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The SNL100-03 Blade: Design Studies with Flatback Airfoils for the Sandia 100-meter Blade

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Abstract

A series of design studies were performed to investigate the effects of flatback airfoils on blade performance and weight for large blades using the Sandia 100-meter blade designs as a starting point. As part of the study, the effects of varying the blade slenderness on blade structural performance was investigated. The advantages and disadvantages of blade slenderness with respect to tip deflection, flap-wise & edge-wise fatigue resistance, panel buckling capacity, flutter speed, manufacturing labor content, blade total weight, and aerodynamic design load magnitude are quantified. Following these design studies, a final blade design (SNL100-03) was produced, which was based on a highly slender design using flatback airfoils. The SNL100-03 design with flatback airfoils has weight of 49 tons, which is about 16% decrease from its SNL100-02 predecessor that used conventional sharp trailing edge airfoils. Although not systematically optimized, the SNL100-03 design study provides an assessment of and insight into the benefits of flatback airfoils for large blades as well as insights into the limits or negative consequences of high blade slenderness resulting from a highly slender SNL100-03 planform as was chosen in the final design definition. This document also provides a description of the final SNL100-03 design definition and is intended to be a companion document to the distribution of the NuMAD blade model files for SNL100-03, which are made publicly available.

A summary of the major findings of the Sandia 100-meter blade development program, from the initial SNL100-00 baseline blade through the fourth SNL100-03 blade study, is provided. This summary includes the major findings and outcomes of blade design studies, pathways to mitigate the identified large blade design drivers, and tool development that were produced over the course of this five-year research program. A summary of large blade technology needs and research opportunities is also presented.

ACKNOWLEDGMENTS

The authors wish to thank the DOE Wind and Water Power Technology Office for the support to perform this work. The authors would like to acknowledge the assistance of Dr. David Maniaci of Sandia National Laboratories with Betz-optimal blade design calculations.

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1. INTRODUCTION

Design and development of large wind turbine blades is challenging due to a variety of competing requirements related to economic, logistic, manufacturing, and technical constraints. Regarding the technical requirements, blade designs must satisfy deflection, buckling, fatigue, and stability requirements. This is a very challenging design problem, and one that becomes more challenging to do cost-effectively as designers pursue even longer blades designs. Sandia National Laboratories Wind and Water Power Technologies Department creates and evaluates innovative large blade concepts for horizontal axis wind turbines to promote designs that are more efficient aerodynamically, structurally, and economically. Recent work has focused on the development of a 100-meter blade for a 13.2 MW horizontal axis wind turbine and a series of large blade design studies for 100-meter blades. A link to the project website can be found in Reference 1. Through this work, several key design barriers for large blades have been identified and documented including panel buckling, weight growth & gravitational fatigue loading, and aero-elastic stability [2, 3].

The present report summarizes a fourth and final series of 100-meter blade design studies. Here, the effect of a new blade geometry using flatback airfoils is investigated. A combined aerodynamic and structural design procedure is employed to produce new blade geometries. In addition to investigating the effects of flatback airfoils versus conventional sharp trailing edge airfoils, the effect of varying blade slenderness is also evaluated in this SNL100-03 study. The prior blade design studies in this project began with an all-glass baseline design (SNL100-00) followed by investigation of carbon fiber materials (SNL100-01) then advanced core materials and a new core materials strategy (SNL100-02):

All-glass Baseline Blade:	**SNL100-00**	***114 ton weight***	***Reference 4***
Carbon Design Studies:	**SNL100-01**	***74 ton weight***	***Reference 5***
Advanced Core Material:	**SNL100-02**	***59 ton weight***	***Reference 6***
Advanced Geometry:	**SNL100-03**	***49 ton weight***	***Present Study***

These designs are included in Figure 1 along with a survey of blade weights for commercial industry and research concept blades including the most recent data on new blades reported in the public domain. Note the Sandia SNL100-XX 100-meter series of designs (at 102.5-meter rotor radius in the figure), which demonstrates the weight reduction trajectory in this series of blade design studies. The industry survey includes recent large blades including the 73.5-meter (LM), 75-meter (Siemens), 83.5-meter (SSP/Samsung) and 81.6-meter (Euros/Mitsubishi) blades, which are plotted as diamonds in the figure. This data was gathered from web searches and is public domain. A few projections from 61.5-meter carbon blades are made in Figure 1 to project traditional and higher innovation weight growth to 102.5-meter rotor radius and beyond. The recent large blade data from industry indicates scaling between 2.0 and 2.5 being realized in actual designs, so a conservative projection for a 100-meter design with weight in the 50-60 ton range should be achievable although designs in the 40-50 ton range and lower should be possible through application of innovations. Of course, as evidence, the final SNL100-03 design is 49 tons and an optimized version of the design in the 40-50 ton or lower range should be possible.

The design conditions and materials are largely unknown for these industry designs, thus this data provides a broad perspective of the industry blade designs rather than one particular technology approach or set of design conditions. For example, IEC design load classes and choices for spar material (i.e. glass versus carbon) and core materials, which have a very large effect on blade weights, vary a great deal across the industry commercial and prototype designs. The SNL 100-meter designs include parasitic and coating weights in order to provide more realistic blade weights. In addition to the diversity among these designs in terms of design class, material constraints, and manufacturing methods, some caution should be exercised as the blade costs and overall rotor economics (e.g. AEP) are not addressed here. Also, the more aggressive projections of weight reduction must assume that technical barriers (such as gravitational loads, fatigue, buckling, deflection constraints, and aeroelastic stability) can be overcome in design. The extent to which these barriers can be overcome in a cost-effective way while maintaining weight targets is an important motivation for this study. Although not exercised in this work, a blade manufacturing cost tool was developed within this program of study to aid in answering economics and manufacturing related questions for large blades, as documented in References 7 and 8. This tool could be used to systematically reduce costs in a design optimization.

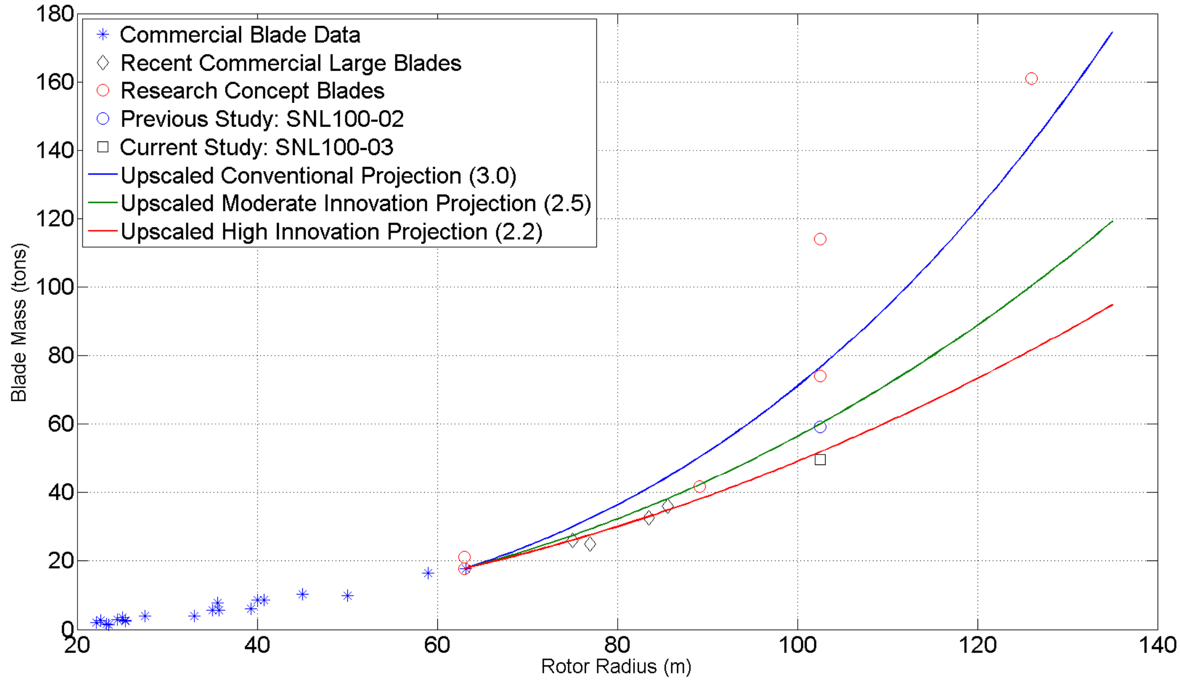

Figure 1. Blade Mass Survey and Projections Versus Rotor Radius

The pre-design work in the Upwind 20MW turbine study resulted in a design with 126-meter rotor radius and a blade mass of 161,000 kg (Reference 9), which is also plotted in Figure 1. Similar to the Sandia All-glass Baseline Blade (SNL100-00) the Upwind 20MW blade design utilized only glass materials, and structural requirements on buckling necessitated a 3rd shear web. These choices contributed to both of these initial designs to have mass well above classical scaling exponent value of 3.0. A more recent concept design is the DTU Wind 10MW concept blade (at 89-meter radius in Figure 1, Reference 10), which shows a weight growth exponent just under 2.5.

In the current study, a series of design studies were performed to investigate the effect of flatback airfoils for large blades using the Sandia SNL100-02 blade (Reference 6) as a starting point. This report provides a description of the final blade design, termed as SNL100-03. This report includes a summary of the design modifications and a description of the NuMAD [11, 12] model files that are made publicly available.

