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Challenges and Opportunities in Large Offshore Rotor Development: Sandia 100-meter Blade Research

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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 and is targeted for offshore rotors. This paper summarizes the design and development of the Sandia 100-meter All-glass Baseline Wind Turbine Blade, termed as "SNL100-00". This model employs conventional architecture and fiberglass-only composite materials to arrive at a working baseline model of 100-meter length with conventional design constraints. A certification-like design process was followed for the design of the baseline SNL100-00 blade. The resulting performance margins for a suite of analyses along with new trends in design drivers are reported. The SNL100-00 design model was made publicly available in June 2011 for use by other researchers and internal blade studies at Sandia. The paper also includes initial parameter studies to apply innovations to SNL100-00 that target reductions in weight. The focus is material selection and usage with deployment of carbon fiber into the all-glass baseline. The results of these studies include quantification of weight reduction while observing tradeoffs in performance margins for the principal new large blade design drivers, including buckling, gravitational fatigue loading, and aeroelastic stability. This study will ultimately culminate in dissemination of an updated design model (e.g. "SNL100-01") that incorporates carbon fiber for a large blade in an effective way.

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]. Designs for even larger machines continue to push the extremes of the design envelope, which is primarily limited by the penalty of weight growth.

The goal of this work is to study the issues associated with development of even larger blades and the approach is through the detailed design of a 100-meter all-glass baseline blade design model. An important aspect of this work is that a certification-like set of analyses are performed to ensure that the design is acceptable with respect to loads from internationally accepted blade design standards. Through this process, a detailed design model was developed and made publicly available to other researchers. In addition, new design drivers for large blades were identified throughout the stages of the design process and documented. These new drivers include buckling, gravitational fatigue loading, and flutter. The hope is that dissemination of the models and identification of large blade design challenges will both lead to useful information to focus and enable research investments in large blade technology by industry and university researchers.

The baseline design, termed as SNL100-00, was provided in Reference 4. References 4 and 5 summarize the design definition (geometry, layup, bill of materials, etc.), the analyses, and the performance margins. The 13.2 MW turbine model associated with the SNL100-00 blade has been made publicly available[6-8] as well. 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. The detailed design model also provides the opportunity to quantify how changes in blade design parameters (e.g. geometry, materials, layup) at the blade scale propagate through the performance and cost at the system level. For example, with respect to offshore

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siting, reduction in rotor weight for development of advanced large offshore rotors can; for example, provide significant cost reductions not only in the rotor but throughout the entire turbine (especially in the foundation).

In addition, the paper includes results from parameters studies to improve upon the baseline all-glass SNL100-00 model. This initial focus has been material selection and usage through deployment of carbon fiber to replace uni-axial fiberglass in SNL100-00. This is only one potential area of innovation and is a logical first step. The resulting weight reduction and tradeoffs for various usages of carbon fiber with respect to performance relating to the primary design drivers (e.g. fatigue, tip-tower clearance, and buckling) are reported. Although a final 100-meter length carbon design is not specified, these studies will ultimately lead to dissemination of a new 100-meter design model.

II. Early 100-meter Blade Design Studies

The initial work of this 100-meter blade program focused on development of preliminary structural models: (1) an initial composite layup for a 100-meter blade for detailed design and analysis and (2) a 13.2 MW turbine model incorporating the 100-meter blade design for full system aeroelastic design calculations under inflow. Earlier studies on 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[9,10]. 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[11] and DOE/NREL work[12,13]. 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.

In addition to upscaling of these 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. A cross-sectional analysis code, PreComp (Ref. 14), 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. Although this targeted layup design was not evaluated for strength or for buckling resistance, it was found to be useful for preliminary laminate sizing of the SNL100-00 design.

Initially, blade scaling studies were performed using the publicly available blade and turbine data. One of the key findings of these scaling studies was 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 from scaling relations 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 (which has been experienced in these studies). Observing such trends is important to design to strength and fatigue requirements and demonstrates one important change in the design approach to mitigate growing edge-wise strains due to growing gravitational loads for larger blades.

III. Load Cases and Guiding Standards for the Design Analysis

The load cases (inflow conditions) utilized to evaluate the candidate 100-meter blade models are summarized. A subset of IEC design load conditions[15] considered as bounding cases is listed in Table 1. Germanischer Lloyd (GL)[16] 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 were performed to determine strains and deflections and also to perform the fatigue analysis for the 13.2 MW turbine with candidate 100-meter blade models. In large part, most of the 13.2 MW turbine parameters (other than the blades of course) were upscaled from the NREL 5 MW model. More details regarding the analyses, loads, and safety factors can be found in Reference 4.

