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Carbon Design Studies for Large Blades: Performance and Cost Tradeoffs for the Sandia 100-meter Wind Turbine Blade

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Sandia National Laboratories' (SNL) Wind & Water Power Technologies Department, as part of its ongoing R&D efforts, creates and evaluates innovative large blade concepts for horizontal axis wind turbines to promote designs that are more efficient aerodynamically, structurally, and economically. A 100-meter all-glass blade, termed "SNL100-00", for a 13.2 MW horizontal axis wind turbine was designed at Sandia with acceptance to loads and safety factors defined by international blade design standards. This blade is significantly longer than the largest commercial blades of today (approximately 75 meters long) and its design provided an opportunity to identify and document large blade technology trends and potential future large blade technology barriers. Key concerns for large blades include blade weight growth, increased gravitational fatigue loading, reduced buckling resistance, and increased susceptibility to flutter instability.

Recent studies at Sandia have focused on improving performance and reducing the weight of the baseline SNL100-00 design. Our recent studies have focused on the effects of incorporation of carbon fiber into the 100-meter blade design. *Quantifying the effects of carbon fiber usage on blade performance, blade weight, and cost when introduced and compared with the Sandia 100-meter all-glass blade is the focus of the paper. A blade cost model is developed to quantify total blade cost for design variants.*

I. Introduction

A consistent trend and technology development focus in commercial utility-grade wind turbine production throughout the years has been growth in the size of the rotor and lowered cost-of-energy. Advancements in blade design technology have been achieved through more efficient structural and aerodynamic designs and optimal material usage. Future designs for even larger machines will continue to push the extremes of the design envelope, which is primarily limited by the penalty of weight growth.

A 100-meter all-glass blade, termed "SNL100-00", for a 13.2 MW horizontal axis wind turbine was designed at Sandia with acceptance to loads and safety factors defined by international blade design standards. This blade is significantly longer than the largest commercial blades of today (approximately 75 meters long) and its design provided an opportunity to identify and document large blade technology trends and potential future large blade technology barriers. The SNL100-00 design model was made publicly available for use by other wind turbine blade researchers.

Recent studies at Sandia have focused on application of innovations to improve performance and reduce the weight of the baseline SNL100-00 design. The recent studies have focused on the effects of incorporation of carbon fiber into the 100-meter blade design. With carbon, a key consideration is material cost; therefore, our recent studies have also included development of blade manufacturing and cost estimation tools so that blade cost can be quantified for various design choices, including carbon

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fiber usage or other materials usage changes. This tool, which will be discussed in the full paper, provides important cost metrics that complement the structural performance metrics associated with each of the principal blade design drivers. The effects of carbon fiber usage on blade performance, blade weight, and cost, when introduced and compared with the Sandia 100-meter all-glass blade, is the focus of the paper.

The full paper will include

- A review of the Sandia Large Offshore Rotor Project and a summary of the baseline SNL100-00 blade design
- A review of prior carbon design and costing studies for blades in the 30-60 meter length range
- Development of a manufacturing and costing model for blades, which is demonstrated and applied to the SNL100-XX series of blades. Cost estimation for the principal cost components (materials, labor, and capital equipment) is performed.
- Cost trends with blade length and application of the tool to 100-meter blade variants during the design process.
- Summary of a refined 100-meter reference blade design, to be termed SNL100-01, which includes carbon fiber usage along with a summary of the impact of carbon on blade performance, weight, and cost.

Specific goals of this work include (1) providing early design studies of strategic cost-effective deployment of carbon fiber into 100-meter and beyond length blades, (2) development of tools to quantify the performance-cost tradeoffs, and (3) public dissemination of a lightweight 205-meter diameter offshore rotor for advanced rotor and system-level design studies within the wind research community.

II. Review of Sandia Large Offshore Rotor Project

A. Large Blade Trends and Potential Barriers

The principal drivers in the design of a blade include tip deflection (i.e. tip-tower clearance), maximum strains, buckling, and fatigue life. Of course, minimization of blade weight and blade cost while satisfying the structural and aerodynamic performance requirements is also important. Based on structural analysis and design of the SNL100-00 baseline blade, it was found that the relative importance of the above design drivers do, in fact, change as blades increase in length. For example, due to growth in gravitational loads, fatigue life was found to be driven by gravitational loads whereas smaller blades were fatigue driven by aerodynamic loads. Panel buckling was also found to be a more significant issue for large blades, which requires additional reinforcements using thicker core materials or usage of additional shear webs (an architecture change). Of course, these additional reinforcements increase the blade weight and then result in increased gravitational loads. In addition to changes in fatigue loads and reduction in buckling resistance, large blades also show an increase in susceptibility to aeroelastic instability through decreased flutter margins.

