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Large Offshore Rotor Development: Design and Analysis of 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. Recent work has focused on the development of a 100-meter blade for a 13.2 MW horizontal axis wind turbine, a blade that is significantly longer than the largest commercial blades of today (approximately 60 meters long). This paper summarizes the design development of the Sandia 100-meter All-glass Baseline Wind Turbine Blade, termed as "SNL100-00", which employs conventional architecture and fiberglass-only composite materials. The paper provides a summary of performance margins from a series of analyses that demonstrate changes in various design drivers for large blade technology. Recommendations for improvements to large blade design and future research investment needs are discussed.

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. Earlier WindPACT studies investigated and evaluated design, materials and manufacturing issues for large wind turbine blades and rotors that resulted in design specifications and preliminary designs for candidate blades in the range of 30 to 70 meters in length[1,2] and rotors in the range of 80 to 120 meters in diameter[2,3]. 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.

The focus of the work reported here is the development of even larger blades than the earlier studies in design of a 100-meter all-glass baseline blade design model. An important aspect of this work is that a set of certification analyses are performed to ensure that the design is acceptable with respect to loads from internationally accepted blade design standards. A detailed design for this model, termed as the "SNL100-00" design, is provided in Reference 4. This paper summarizes this baseline 100-meter blade design including a description of the design iterations, the final design parameters, and performance margins & trends for the primary design drivers (e.g. buckling margin, fatigue life, etc.)

The development of SNL100-00 began with studies of 5 MW turbine models (with 61.5 meter blades) that were publicly available at the onset of the project. Geometric scaling of the available blade and turbine models was performed to produce aeroelastic turbine models with 100-meter blades. These models were then analyzed to study the effects of scale for large blades, identify trends and to verify traditional scaling laws. Based on these preliminary analyses, a series of composite layups with various shear web configurations were developed and analyzed. Both high-fidelity and simplified blade models were analyzed. High-fidelity blade models were developed to perform buckling analysis and to support re-design efforts to satisfy buckling requirements. Simplified blade models were created and included in the complete turbine aeroelastic model to compute maximum strains and maximum tip deflections under operating inflow conditions. The simplified model was also used to assess the fatigue life. Several iterations through the design process were required to arrive at the final blade design, which is designated as the "Sandia 100-meter All-glass Baseline Blade: SNL100-00" [Ref. 4].

In this paper, the detailed blade geometry, composite layup and materials are summarized. Analyses of the baseline model for design loads from international standards are presented to demonstrate acceptance of the design

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with respect to strength, fatigue, deflection, and buckling considerations. Results of a flutter calculation are also presented. A summary of the design information and performance margins are provided in a "design scorecard" format that summarizes the most important blade specifications, the performance margins, and the bill of materials. The SNL100-00 blade model and associated 13.2 MW turbine model have been made publicly available to other researchers. The hope is that this model will serve as a platform for evaluating a variety of modern innovations and design tools with the potential to enable cost-effective, large turbine designs of 13.2 MW and beyond.

II. Prior Large Turbine Work and Initial 100-meter Blade Design Developments

The initial work focused on development of preliminary structural models for a 100-meter blade and an associated 13.2 MW turbine. These models were needed, of course, to perform structural analysis for evaluating design trade-offs. As it was desired to have the most realistic structural model in the initial phases of the 100-meter blade development, existing large blade and turbine models were utilized as much as possible. Technical data from manufacturers is, of course, very limited. However, distributed structural model properties from studies of large turbines and blades were available from previous independent, "public" studies. These studies focused on turbines with ratings of 5-6 MW and blade lengths in the range of 61.5 to 64.5 meters.

The earliest study was the DOWEC (Dutch Offshore Wind Energy Converter) study[5,6]. The DOWEC reports provided blade data including span-wise structural properties as well as external geometry information such as the airfoil, chord length and twist schedules. However, no detailed composite layup data was made available. More recent large blade/turbine studies, which reference the DOWEC studies, include the UpWind Project[7] and DOE/NREL work[8,9]. The UpWind project included a wide variety of large blade and turbine research efforts; however, most relevant to development of SNL100-00 is a composite layup concept that was developed within UpWind. NREL developed a 5 MW turbine reference model that has been widely used by the wind energy research community. The NREL 5 MW turbine model was useful for upscaling of the turbine components and for adaptation of its controller to 13.2 MW scale. The NREL 5 MW blade properties were adopted from the DOWEC study. Although these models did not provide all of the information needed for the SNL100-00 design development, they did provide an approximately 60-meter layup concept (UpWind), a few span-wise airfoil definitions and span-wise blade properties (DOWEC), and 5 MW turbine and controller models (NREL). A more detailed summary of these previously published models, which document blade and turbine model properties, is provided in Reference 4.

Initially, blade scaling studies were performed using the publicly available blade and turbine data. Scaling laws can be used to extrapolate existing model properties to larger turbine sizes. These include; for example, span-wise stiffness properties for the simple blade models from DOWEC and NREL or thicknesses of the UpWind layup. Also, scaling laws were evaluated and developed to predict the effect of blade length on design trends such as root bending moments and natural frequencies. The approach adopted here involved conventional scaling of turbine and blade properties whereby geometric similarity, material similarity and constant tip speed ratio are assumed when upscaling the length dependent variables.

A few of the scaling equations considered in the work are now presented. A scale factor, α, is defined as the ratio of the scaled blade length (L_U) to the nominal blade length (L_B):

$$\alpha = \frac{Scaled\ Length}{Nominal\ Length} = \frac{L_U}{L_B} \tag{1}$$

where "U" refers to the up-scaled blade and "B" refers the nominal blade. Alternatively, the scale factor can be defined as the ratio of the scaled rotor radius to the nominal rotor radius.

The total blade mass follows this relationship:

$$m_U = \alpha^3 m_B \tag{2}$$

and the rotor power:

$$P_U = \alpha^2 P_B \tag{3}$$

We now consider bending moments due to aerodynamic loads:

$$M_U^{Aero} = \alpha^3 M_B^{Aero} \tag{4}$$

And, root bending moments due to gravitational loads:

$$M_U^{Gravity} = \alpha^4 M_B^{Gravity} \tag{5}$$

In examining one scaling result in more detail, it can be seen from Equations 4 and 5 that root bending moments due to gravitational loads scale at a faster rate than aerodynamic loads. For blades on today's machines, aerodynamic loads are typically much larger than gravitational loads. Thus, root bending moments due to aerodynamic loads have been a principal design driver especially in the flap-wise direction. However, it is clear that as blade length increases, root bending moments (and bending moments in general) due to gravitational loads will eventually grow to exceed moments due to aerodynamic loads. Gravity loads are primarily resisted in the edge-wise (lead-lag) direction. As a result; for example, much larger gravity loading will require additional reinforcement and design adjustments in the edge-wise direction. The bending moment relations can be re-written in terms of stress or strain. Observing these trends is important for strength and fatigue calculations, and demonstrates one important change in the design approach with consideration of growing edge-wise strains due to growing gravitational loads for larger blades.

Table 1 lists some of the general rotor and blade parameters for the upscaled models, based on the NREL 5 MW model. Note that the blade mass and span-wise CG location increase with blade length; together these result in growth of the root bending moment due to gravitational loads to the 4^{th} power (Note Equation 5). Also note that the maximum operating speed is reduced with blade length to maintain the same velocity field over the blade span.

Table 1. Selected Upscaled Rotor Properties

Machine Size	Rotor Diameter (m)	Blade Length (m)	Blade CG Location (m)	Blade Mass (kg)	Max Operating Speed (RPM)
5 MW	126	61.5	20.5	17740	12.1
10 MW	178.2	87.0	29.0	50184	8.56
13.2 MW	205	100.0	33.4	76402	7.44
15 MW	218.2	106.5	35.6	92131	6.99

In addition to upscaling of publically available models, an initial "targeted layup" was created to match the upscaled span-wise stiffness properties and then assess the performance of this design under loads. The external geometry of the targeted layup was based on scaling of the DOWEC geometry. A cross-sectional analysis code, PreComp (Ref. 10), was used to compute the flap-wise and edge-wise bending stiffnesses for various laminate thickness sizings to closely match the DOWEC/NREL blade properties. While matching these properties, constraints were imposed on the layup including considerations for shear web placement and ply drops to ensure that the layup was realistic with respect to traditional blade manufacturing considerations. After performing the calculations, it was found that it is possible to design an all-glass layup for a 100-meter blade with realistic manufacturing considerations and blade weight to match the scaled-up bending stiffnesses. Although this targeted layup design was not evaluated for strength or for buckling resistance of the two shear web design (as shown in Figure 1), it was found to be useful for preliminary laminate sizing of the SNL100-00 design.

