9	19.35	660

5.3 Thermoplastic Resins

Thermoplastic resin systems are widely used in commercial applications and can provide structure that is low-cost, lightweight, and rugged. However, for the following reasons they were not considered as showing promise for application to large wind turbine blades:

- Bonding of thermoplastic materials is not readily achieved with adhesives. Therefore some form of heated bonding process would be required to join blade shells that were fabricated separately, as well at the shear web bond lines. A fully-integrated structure is a possible alternative to secondary bonding, but as discussed in Section 5.4, is not considered to be a cost-effective alternative for manufacture of large wind turbine blades. Bonding characteristics would also complicate the field repair of blades incorporating thermoplastic resins.
- Thermoplastic resins are prone to creep, which would be problematic both at details (i.e. bonds and root connections) and in the global blade properties.
- GEC obtained one cost estimate of $17.6/kg for finished fiberglass structure manufactured from a "low cost and weight" thermoplastic resin system. Conversely, the baseline (finished) fiberglass structure for this study was estimated at about $10/kg. Although the thermoplastic resin is lighter than epoxy, GEC estimated that the weight savings for equivalent laminate strength would be no greater than 20%. Therefore, the costs for this material are unlikely to be competitive with the baseline epoxy resins.

5.4 Fully Integrated Structures

A potential benefit of composite manufacturing in general, and infusion processes in particular, is the ability to reduce the part count and associated assembly costs for structural systems. A recent example of this is the fabrication of a fastenerless horizontal tail for the Joint Strike Fighter (JSF) Concept Demonstration Program[14]. The prepreg carbon/epoxy JSF tail has a span of approximately 1.4 m, with a base chord of 2.9 m and a tip chord of 0.6 m. In fabricating the internal structure of JSF horizontal tail, a series of aluminum mandrels were wrapped with biaxial fabric and inserted into the rigid matched-metal tool. The part had continual taper, with both chord and thickness increasing toward the root. As a result, the rigid aluminum rib mandrels could be removed (taking advantage of the differential in the coefficient of thermal expansion between aluminum and carbon/epoxy) through the open root-end of the part. Under a parallel program, a unitized JSF vertical tail was fabricated by a very similar approach, but using RTM infusion rather than prepreg materials.[15] These unitized assemblies are considered to be at the forefront of manufacturing technology for such a size and part complexity. The part count for the JSF vertical tail was reduced from thirteen to one (not including fasteners) relative to the baseline tail design.

Manufacture of fully-integrated assemblies is also common for relatively small wings, propellers, fan and turbine blades. In these applications, a two-way taper is common, so that it may not be feasible to remove rigid mandrels used for the internal spar structure through the root end of the part. In such cases, the typical approach is to either use foam core that remains in the part, or to use inflatable mandrels that can be deflated and removed after curing.

Considering large wind turbine blades, the baseline structural design and manufacturing approach includes four major parts (two shells and two shear webs) and one or more pieces of root connection hardware, all of which are bonded together in a series of operations. Although the part count reduction is not as great as would be for a design with many fasteners, there are still potential benefits for manufacture of a large blade as a unitized structure. These could include reduced labor and tooling requirements for the bonding operations, improved structural strength and reduced weight by elimination of bond lines, and decreased cycle times. However, the physical scale of large wind turbine blades greatly complicates the realization of these benefits. While GEC is continuing to investigate this option, it appears unlikely at present that manufacture as a unitized structure will prove to be cost-competitive for large wind turbine blades.

5.5 Separately-Cured Spar Structure

In the baseline manufacturing process, the structural spar cap is built integrally into the blade shell halves, and the sandwich-style shear webs would be cured and shaped prior to bonding with the shells. An alternative manufacturing approach is to fabricate and cure the entire box spar (including the spar cap reinforcement) as a stand-alone operation, with subsequent bonding to the blade shells.

The primary advantage of a separately-cured spar structure is that it might be used to realize the full benefit from automated processes such as 3-D braiding over a mandrel, filament winding, tape laying, or 3-D weaving. Curing could be accomplished on the mandrels that were used in the shaping process, or on relatively simple secondary tooling. Oven or tool-heating requirements would be reduced, and design of removable tooling would be accomplished much more readily for a separately-cured spar than for co-curing the spar with the blade shells.