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[17] 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 1. 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)

The IEC and GL standards were also followed for analysis of the detailed blade model with loads applied from the subset defined in Table 1. Sandia's NuMAD[18] blade modeling code was utilized to develop the blade model to be analyzed in ANSYS. The principal purpose in developing this model was to perform the buckling analysis. 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. However, the model was also utilized to perform detailed stress and deflection analyses that were compared to the results of the FAST model for the corresponding load cases.

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[19-21]. As expected, the flutter mode manifested as a coupling of a flap-wise and a torsional mode and occurred when the total damping (aeroelastic and structural) became negative.

IV. Sandia 100-meter Baseline Blade (SNL100-00) 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 all-glass baseline blade design. In the following section, parameter studies that introduce carbon into the baseline model are presented.

A. 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[9,10] 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. A plot of the planform is shown in Figure 1. Figure 2 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.

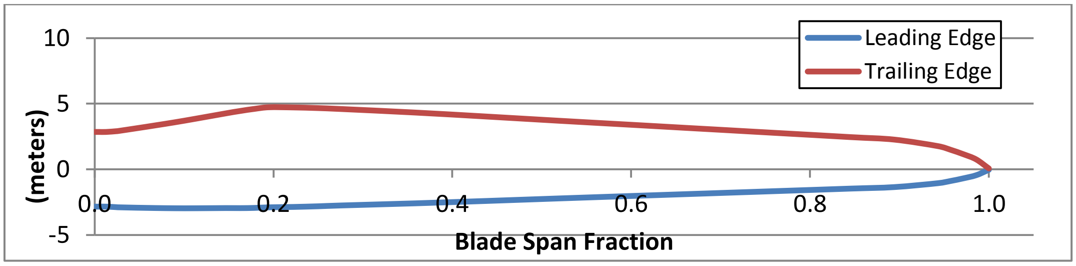

Figure 1. Planform for the SNL100-00 Blade (not to scale)

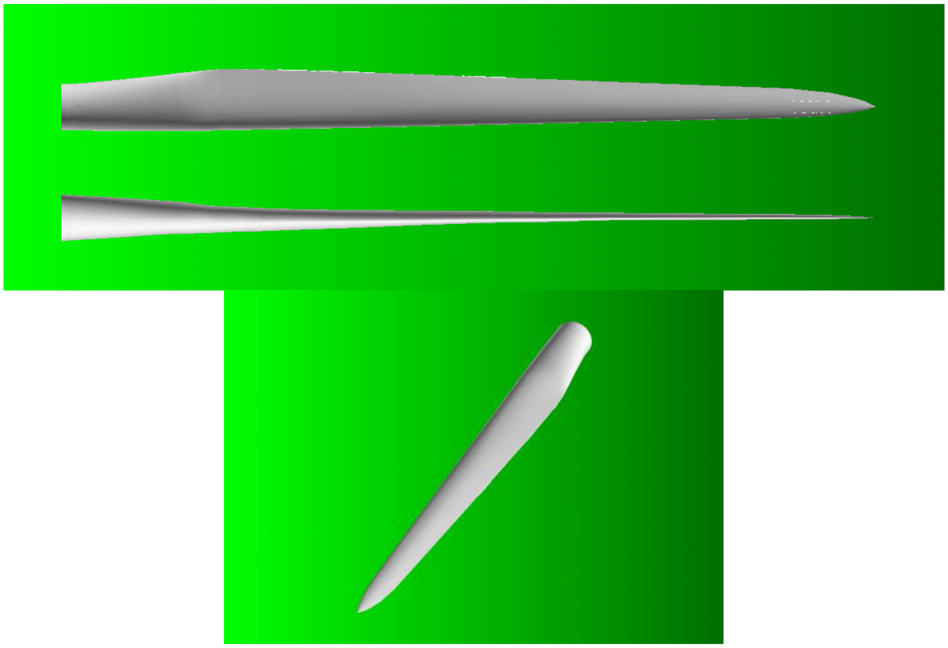

Figure 2. Views of Blade Surface Geometry for SNL100-00

B. Blade Architecture and Other Design Constraints and Assumptions

In the initial SNL100-00 design phase, a conventional architecture was assumed with no inclusion of novel airfoils (e.g. flatbacks) and also a two shear web approach – these choices have been the typical design choices for state of the art of large blades with representative blade cross section of Figure 3. 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 3. The layup was designed initially using information gained from the scaling studies and targeted layup discussed in the previous sections.

