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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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A consistent trend in wind turbine development is growth in the length of the blade to increase energy capture by increasing the swept area of the rotor. To enable future very large rotors for wind turbines, targeted technical research is needed to identify and mitigate the technical barriers that limit cost-effective large rotor technology. A few years ago, Sandia National Laboratories (SNL) Wind and Water Power Technologies Department initiated a study of future large blades of length 100-meter and greater in order to produce public domain blade design models and identify large blade technology barriers. In the initial design study, a baseline 100-meter all-glass blade, termed SNL100-00, was designed to serve as a baseline reference model. Through this design process, large blade technology trends were identified including blade weight growth, increased gravitational fatigue loading, reduced buckling resistance, and increased susceptibility to flutter instability. One of the recent follow-on studies has focused on incorporation of carbon fiber into the 100-meter blade design to reduce the weight of the baseline SNL100-00 all-glass design. The focus of this paper is on the effects of carbon fiber usage on large blade performance, weight, and cost. A blade cost model is developed to and demonstrated. A design definition for a new 100-meter reference blade design with carbon spar, termed as SNL100-01, is also presented.

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. However, targeted technical research is still needed to enable cost-effective future large blades. The hope is that this program of research can make a meaningful contribution to large blade technology development through a public domain blade project by performing advanced design studies and by providing useful public domain blade reference models and blade manufacturing cost analyses.

A few years ago, SNL Wind and Water Power Technologies Department initiated a study of large blades in order to produce public domain blade design models and identify and document large blade technology trends[1]. The initial design study produced the Sandia 100-meter All-Glass Baseline Blade, termed SNL100-00[2]. Detailed designs are produced in this work through the selection of airfoils, materials and composite layup, and blade architecture along with a complete set of analyses to demonstrate acceptance of the design to loads and safety factors defined by international blade design standards. The baseline

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design provided an opportunity to identify, quantify, and document large blade technology trends and potential future large blade technology barriers, which include blade weight growth, gravitational fatigue loading, reduced buckling resistance, and increased susceptibility to flutter aeroelastic instability as documented in References 2 and 3.

Recent follow-on studies to the SNL100-00 design study at Sandia have focused on application of innovations to improve performance and reduce the blade weight. One of these studies has focused on the effects of incorporation of carbon fiber into the 100-meter blade design[4]. Specific goals of this current work include (1) providing early design studies for deployment of carbon fiber into a 100-meter blade, (2) development of tools to quantify the performance-cost tradeoffs, and (3) public dissemination of a lightweight 205-meter diameter rotor for advanced rotor and system-level design studies within the wind research community. With carbon, a key consideration is material cost; therefore, our recent studies have also included development of refined blade manufacturing cost estimates that have the flexibility to include the detailed blade design information including materials selection or other important design changes/innovations. We also adapt the blade cost analysis to do an analysis of the effects of scale and how scaling to larger blades affects costs associated with blade materials, labor content, and capital equipment.

The paper is organized as follows. First, a review of the Sandia Large Rotor Project and a summary of the baseline SNL100-00 all-glass blade design is presented. Next, an approach for blade manufacturing cost analysis for blades is described including a discussion of the key components of this model (materials, labor, and capital equipment). Then, a series of carbon design studies are presented including presentation of a final 100-meter carbon reference design, termed SNL100-01[4]. Finally, the blade manufacturing cost model is exercised to examine a few of the uses for this model including cost trends (for materials, labor content, and capital equipment) with blade length.

II. Overview of the Sandia Large Rotor Project and the SNL100-00 Baseline Blade

A. Large Blade Trends and Technology Barriers Identified in the Initial Design Studies

The principal structural design considerations in the design of any blade include tip deflection (i.e. tip-tower clearance), maximum strains, buckling, and fatigue life. Of course, minimization of blade weight and blade cost are driving factors that must be assessed while also satisfying the structural and aerodynamic performance requirements. Based on structural analysis and design of the SNL100-00 baseline blade[2,3], 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 the gravitational loads, fatigue life was found to be driven by in-plane (edge-wise) gravitational loads whereas for smaller blades fatigue is driven by the out-of-plane (flap-wise) aerodynamic loads. The result is need for additional edge-wise reinforcement usually included through reinforcement of the trailing edge. Panel buckling was also found to be a more significant issue for large blades, which requires additional reinforcement through thicker core materials in the panels or an architecture change (e.g. additional shear webs). 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[2,5].