The same design process was once again used; therefore, prior work can be consulted for additional information that may be omitted in this design report. One key point is that all design requirements for the SNL100-03 design are also satisfied according to international blade design standards (IEC and GL, References 13 and 14); these requirements or drivers include maximum strains, tip-tower clearance, buckling resistance, and fatigue life to demonstrate acceptance of the design concept to loads and safety factors from international design standards. The design safety factors and associated design standard are the same for this study as discussed in References 4, 5, and 6 for SNL100-00, SNL100-01, and SNL100-02.

The new SNL100-03 blade can be included in the Sandia 13.2 MW reference turbine model by simply swapping the blade definition file. The Sandia 13.2 MW turbine model is documented in Reference 15, and is also publicly available by request on the project website noted in Reference 1.

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2. PRE-DESIGN WORK FOR SNL100-03: A 100-METER BLADE USING FLATBACK AIRFOILS

This section describes the pre-design work for SNL100-03, which was initially documented in Reference 16. Here the airfoils and design process are described. A summary of the design studies is provided that compares the SNL100-02 blade predecessor with three new variants: (1) a new geometry with reduced solidity using the same (original) sharp trailing edge airfoils, (2) a highly slender design using flatback airfoils, and (3) a less slender design using flatback airfoils.

Description of Flatback Airfoils

The FB-series of flatbacks utilized in the Sandia BSDS (Blade System Design Study) blade [17] are utilized in this study, as shown in Figure 2. The foils were selected based on the availability of their performance data, based on prior testing, as well as being previously published foils.

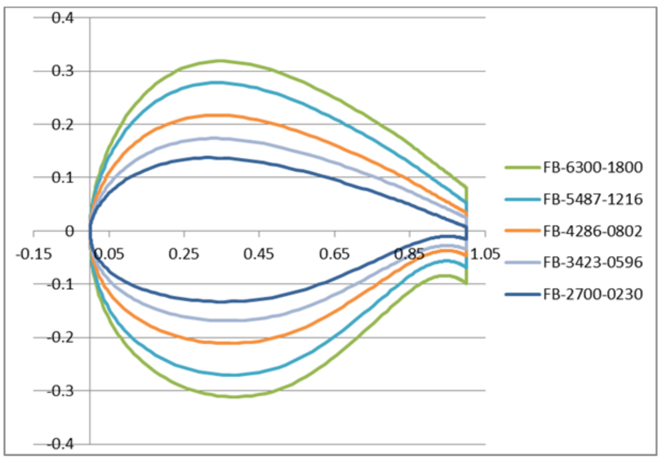


Figure 2. Family of BSDS Flatback Airfoils from 27% to 63% Thickness

Description of the Aero-Structural Design Process for the New External Geometry

The design code HARP_Opt (Horizontal Axis Rotor Performance Optimization) [18] was used to design the 100-meter blade external geometry. HARP_Opt performs a dual-objective genetic algorithm optimization, where the objectives are annual energy production (AEP) and blade weight. The design variables for this optimization tool are control points for the twist and chord profiles of the blade along with variables to determine airfoil placement. For the aerodynamic model, HARP_Opt uses WT_Perf, which is a blade-element momentum theory wind turbine analysis code, also provided by NWTC. The airfoil data was provided to WT_Perf in the form of multiple Reynold's number data tables, with Reynold's numbers spanning the range of 7.5e5 to 20e6. A preliminary aerodynamic design was generated using this tool for the case of sharp trailing edge airfoils and is shown in Figure 3, along with the baseline design and two Betz optimum designs. The first Betz optimum design was created by matching the c_l distribution of the aero optimized design and calculating the optimum chord required to maintain a constant axial induction factor of 0.33 over the blade (using blade element momentum theory). The second design was created by using a design c_l of 0.9, which approximated the optimized c_l distribution over the last 50% of the blade. This figure shows the aero optimized profile produced using HARP-Opt has a reduced solidity and is very close to a "Betz optimum" design.

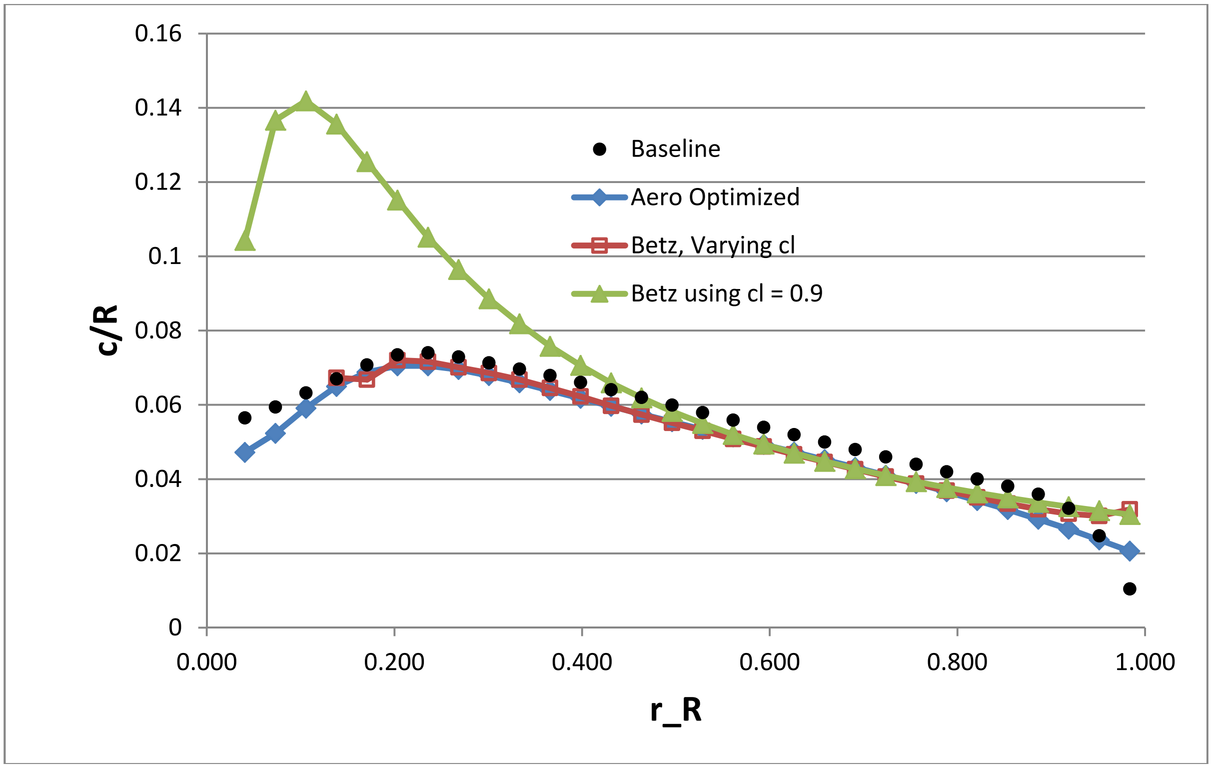


Figure 3. Comparison of Chord for SNL100m Baseline, Updated SNL100m (DU foils, pure Aero Optimization), and Betz Optimal Designs

The current design approach has the options to design the blade geometry considering only aerodynamic considerations or both aerodynamics and structural considerations simultaneously. Thus, one objective of this work, as noted in Reference 16, is to evaluate and exploit this capability in these design studies wherein the structural performance is also included with aerodynamic performance objectives in producing the external blade geometry definition. This can be a key step to meeting the stringent cost and structural performance objectives for large blades. Some of these initial calculations are described in the following section.

The structural analysis aspect of the optimization tool HARP_Opt was integrated with Sandia National Laboratories NuMAD toolbox [12] and an open source code for composite wind turbine blade structural analysis, CoBlade [19]. In this way a consistent and accurate structural representation was available throughout the optimization process. Then, designs were made with the baseline set of airfoils as well as the set of flatbacks shown above, while maintaining the same approximate thickness distribution for each blade. The root chord of the "structurally optimized" blades was reduced to 4.5m from 5.86m (scaled up from prior DOWEC 6MW blade studies) with the maximum chord at around 20% of the span. Preliminary and intermediate results identified the "extreme gust with coherent direction change" or ECD design load case as a design driver. Because the ECD analysis can take several seconds to run, an approximate deflection ratio between the ECD deflections and static deflections predicted by CoBlade was calculated, and the CoBlade static deflections were appropriately constrained throughout the optimization. The deflection ratio was updated at several stages of the process for each aero-structural optimization. This novel approach to blade conceptual/preliminary design therefore captures aspects of aerodynamic performance, static structural performance, and aeroelastic performance. For each candidate aerodynamic evaluation, a parametric sweep of tip speed ratio (TSR) was performed in WT_Perf, and the speed controller scheduling for each candidate was adjusted to meet the optimum TSR for that candidate.

In this way, TSR was allowed to vary throughout the optimization and the choice of TSR did not limit the design space.

Since the multi-objective genetic algorithm is used, each aero/structural optimizer run produced a Pareto front of candidates. The candidate from each optimization that has the same AEP as the baseline design was chosen. The geometry optimization with flatback airfoils resulted in two blade geometries for analysis – the first ("Rev1") having a more slender planform than the second ("Rev2") having a less slender planform. Of course, both of these designs are significantly more slender than the initial Sandia 100-meter blades studies. These designs provide insight into the appropriate degree of slenderness for blades of this size in this pre-design work.