The design analysis for the baseline SNL100-00 design demonstrated the reduction in performance margins for these design drivers. The aim of the current study includes quantifying the effect of new materials usage, in case carbon fiber usage, on reducing gravitational loads through blade weight reduction for a blade of length 100-meters. Secondary benefits to the performance margins are also assessed. Of course, the cost-performance trade-offs are important for carbon, so in this work we also develop and demonstrate an initial manufacturing and cost estimation tool for blades.

B. SNL100-00: Sandia 100-meter All-glass Baseline Design

Figure 1 shows the external geometry for the baseline SNL100-00 design. For these studies, the external geometry for the carbon blades will not be changed in order to focus the study on structural performance and cost metrics. However, current and future work will include external geometry changes for SNL100-XX studies aimed to study aerodynamic and structural trade-offs.

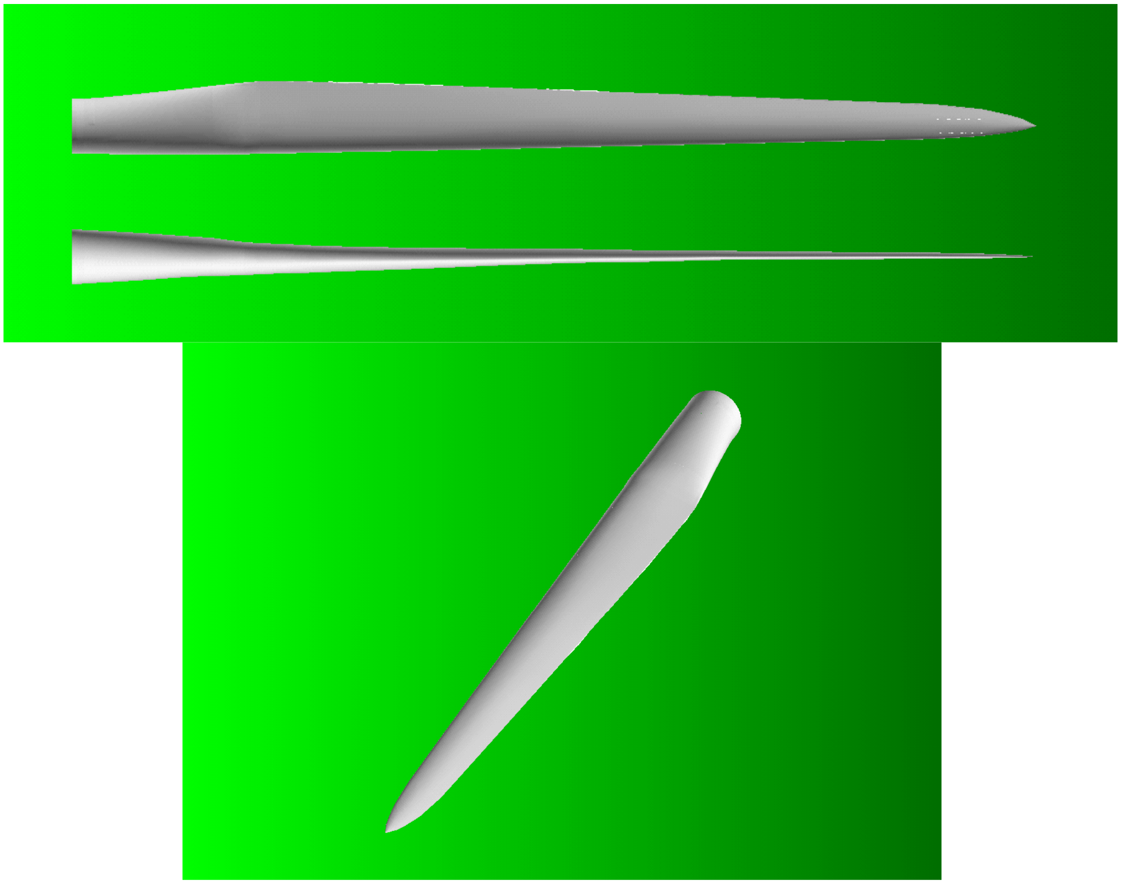

Figure 1. Views of Blade Surface Geometry for SNL100-00

Figure 2 shows a planform view with illustration of the location of the spar cap, trailing edge reinforcement, and the third shear web. For the current study, modifications to the blade architecture that become possible with usage of carbon fiber will be explored. For example, usage of carbon fiber in the spar reduces the blade weight and results in less material needed for trailing edge reinforcement.