However, for a conventional structural design this approach would result in a substantial increase in bonding requirements. For a 1.5 MW blade, the baseline manufacturing approach includes a total of approximately 67 m of bond-line at the interface between the shear webs and the blade skins. Assuming that the bond line averages 8 cm of width, the total bond area would be 5.4 m^2. By contrast, the bonding area would increase to about 25 m^2 if the entire spar cap surfaces were bonded to the skins. In addition to the increase in bonding area, the bond itself would become more critical, as all stresses in the blade shell would need to be carried across the bond line into the primary load-carrying structure. Because of this aspect, a separately-cured spar structure may be of greatest benefit if the load carried by the blade skins can be minimized.

Separately-cured spar structure is used by some manufacturers of current commercial wind turbine blades. However, in the present study GEC has not identified this option as showing a substantial improvement over the baseline manufacturing process for application to MW scale blades.

6. Alternative Structural Configurations

In this section, alternative structural configurations are investigated. These may be directed toward mitigating the costs associated with transporting large blade structures or achieving improvements in the areas of blade quality, manufacturing cost or structural efficiency.

6.1 Jointed Designs

The primary motivation for a jointed design is a reduction in transportation costs. As indicated in Section 3.1, a sharp increase in transportation costs occurs for blade structure with length exceeding 46 m, and at lengths greater than 61 m the cost of long-haul ground transportation may become prohibitive. At a turbine specific power rating of 0.44 kW/m^2, these dimensions correspond to rotors of about 3.0 and 5.5 MW, respectively. Although these breakpoints occur at relatively high turbine ratings, it is possible that jointed designs could yield meaningful improvements in transportation costs for smaller turbines as well. Additional transportation economy might be achieved at 1.5 MW or smaller ratings if the entire blade structure could be efficiently containerized. Another possible benefit from blade-joining technology could be the use of varying tip sections for a given inboard blade design, effectively increasing the range of blade designs that could be manufactured while minimizing mold requirements.

6.1.1 Bolted Joints

In general design of composite structures, a bolted joint has the advantages of being a relatively straightforward design, inspectable, repairable, and capable of disassembly. Disadvantages include an increase in part count, requirements for sealing, accessibility and surface finish, and problems with fatigue, fretting and corrosion.

Most wind turbine designs incorporate only one major bolted joint, at the root / hub interface. A variety of root connection designs have been used by the industry, but this joint remains a critical part of blade design in terms of reliability, weight and cost. For megawatt-scale blades, the cyclic gravity loading at the root has become of increasing importance for the design of the blade root, including the bolted connection. While the bending loads (both aerodynamic and gravity) decrease steadily away from the blade root, the blade cross-section dimensions and structural reinforcement also decrease. There is no reason to expect, therefore, that the weight and mechanical complexity of a mid-span bolted joint would be any less (in proportion to the local blade structure) than the root connection. Further, the mid-span bolted joint is complicated by the need to maintain a high-quality aerodynamic surface while maintaining accessibility for joint inspection and maintenance.

A European research project has recently investigated design concepts for sectional wind turbine blades.[16] Under this work, directed at improving transportability of megawatt-scale blades, a wide range of concepts were evaluated for mid-span bolted connections. Of the concepts evaluated, two were selected for detailed design and testing under that program. The most promising option studied in that work is an "embedded bushing with stud bolt," which is similar in design to a T-bolt connection, but holds the potential of requiring less frequent inspection.

6.1.2 Bonded Joints

Bonded joints were given very little consideration under the work of Reference 16. The only bonded joint design evaluated was a laminated scarf joint. The laminated scarf joint outscored the highest-ranked bolted connection (embedded bushing with stud bolt) in the categories of reliability, production complexity, mold costs, tolerance requirements, maintenance and weight. However, the embedded bushing concept was ranked higher than the laminated scarf joint in the categories of quality control, on-site assembly, costs, aerodynamics and disconnectability. As a result of the weighting factors assigned to each category, all of the bolted connection concepts considered were ranked higher than the laminated scarf joint.

If the ability to disassemble a blade is an absolute design objective, then bolted designs will have a clear advantage over bonded joints. However, if overcoming transportation constraints from the factory to the project site is the primary objective, then either bonded joints or on-site fabrication may offer the lowest cost and highest reliability solution. On-site manufacture of blades is currently under investigation by TPI composites under the Sandia Blade Manufacturing Improvements (BMI) project.

Considerable effort went into the question of how to efficiently join large wood / epoxy rotor blade segments during the work by NASA and GE on the MOD-5A wind turbine program.[17] The favored method that arose from that work was finger joining. The results from this work in joining wood / epoxy laminate were favorable, and a derivative technique was used to replace a blade tip damaged by tower strike on a 43 m diameter Westinghouse turbine.