The optimization results for chord and twist are summarized in Figure 4. Table 1 gives more details about the optimized designs. Baseline refers to the upscaled DOWEC chord data to 100-meter blade length used in the earlier designs (SNL100-00 through SNL100-02) with DU-series airfoils. "DU Optimized Rev0" refers to the updated/refined chord and twist for 100-meter blade length using the same/original airfoil schedule. "Rev1" and "Rev2" are 100-meter blades with flatback airfoils from the series plotted in Figure 2. Polars for the maximum chord airfoils are shown in Figure 5.

Table 1. Details about the baseline and three new 100-meter design variants.

Design	AEP (kWh)	ECD Deflection (m)	Optimum TSR
Baseline	6.67e7	13.4	7.2
DU Optimized Rev 0	6.67e7	13.23	9.35
FB Series Rev 1	6.67e7	13.35	9.85
FB Series Rev 2	6.67e7	13.24	9.66

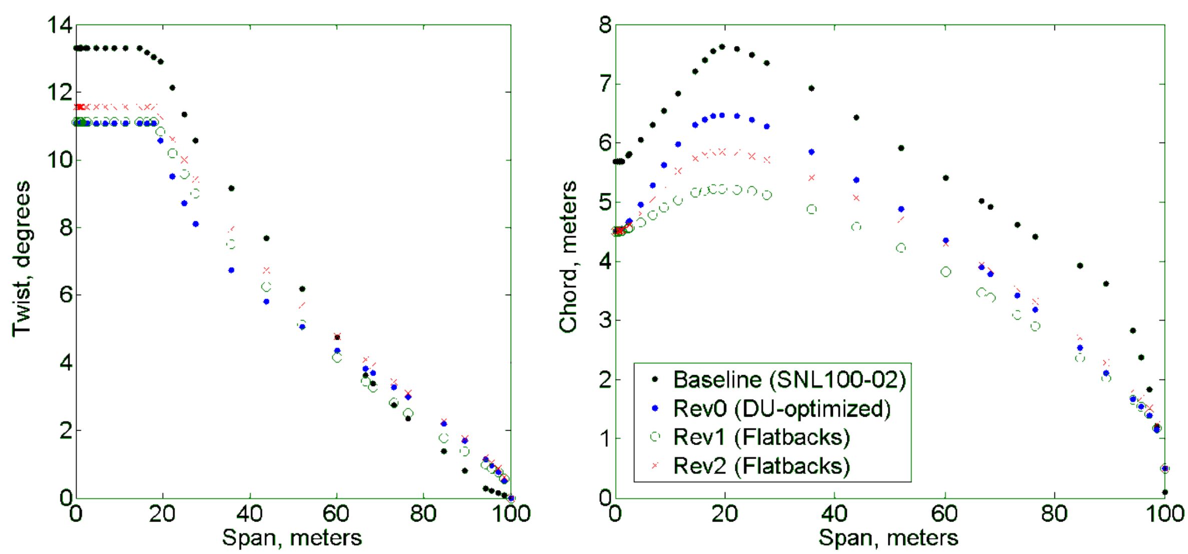


Figure 4. Chord and twist distributions for the baseline and three new 100-meter design variants.

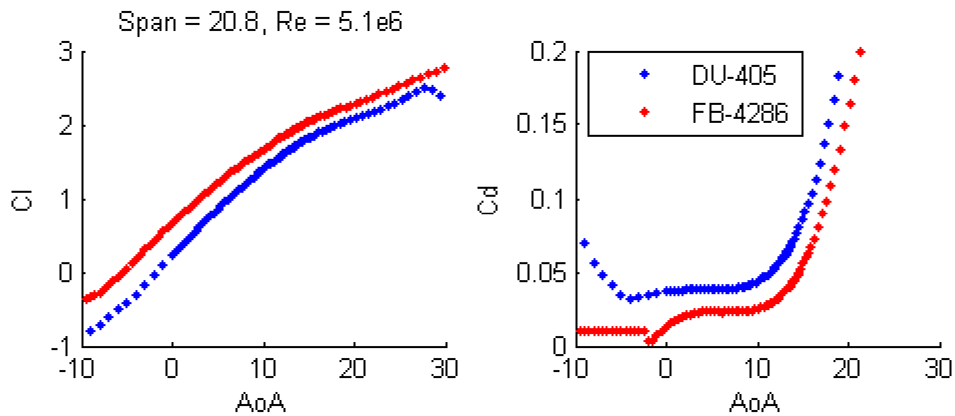


Figure 5. Polars for Maximum Chord Airfoils in this Study.

The optimized designs were able to produce the same AEP but at a lower solidity by increasing the optimum TSR of the design from 7.3 to around 9.6 (see Table 1). This was accomplished by altering the speed controller so that the optimum TSR is met at slightly lower wind speeds. Figures 6 and 7 show some details about the aerodynamic performance of the different designs compared with the baseline. Figure 6 shows the power coefficient, *Cp*, as a function of wind speed, showing that the optimized designs reach a higher maximum *Cp* than the baseline, and the maximum *Cp* is achieved over generally lower wind speeds. At and around the rated speed, where the loads are generally the highest, the maximum *Cp* is lower for the optimized than the baseline design. This has the effect of lowering the maximum loads the optimized blade will be expected to see. Figure 7, a plot of the root bending moment as a function of wind speed, shows the peak bending moment is reduced by ~25% for the optimized designs. Figure 8 demonstrates the difference in control schemes between the baseline and optimized designs.

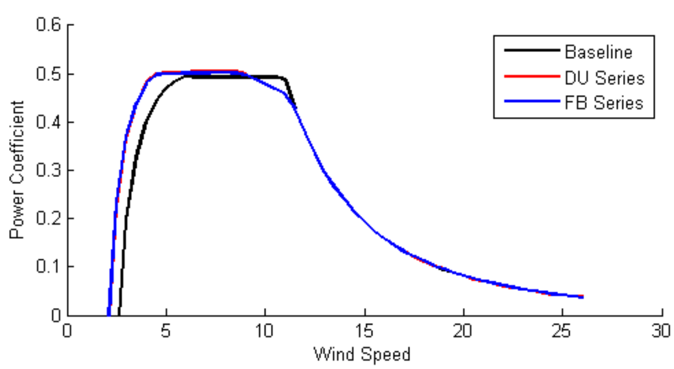


Figure 6. Predicted power output in terms of Cp from the designs.

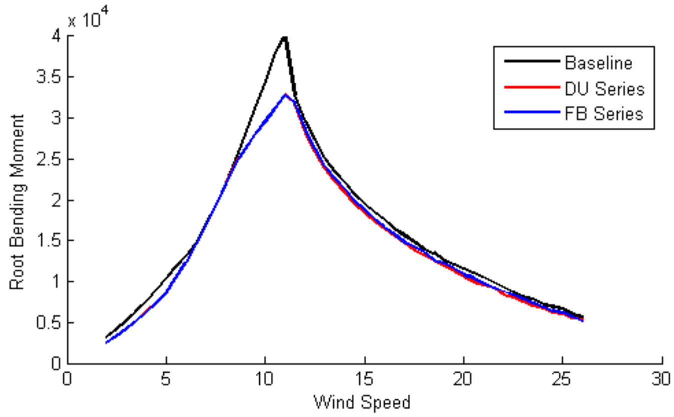


Figure 7. Root bending moment in kN for the designs as a function of wind speed.

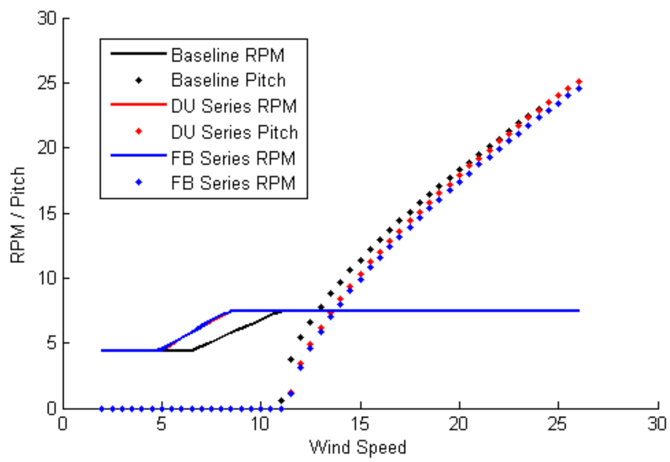


Figure 8. Design control scheduling for the designs. The speed control schedule is given in terms of RPM vs. wind speed, where the pitch control schedule is defined in terms of blade collective pitch angle vs. wind speed.

Initial Trade-off Study for Blades of Varying Slenderness

Table 2 compares the four designs shown in Figure 4 from the highest solidity SNL100-02 design to the lowest solidity SNL-100-03 (rev1). In these results, each design has the same layup and internal spar geometry and spar placement based on the final SNL100-02 layup [6]. This initial comparison of designs was done in this manner to isolate the effect of the new geometry, although this layup is more optimized for the SNL100-02 design with larger chord and DU-series foils. Table 2 clearly shows the advantages of the new more slender designs (Rev0, Rev1, and Rev2) in terms of weight and loads reduction (Flap RBM refers to the flap-wise blade load root bending moment for the EWM50 (50-year occurrence wind speed) with pitch angle of zero degrees).

In comparing the three new designs, the most slender Rev1 design has lowest weight so it will be investigated first in the final series of design studies to come. Rev1 also has the largest excess buckling capacity indicating that core materials can be thinned and/or the design can utilize two shear webs versus the current three shear web architecture. Further, we consider the manufacturing labor operations on the blade surface such as sanding and painting. As noted in References 7 and 8, it is the area operations that grow in significance for large blades (e.g. Paint and Paint Preparation grows from 47% to 77% of the total blade finishing hours for a 40- to 100-meter blade length change). Such cost trend studies are useful to investigate and quantify the benefit of low blade solidity (lower surface area) with respect to labor hours cost and it motivates the inclusion of surface area (i.e. blade labor costs) as a variable for comparison in this study. The Rev1 design has 30% reduced surface area in comparison to the Baseline.