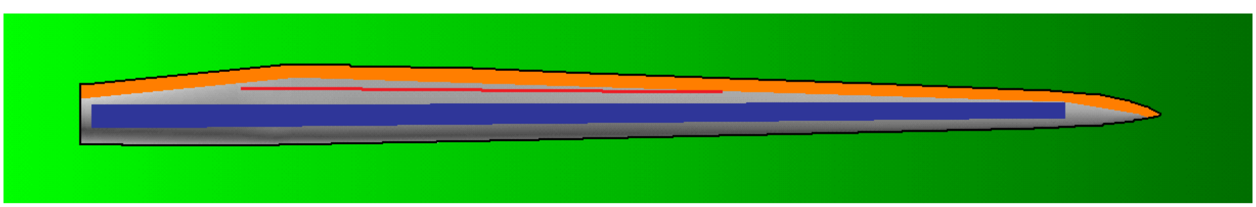

Figure 2. Planform of Sandia 100-m Baseline Blade with Laminate Designations (Blue: Spar Cap, Orange: trailing edge reinforcement, Red: Third Shear Web)

III. Wind Blade Manufacturing Cost Analysis Summary

As wind turbines grow larger in blade diameter (both for onshore and offshore siting), new design approaches and blade architectures must be investigated. For future large 100-meter and beyond blades the effects of the scale of the blades and the changes in design on the manufacturing process are not completely understood. The potential manufacturing process changes resulting from scaling to larger blades need to be considered for a blade manufacturer to approach their construction and plan for the future. Also, designers must have an understanding of how blade designs will affect the manufacturing process and if a blade design is feasible to build. In order to align the efforts of wind blade designers and manufacturers, an approach of designing for manufacturability must be taken. A quantitative measure of manufacturability must be created to incorporate manufacturing concerns into future blade designs. One focus of this paper is development of a tool to investigate the effect of design choices on manufacturability and cost.

The blade cost is divided among three cost components: materials, labor, and capital equipment. These components were chosen because they are all directly affected by the choice of blade design. An additional analysis of cost of energy (COE) for a wind farm was included to compare energy production for blades of different lengths.

Material costs were comprised of unidirectional and bias-ply dry fiberglass, unidirectional pre-preg carbon fiber, epoxy resin, and gelcoat by weight and foam core by thickness and area. Therefore, bill of materials input of a design, foam/core dimensions, and material prices are the key inputs to this module of the cost estimate.

Labor costs were the most complex element of the cost equation because manufacturing processes change at different levels depending on different factors. Our approach is to extrapolate current manufacturing processes to larger blade length to estimate changes in labor content with blade length or architecture change. We apply this approach at a manufacturing operation or substep level. Some operations do not change at all based on changes in blade length or material content and some change at a higher or lower rate than simple scaling equations based on length or any other single factor can predict. The labor-hours for each operation (or substep) are multiplied by a scaling factor based on dimensional analysis to produce a new set of labor hours for a blade with different dimensions. Scaling factors were chosen for operations that were affected by the change in design. A major factor was surface area operations like skin-ply lay-ups, surface sanding, paint-prep, and painting. Another factor was the length of the molds for the prefabs and shell for mold prepping and consumable lay-up, the total length of fabric used in the prefabs for lay-up, and the length of the bond-lines for bond pasting. Operations that had no change included drop tests during vacuum bagging, installing prefabs into the shell, bond paste curing times, and moving the blade in the factory. All of these factors are affected by specific design changes and as a result total labor-hour content changes cannot be attributed to any one design factor. This component of the cost analysis can provide a great deal of knowledge for manufacturers interested in understanding how blade designs affect labor operations. It can also allow manufacturers to weigh the advantages and disadvantages of changing manufacturing processes or including automation.

Capital equipment costs were limited to those directly affected by changes in the blade design which were: the master molds, blade molds, and tooling. The cost for this equipment was based on modified scaling equations based on blade length from previous research and industrial input. The total equipment cost is then divided over the number of blades that the mold is predicted to produce over its projected lifetime. The capital equipment costs are interesting when comparing blades of different sizes but do not change for blades of the same length. This tool may be useful when judging the feasibility of new equipment such as automation which may be added onto the tooling costs.