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 this 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 the present carbon design studies, the external geometry will not change 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 design trade-offs.

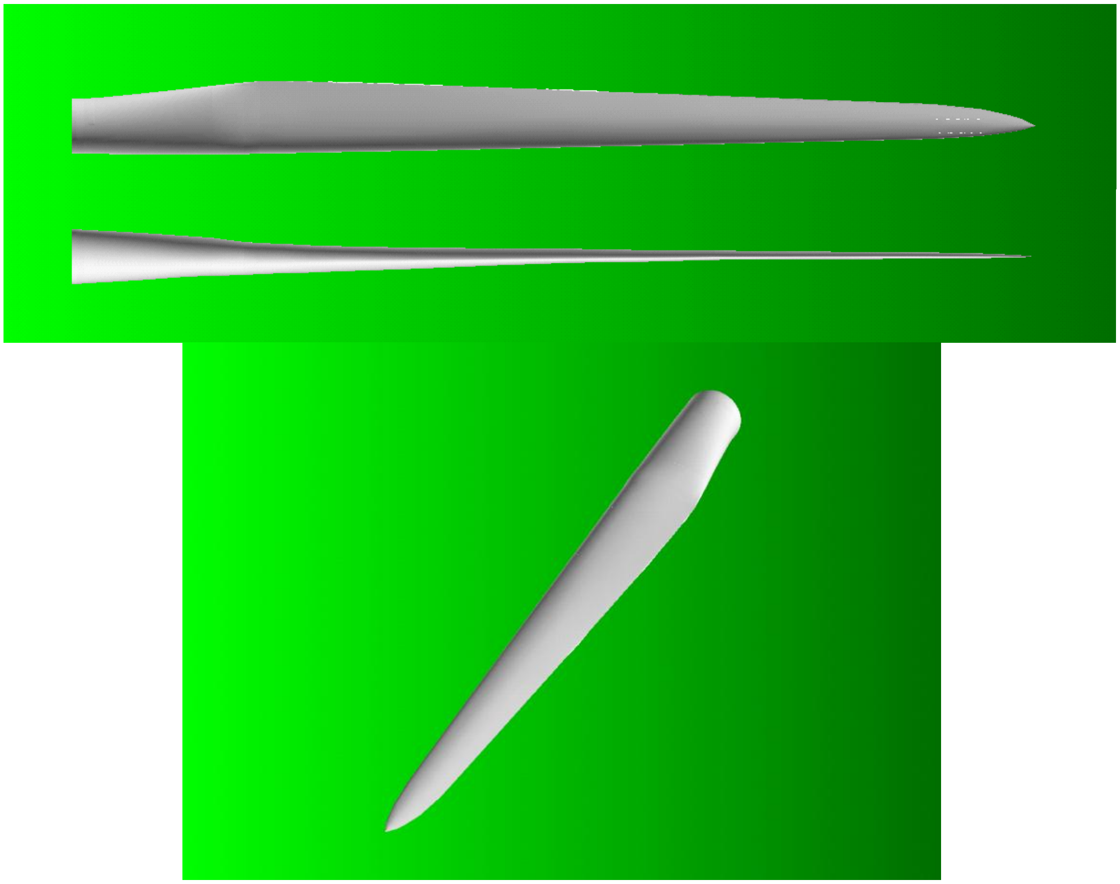

Figure 1. Views of Blade Surface Geometry for SNL100-00 and SNL100-01

Figure 2 shows a planform view with location of the spar cap, trailing edge reinforcement, and the third shear web for SNL100-00. For the present study, modifications to this blade architecture are considered as variables and are changed based on the structural impacts of carbon.

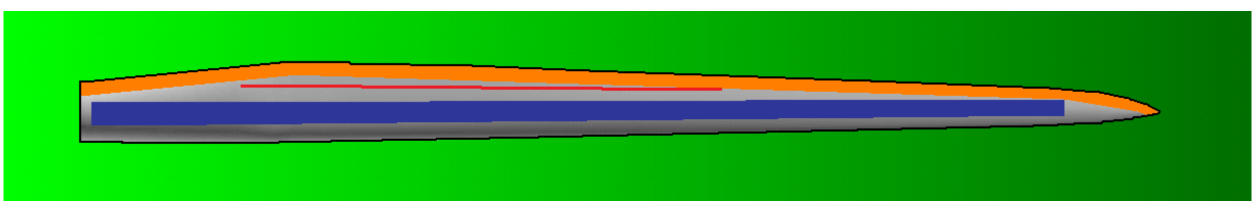

Figure 2. Planform of Sandia 100-m Baseline Blade with Laminate Designations (Blue: Spar Cap, Orange: trailing edge reinforcement, Red: Third Shear Web)