Some of the design loads requirements (e.g. fatigue life greater than 20 years) are not met in this set of designs, and additional work remains to quantify each design driver for final blade designs that satisfy design requirements, which is performed in the next section. Flutter speeds were also computed (ratio of flutter predicted RPM to maximum RPM) and small reductions in flutter speed are noted.

These initial results demonstrate that a systematically optimized design for a 100-meter blade that would be considered highly innovative in relation to the projections in Figure 1 to likely be in the mid-40 ton range for weight.

Table 2. Summary of Blade Performance and Cost Comparisons

	SNL100-02	SNL100-03: Rev0	SNL100-03: Rev1	SNL100-03: Rev2
Geometry Description	Baseline	DU-Optimized	More slender	Less Slender
Airfoil Family	DU	DU	Flatbacks	Flatbacks
Mass (kg)	59,047	53,146	50,530	53,671
Flap RBM (max) (kN-m)	111,900	87,410	74,930	92,600
Tip Deflection (m)	10.51	10.62	13.37	11.02
Spar Fatigue @ 15% span (years)	646	4004	340	2641
Trailing Edge Fatigue @ 15% span (years)	352	31.6	0.3	2.7
Lowest Panel Buckling Freq.	2.10	--	3.60	3.15
Flutter Speed Ratio	1.65	1.67	1.54	1.62
Surface Area (sq. meters)	1262	1021	886	979

In the next section, a final design based on the more slender "Rev1" design is produced that satisfies all the design requirements. In particular, the spar and trailing edge were re-sized for deflection and fatigue requirements; and the core panels were thinned given the excess buckling margins.

3. SUMMARY OF FINAL SNL100-03 BLADE DESIGN SPECIFICATIONS

Summary of Final Design Changes

As indicated in the previous section, several changes were needed when modifying the "Rev1" design in order to satisfy the design loads requirements. These include modifications to the following: (1) Core material and triaxial material in skins: reduction in thicknesses for both given excess buckling margins; (2) Spar: increase in layers/thickness to stiffen blade and satisfy flap-wise fatigue requirements; (3) Trailing edge reinforcement: increased layers/thickness to satisfy edge-wise fatigue requirements; and (4) Parasitic resin: small reduction to maintain parasitic mass percentage.

The major take-ways of these SNL100-03 design studies include:

- The final design weight was 49 tons, which was about a 16% reduction from SNL100-02 (advanced core material) design and more than 56% reduction from SNL100-00 (all-glass baseline) – meeting all design loads requirements as detailed in the remainder of the section
- An increase in spar thickness was needed for the highly slender SNL100-03 planform, which in this case resulted in a large increase in usage of carbon in the spar
- An increase in the trailing edge reinforcement was needed for edge-wise stiffness requirements
- Return to a two shear web solution should be possible, although the removal of a shear web would give only a minor weight decrease
- Decreased flutter speed was observed with the more flexible SNL100-03 design.

Summary of Key Design Loads Analysis: Buckling

The lowest frequency buckling mode, with a frequency of 2.05, is shown in Figure 9.

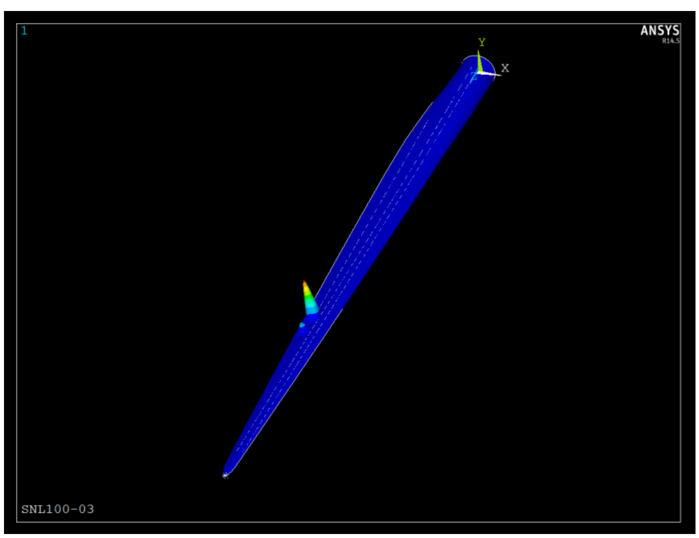


Figure 9. Lowest Frequency Buckling Mode for SNL100-03 in Aft Panel Outboard of Third Shear Web

SNL100-03 Geometry

As described in the prior section, a new geometry was designed for SNL100-03. In Table 3, the key external geometry information is summarized. Two views of the geometry are plotted in Figure 10.

Table 3. Blade Airfoil and Chord Properties for SNL100-03

Note: Thickness to chord ratio in parentheses for transition and modified outboard airfoils

Station Number	Blade Fraction	Chord (m)	Twist (deg)	Pitch Axis (Fraction)	Airfoil Description
1	0.000	4.500	11.130	0.500	Cylinder
2	0.005	4.505	11.130	0.500	Cylinder
3	0.007	4.508	11.130	0.500	Transition (99.25%)
4	0.009	4.510	11.130	0.500	Transition (98.5%)
5	0.011	4.512	11.130	0.500	Transition (97.75%)
6	0.013	4.515	11.130	0.500	Ellipse (97%)
7	0.024	4.551	11.130	0.499	Ellipse (93.1%)
8	0.026	4.560	11.130	0.498	Interpolated
9	0.047	4.656	11.130	0.483	Interpolated
10	0.068	4.779	11.130	0.468	Interpolated
11	0.089	4.901	11.130	0.453	Interpolated
12	0.095	4.933	11.130	0.448	Interpolated
13	0.102	4.970	11.130	0.443	Interpolated
14	0.114	5.034	11.130	0.435	FB-6300-1800
15	0.146	5.155	11.130	0.410	FB-5487-1216
16	0.163	5.193	11.130	0.400	Interpolated
17	0.179	5.222	11.130	0.390	Interpolated
18	0.195	5.226	10.837	0.380	FB-4286-0802
19	0.222	5.213	10.186	0.378	Interpolated
20	0.249	5.181	9.572	0.377	FB-3423-0596
21	0.276	5.124	9.006	0.375	Interpolated
22	0.358	4.883	7.504	0.375	Interpolated
23	0.439	4.576	6.240	0.375	FB-2700-0230
24	0.520	4.225	5.132	0.375	Interpolated
25	0.602	3.825	4.147	0.375	Interpolated
26	0.667	3.472	3.444	0.375	NACA-64-618 (19%)
27	0.683	3.380	3.280	0.375	Interpolated
28	0.732	3.099	2.804	0.375	NACA-64-618
29	0.764	2.900	2.502	0.375	NACA-64-618
30	0.846	2.357	1.783	0.375	NACA-64-618
31	0.894	2.019	1.382	0.375	NACA-64-618
32	0.943	1.653	0.987	0.375	NACA-64-618
33	0.957	1.542	0.874	0.375	NACA-64-618
34	0.972	1.420	0.756	0.375	NACA-64-618
35	0.986	1.183	0.551	0.375	NACA-64-618
36	1.000	0.500	0.000	0.375	NACA-64-618