The work with wood/epoxy laminates indicated improved performance with smaller finger size, and this was thought to be due to size effect, primarily near the finger tips. The MOD-5A test work used fingers nearly 300 mm long, and test lab specimens were used to gather data on 150 mm finger lengths. However, calculations indicated that performance was likely to improve until a finger size around 25 mm, at which point the defect introduced by the finger tips would begin to merge with the level of natural defects in the laminated material. Commercially available finger joint cutters for 2.5 cm fingers were located, and some demonstration finger joints were made with them, but the benefits of this type of finger joint were not fully investigated during that initial work.

It is unlikely that this joint type would perform as well in a fiberglass laminate as in wood/epoxy, because of the higher modulus and strains that fiberglass laminate achieves. There is also a question whether available cutters would be suitable for fiberglass or carbon / fiberglass hybrid, and if they would provide acceptable life. Notwithstanding those challenges, finger joints remain a candidate for mating large fiberglass wind turbine blade sections in the field. However, to establish whether this is potentially a cost effective and structurally efficient joining solution in fiberglass or carbon / fiberglass hybrid blades, the key manufacturing issues would need to be addressed and resolved, and static and fatigue performance demonstrated.

6.2 Multi-Piece Blade Assemblies

During the course of this work some proposed concepts for multi-piece blade designs were considered. The concepts had the following potential benefits:

- Maximum efficiency in shipping, particularly if blade shell sections can be nested.
- Lower capital costs for a single manufacturing facility. For example several smaller facilities could build sub-components rather than requiring all of the manufacturing to flow through one large shop and mold set. The inventory costs per manufacturer could also be decreased.
- Better quality control and inspection on each of the sub-components.

- Possible credit given for use of local assembly labor.

With the potential benefits understood, it is unlikely that these will overcome the labor cost, design complexity, cost of local reinforcements, and aerodynamic finish considerations for a multi-piece blade that includes extensive joints or bonds. The move toward a multi-piece assembly with a large number of mechanical fastener or bonds is in direct opposition to the design trends in the aviation / aerospace field that are aimed toward decreased cost of finished composite structures. Even if the joints are made simple enough so that semi-skilled technicians are able to complete the joining process, it is doubtful that this approach offers enough advantages to be competitive with monolithic structure built in a single factory, or at the most, a blade with a small number of major mid-span joints.

6.3 Decoupled Skins

In the baseline structural configuration, the skins are integrally attached to the spar cap that provides the primary flapwise bending strength for the blade. In a conventional blade design, the majority of bending loads are carried by the structural spar, but the most highly stressed fiber will be the unidirectional content of the outer shell skin (assuming triaxial skin material). Because of the airfoil shape, the blade skins will contribute a major portion of the edgewise bending strength, with the most highly stressed fibers near the blade trailing edge. However, a robust design must have sufficient skin thickness to allow these edge loads to be sheared back into the main structure, and eventually to the blade root. As blade sizes and associated gravity loads increase, it is common for additional unidirectional tape to be placed near the trailing edge of the blade for added edgewise bending strength. While this is very effective at a given blade section, the remaining blade structure must also be reinforced to allow a load path to the blade primary structure and root. Historically, this has proven problematic for large blades, particularly if the planform has high curvature or abrupt transitions between the maximum chord location and the root.

A fundamentally different approach to the baseline structural configuration is to reduce the stresses and load carrying requirements of the skins. In the limit, the concept is one of "decoupled" skins that are just stiff enough to maintain their aerodynamic shape and are attached to the structural spar in a way that allows the aerodynamic forces to be transmitted, but are otherwise largely unstressed. The idea is that the skin weight could then be minimized, reducing the weight of the blade as a whole, and in turn reducing the edgewise strength requirements of the structural spar. Although this approach has some intuitive appeal, GEC has identified several potential barriers to cost-effective implementation, including:

- Designing a feasible and robust way of making the required semi-rigid attachment between skins and structural spar.
- Even if the blade skins remained largely unstressed (effectively eliminating the buckling strength requirements), they would still need to provide sufficient stiffness to maintain their shape under aerodynamic loading and to withstand the stresses incurred during shipping, handling, and installation. Sandwich-style skins are an efficient structure for providing the stiffness needed for stability against aerodynamic deformation, and so would be a likely choice for the uncoupled skin. There is a limit to how thin the outer skin can be and still provide necessary protection against cracking, denting or other defects resulting from impact and handling. As a result, the elimination of buckling considerations from the skin would result in relatively small weight reductions relative to the baseline skin design.
- In the outer 75% span of the baseline 1.5 MW blade design the skins account for 20% of the total blade weight, but at the 25% span station they contribute over 60% of the edgewise bending strength. For this case, if the use of a decoupled-skin design could reduce the skin weight by as

much as 50%, the total blade weight and associated gravity loads would decrease by only 10%. Hence the edgewise bending strength of the spar at 25% span would need to be more than doubled to recover the capability lost by the decoupled-skin design. However, the spar structure has limited chordwise extent (the reason it was not carrying much of the edge loading to begin with), and so the material requirements to obtain a doubling of edgewise bending capability are substantial.

