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The SNL100-01 Blade: Carbon Design Studies for the Sandia 100-meter Blade

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Abstract

A series of design studies to investigate the effect of carbon on blade weight and performance for large blades was performed using the Sandia 100-meter All-glass Baseline Blade design as a starting point. This document provides a description of the final carbon blade design, which is termed as SNL100-01. This report includes a summary of the design modifications applied to the baseline all-glass 100-meter design and a description of the NuMAD model files that are made publicly available. This document is intended primarily to be a companion document to the distribution of the NuMAD blade model files for SNL100-01.

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1. INTRODUCTION

A series of design studies to investigate the effect of carbon on blade weight and performance for large blades was performed using the Sandia 100-meter All-glass Baseline Blade design as a starting point. This document provides a description of the final carbon blade design, which is termed as SNL100-01. This report includes a summary of the design modifications applied to the baseline all-glass 100-meter design and a description of the NuMAD model files that are made publicly available. This document is intended primarily to be a companion document to the distribution of the NuMAD blade model files for SNL100-01.

Sandia National Laboratories Wind and Water Power Technologies Department, creates and evaluates innovative large blade concepts for horizontal axis wind turbines to promote designs that are more efficient aerodynamically, structurally, and economically. Recent work has focused on the development of a 100-meter blade for a 13.2 MW horizontal axis wind turbine and a series of large blade design studies for 100-meter blades. A link to the project website can be found in Reference 1.

The carbon study presented in this report is a follow-on to the initial SNL100-00 design: the Sandia 100-meter All-glass Baseline Blade [2]. The design analysis process for this updated 100-meter carbon blade followed the same design process as for SNL100-00; therefore, Reference 2 should be consulted first for additional information that may be omitted in this short report. One key point is that all design requirements for the updated SNL100-01 design are also satisfied according to international blade design standards; these requirements or drivers include maximum strains, tip-tower clearance, buckling resistance, and fatigue life. The design safety factors and associated design standard are the same for this study as discussed in Reference 2.

Important blade design parameters (basic blade design information, loads analysis results, and bill of materials accounting) are summarized in a Design Scorecard format. The hope is that this format provides an effective way to compare the effects of various innovations including those performed by other researchers that are using these public domain reference designs. The Design Scorecard for the updated SNL100-01 carbon blade can be found in Reference 3 and also Section 3 of this report. This Scorecard can be compared with the Scorecard for the SNL100-00 baseline all-glass blade [4] to quickly compare the two designs; for example, to evaluate weight reduction (35% in this case) and changes in bill of materials (e.g. more foam, less uni-directional glass material) for the carbon blade.

The new SNL100-01 blade can be included in the Sandia 13.2 MW reference turbine model by simply swapping the blade definition file. The Sandia 13.2 MW turbine model is documented in Reference 5, and is also publicly available by request on the project website noted in Reference 1. Although there is additional room for reduction in blade weight for SNL100-01 through application of innovations and systematic structural optimization, use of the SNL100-01 blade model for turbine aero-elastic simulations provides a more realistic rotor weight for 13.2 MW turbine simulations and also for turbine and foundation design studies.

2. SNL100-01 DESIGN DEFINITION

Summary of Design Modifications Leading to SNL100-01

A series of case studies were examined to study the weight reduction potential of carbon in a 100-meter blade. Carbon was considered in either the spar or trailing edge reinforcement; locations in the baseline blade design having uni-directional glass laminates. Four case studies were examined using the SNL100-00 baseline blade as a starting point and concluding with the final SNL100-01 design [see References 6 and 7 for initial documentation of these case studies]:

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

As summarized below, a conceptual uni-directional carbon laminate was determined based on published test data in Reference 8. This blade study is intended to serve as a bounding case on use of carbon as the entire spar was replaced with carbon. Evaluation of specific carbon laminates that have been developed or which are currently under development in the industry; or evaluation of targeted span-wise deployments of carbon in the spar with cost constraints should be subjects of future work. This public domain blade design can provide a reference for such future design trade-off studies of carbon in large blades.