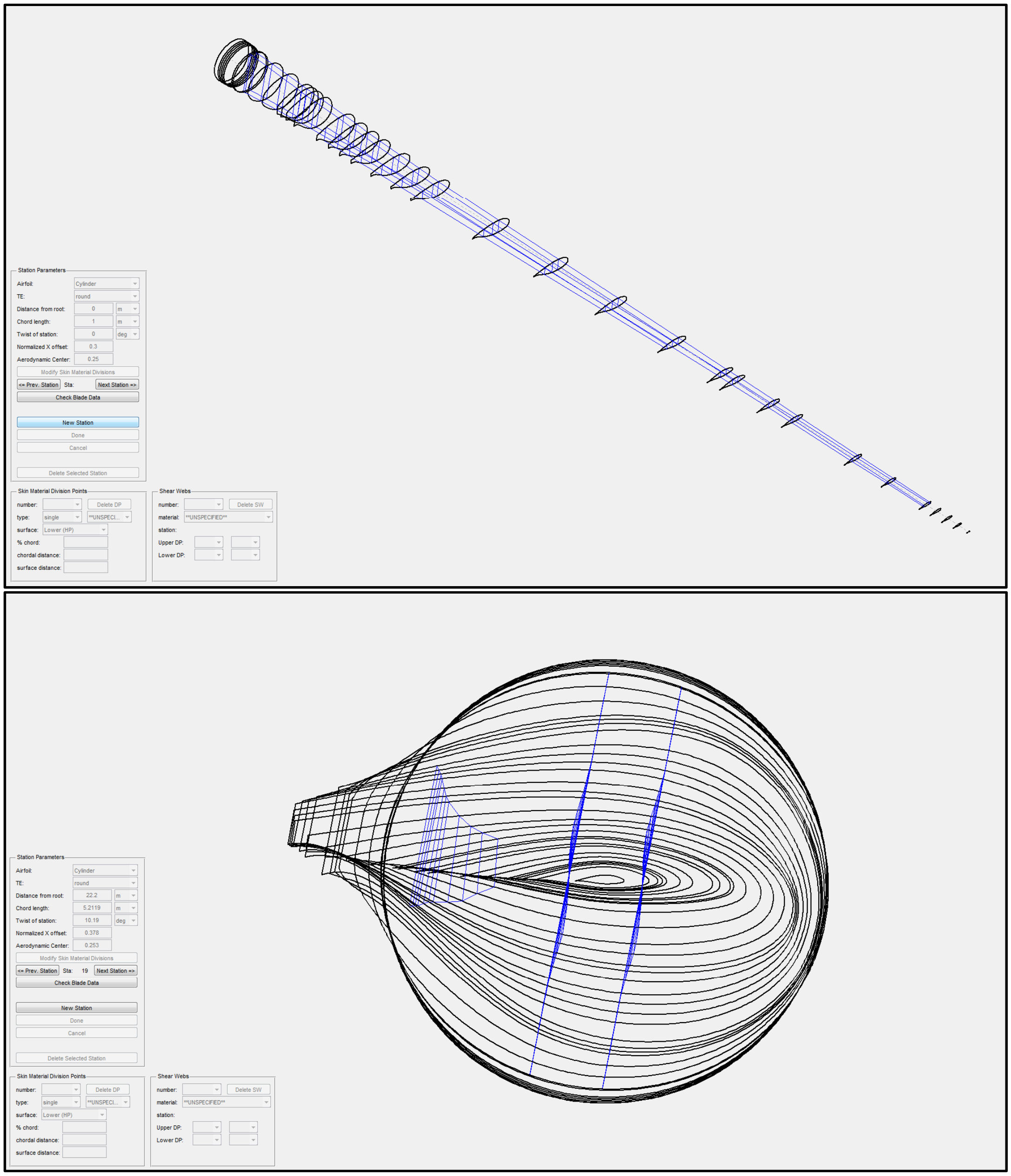


Figure 10. Two Views of the NuMAD Geometry for SNL100-03

SNL100-03 Materials

Table 4, Table 5, and Table 6 list the materials and their properties for the SNL100-03 design, which are unchanged from the earlier design studies. The densities for the glass laminates in Table 4 are 1920, 1780, and 1850 kg/m^3 for the uni-directional, double bias, and triaxial materials, respectively. Core material properties considered in these design studies are listed in Table 7. The modulus in the thickness direction and the shear moduli associated with the thickness direction were modeled as having the same values as noted in the table for both E and G for all core materials.

Table 4. Material Property Data Selected from DOE/MSU Database [20]

Laminate Definition			Longitudinal Direction								Shear
			Elastic Constants				Tension		Compression		
VARTM Fabric/resin	lay-up	V_F %	E_L GPa	E_T GPa	υ_{LT}	G_{LT} GPa	UTS_L MPa	ε_{max} %	UCS_L MPa	ε_{min} %	τ_{TU} MPa
E-LT-5500/EP-3	$[0]_2$	54	41.8	14.0	0.28	2.63	972	2.44	-702	-1.53	30
Saertex/EP-3	$[\pm 45]_4$	44	13.6	13.3	0.51	11.8	144	2.16	-213	-1.80	----
SNL Triax	$[\pm 45]_2[0]_2$	---	27.7	13.65	0.39	7.2	----	----	----	----	----

E_L – Longitudinal modulus, υ_{LT} – Poisson's ratio, G_{LT} and τ_{TU} – Shear modulus and ultimate shear stress. UTS_L – Ultimate longitudinal tensile strength, ε_{MAX} – Ultimate tensile strain, UCS_L – Ultimate longitudinal compressive strength. E_{MIN} – Ultimate compressive strain.

Table 5. 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

Table 6. Material Properties for Additional Materials

Material	E_L GPa	E_T GPa	G_{LT} GPa	υ_{LT}	Density (kg/m^3)
GelCoat	3.44	3.44	1.38	0.3	1235
Resin	3.5	3.5	1.4	0.3	1100

Table 7. Material Properties for Core Materials

Material	E_L MPa	E_T MPa	G_{LT} MPa	υ_{LT}	Density (kg/m^3)
Representative Balsa	50	50	175	--	155
Representative PET Foam	106	106	24	--	100

SNL100-03 Laminate Schedule

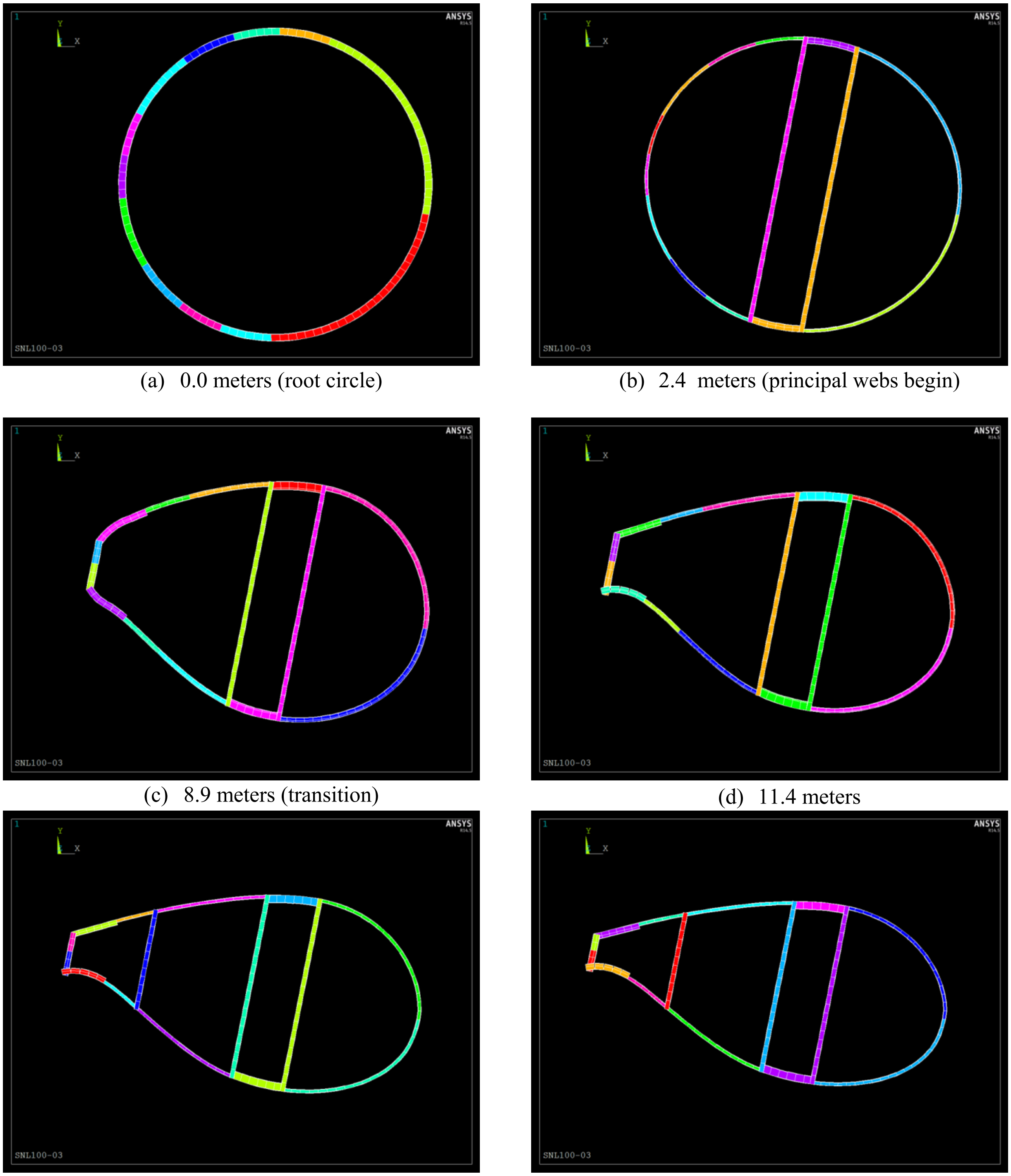
Table 8 shows the laminate schedule for SNL100-03. Note that in the trailing edge reinforcement ("TE Reinforcement") the glass uniaxial material and balsa are listed together as the glass uniaxial thickness is provided in the first number and the balsa thickness provided after the comma. Also note that the trailing edge aft panel is divided into inboard and outboard sections with balsa terminating and PET foam beginning at the 43.9 meter span location. This data is also provided in NuMAD.xlsx spreadsheet.

Table 8. Laminate Schedule for SNL100-03 (* indicates termination)

Station Number	Blade Span	Root Buildup	Spar Cap	TE Reinforcement	LE Panel	TE (Aft) Panel	
		Triax/EP-3	Carbon	E-LT-5500/EP-3, Balsa	PET Foam	Balsa Inboard	PET Foam Outboard
	(-)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
1	0.000	96					
2	0.005	77	3				
3	0.007	66	10				
4	0.009	55	20				
5	0.011	44	30				
6	0.013	39	40		1	1	
7	0.024	35	50		3.5	3.5	
8	0.026	31	60		13	10	
9	0.047	31	70		30	39	
10	0.068	31	80		40	39	
11	0.089	20	90	38, 33	40	39	
12	0.095	18.8	100	38, 33	40	39	
13	0.102	17.4	100	38, 33	40	39	
14	0.114	15	105	38, 33	40	39	
15	0.146	10	105	38, 33	40	39	
16	0.163	5	105	50, 33	40	39	
17	0.179	1	105	50, 33	40	39	
18	0.195	*	105	50, 33	40	39	
19	0.222		105	50, 33	40	39	
20	0.249		105	50, 33	40	35	
21	0.276		105	38, 33	40	35	
22	0.358		105	38, 30	40	35	
23	0.439		105	20, 20	40	*	32
24	0.521		105	10,10	40		32
25	0.602		105	0, 5	40		32
26	0.667		90	0, 5	40		32
27	0.683		80	0, 5	40		32
28	0.732		70	0, 5	40		32
29	0.765		60	0, 5	30		24
30	0.846		50	0, 5	15		12
31	0.895		40	0, 5	10		8
32	0.944		10	0, 5	5		4
33	0.957		10	0, 5	5		4
34	0.972		10	0, 5	5		4
35	0.986		10	0, 5	5		4
36	1.000		*	*	*		*

In addition to the detailed span-wise layup data in Table 8, the entire blade internal and external surfaces have 3 mm of triaxial material. Extra parasitic mass is included by modeling 2.5 mm of epoxy resin on the internal blade surface; this value was reduced from 3 mm in the SNL100-02 blade. The external surface includes 0.6 mm of gelcoat (surface paint), which was again unchanged. Again, the inclusion of extra epoxy resin and surface gelcoat are included to produce a more realistic blade design weight.