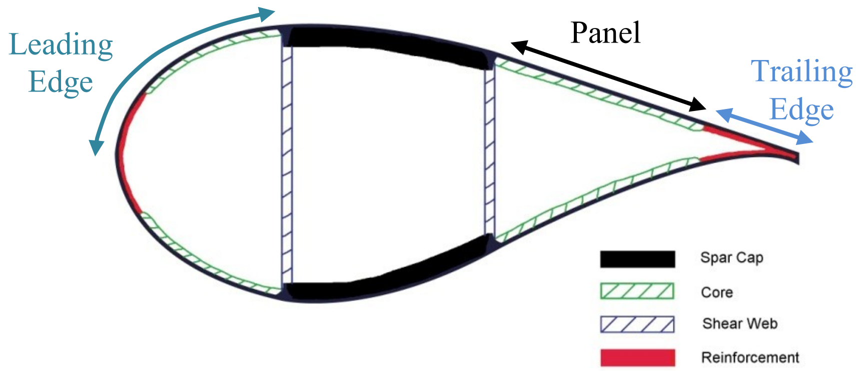


Figure 1. Representative Airfoil Cross Section with Two Shear Webs

III. Preliminary Analysis: Upscaled Models and Load Case Selection

The analysis performed to evaluate the 13.2 MW turbine models upscaled from the 5 MW baseline model of the NREL/DOWEC turbine is summarized. The subset of IEC design load conditions[11] considered as bounding cases is listed in Table 2. Germanischer Lloyd (GL)[12] was referenced to determine partial safety factors for materials and loads along with the combined partial safety factors used to evaluate (1) ultimate strength, (2) tip deflection, (3) fatigue, and (4) bucking stability. Full system dynamics calculations using FAST[9] were performed to determine strains and deflections due to design load conditions for the upscaled full-turbine models (13.2 MW) based on the NREL/DOWEC blade (and the UpWind blade in Ref. 4). These results were then used to guide the design of SNL100-00. More details regarding the analyses, loads, and safety factors can be found in Reference 4.

A. Load Cases and Partial Safety Factors for Analysis

A Class IB site was chosen for siting of the turbine, which is considered to be a conservative choice with potential for offshore siting. The program IECWind[13] was used to generate the transient wind condition files needed for the FAST calculations. The wind conditions selected include extreme conditions for both operating and parked rotors.

Table 2. IEC Design Load Cases for Ultimate Strength and Deflection Analysis

Wind Condition	Description	IEC DLC Number	Design Situation (Normal or Abnormal)
ETM (Vin < Vhub < Vout)	Extreme Turbulence Model	1.3	Power Production (N)
ECD (Vhub = Vr +/- 2 m/s)	Extreme Coherent Gust with Direction Change	1.4	Power Production (N)
EWS (Vin < Vhub < Vout)	Extreme Wind Shear	1.5	Power Production (N)
EOG (Vhub = Vr +/- 2 m/s)	Extreme Operating Gust	3.2	Start up (N)
EDC (Vhub = Vr +/- 2 m/s)	Extreme Wind Direction Change	3.3	Start up (N)
EWM (50-year occurrence)	Extreme Wind Speed Model	6.2	Parked (A)
EWM (1-year occurrence)	Extreme Wind Speed Model	6.3	Parked (N)

B. 13.2 MW Turbine Analysis (with NREL 5 MW Blade as Baseline)

Aeroelastic simulations were performed using FAST for the NREL 5 MW turbine model and a 13.2 MW upscaled version of that model. One selected result from these calculations is shown in Table 3. Here, it can be seen that the root flap-wise strains are similar for both the 5 MW and 13.2 MW sized machines. This is expected from scaling laws presented earlier (based on Equation 4). However, edge-wise strains grow for the operating cases (ECD+R and NWPR) for the longer blade length at a rate slightly higher than the expected linear growth rate (based on Equation 5). The results in Table 3 also demonstrate the difference in the effect of scale for operating versus non-operating cases as the strains are nearly unchanged from 5 to 13.2 MW for the parked EWM50 case, while the strains grow for the operating ECD+R and NWPR case with larger gravitational loads. Although strains were small with respect to allowable strains, these simulations confirm scaling law indications of the potential need for additional edge-wise reinforcement as blade length increases beyond 61.5 meters.

Table 3. 13.2 MW (with NREL/DOWEC 5 MW Baseline) Peak Strains at the Root (0% span)

Machine	Load Case	Flap-wise Micro-strain	Edge-wise Micro-strain
5 MW	*ECD+R*	*1604*	*487*
13.2 MW	ECD+R	1410	856
5 MW	*EWM50(0^o pitch)*	*2390*	*338*
13.2 MW	EWM50(0^o pitch)	2294	364
5 MW	*NWPR*	*1036*	*483*
13.2 MW	NWPR	971	865

IV. Sandia 100-meter Baseline Blade Design and Structural Analysis

In this section, we present the design process and evolution, a summary of the final design specifications, and blade performance characteristics for the SNL100-00 blade design.

Some general considerations for design at a particular blade cross section include the number and location of shear webs, spar dimensions, utilization of leading edge and/or trailing edge reinforcements, skin and core thickness, materials and airfoil thickness ratio. These choices are dictated by loads and resulting strains, and aerodynamic design in the case of t/c ratio and twist. The chord schedule is an important consideration which impacts both aerodynamic and structural design, although it is mostly dictated by aerodynamic requirements.

In the initial SNL100-00 design phase, a two shear web design was pursued as this has been the typical design choice for state of the art of large blades as shown in the representative blade cross section of Figure 1. At each station along the span of the blade, the layup design considered material choice and thickness of four regions at the station including: (1) spar cap, (2) core panels, (3) shear webs, and (4) leading and trailing edge reinforcements, which are each indicated by color in Figure 1. The layup was designed initially using information gained from the scaling studies and targeted layup discussed in the previous sections.

One consideration included the addition of weight for extra resin that is typical in traditional manufacturing processes. While extra adhesive from excessive bond line thickness was not explicitly captured, the added extra resin was considered to include all the parasitic mass. During fabrication extra resin may be supplied to the mold to ensure that fibers are properly wetted. Extra resin is also likely absorbed into core materials (especially in foam core). As a result, blade weight was expected to be representative of an as-built blade.

Another consideration was ply-dropping as constraints were placed on span-wise thickness transitions of laminates to ensure realistic manufacturability of the layup design. For example, the spar cap and trailing edge reinforcement laminate thicknesses were constrained such that they began with a single layer inboard, transitioned to a larger thickness outboard and then tapered down to a single layer outboard.

A. Initial Design Results and Observations

For the analyses of the initial 100-meter baseline layup design, tip deflection and span-wise strains were calculated for the all-glass, two shear web design. The results demonstrated that tip deflection and strains (strength) were within specifications considering design standard safety factors for materials and loads. Next, a buckling analysis was desired. Therefore, a high-fidelity finite element model was created using the Sandia NuMAD blade modeling code[14], and the buckling calculation was performed.

A linear buckling analysis was chosen with loads applied in the flap-wise direction corresponding to the EWM50 condition at zero degree pitch angle. The blade loads were exported from FAST. This condition corresponds to IEC DLC 6.2, which is an abnormal condition with electrical grid power loss. It is assumed this is a worst case for buckling with no ability to pitch the blades out of the wind. The initial model failed to satisfy the design buckling loads with safety factors as the aft panel demonstrated buckling modes near maximum chord and outboard of maximum chord along the trailing edge. Re-design efforts included increasing the foam thickness and adding additional layers of uni-axial materials in the aft core panels. Although the buckling criterion was satisfied after a few design iterations, it was determined that the final blade weight was unrealistically high for this initial two shear web design. Attempts to optimally place the two shear webs did not provide a suitable design solution to satisfy the buckling requirement either.