As part of this project, a Design Scorecard has been introduced to summarize the pertinent blade design information including important blade design parameters, a summary of blade structural performance metrics, and the bill of materials usage summary. The Design Scorecard for the baseline SNL100-00 design is reported in Reference 6. In addition to providing a succinct summary of the key design information, the Design Scorecard can also be used as a reference in assessing the effects of innovations.

The key information to be compared from the Design Scorecards within the present study is the total blade weight and the bill of materials usage summary. The weight for the baseline all-glass SNL100-00 blade was very high at 114,197 kg. The weight reduction potential with carbon is examined in Section IV; however, blade costs are addressed first in the next section.

III. Blade Manufacturing Cost Analysis

As wind turbines grow larger (both for onshore and offshore siting), new design approaches and blade architectures must be investigated. For future large blades 100-meter and beyond the effects of the scale of the blades and the effects of the required changes in the design concepts on the manufacturing process are not completely understood. The optimal manufacturing processes for larger blades need to be considered by blade manufacturers to plan their future operations and infrastructure. Also, designers must have an understanding of how new blade design concepts will affect the manufacturing process including a means to quantify the cost-effectiveness of a design option. In order to align the efforts of wind blade designers and manufacturers, an approach of designing for manufacturability must be taken. Therefore, one focus of this work has been development of a tool to investigate the effect of design choices (design innovations) on manufacturability and cost.

Reference 7 documents a cost study for blades in length from 30 to 70 meters performed under the U.S. Department of Energy funded WindPACT program. The WindPACT cost study provided a comprehensive assessment of blade costs including (1) “direct manufacturing costs” such as materials and labor, (2) “indirect manufacturing costs” such as overhead, development, and facilities cost, and (3) transportation costs. Conceptual blade design definitions for blades of lengths 30, 50, and 70 meters were developed based on scaling and simplified structural analysis and then used to estimate the above individual cost components and their trends with blade length. The study assumed that the fundamental design concept and choices for materials within the design were the same for each blade length that was examined. In this sense, this study provided a valuable baseline for both blade cost and trends of costs components (i.e. scaling exponents) for conventional blade designs of length 30 to 70 meters so as to have a reference to compare cost (and weight) of future innovative blade designs.

In the present work, an approach to account for design innovations directly in the cost model is considered. As described above, the blade designs in the Sandia Large Rotor Project are detailed specifications determined in reference to design standards with a complete set of structural analyses. The Sandia NuMAD blade modeling code[8,9] is used to manage the detailed blade design information and produce the structural models needed for the design calculations. In addition, NuMAD can produce the information that is needed for this cost analysis including the materials usage summaries and manufacturing geometry information (e.g. bond line lengths, surface areas, and layer lengths). This approach permits the effects of design innovations to be included directly in the cost estimates using the actual blade definition. In this initial effort the blade manufacturing cost model is comprised of three cost components (materials, labor, and capital equipment) as they are the ones that are strongly affected by blade design decisions. A simple example, relevant to this study, is a change from glass to carbon spar where there is a trade between bill of materials and labor content costs. In the following paragraphs each of these three cost components is reviewed.

Material costs for; for example, unidirectional and bias-ply dry fiberglass, unidirectional pre-preg carbon fiber, epoxy resin, and gelcoat were determined in a standard way by their weight. However, a refined model for foam core cost was determined as a function of both core 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. Once a 100-meter design variant is accepted to design standards loads analysis, following the approach established in Reference 2, then these blade design quantities feed directly to produce the material cost estimate.