Cross sections are plotted for key stations along the span in Figure 11. The thickness representation is true scale for each of the shell elements about the station. The coloring is by section number. Note that the root section is composed of multiple sections in this model although the layup properties are the same for each section of the uniform root according to Table 8. A better understanding of these plots involves interpreting them with the detailed layup schedule from either Table 8 or the NuMAD spreadsheet as a reference aid.



(a) 0.0 meters (root circle)

(b) 2.4 meters (principal webs begin)

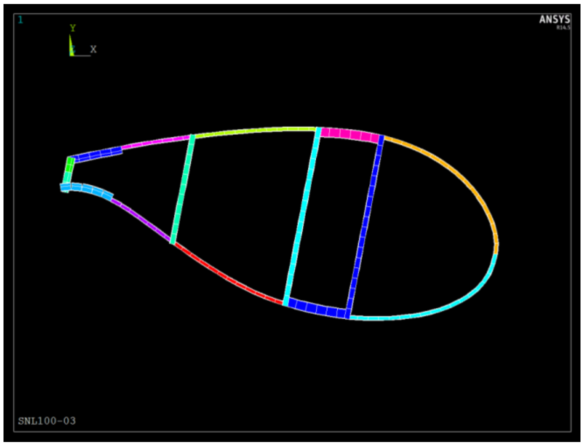
(c) 8.9 meters (transition)

(d) 11.4 meters

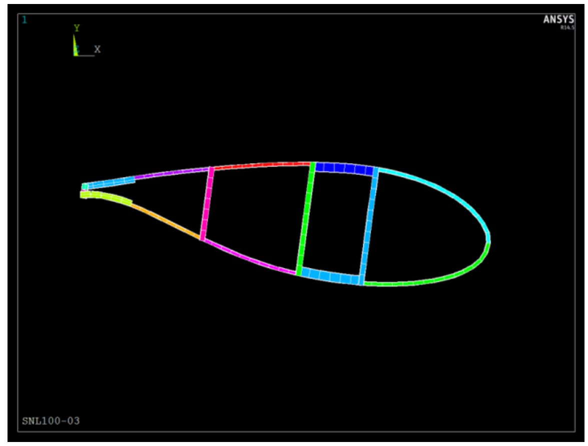
(e) 14.6 meters (third web begins)

(f) 16.3 meters

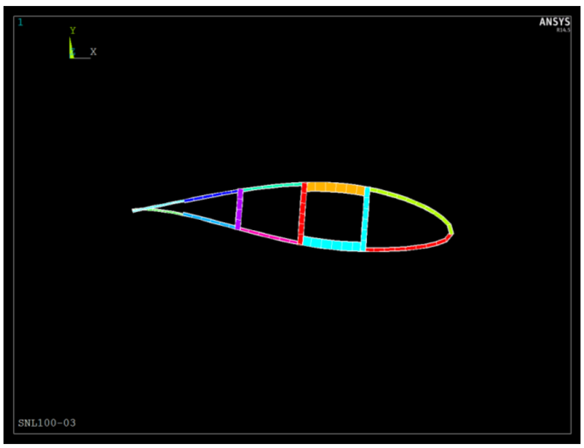
Figure 11. Selected Cross-section plots for SNL100-03



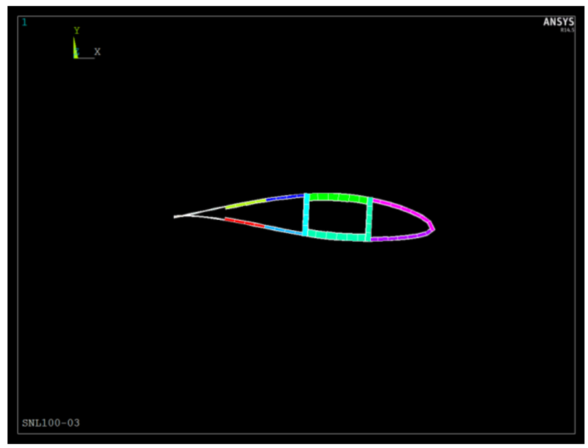
(g) 19.5 meters (maximum chord)



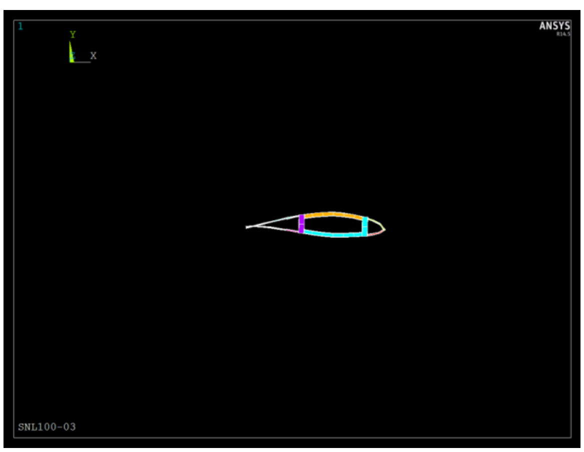
(h) 35.8 meters



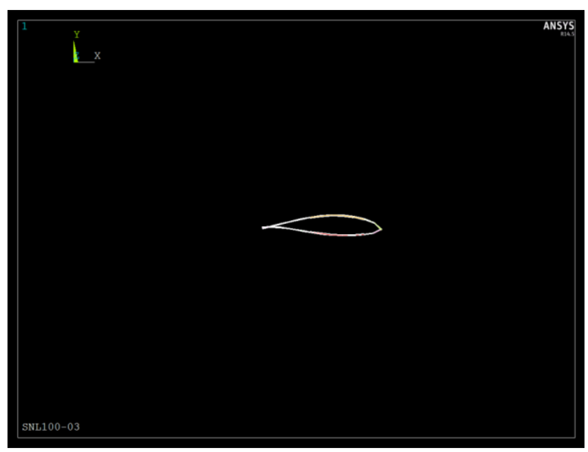
(i) 60.2 meters (third web ends)



(j) 73.2 meters



(k) 94.3 meters (principal webs end)



(l) 97.2 meters

Figure 11. Selected Cross-section plots for SNL100-03 (cont'd)

SNL100-03 Bill of Materials Analysis

For the six materials used in this design, listed above, their contribution to the total blade weight was calculated using PreComp [21]. Based on using the FAST code, the total blade weight is 49,519 kg. This analysis was performed for individual laminates and also the traditional bill of materials summary. The bill of materials summary is provided first in Table 9. Here quantities of dry fibers and resin are computed separately, with the exception of the carbon prepreg material. The resin weight includes only the infused resin, which includes the parasitic resin, but not the resin in the prepreg. The most notable changes from the SNL100-02 are the reduction in core materials and the increase in carbon fiber usage. These changes are the result of the more slender planform with reduced absolute thickness of the blade in the flatback direction. The results are less core material need due to the improved buckling resistance with smaller panel sizes and increased spar material need with the reduced absolute blade thickness.

Table 9. Bill of Materials for SNL100-03

Material	Description	Mass (kg)	Percent Blade Mass
E-LT-5500	Uni-directional Fiberglass	7,691	15.5%
Saertex	Double Bias Fiberglass	5,641	11.4%
Carbon Prepreg	Conceptual Laminate	14,906	30.1%
EP-3	Infused Resin	16,152	32.6%
Balsa	Balsa Core	1,229	2.5%
PET Foam	Foam Core	3,229	6.5%
Gelcoat	Coating	652	1.3%

Table 10 provides an analysis of the laminate usage in the design along with total mass and percentage of total blade mass. This provides an assessment of material usage in the various blade components. The table shows that 9.5% of the blade weight is composed of uni-directional glass laminates used in trailing edge reinforcement, which is a significant increase from trailing edge uni-axial glass in SNL100-02. The carbon spar caps are 30.1% of the blade weight (up from 17.1% of the total for SNL100-02). The largest contributor to blade weight is the triaxial laminates in the root buildup and skins with 38.5% of the blade weight. The extra (parasitic) resin accounts for 2,421kg of the blade weight while the gelcoat accounts for 625 kg. In total, the inclusion of extra resin and gelcoat comprise 7.9% of the total blade weight.