It was decided that a better design solution was to include a third shear web due to the reduced buckling capacity of the 100-meter blade. A "short" shear web beginning inboard of maximum chord and running just beyond midspan was added in the aft panel regioin. As a result, the two principal shear webs could be located at a constant separation distance providing a constant width, "box beam" spar construction. From a manufacturing point of view, this is an improvement over the initial tapered-width spar cap approach because the spar design and manufacturing is simpler. And, it was expected that the third web would enable satisfaction of the buckling criterion while reducing blade weight.

The subsequent sections provide the detailed design geometry and analysis of the final design satisfying strength, tip deflection, buckling, and fatigue criterion. A flutter analysis was also performed. In this design, only glass materials with foam core materials were considered. As described, a three shear web design was selected for the final design.

B. Sandia 100-meter Baseline Blade Geometry

As mentioned earlier, the external geometry of the SNL100-00 uses upscaled chord and airfoil definitions from the DOWEC study. The detailed chord distribution used in this study is provided in publicly available reports[5,6]; however, limited span-wise airfoil definitions were included. Transition airfoil specifications between the root circle and maximum chord were not documented in the DOWEC report. Therefore, required transition airfoil shapes were generated by interpolation resulting in a gradual transition from the maximum chord airfoil to an elliptical shape and finally to a circle at the root. This was purely a geometric interpolation. No consideration was given to aerodynamic properties at this stage of the blade development; although aeroelastic tailoring could be considered in future work.

The chord schedule for the SNL100-00 blade is plotted in Figure 2. The inboard airfoil geometries including the newly created transition airfoils are plotted in Figure 3 while the outboard airfoils are plotted in Figure 4. A plot of the planform is shown in Figure 5. Figure 6 provides three views of the blade surface geometry: flap-wise, edge-wise, and isometric. This collection of plots only provides a summary of the design geometric information; however, a more detailed summary can be found in Reference 4.

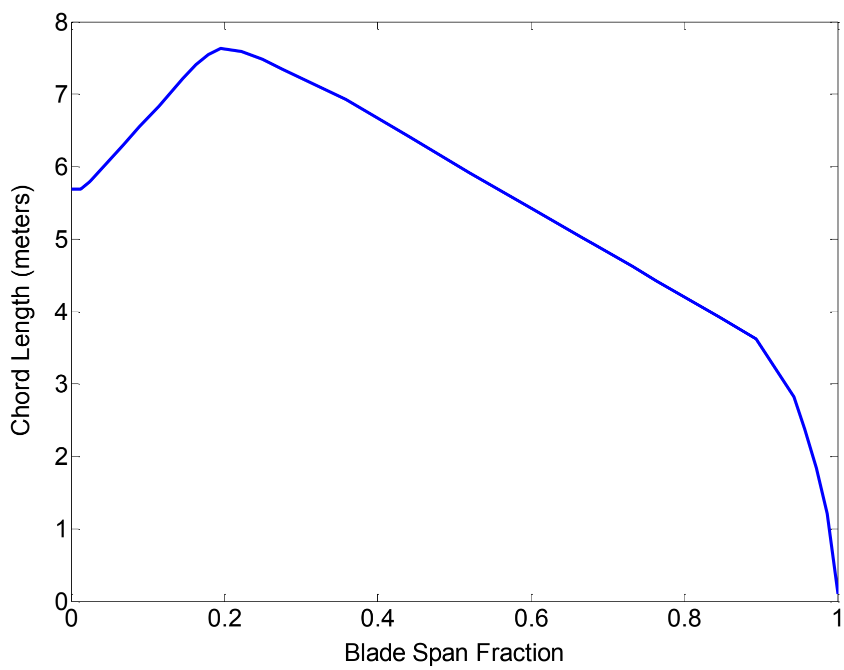


Figure 2. Chord Schedule for the SNL100-00 Blade

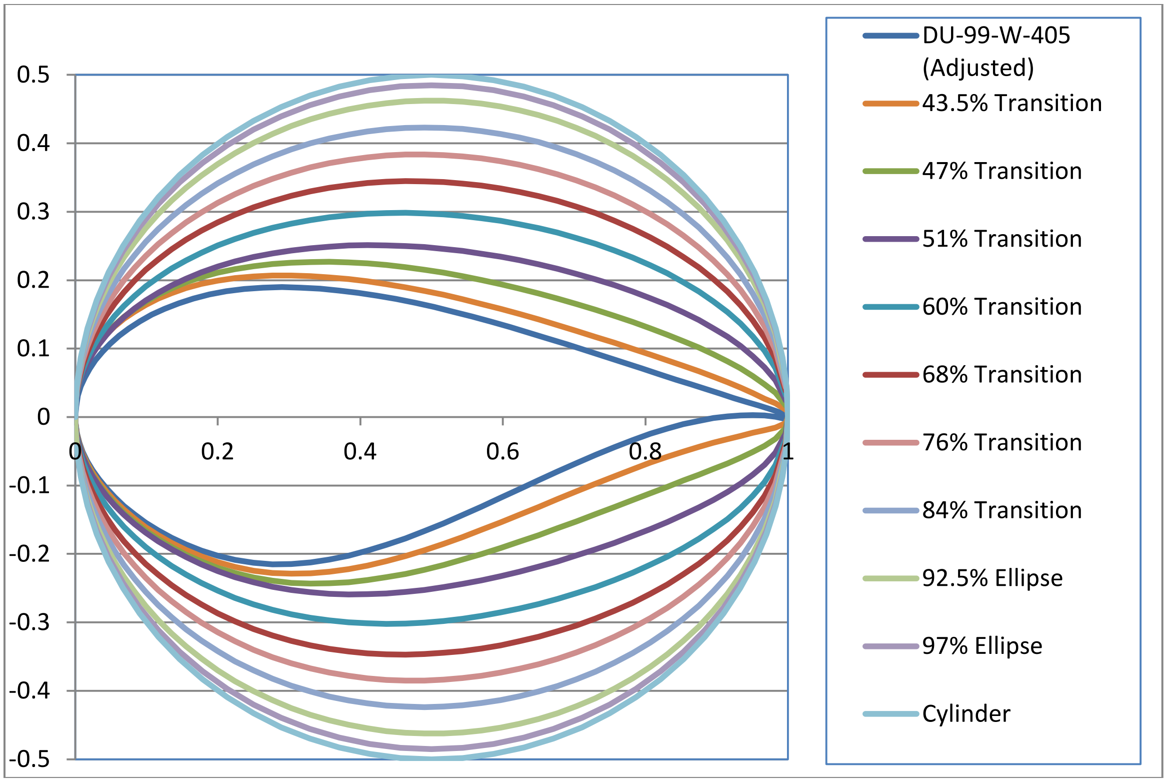


Figure 3. Transition Airfoil Geometries for the SNL100-00 Blade (from Root to Maximum Chord)