This final observation points to the fundamental difficulty of realizing weight and cost savings in large wind turbine blades using the decoupled skin concept. The airfoil shape is well-suited to carrying edgewise loading, and it is natural to exploit that shape capability in an efficient blade structural design. If a decoupled skin is used, the weight reductions possible in the skins are constrained by other practical design considerations, and the structural spar must be substantially reinforced to recover the edgewise bending strength given up by the skins. As a result, at the megawatt scale where edgewise gravity loading begins to dominate the design of inboard blade sections, the use of decoupled skins would tend to increase, rather than decrease, the blade structural weight and cost.

7. Material, Manufacturing and Structural Design Issues

The following sections discuss design trade-offs, identify areas of technical uncertainty that must be addressed in order to realize the potential benefits of candidate alternative technologies, and present recommendations for follow-on work under the current project.

7.1 Fabric / Preform Weight and Architecture

Several of the materials modeled in the current study are of relatively heavy fabric weight and tow size. In some cases, the materials are known to be in successful commercial application in large wind turbine blades. In other cases the combination of fabric weight, process, laminate thickness and fiber volume fraction is hypothetical. The following sections present technical considerations for the use of heavy weight fabrics, thick preforms, and for the realization of high fiber volume fractions.

7.1.1 Ply Drops

In terms of materials processing and manufacturing costs, there is an apparent economy in using the heaviest fabric and largest tow size that is appropriate for the blade size. However, the use of heavier fabrics implies larger ply drops, and a corresponding decrease in tensile fatigue strength. This issue is of equal importance for structure built from either infused or prepreg materials.

Research at MSU has quantified the effects of ply drop size, and evaluated methods for improving the fatigue performance of ply drops.[18] The work of MSU illuminates the importance of this issue, but further work will be required to establish:

- The extent to which ply-drop considerations may constrain the use of (or mitigate the economic benefits of) heavy-weight fabrics for megawatt-scale blades.
- How these trends might shift for ply drops in carbon or carbon / fiberglass hybrid laminate, where the carbon-fiber laminate has excellent fatigue properties, but the matrix at the ply drop would be more highly stressed (relative to the fiberglass design) due to the higher carbon modulus.
- Whether an alternative automated manufacturing process (such as a 3-D woven preform with internal tow drops or a cut-and-sew preforming method with through-the-thickness stitching) could provide a low-cost method for improved ply drop performance.

7.1.2 Resin Flow

For all non-prepreg approaches, the ability to achieve flow of wet resin through the fabric or preform is of practical concern. The issue of resin flow is fundamental to the size scaling of infused wind turbine blades. For larger surface areas, the flooding of the part surface area can be accommodated by adding to the number of ports where resin is introduced. However, the through-the-thickness infusion time is a function of the preform permeability, thickness, and the resin viscosity. There is also a trade-off for infused structure between permeability and fiber volume fraction. VARTM processes can typically achieve fiber volume fractions of about 50% with relatively few problems. Higher fiber volume fractions can be achieved, but will inhibit the resin flow through the preform.

As a result of these issues, the infusion process can not be scaled linearly with part thickness. As wind turbine blades are increased in size, the best design-for-manufacture must balance considerations of laminate thickness, fiber volume content, fiber architecture within the preform, infusion time, resin viscosity and the viscosity time / temperature profile.

7.1.3 Fabric / Fiber Architecture

In Section 5.2.1, stitched hybrid fabrics were discussed, with improved efficiency of the material in handling and static compression strength noted as the primary benefits. For infusion processes, an additional benefit of any stitched fabric may be increased permeability.