Table 10. Materials Usage Summary for SNL100-03

Material	Usage/Location	Mass (kg)	Percent Blade Mass
E-LT-5500/EP-3	Trailing edge	4,709	9.5%
Carbon Prepreg	Spar cap	14,906	30.1%
SNL Triax/EP-3	Root build-up, internal & external surfaces	19,067	38.5%
Balsa	Core panels	1,229	2.5%
PET Foam	Core panels, shear webs	3,229	6.5%
Resin (parasitic)	Extra weight (interior surface)	2,421	4.9%
Saertex/EP-3	Shear webs	3,287	6.6%
Gelcoat	Coating	652	1.3%

It can be noted that if SNL100-03 had been based on the less slender “Rev2” geometry, it should be expected that more core material would be needed with less need for carbon in the spar and glass in the trailing edge. It would be likely the design would be somewhat heavier, but more cost-effective with the expected bill of materials. This should be part of future work to optimize this design for cost and weight.

SNL100-03 Span-wise Properties

Blade span-wise properties were calculated using PreComp [21] as implemented within the NuMAD v2.0 Matlab-based graphical user interface. Table 11 lists the blade span-wise properties including flap- and edge-wise EI, EA, GJ, and mass distributions. Additional span-wise information (e.g. airfoil and chord schedules) can be found above or in the file package for SN100-03. The data in Table 11 is also found in the FAST blade input file as described in Table 15.

Table 11. SNL100-03 Span-wise Blade Properties

Station Number	Span Fraction	mass_den	flp_stff	edge_stff	tor_stff	axial_stff	flp_iner	edge_iner
(-)	(-)	(kg/m)	(N-m^2)	(N-m^2)	(N)	(N-m^2)	(kg-m)	(kg-m)
1	0	2732	9.90E+10	9.76E+10	5.10E+10	4.03E+10	6706	6614
2	0.005	2241	8.42E+10	8.06E+10	4.22E+10	3.34E+10	5574	5473
3	0.007	1958	7.86E+10	7.00E+10	3.67E+10	3.02E+10	4860	4768
4	0.009	1682	7.55E+10	5.96E+10	3.14E+10	2.75E+10	4189	4064
5	0.011	1408	7.24E+10	4.90E+10	2.59E+10	2.49E+10	3531	3356
6	0.013	1293	7.47E+10	4.42E+10	2.34E+10	2.46E+10	3255	3030
7	0.024	1337	7.49E+10	4.04E+10	2.07E+10	2.53E+10	3101	2786
8	0.026	1266	7.90E+10	3.70E+10	1.90E+10	2.55E+10	2986	2579
9	0.047	1281	7.55E+10	3.72E+10	1.76E+10	2.70E+10	2720	2626
10	0.068	1278	6.84E+10	3.79E+10	1.66E+10	2.84E+10	2304	2675
11	0.089	1191	5.82E+10	4.78E+10	1.10E+10	2.97E+10	1656	2870
12	0.095	1180	5.94E+10	4.73E+10	1.01E+10	3.11E+10	1589	2814
13	0.102	1161	5.65E+10	4.56E+10	8.90E+09	3.08E+10	1519	2695
14	0.114	1069	5.18E+10	4.46E+10	7.62E+09	3.01E+10	1269	2587
15	0.146	692.4	3.56E+10	2.89E+10	2.07E+09	2.41E+10	649.2	1531
16	0.163	709.6	3.00E+10	3.36E+10	1.77E+09	2.46E+10	541.9	1651
17	0.179	691.3	2.54E+10	3.34E+10	1.52E+09	2.44E+10	454.8	1623
18	0.195	680.3	2.19E+10	3.39E+10	1.34E+09	2.43E+10	390.8	1617
19	0.222	651.9	1.64E+10	3.19E+10	1.02E+09	2.39E+10	288.7	1516
20	0.249	634.3	1.33E+10	3.10E+10	8.41E+08	2.38E+10	231	1455
21	0.276	585.1	1.14E+10	2.45E+10	7.06E+08	2.29E+10	194.6	1233
22	0.358	553.1	8.09E+09	2.06E+10	4.82E+08	2.25E+10	134.7	1026
23	0.439	469.4	5.96E+09	1.15E+10	3.17E+08	2.12E+10	95	642.6
24	0.52	413.8	3.75E+09	6.54E+09	1.79E+08	2.04E+10	57.57	395.3
25	0.602	361.3	2.15E+09	2.94E+09	8.93E+07	1.96E+10	31.81	206.0
26	0.667	307.5	1.23E+09	2.25E+09	5.42E+07	1.69E+10	18.14	147.7
27	0.683	284.9	1.03E+09	2.06E+09	4.86E+07	1.52E+10	15.4	136.1
28	0.732	253	6.93E+08	1.64E+09	3.46E+07	1.33E+10	10.46	104.5
29	0.764	223.1	5.30E+08	1.37E+09	2.95E+07	1.15E+10	8.139	83.86
30	0.846	179	2.79E+08	8.78E+08	1.69E+07	9.55E+09	4.219	45.45
31	0.894	146.7	1.61E+08	6.22E+08	1.11E+07	7.70E+09	2.466	29.22
32	0.943	76.87	3.41E+07	2.45E+08	6.13E+06	2.37E+09	0.801	14.68
33	0.957	64.79	2.73E+07	1.95E+08	4.93E+06	2.18E+09	0.62	10.98
34	0.972	59.63	2.10E+07	1.52E+08	3.79E+06	2.01E+09	0.476	8.553
35	0.986	49.72	1.18E+07	8.78E+07	2.12E+06	1.67E+09	0.267	4.952
36	1	20.99	6.80E+05	6.54E+06	1.19E+05	7.06E+08	0.015	0.369

4. SANDIA LARGE ROTOR DESIGN SCORECARD (SNL100-03)

Design scorecard summary for SNL100-03 100-meter blade. Significant design changes from the SNL100-02 blade (see report SAND2013-10162) include: (1) change from conventional sharp trailing edge airfoils to flatback airfoils, (2) redesign of chord/twist with significantly reduced blade chord, (3) reductions in triaxial material usage and parasitic resin, and (4) less core material and more carbon spar material.

Table 12. Design Scorecard: Blade Parameters

Parameter	Value
Blade Designation (name)	SNL100-03
Design Wind Speed Class	IB
Blade Length (m)	100
Blade Weight (kg)	49,519
Span-wise CG location (m)	31.55
# shear webs	3
Maximum chord (m)	5.226 (19.5% span)
Lowest fixed base natural frequency (Hz)	0.49 Hz (NuMAD/ANSYS)
Control	Variable speed; collective pitch
Special notes:	Updated design with flatback airfoils and highly slender planform; Started with SNL100-02 blade (includes new core material strategy and carbon spar); 4.9% of blade weight is parasitic/extra weight (resin)

Table 13. Design Scorecard: Blade Design Performance Metrics Summary

Analysis	Design Load Condition (DLC) designation	Metrics	Notes/method
Fatigue	Turbulent Inflow (NTM) (4 to 24 m/s)	590 years fatigue life at 15% span in spar *21 years fatigue life at 50% span in spar* *77 years fatigue life at 15% span in TE* 206 years fatigue life at 50% span in TE	MSU/DOE Database provided single cycle failure values and GL was referenced for slope values (10 for glass and 14 for carbon); Miner's Rule calculation
Ultimate	EWM50; 0 degree pitch with 5 degree yaw error	Max strain = 3552 micro-strain Allowable strain = 5139 micro-strain Max/allowable = 69.1%	At 24.3% span (near root); flap-wise; FAST
Deflection	ECD-R	Max (13.11 m) vs. allowable (13.67 m); Clearance = 0.56 m = 4.1%	FAST, NuMAD/ANSYS
Buckling	EWM50; 0 degree pitch	Min load factor (2.05) vs. allowable (2.042); Aft panel buckling outboard of 3rd shear web	Linear, ANSYS
Flutter	--	Flutter margin 1.40 (@ 10.44 RPM)	Sandia NuMAD-based Flutter Tool (BLAST); updated tool since SNL100-00 calculations

Table 14. Design Scorecard: Blade Design Bill of Materials

Material	Description	Mass (kg)	Percent Blade Mass
E-LT-5500	Uni-directional Fiberglass	7,691	15.5%
Saertex	Double Bias Fiberglass	5,641	11.4%
Carbon Prepreg	Conceptual Laminate	14,906	30.1%
EP-3	Infused Resin	16,152	32.6%
Balsa	Balsa Core	1,229	2.5%
PET Foam	Foam Core	3,229	6.5%
Gelcoat	Coating	652	1.3%

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5. DESCRIPTION OF ARCHIVED BLADE MODEL FILES FOR SNL100-03

The blade model file package for SNL100-03 includes both the NuMAD [11, 12] blade design files and input files for ANSYS [22] generated by NuMAD. The blade was designed using NuMAD (version 2.0) and analyzed using ANSYS (version 14.5). Table 15 provides a summary of the available model files. Please note that the *.mac files, which are distributed with NuMAD, are also included in this blade file package for convenience as they are needed when reading the *.src files into ANSYS.