Labor costs were the most complex element of the cost equation because manufacturing labor processes change at different levels depending on a number of different factors. Our approach to modeling labor content is to start with a conceptual labor process defined for an example 40-meter wind turbine blade. In order to analyze labor content for larger blades, the approach is to extrapolate the manufacturing processes to larger blade lengths using dimensional up-scaling analysis. For each manufacturing operation or substep in the conceptual labor process the dimensional analysis is applied based on the geometric scaling associated with that particular operation. As was mentioned above the geometric information is coming from the SNL NuMAD blade modeling software. Some operations do not change 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 area. 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 were assumed to have essentially no change included drop tests during vacuum bagging, installing prefabs into the shell, bond paste curing times, and moving the blade in the factory. 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 considered in this analysis 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 is based on modified scaling equations based on blade length from the WindPACT study[7]. The total equipment cost is then divided over the number of blades that the mold is estimated to produce over its projected lifetime. The capital equipment costs are interesting when comparing blades of different sizes but do not change much for blades of the same length in the initial cost estimates although mold cost variability with material choices and associated mold heating requirements; for example, may be considered. This tool may be useful when judging the feasibility of new equipment such as automation which may be added onto the tooling costs.

IV. Carbon Studies for the Sandia 100-meter Blade: Definition of the SNL100-01 Blade

First, prior carbon design and costing studies for blades in the 30-60 meter length range are presented. 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 10, the strategic use of carbon including cost estimates considering both the material and tooling costs was studied for a SERI-8 Blade. In References 11-15, 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 14. In Reference 15, concepts for large blades including usage of carbon laminates is reported. Again, in Reference 7, cost studies for blades are performed.

In this work, we build upon the prior studies (References 7-15, for example) by performing carbon design studies for a 100-meter length blade with cost analysis as described in the previous section.

A. Determination of Uni-directional Carbon Material Properties for Conceptual Laminate

These studies are focused on usage of uni-directional carbon in the spar caps and/or trailing edge reinforcement to replace uni-directional glass as designed in the SNL100-00 baseline. To perform the design analysis for the blade estimates for elastic and strength properties of a conceptual uni-directional

(UD) carbon fiber laminate were produced using data from the Sandia/MSU materials database[16], shown in Table 1. Additional material property information is reported in the SNL100-01 design report[4].

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. Summary of Carbon Design Studies Leading to SNL100-01

As detailed in Reference 4, a series of case studies were examined to study the weight reduction potential of carbon in a 100-meter blade. Carbon was considered in either the spar or trailing edge reinforcement; locations in the baseline blade design having uni-directional glass laminates. Four case studies were examined using the SNL100-00 baseline blade as a starting point and concluding with the final SNL100-01 design:

Starting Point: All-glass baseline blade, SNL100-00
Case study 1: Replace glass in spar with carbon, no geometry change
Case study 2: Replace glass in trailing edge with carbon
Case study 3: Case study 1 with foam added to spar to prevent spar buckling
Case study 4: Carbon spar with spar width reduction (i.e. geometry/architecture change)
Final design (based on Case study 4): SNL100-01

As summarized above, a conceptual uni-directional carbon laminate was determined based on published test data in Reference 16. This blade study is intended to serve as a bounding case on use of carbon as the entire spar was replaced with carbon. Evaluation of specific carbon laminates that have been developed or which are currently under development in the industry; or evaluation of targeted span-wise deployments of carbon in the spar with cost constraints should be subjects of future work. This public domain blade design can provide a reference for such future material development efforts and design trade-off studies of carbon in large blades.

Case study 1 simply involved replacing the all-glass spar from SNL100-00 with the conceptual carbon laminate. The width of the spar remained the same, although the layer thickness was reduced in accordance with the higher longitudinal modulus of the carbon laminate so as to approximately maintain the same flap-wise stiffness along the span. The spar thickness was reduced by about 63% along the entire span to accomplish this. *The principal issue with the Case study 1 design is that the new spar cap was not acceptable because of buckling in the new thinned-down carbon spar.*

Case study 2 focused on carbon in the trailing edge reinforcement only. 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. Only small weight reduction was found with this design change in comparison to the carbon spar re-design, so it was not pursued in subsequent case studies. However, it could be considered that this type of modification could be useful for passive flutter mitigation (see Reference 5) by reducing the weight of the trailing edge and moving the chord-wise CG forward.

Case study 3 is a variant of the first case study whereby foam was added to the carbon spar to prevent buckling in the spar. In the end, this approach solved the buckling issue and also reduced the blade weight significantly from the baseline blade. However, the amount of foam required in the design increased significantly, so it was decided to investigate other design options.