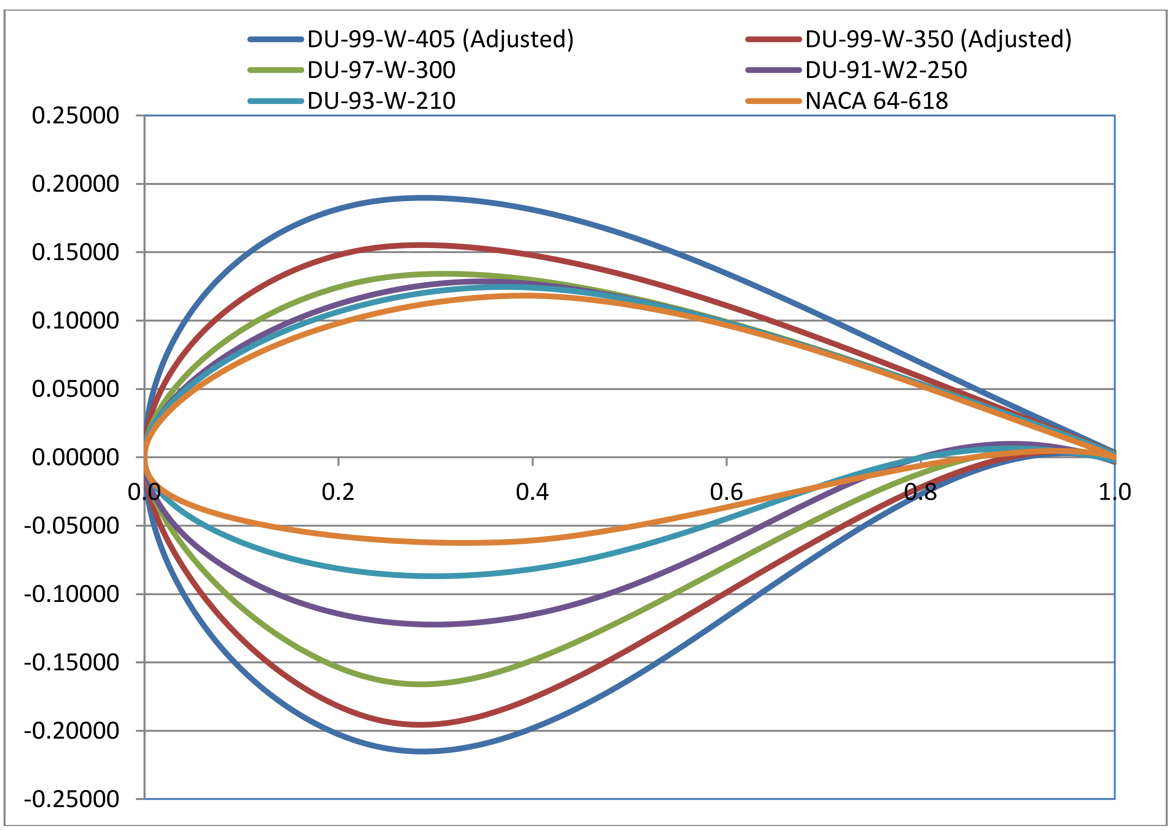


Figure 4. Outboard Airfoil Geometries for the SNL100-00 Blade (from Maximum Chord to Tip)

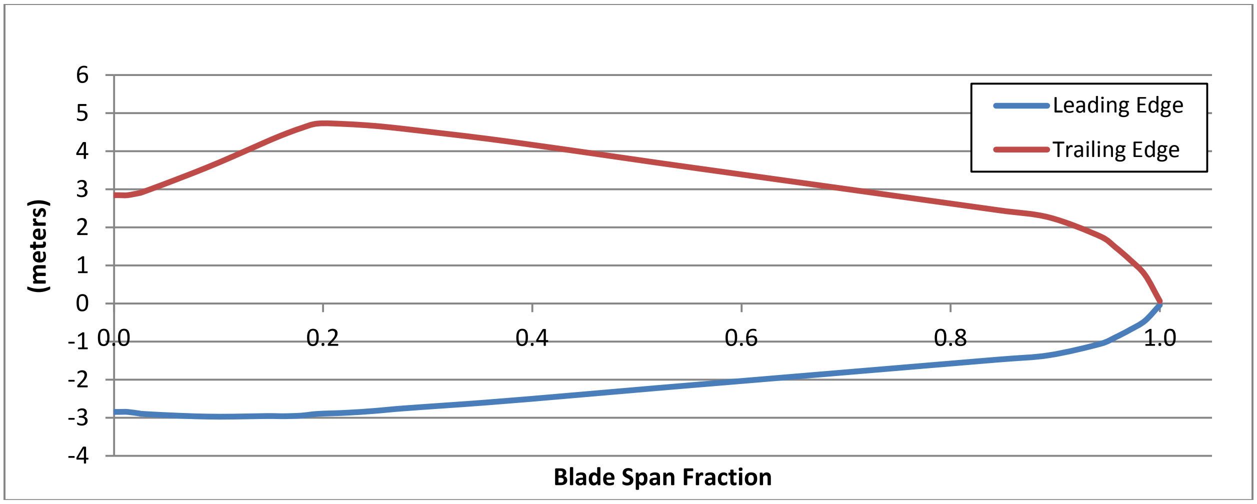


Figure 5. Planform for the SNL100-00 Blade

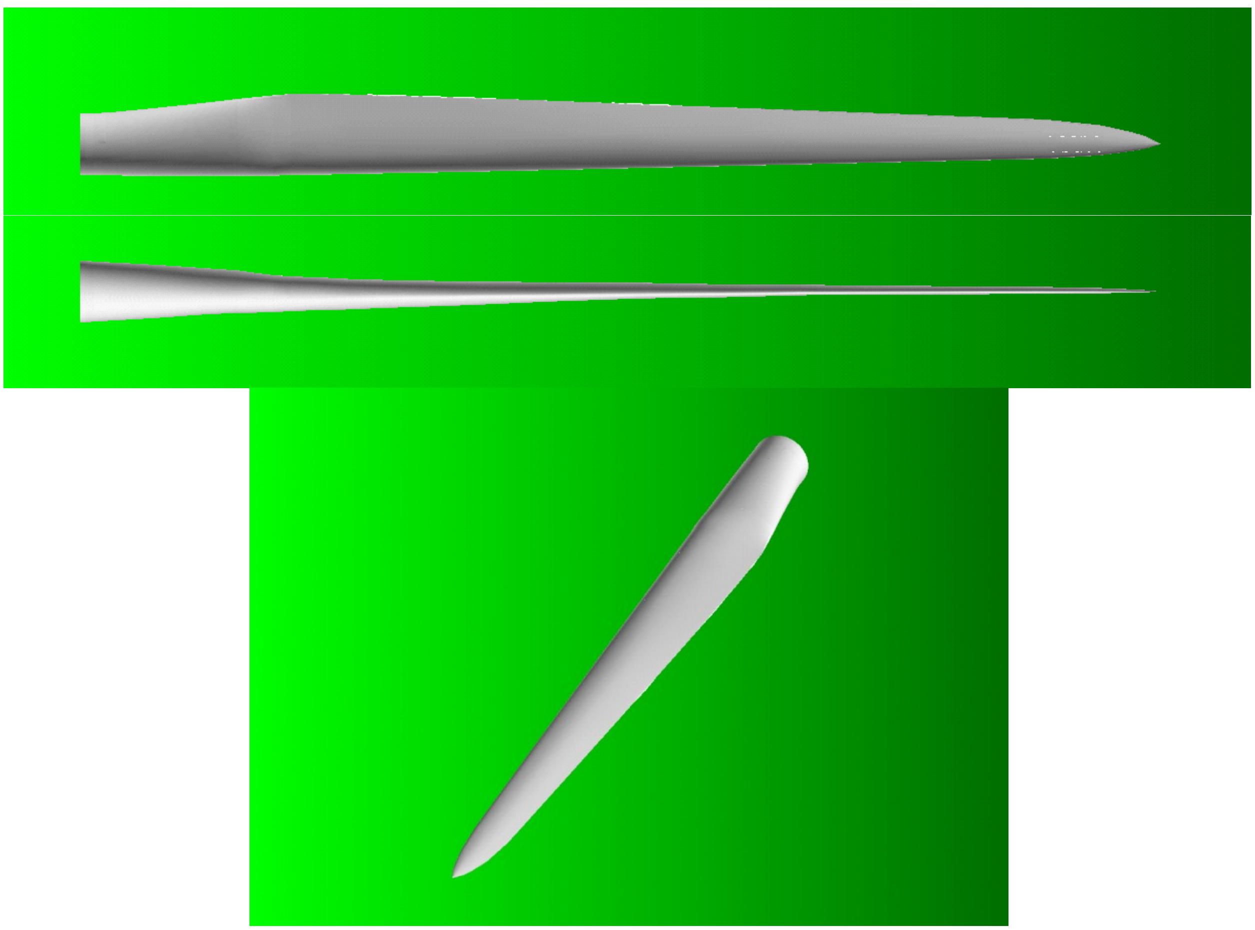


Figure 6. Views of Blade Surface Geometry for SNL100-00

C. Sandia 100-meter Baseline Blade Layup Definition

Table 4 lists the elastic and ultimate strength material property data for the laminates chosen for this design. These are glass fabrics and epoxy resin materials, which were selected from the DOE/MSU Composite Material Fatigue Database[15]. E-LT-5500 was chosen for the uni-directional material, and Saertex was chosen for the double bias material. Epoxy resin (EP-3) was selected as the matrix material. The ultimate strength properties are 95/95 fits to multiple single cycle failure data points in tension and compression[15] for the uni-axial E-LT-5500/EP-3 laminate and are mean data for the Saertex/EP-3 double bias laminate. Based on the volume fractions indicated in Table 4, the mass density of the E-LT-5500 uni-directional laminate is 1920 kg/m^3 and the mass density for the Saertex-based double bias laminate is 1780 kg/m^3. Properties for the triaxial material, which we denote as SNL Triax, were determined by averaging the test-derived data for the uni-axial and double bias material. Fatigue properties for a laminate consisting of uni-axial and double bias materials were derived from the Database.