Table 15. SNL100-03 Blade Model Files Summary

Filename	Usage	Description
NuMAD.xlsx	Primary input file for Matlab-based NuMAD Code (NuMAD v2.0)	Spreadsheet blade model data including detailed blade geometry, materials, and layup information
SNL100-03.nmd	NuMAD model file	Produced using NuMAD v2.0 with input from NuMAD.xlsx spreadsheet
MatDBsi.txt	NuMAD materials database	Contains material/laminate property information
SNL100-03_FASTBlade_precomp.dat	Can be used with SNL13.2MW FAST turbine model for aeroelastic simulations and design loads analysis	FAST blade file for SNL100-03; Produced using NuMAD v2.0
"airfoils" folder	NuMAD airfoil geometry coordinates	Contains a set of files with coordinates for blade cross section geometries
"docs" folder	documentation	Contains associated documents including most of the references to this report
SNL100-03.src	NuMAD output file; ANSYS model input file	Text file formatted for input to ANSYS to generate a finite element model
master.db	ANSYS database file	Created using SNL100-03.src input to ANSYS
SNL100-03.p3d	Blade external geometry file	Plot 3D file format

The NuMAD input files are useful to investigate blade re-design efforts (e.g. changes in material selection and placement or changes in geometry). NuMAD can produce two types of input files for ANSYS, which include the text input file (*.src) and the ANSYS database file (*.db). A complete set of files for NuMAD and ANSYS is included so that the blade data can be verified by reproduction and also so that modified design solutions can be compared with the provided SNL100-03 design.

The provided files should provide multiple paths for verification of blade model data. For example, SNL100-03.src can be read directly into ANSYS to produce the SNL100-03 finite element model (e.g. "/input, SNL100-03, src").

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6. SUMMARY OF MAJOR FINDINGS OF THE SANDIA 100-METER BLADE DEVELOPMENT PROJECT

Major Findings and Outcomes

The major findings and outcomes of Sandia 100-meter blade development project are summarized here. These findings cover the five-year timeframe of this research program from the initial baseline blade (SNL100-00) to the current design study (SNL100-03).

1. **Identification of large blade design drivers (SNL100-00):** Buckling, gravitational loading and edge-wise fatigue life, flutter and blade tip deflection were identified as key design drivers for large blades in the all-glass baseline blade (SNL100-00) design study [4]. Subsequent work, as summarized in the following points, included blade design studies and tool development to mitigate the trends in these design drivers.

2. **Public domain large blade and turbine reference models:** Four blade design studies were performed starting with the all-glass baseline (SNL100-00) and concluding with the current study (SNL100-03) as documented in References 4, 5, 6, 16 and the present study. These four blade design models were made available to other researchers along with a 13.2 MW turbine reference model (Reference 15). These models have been utilized and referenced extensively by other researchers demonstrating value to the research community in this open source approach.

3. **Blade manufacturing cost model and analysis:** In order to address manufacturing issues and costs for large blades, a blade manufacturing cost model was also developed (References 7 and 8). The model was used to perform trend analysis including analysis of blade labor operation costs with blade length and analysis of materials, labor, and capital equipment trends with blade length. This model was also made publicly available, and is currently being integrated into the SNL NuMAD blade design software [12] for use in blade design optimization and manufacturing cost analysis.

4. **Large blade flutter analysis and flutter tool development:** Aeroelastic instability (flutter) potential was examined for large blades (References 4) including parametric design studies for flutter speed (Reference 23) and flutter tool development (Reference 24).

5. **Carbon design studies (SNL100-01):** Design considerations for a switch from glass to carbon spar caps were examined in Reference 5 and cost comparisons & cost targets were examined in Reference 25. This study provided baseline values for weight reduction potential as well as price targets for cost-effective carbon usage in comparison to glass.

6. **Advanced core materials and core strategy (SNL100-02):** Starting with an industry survey of core materials, various foams, balsa, and structured (engineered) core were evaluated along with a new core material strategy in a series of structural design studies. The new strategy utilized balsa in critical buckling areas and PET foam in the non-critical buckling areas. In addition to the weight reduction achieved, a secondary benefit was found in that these core materials are regrowable (in the case of balsa) and recyclable (in the case of PET foam).

7. **Flatback airfoils with aero-structural design procedures (SNL100-03):** Sharp trailing edge airfoils were replaced with flatback airfoils. A new combined aerodynamic-structural design process was utilized to design the blade external geometry. The major results, including further weight reduction and a summary of advantages and disadvantages of higher blade slenderness, are described in Reference 16 and the present report.

Large Blade Technology Needs and Research Opportunities

Several large blade technology needs have been identified in this research program that are needed to achieve a future large, lightweight, cost-effective, aeroelastically stable, and manufacturable blade. This list builds upon the technology needs documented previously in References 4 and 2.

1. **Materials:** Development is needed in new materials such as carbon, advanced core, and high-modulus glass that are tailored for cost-effective usage in large blades. In addition, design and manufacturing research for more cost-effective usage of new materials is needed. The SNL100-01 and SNL100-02 design studies contribute cases studies on the pros and cons of carbon and advanced core, respectively, and provide reference designs for material trade-off studies and comparisons (e.g. evaluation of a new carbon laminate using the SNL100-01 or SNL100-02 blade as a reference).

2. **Airfoils, Geometry, and Aero-structural Design Procedures:** New airfoil development is needed to address the evolving design requirements for large blades, which puts pressure on structural and aerodynamic factors. In addition, design procedures that incorporate both structural and aerodynamic design considerations, such as that used in the present work, are needed to systematically optimize designs for performance and cost. A thorough understanding of high Reynolds number effects; usage of higher thickness airfoil outboard are needed.

3. **Turbine and Rotor Design Codes; Aeroelastic Stability Code Validation:** Special issues such as spatial variation of inflow conditions across large rotors need to be considered in design codes and evaluated in design loads analysis to ensure designs meet design life requirements. In addition, codes for prediction of aeroelastic stability should be validated with experimental data.

4. **Transportation and Logistics of Large Blades:** Research and development of special transportation methods and methods for blade segmentation and blade joining are needed.

5. **Manufacturing Innovation for Large Blades:** Several important manufacturing considerations were identified and include automated finishing operations to mitigate growing labor content in surface-area driven labor operations, infusibility of very thick laminates in large blades, quality of material layup to avoid defects and minimize losses due to high scrap rates, and inspection of thick laminates in large blades.

6. **Active and Passive Controls:** Research in rotor controls are needed to investigate the effects of both active (e.g. trailing edge flaps) or passive (e.g. bend-twist coupling or sweep) controls on improving blade performance, stability, and economics.

7. CONCLUDING REMARKS

This report presents design studies for a 100-meter wind turbine blade using flatback airfoils, termed SNL100-03. In the pre-design work, the effects of varying the blade slenderness on blade structural performance were investigated. The advantages and disadvantages of blade slenderness with respect to tip deflection, flap-wise & edge-wise fatigue resistance, panel buckling capacity, flutter speed, manufacturing labor content, blade total weight, and aerodynamic design load magnitude were quantified. The design weight for the final SNL100-03 blade is 49.5 tons. When comparing to other conceptual and commercial designs, SNL100-03 has a favorable mass scaling factor (exponent) of less than 2.2, which is considered a highly innovative weight. The SNL100-00 all-glass baseline blade yielded a mass scaling factor of over 3.0 while the SNL100-01 carbon blade was just under 3.0. The SNL100-02 blade was located just under a scaling exponent of 2.5 (i.e. moderate innovation). These demonstrate a weight reduction pathway through this series of Sandia 100-meter blade designs.

A summary of the major findings and outcomes of the Sandia 100-meter blade project has also been presented. The Sandia 100-meter blade (SNL100-XX) series of design studies started with a conventional all-glass material baseline (SNL100-00), then investigated a carbon spar blade (SNL100-01), followed by an advanced core materials design (SNL100-02), and concluded in the present study with a design using flatback airfoils (SNL100-03). In summary, the major findings include weight reduction opportunities and mitigation of technical challenges such as gravitational fatigue loading, panel buckling, and aeroelastic stability through design studies and tool development. Weight reduction led to reduction in gravitational loadings that improved edge-wise fatigue resistance and led to subsequent (secondary) weight reduction through reductions in trailing edge reinforcements (as exemplified in the SNL100-01 and SNL100-02 studies). Panel buckling was mitigated via new materials (balsa and PET foam) and a new core strategy in the SNL100-02 study. Further improvement in panel buckling was found via new geometry/airfoils with a more slender planform (in the SNL100-03 study). In addition, the current design study for SNL100-03 provided insight into the advantages and disadvantages of slender blade planform by quantifying blade structural performance (e.g. buckling, fatigue, deflection, surface area) for various levels of slenderness.

Aeroelastic instability (flutter) was found to be above the operating range for all designs; however, the flutter margin was found to be diminishing as blade weight was reduced and as blade flexibility increased in this series of design studies; therefore, it is recommended that aero-elastic stability continue to be addressed in design work and tool development. Legacy Sandia flutter tools were evaluated in this study and a revised flutter tool was developed in a companion study with an improved structural representation and improved computational approach. Another outcome of this research program was development of a blade manufacturing cost model to address manufacturing cost trends (most notably in materials and labor content) and to estimate blade costs. The manufacturing cost model was also made publicly available.

As was the case with the prior SNL100-XX series designs, SNL100-03 can be used as a reference blade for both performance and cost studies. While this study focused on structural performance and weight reduction, future work could use this reference design as a basis for blade cost studies and evaluation of the performance, weight and cost impacts of carbon usage, alternative core materials, new airfoils, and other new concepts. The SNL100-03 design is a 16% reduction in weight from the most recent SNL100-02 design and over 56% reduction in weight from the initial SNL100-00 baseline. In terms of material usage, about 30% of the SNL100-03 blade weight is carbon. One concern for highly slender blade designs, such as SNL100-03, is the ability to sufficiently stiffen the blade, which requires more materials usage (e.g. in the case of SNL100-03, more carbon in the spar caps). The optimal usage of materials through systematic optimization of the geometry and materials layup was not part of this study; however, these results indicate key trends and opportunities that should be the focus of such design processes in order to achieve a future large, lightweight, cost-effective, aeroelastically stable, and manufacturable blade.

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