Two key sets of results of the blade cost model will be included in the full paper:

1) *Trends in cost breakdown (materials, labor content, and capital equipment) for a 40- to 100-meter length change*
2) *Cost comparisons for 100-meter blade design variants: lighter carbon blade cost versus heavier all-glass blade cost?*

IV. Preliminary Carbon Studies: Introduction of Carbon into the SNL100-00 Baseline 100-meter Blade

Carbon usage in blades has been studied by a number of authors including conceptual design studies, manufacturing demonstrations, and blade tests. Here, a brief summary of these works are reported. In Reference 3, the strategic use of carbon including cost estimates considering both the material and tooling costs was studied for a SERI-8 Blade. In References 3-6, design of a carbon spars for 9-meter Sandia research-sized blades (including CX-100, TX-100, and BSDS blades) are described. These reports also provide manufacturing summaries along with carbon and carbon hybrid materials testing results. Structural testing of carbon blades is reported in Reference 7. In Reference 8, concepts for large blades including usage of carbon laminates is reported.

A. Determination of Unidirectional Carbon Material Properties

Our study is focused on usage of uni-directional carbon in the spar caps and/or trailing edge reinforcement. To perform the design analysis for the blade we produced estimates for elastic and strength properties of a conceptual carbon fiber laminate (85% uni-directional, 15% biased) by using data from the Sandia/MSU materials database (examples in Table 1).

Table 1. Material Properties for Conceptual UD carbon laminate

	Value
Density (kg/m^3)	1220
E_L (GPa)	114.5
E_T (GPa)	8.39
G_{LT} (GPa)	5.99
υ_{LT}	0.27

B. Initial SNL100-01 Parameter Studies: Carbon Usage in 100-meter Blade

A set of parameter studies are performed by replacing UD glass in the baseline SNL100-00 design with UD carbon (as defined in Table 7). No changes are made to the blade architecture or geometry. Modifications to the baseline layup are only made in the spar cap and trailing edge reinforcement where significant UD layers are present. Three variations of the baseline, with incorporation of carbon, are studied: (1) all carbon spar cap, (2) all carbon trailing edge reinforcement, and (3) all carbon spar cap with foam.

For the initial study (Case Study #1) the carbon thickness in the spar cap was sized to retain the flap- and edge-wise stiffnesses of the baseline design. The spar cap width was not changed. Then, analyses were formed to calculate performance margins and identify possible need for additional modifications. Throughout the span, the resulting thickness of the spar cap for Case Study #1 was reduced by approximately 63% for the carbon spar versus the glass spar.

For Case Study #2, the fiberglass trailing edge reinforcement was replaced with carbon. The initial modification here included reducing the width of the trailing edge reinforcement laminate from 1.0 meter to 0.3 meters, while maintaining the same laminate thickness. No additional modification was needed to satisfy the buckling requirement. Case Study #3 is effectively the first case study with the addition of foam in the spar cap to ensure that buckling requirements are satisfied. As noted below, buckling was not satisfied for Case Study #1 as this case is essentially used as a reference configuration with respect to the SNL100-00 all-glass baseline for a carbon spar cap.

A subset of certification-like analyses were performed that included computation of tip/tower clearance (deflection), fatigue life, and buckling capacity. As identified in the development of the baseline model, buckling and fatigue were critical design drivers for large blades so these were the focus of these initial analyses. These analyses were particularly interesting to perform and study initially for several reasons including: (1) addition of carbon results in blade weight reduction and as a result reduction in the magnitude of gravitational loads that dictated fatigue life in the baseline model and (2) thinning of the carbon laminates in the spar cap would likely reduce buckling capacity. Both of these effects of carbon needed to be analyzed and quantified in these parameter studies because of the clear tradeoffs in performance using carbon. Strain and flutter analyses, although important, were not performed in these initial analyses but will be included with the final analysis and updated 100-meter blade design report for SNL100-01.

Table 2. Summary of Carbon Parameter Studies Results: Comparisons with SNL100-00 All-glass Baseline Blade

	SNL100-00 Baseline[**]	**Case Study #1**	**Case Study #2**	**Case Study #3**
	All-glass baseline blade	*Carbon Spar Cap*	*Carbon Trailing Edge Reinforcement*	*Carbon Spar Cap plus Foam*
Deflection (m)	11.9	10.3	12.0	10.3
Fatigue Lifetime (years)	1000	N/A	N/A	281
Governing location for fatigue lifetime	*15% span edge-wise*	N/A	N/A	*15% span flap-wise*
Lowest Buckling Frequency	2.365	0.614	2.332	2.391
Blade Mass (kg)	114,197	82,336	108,897	93,494
Span-wise CG Location (m)	33.6	31.0	32.1	34.0
E-LT-5500 Uni-axial Glass Fiber (kg)	39,394	16,079	34,952	16,079
Saertex Double-bias Glass Fiber (kg)	10,546	10,546	10,546	10,546
Foam (kg)	15,068	15,068	15,917	26,600
Gelcoat (kg)	927	927	927	927
Total Infused Resin (kg)	53,857	33,996	50,072	33,996
Newport 307 Carbon Fiber Prepreg (kg)	0	10,208	1,902	10,208