A seemingly next logical choice to solve the buckling issue in the carbon spar included modifying the blade architecture by reducing the width of the spar cap. This type of design change was very easily accommodated using NuMAD[8,9]. In Case study 4, the spar width was reduced by 50% -- as shown in Figure 3. As a result, the two principal shear webs were brought closer together to maintain the box beam construction. More importantly, the carbon spar could be designed using no foam to solve the buckling constraint. In the end, the spar width reduction resulted in even larger weight reduction and satisfaction of the design requirements in excess when compared to Case study 3. *As a result of the weight reduction, secondary reductions in the blade laminates were made possible primarily through the reduction of the gravitational loads that resulted from weight reductions made possible by the carbon spar.* The reduction in gravitational loads permitted reduction of the trailing edge reinforcement, which was reduced in both width and thickness by approximately 50% in the final SNL100-01 design.

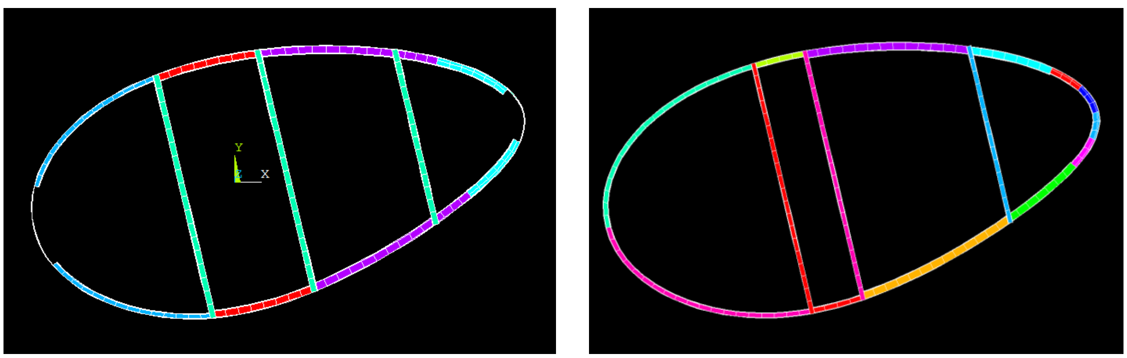

Figure 3. Comparison of Cross-sections at the 14.6 meter Station: SNL100-00 (left) and SNL100-01 (right). *(Note the repositioning of the two principal shear webs; Also, leading and trailing edge elements are 1/10th actual thickness as plotted on left for SNL100-00.)*

Additional but lesser weight reductions were also made possible and were included in the final SNL100-01 carbon spar design by thinning the root buildup, reducing the foam thickness in all three shear webs, and reducing the assumed parasitic resin thickness by 20%. The latter was justified to keep the parasitic blade weight percentage similar to that of the baseline blade, at about 7% of the total blade weight (7.4% for SNL100-01 while it was 6.8% of the total blade weight for SNL100-00).

These design changes from the baseline SNL100-00 blade (see Reference 2) resulted in a 35% weight reduction and can be summarized (again) as follows:

(1) entire spar cap is replaced with carbon and thickness re-sized,
(2) width of spar reduced by 50% with both principal shear webs moved accordingly,
(3) trailing edge reinforcement was significantly reduced in thickness (~50%) and width (~50%),
(4) root build-up was thinned (between the root and 4.7 meters),
(5) foam core in shear webs reduced thickness in all three webs (25% reduction),
(6) parasitic resin thickness reduced from 5mm to 4 mm (20% reduction).

The pertinent results for these carbon design parameter studies are summarized in Table 2. The performance margins are tabulated for the deflection, fatigue, and buckling analyses in the upper section of the table. This is followed by a summary of the total blade mass and CG location (both computed using FAST). The lower section of the table compares the bill of materials summary for each design variation.

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	Case Study #4	SNL100-01
	All-glass baseline blade	*Carbon Spar Cap*	*Carbon Trailing Edge (TE)*	*Carbon Spar Cap plus Foam*	*Carbon Spar width and TE Reduction*	***Carbon Spar Blade***
Deflection (m)	**11.9**	10.3	12.0	10.3	12.7	**10.5**
Fatigue Lifetime (years)	**1000**	N/A	N/A	281	72	**202 (570)**
Governing location for fatigue lifetime	***15% span edge-wise***	N/A	N/A	*15% span flap-wise*	*11% span flap-wise*	***50% span flap-wise (15% span flap-wise)***
Lowest Buckling Frequency	**2.365**	0.614	2.332	2.391	2.158	**2.077**
Blade Mass (kg)	**114,197**	82,336	108,897	93,494	78,699	**73,995**
Span-wise CG Location (m)	**33.6**	31.0	32.1	34.0	31.3	**33.1**
E-LT-5500 Uni-axial Glass Fiber (kg)	**39,394**	16,079	34,952	16,079	13,894	**10,924**
Saertex Double-bias Glass Fiber (kg)	**10,546**	10,546	10,546	10,546	10,623	**9,368**
Foam (kg)	**15,068**	15,068	15,917	26,600	16,798	**15,948**
Gelcoat (kg)	**927**	927	927	927	927	**927**
Total Infused Resin (kg)	**53,857**	33,996	50,072	33,996	32,234	**26,723**
Newport 307 Carbon Fiber Prepreg (kg)	**0**	10,208	1,902	10,208	8,586	**10,094**