Samborsky et. al. investigated several fabric architectures for their suitability in resin-infusion methods (i.e. permeability) and the fatigue behavior of the resulting laminate.[19,20] Not surprisingly, this work identified fabric-architecture details as a two-edged sword. Stitched triaxial fabrics showed good compressive static strength but preformed relatively poorly in fatigue. Details that allow good resin flow, such as stitching or local bunching of the fibers also introduce resin-rich pockets and stress concentrations that dominate the fatigue failure. Further work is required to determine:

- The fatigue performance of laminate fabricated from a stitched carbon / glass hybrid fabric, where the material will be designed to work at lower strain levels.
- The potential of automated manufacturing process (such as a 3-D woven preform) to efficiently create preforms with a fiber architecture that is amenable to resin infusion, without the introduction of details that become critical fatigue defects.

7.2 Volume Effects

If a volume of composite material is put under uniform stress, the failure (static or fatigue) will initiate at the worst defect. The larger the volume, the greater the probability that the worst defect is farther from the mean material properties. The general result of this "volume effect" is that the strength of a large laminate structure is lower than that implied by coupon test data, and the differential between the coupon data and the structure will grow with increasing volume of stressed laminate.

This volume effect is recognized as being of importance in thick-section laminates, and was evaluated for wood-epoxy structures during the work of Reference 17. However, for wind turbine blade design the default GL partial safety factors do not include an explicit adjustment for volume effects. The GL partial safety factors may contain sufficient conservatism so as to cover any anticipated volume effect. Also, it may be argued that the GL factors include an adjustment that is related to inherent material variability (higher safety factor for woven materials and hand lay-up, lower for semi-automated manufacturing). However, this interpretation does not account for:

- The increased importance of volume effects as laminate thickness increases at the megawatt scale.
- Any credit that should be given to a design that reduces the amount of stressed volume.
- The actual dependence of volume effects on inherent material variability

An explicit treatment of volume effects may become of increased importance as blades grow in size and as the material and manufacturing approaches deviate further from the baseline. For instance, a highly automated process may result in a decrease in volume effects. Conversely, a material or process that has higher degree of variability (such as the oriented sprayed-fiber preform) may be expected to exhibit significantly greater volume dependence.

7.3 High-Strain versus Low-Strain Blade Designs

Within the context of materials considered under this study, two fundamental approaches were identified by which significant and cost-effective weight reductions can be realized in the blade structure. The first involves achieving the best possible structural performance from an all-fiberglass laminate (high-strain design), and the second involves the use of comparatively stiff, light, carbon fibers in a hybrid laminate (low-strain design).

These design approaches can not be evaluated by considering the blade as an isolated system. In addition to designing for required static and fatigue strength, rotor systems must be designed to maintain acceptable blade / tower clearance. For a given bending load, allowing higher material strains will result in larger deflections. There are a large number of design variables that can be used to either effectively stiffen a blade or to increase the blade / tower clearance margin, including: thicker airfoil sections, rotor pre-coning, nacelle tilt, and increased rotor overhang. Clearly, the entire turbine system must be considered to evaluate the tradeoffs on cost, weight, aerodynamic and structural performance.

Figure 9 shows the Vestas V-47 rotor blades operating under normal aerodynamic loading. The V-47 blades are constructed from prepreg fiberglass laminate and can be considered a relatively high-strain design. The photograph illustrates the extent to which this turbine system has been designed to accommodate substantial blade deflections.