[**]Note: The SNL100-00 Baseline properties reported here are slightly different than those originally reported as these calculations utilize an updated version of the Sandia/NuMAD software.

The results for the carbon parameter studies are summarized in Table 2 for the deflection, fatigue, and buckling analysis. The performance margins are tabulated along with a summary of the total blade mass and CG location (both computed using FAST) and the bill of materials summary (each computed using the ANSYS model) for each design variation. As in the SNL100-00 Baseline, the allowable tip/tower clearance is 13.67 meters here as well. All of these design variations are then acceptable with respect to deflection for the extreme coherent gust with direction change (ECD) at rated wind speed condition, which was found to be the driving load case for deflection analysis[4].

For Case Study #1, significant weight reduction is found when the glass spar cap is replaced with a carbon spar cap. This can be considered a near bounding case for large usage of carbon in the design, although no carbon was placed in the trailing edge. This case is a reference case to the two other case studies with regard to weight and CG location. This case also demonstrates that although weight is reduced significantly, buckling capacity is significantly reduced with the thinner spar cap (this is solved for Case Study #3 though).

For Case Study #2, reduction of the width of the trailing edge reinforcement and replacement of glass with carbon required no additional modification to satisfy buckling. Although no fatigue calculation was performed to further evaluate this approach, this modification was found to have only a small decrease in blade weight and CG location. The use of trailing edge carbon will be studied in greater detail once aeroelastic stability calculations are performed because reduction in trailing edge reinforcement mass tends to move the chord-wise CG location toward the leading edge of the station to improve the flutter margin.

For Case Study #3, the layup was modified by adding thickness to the spar cap in the form of foam until buckling requirements were satisfied as in the baseline model. Over 20,000 kg of mass was removed in comparison to the all-glass baseline blade through use of the carbon fiber spar cap with foam reinforcements in the spar cap to resist buckling. Of course, additional parameter studies must be performed to understand how much this configuration can be optimized. One important observation is that through weight reduction, flap-wise fatigue became the driver for the Case Study #3 blade whereas edge-wise fatigue was dominant in the baseline SNL100-00 blade, in which loads are dominated by gravity loads.

In summary, these parameters studies guide an optimal usage of carbon for a 100-meter length blade through comparison to the all-glass SNL100-00 baseline design. The full paper will explore architecture changes, namely re-positioning of the two principal shear webs, to satisfy buckling requirements of the carbon spar without use of foam in the spar. Furthermore, the cost-benefit of replacing glass with carbon must also be included in the decision-making process. The full paper will include cost comparisons, using the tool described in Section III, to be included along with design info of Table 2. These studies will lay the groundwork for subsequent studies that identify selective or optimal usage of advanced materials in a cost-effective way.

V. Discussion and Conclusions

In summary, there are a number of challenges with large blade development such as: (1) blade weight growth, (2) manufacturing and reliability, (3) material volumes/cost, (4) transportation and (5) new design drivers including aeroelastic stability (flutter), panel buckling, and gravitational fatigue loading as identified in prior work. Many opportunities exist for research and development to enable cost-effective large blades.

This paper documents the design studies of a series of 100-meter wind turbine blades. The baseline model, termed SNL100-00, incorporates conventional geometry, all-glass materials, and traditional manufacturing assumptions. The SNL100-00 design is documented and made publicly available to be used as a research tool/model for evaluating new design options to overcome challenging large blade design issues.

The major focus of this paper is development of an updated 100-meter blade design by replacing uni-directional glass in the baseline all-glass design with carbon fiber. Initial parameter studies were performed to reduce weight of the baseline design through usage of uni-directional carbon in both the spar and trailing edge reinforcement. The resulting weight reduction and impact on deflection, fatigue life, and buckling resistance was quantified. A blade cost model was developed and applied to the 100-meter blade models. The final paper will include additional carbon parameter studies along with cost estimate comparisons of design options to guide cost-effective usage of carbon fiber in large blades.

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