**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 [9].

It should also be noted that the thickness of the carbon spar was adjusted along the span to ensure that there were no buckling or fatigue issues in the final SNL100-01 design. The buckling issue was solved well with the reduced spar width while maintaining the span-wise spar thickness derived for Case study 1; however, the final fatigue analysis showed that some regions of the spar required additional reinforcement to ensure sufficient fatigue life. Therefore, the final set of design iterations included adding a few layers of carbon in the spar near maximum chord and also in the mid-span region to satisfy fatigue life requirements.

In addition, note that (1) the external geometry for SNL100-01 is unchanged from the baseline SNL100-00 design and (2) regarding the shear web placement, although the two principal web locations both changed in SNL100-01, it was decided not to re-position the 3rd web. Optimal placement of the 3rd web and sizing of the aft panel foam thickness could be the subject of subsequent efforts by the research community as the panel buckling capacity of this design is in excess of the requirement.

C. SNL100-01 Discussion and Potential Future Work

As noted above, this carbon study was intended to serve as a bounding case on use of carbon as the entire spar was replaced with carbon. Cost optimization should be the subject of targeted follow-on studies to investigate strategic deployment of carbon. This cost optimization could utilize tools such as those discussed above and in the next section. *The all carbon spar and associated reductions resulted in a significant weight reduction of 35%.* However, future work remains and can address application of carbon materials tailored to the large blade application (including; for example, those with better suited fatigue properties) as well as manufacturing impacts with use of carbon.

In addition, the approach of these design studies and cost analysis can also be used to evaluate the cost-effectiveness of other material choices in the blade design such as core materials. A core study could be a valuable area to investigate – the amount of core material was about the same for the SNL100-01 blade in comparison to SNL100-00; however, the percentage of core increased from about 13% to over 21% with the carbon spar. New core materials or better use of core should be investigated in the buckling design.

Again, targeted deployment of carbon in the outboard blade spar should be considered along with cost constraints from a blade cost model. Further, a two shear web solution and/or reduction in aft panel foam thickness may be possible and should be analyzed in future work. These constitute a set of directions that seem logical to begin from where this study has ended; however, there are numerous innovations that can be considered to provide additional blade weight and cost reductions for large blades.

V. Initial Blade Cost and Cost Trends Analysis

Two example cost studies are presented to accompany the carbon structural design studies presented in the previous section – these include a comparison of costs for the SNL100-00 glass blade and the SNL100-01 carbon blade and an analysis of blade cost trends with blade length scale using the approach outlined in Section III.

First, the costs for two different 100-meter blade designs are estimated to demonstrate a use of the cost analysis. It should be kept in mind that neither of these designs is an optimized design; however, this analysis provides a test case to demonstrate the utility of the cost analysis tool to compare the effect of design choices. The bill of materials information and material pricing was input into the cost analysis along with blade geometry information such as area of the foam core and the total ply lengths for the spar caps, trailing edge reinforcements, and root buildup for both the SNL100-00 and SNL100-01 designs. The result was estimates for costs of materials, labor, and molds as described in Section III. *Although the SNL100-01 carbon design was 35% lighter than the SNL100-00 glass design, it was found that the material cost was about 16% higher for SNL100-01 assuming the price for the conceptual carbon laminate to be about 7 times that of the glass materials.* The analysis of labor content relied upon scaling the individual labor operations using geometric upscaling, as detailed above, from the conceptual process defined for the example 40-meter blade to 100-meter length. The resulting labor content for the SNL100-01 carbon blade was found to only be minimally reduced owing to the fewer layers required to be placed in the spar and trailing edge molds. Of course, the molds cost was the same for both designs as no change was made to the external geometry.