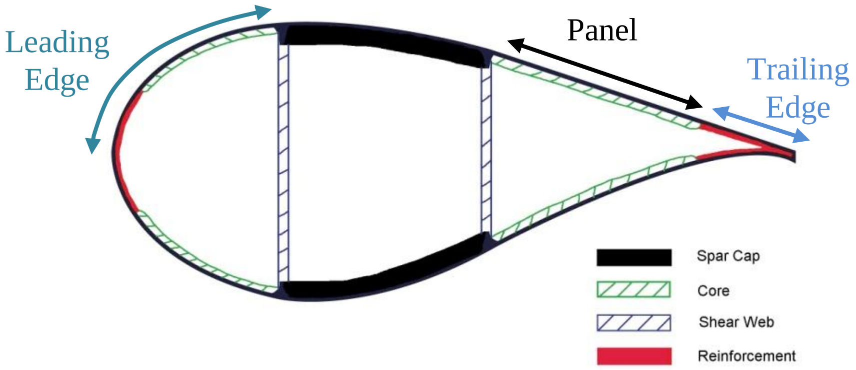

Figure 3. Representative Airfoil Cross Section with Two Shear Webs

In addition to architecture, manufacturing approach and manufacturability were also considered. Extra parasitic resin and bond adhesive weight was added that is typical in traditional blade manufacturing processes. Another consideration was ply-dropping as constraints were placed on span-wise thickness transitions of laminates. As a result, the hope was that the layup would have more realistic manufacturability and that the final design weight would be representative of an as-built blade. In addition, the laminate thickness at the root was sized for inclusion of potentially large root bolts, although it was thicker than needed by strain requirements as verified through analysis.

Once again, another constraint in the design of the SNL100-00 baseline model was use of glass-only materials. Although there is evidence that some utility-scale blades utilize carbon fiber, our goal was to study the viability of glass-only for a very large blade design. Of course, with consideration to cost reduction, glass is a good choice. However, future studies to optimize blade weight and cost for large blades (including studies reported here in the next section) will focus on strategic usage of new materials.

C. *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, and the buckling calculation was performed.

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. 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 region. As a result, the two principal shear webs could be located at a constant separation distance providing a constant width, “box beam” spar construction, which is a benefit from a manufacturing point of view.

With inclusion of the third shear web, the fundamental architecture for SNL100-00 was defined. Subsequent iterations on the layup were performed to minimize blade weight while satisfying buckling and fatigue requirements.

D. *Sandia 100-meter Baseline Materials Summary*

Table 2 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[22]. 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[22] 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 2, 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 2. 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 moduli, 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.

Table 3 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 3. 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

A complete layup table is provided in Reference 4 and the model files are also available on the project website[6]. Figure 4 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 4. The third shear web resides within the aft panel region, as shown in the included cross section at the maximum chord location.

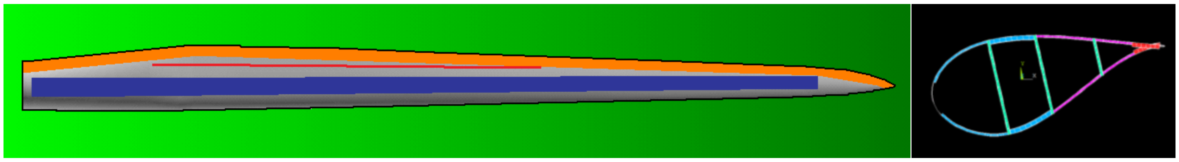

Figure 4. Planform of Sandia 100-m Baseline Blade with Laminate Designations (Blue: Spar Cap, Orange: trailing edge reinforcement, Red: Third Shear Web)

E. Sandia Design Scorecard and Summary of Analysis Performance Margins

A "design scorecard" (Ref. 8) that summarizes important blade design information (Table 4), performance margins (Table 5), and the bill of materials (Table 6) the SNL100-00 blade is summarized below and also available on the Sandia project website[6]. This Design Scorecard is intended to summarize the key design parameters and provide a convenient means to compare innovations applied to the baseline model by blade researchers. 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.