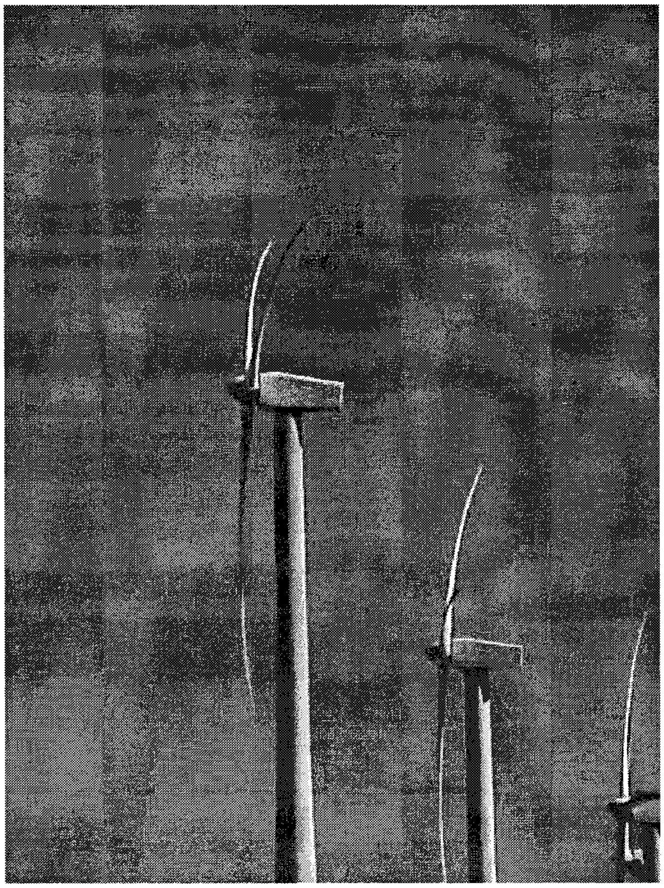

Figure 9 Vestas V-47 Rotors under Aerodynamic Loading

As a result of decreased blade deflections, a low-strain design may allow the turbine system to incorporate some combination of thinner airfoil sections, reduced pre-coning and nacelle tilt, and reduced overhang dimensions. The effect on fatigue performance is less clear. In the primary structural laminate, it may be expected that the carbon-dominated material has very good fatigue performance. However, at ply drops and other structural discontinuities, the resin matrix may end up carrying higher shear stresses, and become more fatigue-critical.

A similar trend may be found for the use of higher-strain fiberglass. In terms of the structural laminate, many of the factors that contributed to an increase in the design value for static strain under the GL design regulations (i.e. non-woven fabric, prepreg material, post-cure) also result in favorable partial safety factors for fatigue strength. Therefore, a blade section analysis may show that the fatigue properties are improved for a high-strain fiberglass design. However, the strain levels will also increase at ply drops and other discontinuities, as will the magnitude of the load dropped across each interface (because of the higher stress levels in the loaded fibers). As in the case of the carbon / glass hybrid, it is expected that this will increase the importance of ply drops for the high-strain fiberglass designs.

It must also be recognized that the blade design loads will depend on the aeroelastic behavior of the turbine system, which will in turn depend on the blade stiffness and mass distributions. These aspects of high-strain and low-strain blade designs are currently being investigated under the WindPACT Rotor System Design Study, where full aeroelastic simulations are being performed to evaluate the turbine system dynamics, loads, and resulting cost and weight of each major turbine component. Results from the Rotor System Design Study will be used, as appropriate, to provide additional insight and guidance during follow-on activities of the Blade System Design Study.

7.4 Recommended Alternatives for Further Evaluation

Based on the work of this report, a number of alternative materials, manufacturing processes, and structural designs have been identified as showing substantial promise for cost-effective application to megawatt-scale wind turbine blades, and are recommended for further evaluation under the current Blade System Design Study. Table 18 lists promising alternative materials and processes, and summarizes some of the potential benefits and technical uncertainties associated with each.

Infusion processes are not explicitly listed in Table 18. Based on current manufacturing of large boat hulls and transportation-industry structure, it is accepted that infusion methods will be cost-effective for large wind turbine blades. However, to realize the full potential of VARTM-type processes may require a synergy with alternative materials, fabric architectures, and automated preforming technologies. Prepreg material forms and RFI impregnation will also be considered for each of the material combinations listed in Table 18.

In terms of alternative structural configurations, neither the multi-piece assemblies nor the decoupled skin designs appear likely to be cost-competitive for application to megawatt-scale wind turbine blades. For the purposes of overcoming cost barriers to shipping of large blades, the least-risk and lowest-cost method is expected to be either on-site manufacturing or the inclusion of a limited number of major structural joints. A bonded finger joint has been identified as showing potential for field-joining of blade sections. However, it is unclear whether this option shows sufficient promise to merit further evaluation under this project.

Table 18 Alternative Materials and Processes Recommended for Further Evaluation

Material / Process	Potential Benefits	Technical Uncertainties
Carbon / fiberglass hybrid	• Decreased weight • Increased stiffness • Ability to incorporate thinner airfoil sections and/or more slender planforms	• Static and fatigue strength for hybrid laminate, dependence on fabric architecture and layup • Effect of hybrid laminate on fatigue strength at ply drops
"Next-generation" low-cost, large-tow carbon fibers	• Significant reduction in cost of carbon fibers	• Processability of tow, and whether desirable mechanical properties of laminate are maintained • Production cost
Stitched hybrid fabrics	• Reduced labor and efficient material use for construction of hybrid blade spar structure • Low cost for processing of constituent fibers • Possible combination with automated cut-and-sew preforming	• Static and fatigue strength of resulting laminate • Effect of stitching on fatigue performance
Oriented chopped fibers	• Reduction in hand labor cost • Minimal waste of raw materials • Good control of fiber placement, orientation, and part thickness • Ability to combine the structural efficiency that results from having most fibers in close alignment with the loading axis with the damage-tolerance introduced by the off-axis fibers • Ability to taper thickness with minimal geometric discontinuities (effectively eliminated ply drops) • Cost / benefit assessment shows very strong potential for this material	• Static and fatigue strength not yet determined for structure representative of turbine blade application • Volume effects may be greater than more deterministic material forms