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

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	$[\pm45]_4$	44	13.6	13.3	0.51	11.8	144	2.16	-213	-1.80	----
SNL Triax	$[\pm45]_2[0]_2$	---	27.7	13.65	0.39	7.2	----	----	----	----	----

E_L and E_T - Longitudinal & transverse modulii, υ_{LT} - Poisson's ratio, G_{LT} & 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. ε_{MIN} - Ultimate compressive strain.

Based on the maximum strain data from tests and combined safety factors, +8,196 and -5,139 micro-strain allowables are determined for the uniaxial laminate by dividing the ultimate tensile and compressive strain values in Table 4 by a combined safety factor of 2.977. Computed in the same fashion, the allowables for the double bias laminate are computed to be +7,255 and -6,046 micro-strain in tension and compression, respectively. Of course, a comparison of the two materials is not equitable because the uni-axial material properties are 95/95 fits while the double bias material properties are from mean data. If additional testing was conducted on the double bias material, we would expect the allowable strain to be reduced by 10-15%.

In the previously discussed scaling studies, all strains were well below these allowable values. This means as we move into this baseline design it is also likely that strains will be below allowable maximum strains. A traditional design practice has included applying further "knock-down" factors to these allowable strains to account for fatigue and stability considerations; however, our approach involves performing the complete suite of analyses to verify that all design criteria are satisfied.

Table 5 lists additional materials used in this design. These include coating material, extra resin, and foam core material. The foam properties were chosen to correspond with those used in the UpWind layup.

Table 5. 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
Foam	0.256	0.256	0.022	0.3	200

Figure 7 plots the laminate schedule for the principal reinforcements at 34 stations along blade span. This laminate schedule was utilized on both the high and low pressure surfaces; no attempt was made to optimize the layup. A complete layup table is provided in Reference 4. The plot shows graphically how the design is reinforced in various parts of the cross-section along the span. Figure 8 shows graphically the laminate placement and shear web locations. The trailing edge reinforcement is highlighted in orange. The spar cap placement is highlighted in blue. The two principal shear webs are located to the top and bottom sides of the spar cap. The third shear web location is shown by the red line in Figure 8. The third shear web resides within the aft panel region.

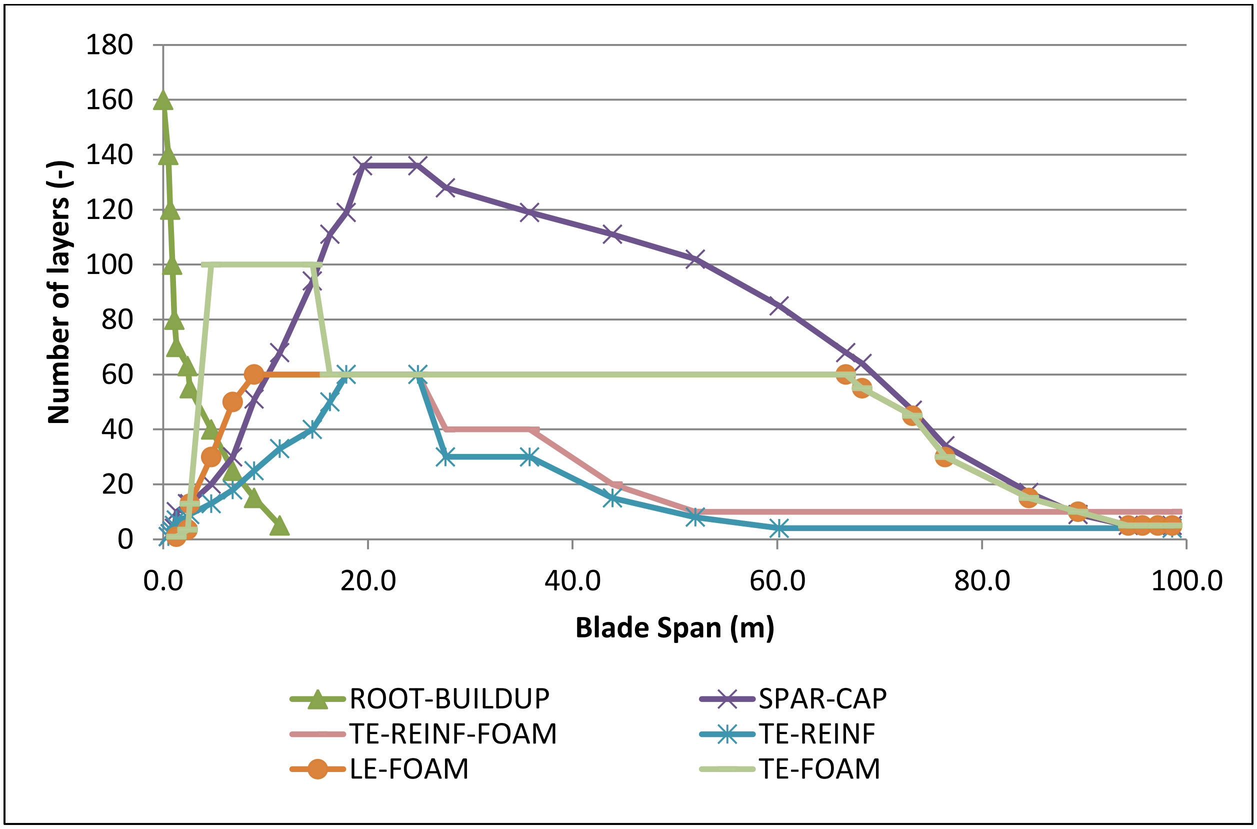


Figure 7. Plot of SNL100-00 Layup Thicknesses

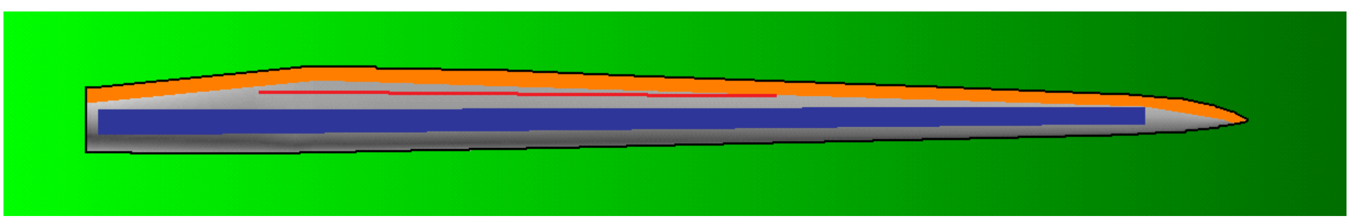


Figure 8. Planform of Sandia 100-m Baseline Blade with Laminate Designations (Blue: Spar Cap, Orange: trailing edge reinforcement, Red: Third Shear Web)

For the six materials used in this design, which are listed in Tables 4 and 5, their contribution to the total blade weight was calculated using the PreComp code. These results are listed in Table 6, and provide a description of the placement of laminates/materials in the design along with total mass and percentage of total blade mass. The table shows that 42.8% of the blade weight is composed of uni-axial material laminates used in the spar caps and trailing edge reinforcements. The extra resin accounts for 6,863 kg of blade weight while the gelcoat accounts for 920 kg. In total, the inclusion of extra resin and gelcoat comprise 6.7% of the total blade weight. The shear webs were found to total 10,270 kg or 8.9% of the total blade weight.

A further analysis, separating the fiber and resin content, shows that 32.5 % of the blade weight (37,647 kg) is uni-axial fiberglass, 8.7% (10,045 kg) is double bias fiberglass, and the largest fraction of 44.7% (51,718 kg) is resin. This resin content includes resin used to construct the E-LT-5500/EP-3, SNL Triax, and Saertex/EP-3 laminates as well as extra resin noted in Table 6. The bill of materials summary is provided in Table 7.