A selection of important 13.2 MW baseline turbine design properties is listed in Table 4. The assumed 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 4: Blade Parameters

Parameter	Value
Blade Designation	SNL100-00
Wind Speed Class	IB
Blade Length (m)	100
Blade Weight (kg)	114,172
Span-wise CG location (m)	33.6
# shear webs	3
Maximum chord (m)	7.628 (19.5% span)
Lowest fixed base natural frequency (Hz)	0.42
Control	Variable speed; collective pitch
Special notes:	6% (weight) parasitic resin; all-glass materials

The blade mass reported in Table 4 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.

Table 5 summarizes the certification-like analyses and associated performance margins for the final SNL100-00 design. Notes are included that describe critical design load cases and the codes/method used to perform the calculations.

Table 5. Blade Design Performance Metrics Summary

Analysis	Design Load Condition (DLC) designation	Metrics	Notes/method
Fatigue	Turbulent inflow (4 to 24 m/s)	Critical location: Inboard (edge-wise): 1290yrs at 11.1% span	R=0.1 data used; Miners Rule
Ultimate	EWM50; 0 deg pitch	Max strain = 2662 micro-strain Allowable strain = 5139 micro-strain Max/allowable = 48.2%	At max chord (flap-wise) FAST, NuMAD/ANSYS
Tip Deflection	ECD-R	Max (11.9 m) vs. allowable (13.67); Clearance = 1.77m = 12.9%	FAST, NuMAD/ANSYS
Buckling	EWM50, 0 deg pitch	Min load factor (2.173) vs. allowable (2.042)	Linear, ANSYS
Flutter	--	Flutter margin (1-1.1)	Beam theory (see SAND2011-3779)

To summarize the critical trends identified through the design analysis:

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. 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.
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 (gravitational) loading was the driver for fatigue life over flap-wise (aerodynamic) loading. Surprisingly, flap-wise accumulated fatigue damage was 2-3 orders of magnitude lower than edge-wise at the corresponding span-wise locations.
5) Flutter speed was estimated to occur close to maximum operating speed demonstrating another critical large blade design driver.

Table 6 is the third and final table in the Design Scorecard. This is the traditional bill of materials summary including the glass fabrics, resin, foam, and coating materials.

Table 6. Blade Design Bill of Materials

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%

In addition to buckling and fatigue concerns as blades get longer, flutter is also identified as a critical issue. Reference 23 shows flutter speed estimates for the 100-meter baseline (SNL100-00) as well as several horizontal axis wind turbine blades of shorter blade length. Flutter estimates are produced using the approach described by Lobitz (Ref. 21) which analyzes a single blade turning in still air. Unsteady aerodynamic forces are applied using Theodorsen forcing in the frequency domain. The trend in the analyses show 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 (Ref. 21). The 100-meter (13.2 MW) blade has a very small margin of estimated flutter speed over operating speed. The classical flutter analysis approach of Lobitz has not been validated for HAWT's, but in a field validation of VAWT flutter[19], the flutter speed was under predicted by 10% for a 2-meter rotor. To date, 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 21. In recent work using an updated tool based on Lobitz's approach, the flutter speed margin estimate for SNL100-00 has been estimated to be 1.26:1 (Ref. 23). Regardless of the precise flutter margin, 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 (Ref. 23). 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.

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

Carbon usage in blades has been studied by a number of authors including conceptual design studies, manufacturing demonstrations, and blade tests. Here, a brief summary of these works are reported. In Reference 24, the strategic use of carbon including cost estimates considering both the material and tooling costs was studied for a SERI-8 Blade. In References 24-27, design of a carbon spars for 9-meter Sandia research-sized blades (including CX-100, TX-100, and BSDS blades) are described. These reports also provide manufacturing summaries along with carbon and carbon hybrid materials testing results. Structural testing of carbon blades is reported in Reference 28. In Reference 29, concepts for large blades including usage of carbon laminates is reported.