8. Conclusions

The work conducted under this study has further illuminated the challenge faced by the wind industry in making fundamental improvements to the design, materials, and manufacturing processes for large wind turbine blades. Much of the composites industry literature and advertising concerning "affordable" or "low-cost" processes are based on an aerospace perspective. The price point established by the current commercial manufacturing of wind turbine blades is very low compared with other composite structures, particularly for composites with relatively demanding aerodynamic and structural design considerations. These price points have been realized within the wind industry through substantial fine-tuning of the current manufacturing methods, and are based on well-established properties and performance for the baseline materials and structural design.

For many emerging composite technologies, the thrust of development has been toward addressing the complex shapes, tolerances, and quality control requirements of aerospace-type applications, while reducing labor, material waste, and other costs. By comparison, manufacture of wind turbine blade involves very high material volumes but only moderate shape complexity and tolerance requirements and relatively simple fiber architecture. Therefore, many emerging technologies that show substantial benefits for fabrication of aerospace structures have tolerance and part complexity capabilities that are under-utilized in the wind turbine blade application, and as a result, the production costs for blade structure are prohibitively high. It is possible that derivative technologies, with machinery and throughput optimized for the requirements of wind turbine blade structure, could provide substantial benefits in labor and part quality.

In the project work to date, a number of alternative materials and manufacturing processes have been identified as showing promise for cost-effective application to megawatt-scale wind turbine blades, and are recommended for further evaluation under the Blade System Design Study. In summary, these are:

- Processes with low volatile emissions:
  - Prepreg materials
  - Infusion processes (VARTM, RFI)
- Decreased weight, cost, and improved structural properties:
  - Carbon / fiberglass hybrid blades
  - "Next-generation" large-tow carbon fiber
  - Stitched carbon / fiberglass triaxial fabric
  - Automated preforming technologies for use with infusion processes

For the purposes of overcoming cost barriers to shipping of large blades, the least-risk and lowest-cost method is expected to be either on-site manufacturing or the inclusion of a limited number of major structural joints. A bonded finger joint has been identified as showing potential for field-joining of blade. However, it is unclear whether this option shows sufficient promise to merit further evaluation under this project.

In addition to the options identified above, several other alternative materials, process, and design options have been evaluated in this project. Where technologies were identified as non-competitive for application to large wind turbine blades, these conclusions are not intended to be taken as absolute. Rather, in some cases, an understanding of the constraints for a particular technology's application to large turbine blades may be useful in guiding further innovations within the composites materials and manufacturing industry.

9. References

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H. Ashley
Dept. of Aeronautics and
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Aero Engineering Department
Norman, OK 73069

D. Berry
TPI Composites Inc.
373 Market Street
Warren, RI 02885

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GE Wind
13681 Chantico Road
Tehachapi, CA 93561

C. P. Butterfield
NREL
1617 Cole Boulevard
Golden, CO 80401

G. Bywaters
Northern Power Systems
Box 999
Waitsfield,VT 05673

J. Cadogan
Office of Wind and Hydro Technology
EE-12
U.S. Department of Energy
1000 Independence Avenue SW
Washington, DC 20585

D. Cairns
Montana State University
Mechanical & Industrial Engineering Dept.
220 Roberts Hall
Bozeman, MT 59717

S. Calvert
Office of Wind and Hydro Technology
EE-12
U.S. Department of Energy
1000 Independence Avenue SW
Washington, DC 20585

J. Chapman
OEM Development Corp.
840 Summer St.
Boston, MA 02127-1533

Kip Cheney
PS Enterprises
222 N. El Segundo, #576
Palm Springs, CA 92262

C. Christensen, Vice President
GE Wind
13681 Chantico Road
Tehachapi, CA 93561

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Agricultural Research Service
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Bushland, TX 79012

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Foam Matrix, Inc.
1123 East Redondo Blvd.
Inglewood, CA 90302

J. Cohen
Princeton Economic Research, Inc.
1700 Rockville Pike
Suite 550
Rockville, MD 20852

C. Coleman
Northern Power Systems
Box 999
Waitsfield, VT 05673

K. J. Deering
The Wind Turbine Company
515 116th Avenue NE
No. 263
Bellevue, WA 98004

A. J. Eggers, Jr.
RANN, Inc.
744 San Antonio Road, Ste. 26
Palo Alto, CA 94303

D. M. Eggleston
DME Engineering
1605 W. Tennessee Ave.
Midland, TX 79701-6083

P. R. Goldman
Director
Office of Wind and Hydro Technology
EE-12
U.S. Department of Energy
1000 Independence Avenue SW
Washington, DC 20585