Again, the point of this exercise is to demonstrate the cost analysis for one example set of material properties and their associated price points. It is well-known to designers that the material usage, or amount of material required, as determined from the structural design must be considered with price points to evaluate the cost-effectiveness of a particular design. The hope is that the approach of this cost analysis provides a useful tool to quantify the costs. It is anticipated that these initial test cases will help refine the cost tool before its future documentation and public release.

The second set of cost studies examined is blade cost trends with blade length scale. For materials, conventional scaling was defined for the 40- to 100-meter blade length change (i.e. scaling exponent of 3.0) as this example is for an all-glass comparison. Labor content scaling at the operation or substep level, as described in Section III, resulted in a scaling exponent of about 1.5 for the total labor hours content. For molds/equipment the scaling exponent was 2.1, a value chosen from Reference 7. Applying these scaling exponents to the data for the example 40-meter blade, as shown in the left figure of Figure 4, results in the chart on the right for a 100-meter blade. Clearly the materials cost becomes a more dominant fraction of the cost in this scenario owing to the higher exponent. However, the WindPACT study suggests labor is 2.4 to 2.5 instead of 1.5 (as based on our geometry-based analysis), which indicates that growth in the materials cost share may be exaggerated. Further work to examine the detailed labor breakdown is required to add validity to the labor scaling for blades of today and future large blades.

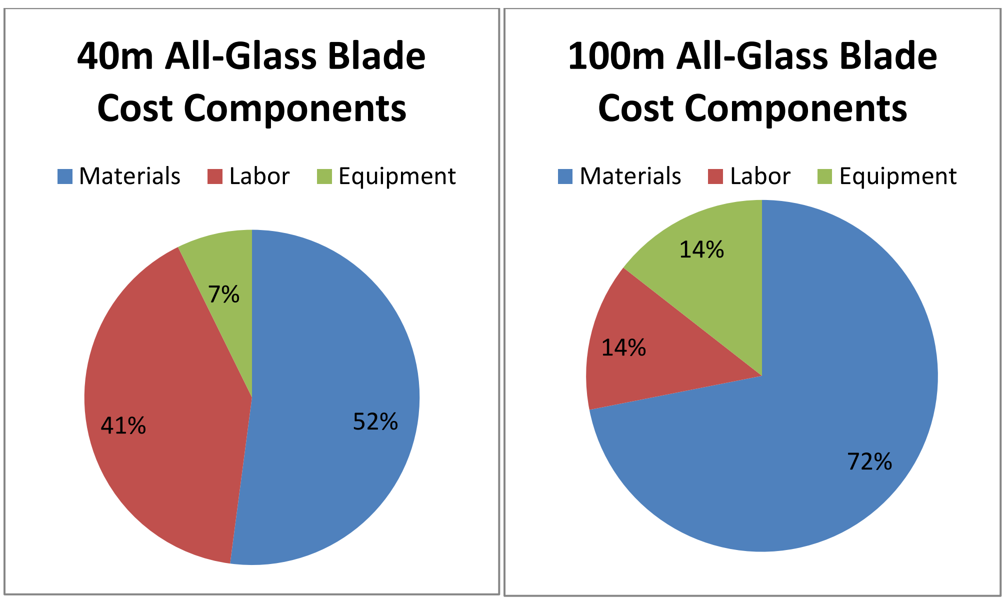

Figure 4. Example Cost Breakdown with Scale: 40-meter blade (left) and 100-meter blade (right)

One of the more valuable aspects of this model is the detail in the labor operations model. For example, based on scaling the breakdown in the labor hours with the blade finishing operations shows a dramatic trend for operations that depend on area such as paint and paint prep. Figure 5 shows the breakdown in labor finishing operations for the same 40- and 100-meter blades considered in Figure 4. Such cost trends studies could be useful to investigate cost tradeoffs between labor content and equipment/automation making the tool useful for design for manufacturability and manufacturing process decisions and will ultimately help reduce blade costs.