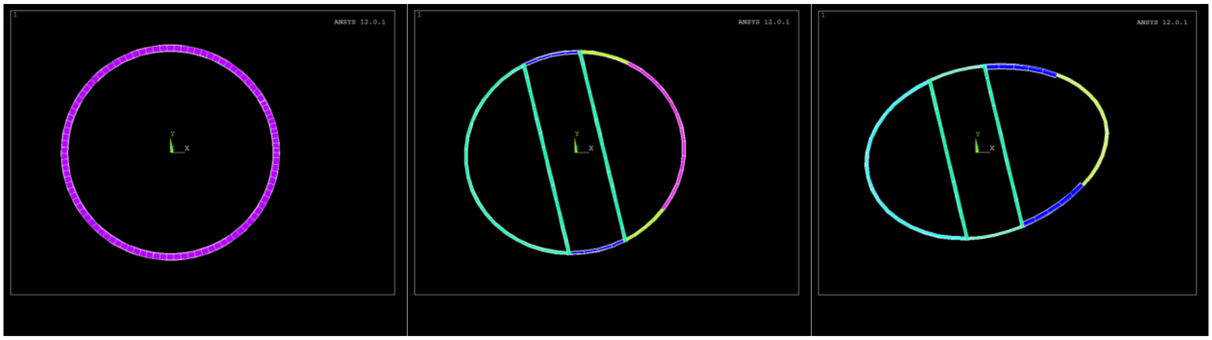
Table 6. Materials Usage Summary for Sandia 100-m Baseline Blade

Laminate/Material	Usage/Location	Mass (kg)	Percent Blade Mass
E-LT-5500/EP-3	Spar caps, trailing edge reinforcement	49,527	42.8%
SNL Triax	Root build-up, internal & external surfaces	38,908	33.6%
Foam	Core panels, shear webs	15,333	13.3%
Extra Resin	extra weight (interior surface)	6,863	5.9%
Saertex/EP-3	Shear webs	4,112	3.6%
Gelcoat	Coating	920	0.8%

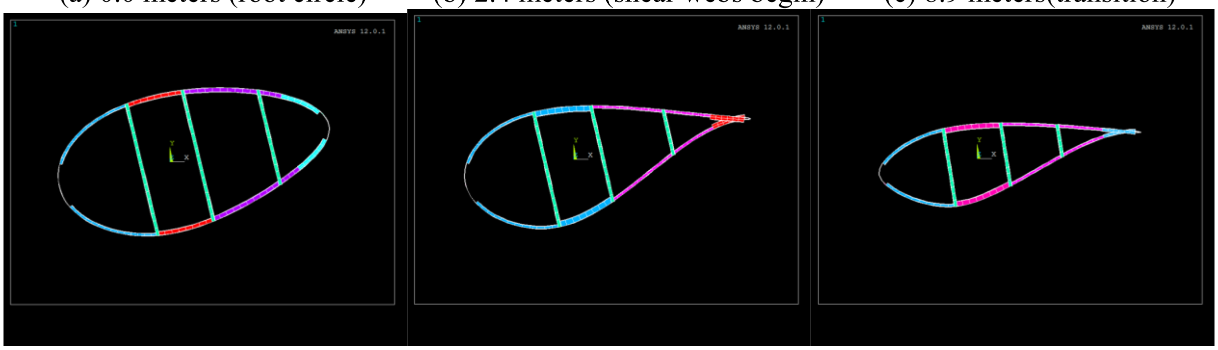
Table 7. Bill of Materials for Sandia 100-m Baseline Blade

Material	Description	Mass (kg)	Percent Blade Mass
E-LT-5500	Uni-axial Fiberglass	37,647	32.5%
Saertex	Double Bias Fiberglass	10,045	8.7%
EP-3	Resin	51,718	44.7%
Foam	Foam	15,333	13.3%
Gelcoat	Coating	920	0.8%

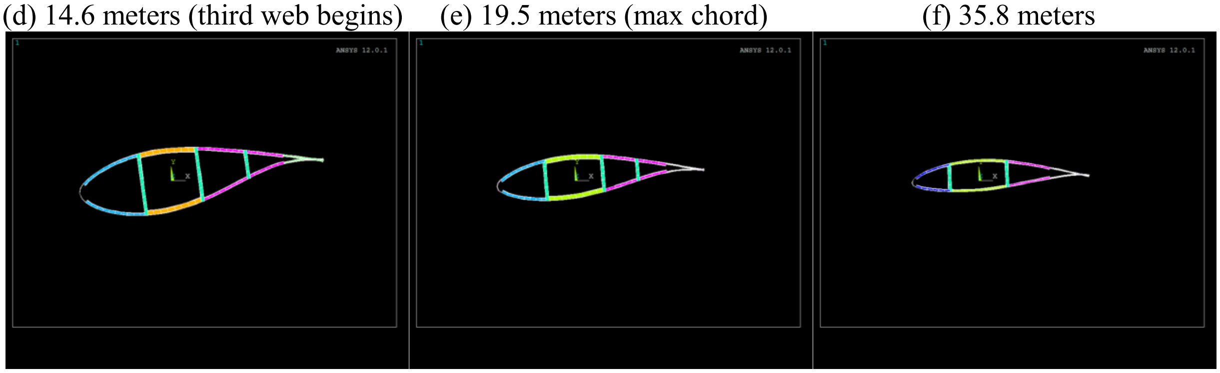
A selection of blade cross sections is plotted in Figure 9. The airfoil geometry is true in scale. Key sections are plotted in which shear webs begin and end. The plots demonstrate the relative thickness of the layup for the various locations about the circumference of the cross section. However, as noted in Reference 4, the leading and trailing edge thicknesses were reduced by a factor of ten (with a modification of material properties by the same factor) at some stations to avoid element quality issues in the high fidelity finite element model. Example of these can be seen in Figure 9 (d) through (i) at the leading and trailing edge.



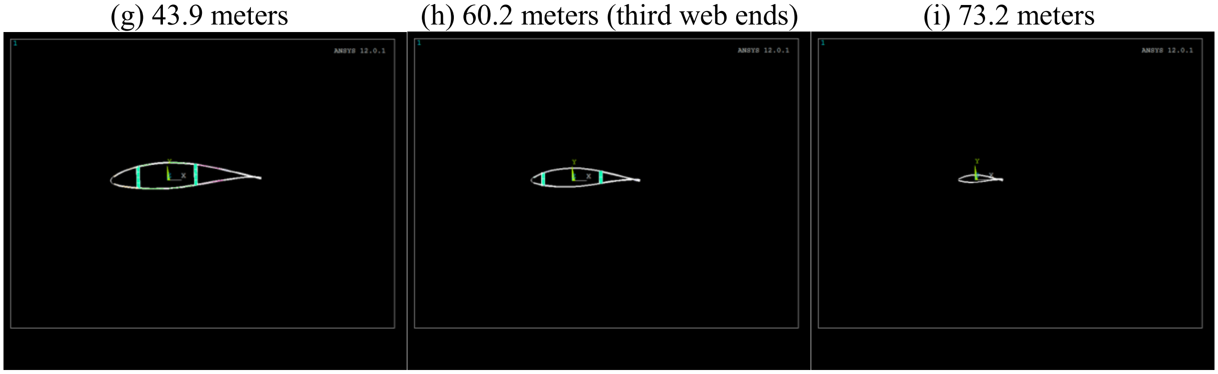
(a) 0.0 meters (root circle) (b) 2.4 meters (shear webs begin) (c) 8.9 meters(transition)



(d) 14.6 meters (third web begins) (e) 19.5 meters (max chord) (f) 35.8 meters



(g) 43.9 meters (h) 60.2 meters (third web ends) (i) 73.2 meters



(j) 84.6 meters (k) 94.3 meters (shear webs end) (l) 98.6 meters

Figure 9. A Selection of Cross Sections along the SNL100-00 Span

D. Sandia 100-meter Baseline Blade Analysis Results

A selection of important 13.2 MW baseline turbine design properties is listed in Table 8. The cut-in and cut-out wind speeds are 3 and 25 m/s. The maximum rotation rate of this variable speed machine is 7.44 rpm. We have chosen to perform the analysis with Class IB loads to not limit the potential siting of this turbine.