D. Griffin (5)
GEC
5729 Lakeview Drive NE, Ste. 100
Kirkland, WA 98033

C. Hansen
Windward Engineering
4661 Holly Lane
Salt Lake City, UT 84117

C. Hedley
Headwaters Composites, Inc.
PO Box 1073
Three Forks, MT 59752

S. Hock
Wind Energy Program
NREL
1617 Cole Boulevard
Golden, CO 80401

D. Hodges
Georgia Institute of Technology
270 Ferst Drive
Atlanta, GA 30332

Bill Holley
3731 Oakbrook
Pleasanton, CA 94588

K. Jackson
Dynamic Design
123 C Street
Davis, CA 95616

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GE Wind
13000 Jameson Rd.
Tehachapi, CA 93561

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University of Houston
Dept. of Mechanical Engineering
4800 Calhoun
Houston, TX 77204-4792

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Foam Matrix, Inc.
PO Box 6394
Malibu CA 90264

A. Laxson
NREL
1617 Cole Boulevard
Golden, CO 80401

S. Lockard
TPI Composites Inc.
373 Market Street
Warren, RI 02885

J. Locke, Associate Professor
Wichita State University
207 Wallace Hall, Box 44
Wichita, KS 67620-0044

D. Malcolm
GEC
5729 Lakeview Drive NE, Ste. 100
Kirkland, WA 98033

J. F. Mandell
Montana State University
302 Cableigh Hall
Bozeman, MT 59717

T. McCoy
GEC
5729 Lakeview Drive NE, Ste. 100
Kirkland, WA 98033

L. McKittrick
Montana State University
Mechanical & Industrial Engineering Dept.
220 Roberts Hall
Bozeman, MT 59717

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NREL
1617 Cole Boulevard
Golden, CO 80401

A. Mikhail
Clipper Windpower Technology, Inc.
7985 Armas Canyon Road
Goleta, CA 93117

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Golden, CO 80401

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West Texas State University
P.O. Box 248
Canyon, TX 79016

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Tim Olsen Consulting
1428 S. Humboldt St.
Denver, CO 80210

R. Z. Poore, President
Global Energy Concepts, Inc.
516 6th St. South
Suite 200
Kirkland, WA 98033

R. G. Rajagopalan
Aerospace Engineering Department
Iowa State University
404 Town Engineering Bldg.
Ames, IA 50011

J. Richmond
MDEC
3368 Mountain Trail Ave.
Newbury Park, CA 91320

Michael Robinson
NREL
1617 Cole Boulevard
Golden, CO 80401

D. Sanchez
U.S. Dept. of Energy
Albuquerque Operations Office
P.O. Box 5400
Albuquerque, NM 87185

L. Schienbein
Sustainable Energy Technologies
422 11th Ave. SE #200
Calgary AB 52G 0N4
CANADA

R. Sherwin
Atlantic Orient
PO Box 1097
Norwich, VT 05055

Brian Smith
NREL
1617 Cole Boulevard
Golden, CO 80401

J. Sommer
Molded Fiber Glass Companies/West
9400 Holly Road
Adelanto, CA 93201

K. Starcher
AEI
West Texas State University
P.O. Box 248
Canyon, TX 79016

F. S. Stoddard
79 S. Pleasant St. #2A
Amherst, MA 01002

A. Swift
University of Texas at El Paso
320 Kent Ave.
El Paso, TX 79922

J. Thompson
ATK Composite Structures
PO Box 160433
MS YC14
Clearfield, UT 84016-0433

R. W. Thresher
NREL
1617 Cole Boulevard
Golden, CO 80401

S. Tsai
Stanford University
Aeronautics & Astronautics
Durand Bldg. Room 381
Stanford, CA 94305-4035

W. A. Vachon
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P.O. Box 149
Manchester, MA 01944

C. P. van Dam
Dept of Mech and Aero Eng.
University of California, Davis
One Shields Avenue
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B. Vick
USDA, Agricultural Research Service
P.O. Drawer 10
Bushland, TX 79012

K. Wetzel
K. Wetzel & Co., Inc.
PO Box 4153
4108 Spring Hill Drive
Lawrence, KS 66046-1153

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