A. Determination of Unidirectional Carbon Material Properties

Properties for pure unidirectional carbon laminate are determined by starting with measured values for a double bias (DB) and unidirectional (UD) mixture of Newport 307 carbon prepreg taken from the Sandia-MSU Materials database (Ref. 22). The material tested for the database was a mixture of 85% UD and 15% DB material. Classical laminate theory (CLT) was used in an inverse manner to estimate the properties of the underlying unidirectional material for use in this model[30]. This resulted in the properties listed in Table 7 for the conceptual carbon laminate. Ultimate stress values in tension and compression were 1546 and 1047 MPa, respectively, as indicated in the Database.

Table 7. Material Properties for Conceptual UD carbon laminate

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

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

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

For the initial study (Case Study #1) the carbon thickness in the spar cap was sized to retain the flap- and edge-wise stiffnesses of the baseline design. The spar cap width was not changed. Then, analyses were formed to calculate performance margins and identify possible need for additional modifications. As a starting point, reduction in spar cap thickness with carbon considered the increased longitudinal elastic moduli for carbon over glass as well as the change in area moment of inertia using analytical expressions for the rectangular and offset spar cap. This provided a good initial guess as to how to match EI, although subsequent finer iterations of the thickness were performed to more accurately match the baseline span-wise stiffness distributions. Throughout the span, the resulting thickness of the spar cap for Case Study #1 was reduced by approximately 63%.

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

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

Table 8. Summary of Carbon Parameter Studies Results: Comparisons with SNL100-00 All-glass Baseline Blade

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

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

The results for the carbon parameter studies are summarized in Table 8 for the deflection, fatigue, and buckling analysis. The performance margins are tabulated along with a summary of the total blade mass and CG location (both computed using FAST) and the bill of materials summary (each computed using the ANSYS model) for each design variation. As in the SNL100-00 Baseline, the allowable tip/tower clearance is 13.67 meters here as well. All of these design variations are then acceptable with respect to deflection for the extreme coherent gust with direction change (ECD) at rated wind speed condition, which was found to be the driving load case for deflection analysis[4].

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

For Case Study #2, reduction of the width of the trailing edge reinforcement and replacement of glass with carbon required no additional modification to satisfy buckling. Although no fatigue calculation was performed to further evaluate this approach, this modification was found to have only a small decrease in blade mass and CG location. The use of trailing edge carbon will be studied in greater detail once aeroelastic stability calculations are performed. As shown in Reference 23, reduction in trailing edge reinforcement mass tends to move the chord-wise CG location toward the leading edge of the station – with improvement in flutter margin.

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

In summary, these parameters studies guide an optimal usage of carbon for a 100-meter length blade through comparison to the all-glass SNL100-00 baseline design. Additional work is needed to develop an updated design model (“SNL100-01”) that deploys carbon in an effective way. Additional analyses need to be performed to understand the carbon trade-offs, these include flutter analysis as well as a complete set of fatigue and stress analyses. Furthermore, the cost-benefit of replacing glass with carbon must also be included in the decision-making process. Therefore, subsequent studies will address selective usage and evaluation of the cost and performance tradeoffs.

VI. Discussion and Conclusions

In summary, there are a number of challenges with large blade development such as: (1) blade weight growth, (2) manufacturing and reliability, (3) material volumes/cost, (4) transportation (5) new design drivers including aeroelastic stability (flutter), panel buckling, and gravitational fatigue loading 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) designs for flutter suppression. These constitute a set of the challenges and opportunities associated with large blades identified in this work.

This paper documents the design of a 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. The final design was demonstrated to be acceptable with respect to loads from international blade design standards following a certification-like design process.

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 is noted for blades up to 100 meters. For SNL100-00, the flutter margin is estimated to be very small compared to today's typical utility-scale turbines.

Initial parameter studies were performed to improve the baseline 100-meter blade design through usage of carbon. Based on the results from the SNL100-00 analysis, it was decided to deploy carbon into the spar caps and trailing edge reinforcement and study the resulting weight reduction and impact on deflection, fatigue life, and buckling resistance. The initial parameter studies demonstrated a nearly 20% decrease in blade weight from the all-glass baseline in using a carbon spar cap with foam added to satisfy buckling requirements. A fatigue analysis was also performed and it was learned that flap-wise fatigue at an inboard location was the critical feature – as opposed to the dominant edge-wise gravitational fatigue of the baseline model. Although the important factor of cost was not included, these initial parameter studies guide the development of a new 100-meter model (i.e. SNL100-01) that utilizes carbon in a cost-effective way while reducing weight. The future work will focus on providing this new design model with the hope to support development of future large offshore blades.

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