Table 8. SNL100-00 General Turbine Properties

Property	Value
Rotor Radius/Hub Radius	102.5m/2.5m
Blade Mass	114,172 kg
Class	IB
Max Rotor Speed	7.44 RPM
Rated Wind Speed	11.3 m/s

The blade mass reported in Table 8 was calculated by the FAST program, and has a mass scaling factor of 3.33 when compared to the UpWind blade. The theoretical weight growth factor is 3.0 (Equation 1); however, the high weight for SNL100-00 can be understood by considering: (1) the need for additional reinforcements to satisfy buckling and fatigue life requirements, (2) the addition of a third shear web, (3) the use of all-glass materials, (4) inclusion of approximately 6% parasitic mass, and (5) no systematic attempt to optimize the layup or shear web thickness for blade weight reduction.

The following sections review the analyses performed in the final design showing satisfaction of design requirements.

1. *Strain and Deflection Calculations*

Bending moments and deflections were computed by running design load cases using the FAST code. Results for bounding case loads at the root are tabulated in Table 9 for the 13.2 MW turbine with SNL100-00 blade.

Table 9. Sandia 100-meter Baseline Blade Root Bending Moments and Tip Deflections for Selected Design Loads

Machine	Load Case	Flap-wise (kN-m)	Edge-wise (kN-m)	Tip Defl (m)
13.2 MW	ECD+R	67,410	47,220	10.1
13.2 MW	ECD-R	74,810	52,460	11.9
13.2 MW	NWPR	49,250	48,600	7.3
13.2 MW	EWM50 (0^o pitch)	110,700	17,300	12.3
13.2 MW	EWM01 (0^o pitch)	73,300	11,320	8.2
13.2 MW	EWSV+R	58,440	47,260	8.6
13.2 MW	EWSH-R	57,450	47,620	8.3
13.2 MW	ETM-R	37,410	45,930	5.4

The allowable tip deflection is calculated with assumed values for rotor overhang, shaft tilt angle, precone angle, and tower radius. These values were selected in these analyses to be 8.16 meters, 5.0 degrees, 2.5 degrees, and 2.0 meters, respectively. As a result, for operating cases the allowable tip deflection is 13.67 meters, which is greater than the largest operating case tip deflection of 11.9 meters (see ECD-R in Table 9). The allowable tip deflection for a parked rotor is 18.56 meters. For the EWM with 50-year occurrence (EWM50), the computed tip deflection is well within this allowable. Although the EWM50 condition produces the largest deflection, it is apparent that the operating condition of ECD-R is the driver for analysis of blade/tower clearance.

2. *Buckling Evaluation*

A high-fidelity ANSYS finite element (FE) blade model was created using the NuMAD code. Both buckling and detailed stress analyses were performed using ANSYS. A linear static analysis with prestress effects was performed with the EWM50 loads derived from a FAST analysis. The forces at the aerodynamic nodes of the FAST model were applied to nearby nodes in the FE model, flap-wise in the down-wind direction. The load was applied at 18 points along the blade span corresponding to the FAST/Aerodyn nodes. An eigen buckling solution was then performed that considers the prestress effects of the linear static solution. Because the full load was applied statically, satisfaction of the buckling requirement is met when buckling mode frequencies are computed to be greater than the required safety factor. This is because the buckling frequencies are equal to the scaling factor of the applied static load at which a particular buckling mode will occur.

The foam in the core panels was thickened, and extra foam and uni-axial material were added to the trailing edge region. Reinforcements were investigated along the entire blade span as additional reinforcements were also added at the tip (outboard of 94.4%) to prevent buckling. Also, the spar thickness was increased in a few critical areas to prevent buckling. As a result, the ultimate strains and deflections were reduced significantly as shown in the previous section when compared to scaling studies results. The iterations required to improve the buckling resistance of the entire blade underlie the importance of a high-fidelity blade structural model in blade design. Further, the early indication that buckling is a significant design driver for very large blades indicates that validated structural models and accurate predictive structural analysis codes will be critical in producing very large blades with high reliability.

The three lowest frequency buckling modes were found to have frequencies of 2.173, 2.184, and 2.229, which are all above the allowable of 2.042. The frequency of the buckling mode provides a prediction of the scaling, or amplification, of the load at which buckling would occur in a region of the blade. A list of the principal buckling modes is provided in Table 10 with buckling frequency and a description of the location of the buckled behavior both chord-wise and span-wise. This table provides a description of the load at which different areas of the blade would be susceptible to buckling under the EWM50 loading with zero degree pitch angle. The table lists the lowest frequency buckling modes that occur in the spar cap, aft panel, leading edge panel, and trailing edge panel. Efforts to improve buckling resistance in the aft panel and trailing edge reinforcement by both adding fiberglass layers as well as increasing the core foam thickness resulted in excess design margins. These design margins could be exploited to reduce blade weight in future optimization studies. Also, no buckling of the shear webs was noted in this analysis. Potential may also exist to reduce the thickness of the shear webs as no buckling issue was found in the shear webs.

Table 10. List of Principal Buckling Modes for the SNL100-00 Blade

Frequency	Chord-wise Location	Span-wise Location
2.173	Spar cap	10 to 15 meters
2.184	Aft Panel	19.5 meters (maximum chord)
2.229	Spar cap and aft panel	72 to 80 meters (outboard)
2.327	Leading edge panel	25 to 29 meters
2.536	Trailing edge reinforcement	23 to 37 meters
2.589	Trailing edge reinforcement	19.5 meters (maximum chord)

3. ***Fatigue Evaluation***

Fatigue properties for materials used in the Sandia 100-meter Baseline Blade design were derived from test data reported in the DOE/MSU Composite Material Fatigue Database. A Miner's Rule calculation was selected to predict the fatigue life of the blade. Only a single R-value of 0.1 was available for the analysis of a laminate of 66% uni-axial and 34% double bias with epoxy (denoted at E-LT-5500-EP in the DOE/MSU database). The S-N curve (failure stress versus number of cycles) for a laminate is defined by the single-cycle failure stress and the slope of the curve of the test data, if available. The fit of material fatigue test data indicates a slope parameter of b=9.13. However, in accordance with GL standards, a fatigue slope of b=10 was used for the fatigue analyses here.

Edge-wise strains were the driver in the fatigue life calculation. For a GL recommended slope of 10, a 1290 year life was calculated, which exceeds the 20 year requirement and corresponds to edge-wise fatigue loading at the 11.1 meter span-wise location. Surprisingly, flap-wise accumulated fatigue damage was 2-3 orders of magnitude lower than edge-wise at the corresponding span-wise locations. The vast majority of laminates in the SNL100-00 blade has greater than 66% uni-axial material composition, and will have higher fatigue resistance than the fatigue properties used in this analysis. Therefore, these calculations are considered conservative in this respect.

4. ***Flutter Analysis***

Classical aeroelastic flutter of a wing (or turbine blade) is a serious condition whereby the structural and aerodynamic damping is insufficient to dampen out large vibratory motions due a coupling of flapwise (bending) and torsional (twisting) modes. It typically has not been an issue in utility-scale wind turbine designs. It has been expected; however, that the continued growth of wind turbine rotors (greater than 10MW) would reach a point where blade flexibility and higher loads would result in aeroelastic instabilities. This would mean that aeroelastic instabilities, such as flutter, would then become one of the principal design drivers.

An estimate of the operating speed for the occurrence of a flutter condition was calculated for the SNL100-00 blade using a technique developed at Sandia for wind turbines. As expected, the flutter mode manifested as a coupling of a flapwise and a torsional mode and occurred when the total damping (aeroelastic and structural) became negative.

> In 1984, Sandia National Laboratories (Lobitz) developed a NASTRAN-based analysis tool that incorporates aeroelastic effects and allows the user to estimate flutter speeds, divergence characteristics and levels of aerodynamic damping for various modes of vibration of Vertical Axis Wind Turbines (VAWT's)[16]. Flutter predictions were validated using field measurements of a 2-m VAWT. This technique was extended to Horizontal Axis Wind Turbines in 1998 as described in Ref. 17. Recently, Resor[18] automated the analysis procedure by developing a MatLab routine that easily sets up the NASTRAN input file and has an option to input structural properties directly from NREL's FAST and AeroDyn inputs, from a Sandia NuMAD finite element blade model or from an NREL PreComp analysis of the blade structure.