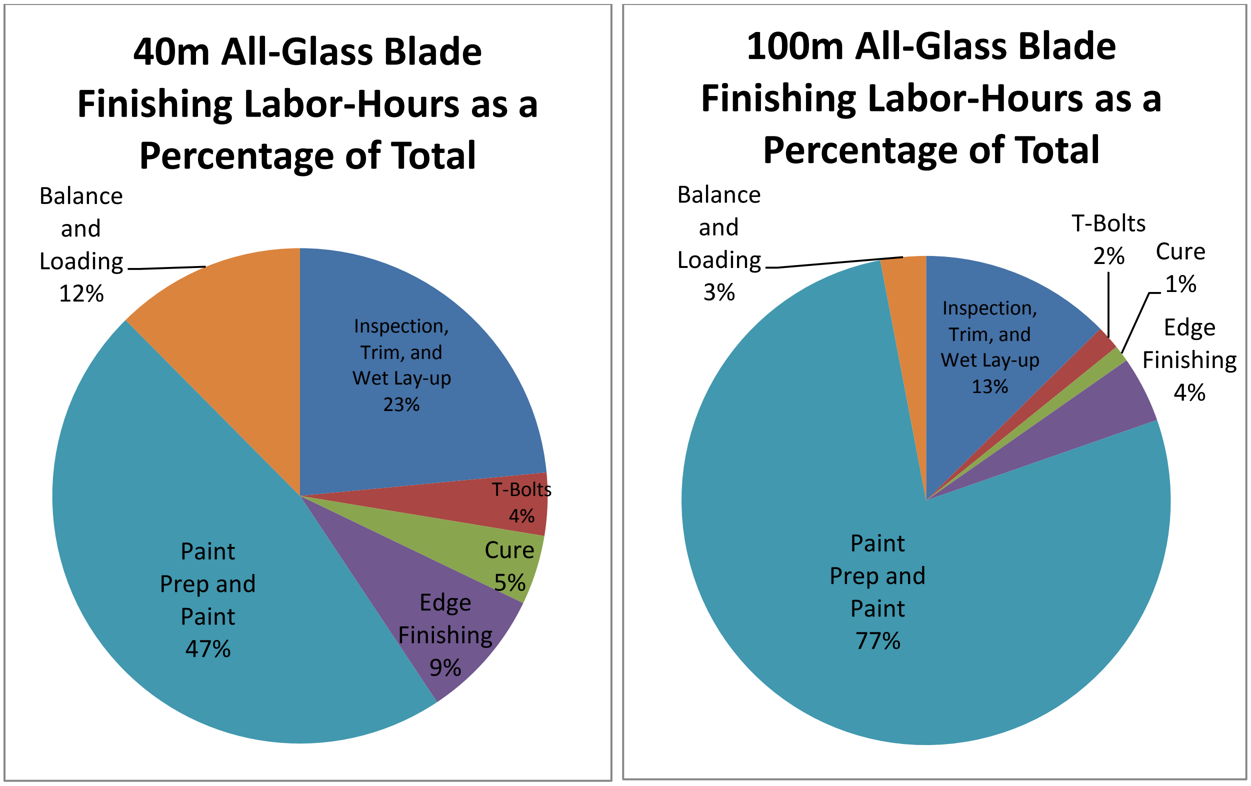

Figure 5. Example Trend of the Breakdown of Labor Finishing Operations

VI. Summary and Conclusions

This paper documents a series of design studies and cost analysis for 100-meter wind turbine blades. The Sandia 100-meter All-glass Baseline Blade (SNL100-00) serves as both a reference and starting point for these studies. A series of carbon design studies were performed to investigate to effect of carbon on blade weight, blade performance and cost. These studies resulted in a final 100-meter carbon reference design, termed SNL100-01, which was 35% lighter than the baseline all-glass blade. The paper documents some of the challenges with incorporating carbon into the blade spar, most notably buckling of the spar when designing thinner carbon laminates into the blade structure. This particular issue was solved with a change to the blade architecture in reducing the carbon spar width. An approach for blade manufacturing cost analysis for blades was also described including a discussion of the key components of this model (materials, labor, and capital equipment). The blade manufacturing cost model was exercised to examine a few uses for this model including cost trends (for materials, labor content, and capital equipment) with blade length.

The contributions of this work include (1) providing early design studies for deployment of carbon fiber into a 100-meter length blade, (2) development of tools to quantify the performance-cost tradeoffs, and (3) public dissemination of a lightweight 205-meter diameter rotor for advanced rotor and system-level design studies within the wind research community. The hope is that this work will contribute in a meaningful way to aid in development of more cost-effective very large blades 100-meters and greater through the public domain design studies and models, and in particular that this current study will provide some guidance to the industry and to researchers in greater incorporation of carbon fiber into blades – a trend of growing interest in the industry but that has been adopted fairly slowly.

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