The following table lists results of flutter speed estimations for the 100-meter baseline as well as several horizontal axis wind turbine blades of increasing blade length. The trend shows that the ratio of flutter speed to turbine rated operating speed drops significantly as the blade grows in length from 5-meters to 9-meters to 34-meters and finally to 100-meters. The 1.5 MW WindPACT turbine with a 34-meter blade has a safety margin of 2-2.5. The 100-meter (13.2 MW) blade has little or no margin on flutter speed. In the one field validation of flutter[16], the flutter speed was under predicted by only 10% for a 2-meter VAWT. However, the flutter analysis technique has been primarily used as a sanity check and the accuracy is unknown due to a number of simplifications in the procedure as described in Reference 19. A more accurate analysis tool may be required when the flutter speed is indicated to be an issue.

Table 11. Estimated Flutter Speed Margins for Several Blades

Blade Length	Ratio of Estimated Flutter Speed to Operating Speed	Cited Reference for Estimation
5 m – CEB	6 : 1	Ref. 17
9-m - CX-100	5 : 1	Ref. 18
34-m - WindPACT	2-2.5: 1	Ref. 19
100-m –Sandia baseline (SNL100-00)	1.0-1.1: 1	Ref. 4

In more recent work, the flutter speed margin estimate for SNL100-00 has been estimated to be 1.26:1 (Ref. 20). This is an improvement in the margin, although the margin itself is small for both Reference 4 (Table 11) and Reference 20 based calculations. In summary, flutter appears to be an issue to consider in the design of very large blades. Continuing analysis has indicated that adjustments to structural and geometrical properties can increase flutter speed away from normal operating speed. For follow-on work, we must develop a refined flutter prediction tool and validate with wind tunnel and field data and then develop best practices and analysis tools for design of aeroelastic stable blades as well as flutter suppression techniques for very large wind turbine blades.

E. Summary of Analyses Results

The layup and geometry presented in this section for the Sandia 100-meter All-glass Baseline Blade design satisfies international design standards for loads and materials. The design was not systematically optimized for weight although design trade-offs were made to reduce weight as much as possible.

To summarize:

1) The resulting design satisfies the allowable strains in both the spar cap and trailing edge with good margins.
2) Tip deflection is acceptable for the assumed overhang distance, and modest tilt and precone angles. The smallest clearance margins were found for extreme operating conditions as opposed to extreme parked conditions.
3) Buckling is satisfied by addition of a third shear web along with reinforcing the preliminary layup (primarily through thickening of the foam panels and addition of uni-axial laminates and foam in the trailing edge).
4) Fatigue life was calculated to be 1290 years based on the slope parameter recommended by GL. Edge-wise (gravitional) loading was the driver for fatigue life over flap-wise (aerodynamic) loading. More certainty in the fatigue life estimate could be gained with additional data for different R-values[21].
5) Flutter speed was estimated to occur close to maximum operating speed; however, subsequent analyses demonstrate ways to overcome this barrier by adjustments to the blade design.

A "design scorecard" (Ref. 22) that summarizes important blade design information, performance margins, and the bill of materials the SNL100-00 blade is available on the Sandia project website[23] or can be searched from the Sandia Wind Power website[24]. The project website provides a summary of the large blade project and links to reports including Reference 4 and more detailed blade and turbine data.

V. Observations Regarding Future Large Blade Research

Through the process of developing the SNL100-00 design a number of challenges and opportunities for development of large, offshore rotors have been identified. Future work would include the application of innovations for weight and load reduction to the Sandia 100-meter All-glass Baseline Blade. The use of carbon fiber, flatback airfoils, bend-twist coupling, geometric sweep, pre-bending, and active control, as demonstrated in prior Sandia blade development projects, will be considered. Additionally, the suitability of design codes for analysis of large-scale machines will be studied.

Other observations regarding future work include:

- documentation of a 13.2 MW reference *turbine* model using the SNL100-00 blade including land-based and offshore foundation options,
- the variability of design wind conditions. Wind conditions were specified to be constant across the entire rotor (e.g. hub height wind files) for most of the analyses, which is a gross over-simplification for a very large rotor diameter. Localized effects will be important to consider for all design load cases,
- additional load cases. Loads determined from extrapolation of extreme events should be analyzed. Also, a more complex analysis of turbulent conditions including spatially-varying effects as well as a more rigorous statistical analysis of turbulence should be investigated,
- power optimization. For example, the effect of aerodynamic twist, chord schedule, and tip speed ratio on the aerodynamic performance could be considered in future studies of the SNL100-00 blade,
- transportation. Since a 100-meter blade will be too large to be transported over the US highway system in one section, blades may need to be constructed and transported in two or more sections and assembled on site using structural joints. Therefore, the addition of joints should be considered in blade modeling,
- application of the 13.2 MW turbine model (with its 100-meter blade) to the development of the model to offshore siting with offshore foundations,

- the effect of blade length on blade buckling capacity. This is a key issue for large blades because the length of unsupported panels will likely increase. Designers will attempt to lower weight by minimizing the use of shear webs and/or optimizing panel laminate thickness and material selection to lower total blade weight.
- a refined flutter prediction tool. A more accurate flutter estimation capability should be developed and validated with wind tunnel and field data. Such a tool could also support development and design of flutter suppression techniques for very large wind turbine blades.
- cost analysis trade-offs for various weight and load reduction innovations.

VI. Discussion and Conclusions

This paper documents the design of a baseline 100-meter wind turbine blade that has been analyzed to demonstrate new trends in blade design drivers with increased blade length. The baseline model, termed SNL100-00, incorporates conventional geometry, all-glass materials, and traditional manufacturing assumptions. The SNL100-00 design is documented and made available to be used as a research tool for evaluating new design options to overcome challenging large blade design issues; many of these challenges have been documented in this paper.

A detailed layup and external geometry for the "Sandia 100-meter All-glass Baseline Blade: SNL100-00" was summarized[4]. The final design was demonstrated to be acceptable with respect to loads from international blade design standards. A series of analyses were performed to demonstrate this acceptance along with identification of regions of the blade with the smallest performance margins that may be targeted in future works. For example, regions of the blade most susceptible to buckling, most likely to experience high operating strain, or having the largest fatigue accumulation are noted. The pertinent design parameters are summarized in a design scorecard[22].

A number of observations regarding trends for large blade were made based on the analyses. First, panel buckling is a significant concern for large blades. For SNL100-00, a third shear web was considered and it was found to satisfy the buckling requirement with significantly less blade weight. Second, the growth in gravitational loading for the larger rotor required significant trailing edge reinforcement to reduce the edge-wise strains. The gravitational loading is a particular concern for fatigue life. It was demonstrated that the edge-wise fatigue life is the driver for the SNL100-00 blade over the traditional aerodynamically-driven, flap-wise fatigue. Third, it was found that the smallest margin on tip/tower clearance was for an operating load case. Although no additional reinforcements were needed to satisfy deflection requirements beyond those needed for buckling and fatigue, the margins were smallest for an operating case corresponding to an extreme coherent gust with direction change. Finally, flutter was identified as a potentially significant issue. The trend of decreasing flutter speed margin with blade length was demonstrated for blades in length between 5 and 100 meters. For SNL100-00, the flutter margin was very small compared to today's typical utility-scale turbines. Early thinking is that the addition of a third shear web for buckling resistance and the addition of trailing edge reinforcement for edge-wise fatigue life extension results in movement of the chord-wise CG location toward the trailing edge, which increases the susceptibility to flutter instability.

In review, 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 (5) aeroelastic stability (flutter) and (6) application of offshore conditions. Many opportunities exist for research and development to enable large blades: (1) airfoil architecture, material lay-ups and material choices, (2) blade planform innovations, (3) multidisciplinary design optimization, (4) blade joints, (5) load alleviation concepts (active and passive) and (6) flutter suppression techniques. These constitute a set of the challenges and opportunities associated with large blades identified in this work.

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