Case study 1 simply involved replacing the all-glass spar from SNL100-00 with the conceptual carbon laminate. The width of the spar remained the same, although the layer thickness was reduced in accordance with the higher longitudinal modulus of the carbon laminate so as to approximately maintain the same flap-wise stiffness along the span. The spar thickness was reduced by about 63% along the entire span to accomplish this. These design modifications and also the conceptual carbon laminate properties (and their derivation) are described in perhaps more detail in Reference 6. *The principal issue with the Case study 1 design is that the new spar cap was not acceptable because of buckling in the new thinned-down carbon spar.*

Case study 2 focused on carbon in the trailing edge reinforcement only. The initial modification here included reducing the width of the trailing edge reinforcement laminate from 1.0 meter to 0.3 meters, while maintaining the same laminate thickness. Only small weight reduction was found with this design change in comparison to the carbon spar re-design, so it was not pursued in subsequent case studies. However, it could be considered that this type of modification could be useful for passive flutter mitigation (see Reference 9) by reducing the weight of the trailing edge and moving the chord-wise CG forward.

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

A seemingly next logical choice to solve the buckling issue in the carbon spar included modifying the blade architecture by reducing the width of the spar cap. This type of design change was very easily accommodated using NuMAD [10, 11]. In Case study 4, the spar width was reduced by 50%. As a result, the two principal shear webs were brought closer together to maintain the box beam construction. More importantly, the carbon spar could be designed using no foam to solve the buckling constraint. In the end, the spar width reduction resulted in even larger weight reduction and satisfaction of the design requirements in excess when compared to Case study 3. *As a result of the weight reduction, secondary reductions in the blade laminates were made possible primarily through the reduction of the gravitational loads that resulted from weight reductions made possible by the carbon spar.* The reduction in gravitational loads permitted reduction of the trailing edge reinforcement, which was reduced in both width and thickness by approximately 50% in the final SNL100-01 design.

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

These design changes from the baseline SNL100-00 blade (see Reference 2) can be summarized (again) as follows:

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

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

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

As noted above, this carbon study was intended to serve as a bounding case on use of carbon as the entire spar was replaced with carbon. Cost optimization should be the subject of targeted follow-on studies to investigate strategic deployment of carbon. Although a blade cost model was developed along with the carbon design studies [See Reference 12]; this model was not applied during the design phase of the current carbon blade design that resulted in the SNL100-01 definition.

The all carbon spar and associated reductions resulted in a significant weight reduction of 35%. However, future work remains and can address application of carbon materials tailored to the large blade application (including those with better suited fatigue properties) as well as manufacturing impacts with use of carbon. Again, targeted deployment of carbon in the outboard blade spar should be considered along with cost constraints from a blade cost model. Further, a two shear web solution and/or reduction in aft panel foam thickness may be possible and should be analyzed in future work. These constitute a set of directions that seem logical to begin from where this study has ended; however, there are numerous innovations that can be considered to provide additional blade weight and cost reductions for large blades.

SNL100-01 Geometry

As noted, the external geometry for SNL100-01 is the same as that of the baseline SNL100-00 design. In Table 1, the key external geometry information is summarized from Reference 2 for convenience. Two views of the NuMAD [11] geometry as plotted in Figure 1.

Table 1. Sandia 100-m Blade Airfoil and Chord Properties for SNL100-00 and SNL100-01

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

Station Number	Blade Fraction	Chord (m)	Twist (deg)	Pitch Axis (Fraction)	Airfoil Description
1	0.000	5.694	13.308	0.500	Cylinder
2	0.005	5.694	13.308	0.500	Cylinder
3	0.007	5.694	13.308	0.500	Transition (99.25%)
4	0.009	5.694	13.308	0.500	Transition (98.5%)
5	0.011	5.694	13.308	0.500	Transition (97.75%)
6	0.013	5.694	13.308	0.500	Ellipse (97%)
7	0.024	5.792	13.308	0.499	Ellipse (93.1%)
8	0.026	5.811	13.308	0.498	Ellipse (92.5%)
9	0.047	6.058	13.308	0.483	Transition (84%)
10	0.068	6.304	13.308	0.468	Transition (76%)
11	0.089	6.551	13.308	0.453	Transition (68%)
12	0.114	6.835	13.308	0.435	Transition (60%)
13	0.146	7.215	13.308	0.410	Transition (51%)
14	0.163	7.404	13.177	0.400	Transition (47%)
15	0.179	7.552	13.046	0.390	Transition (43.5%)
16	0.195	7.628	12.915	0.380	DU99-W-405
17	0.222	7.585	12.133	0.378	DU99-W-405 (38%)
18	0.249	7.488	11.350	0.377	DU99-W-350 (36%)
19	0.276	7.347	10.568	0.375	DU99-W-350 (34%)
20	0.358	6.923	9.166	0.375	DU97-W-300
21	0.439	6.429	7.688	0.375	DU91-W2-250 (26%)
22	0.520	5.915	6.180	0.375	DU93-W-210 (23%)
23	0.602	5.417	4.743	0.375	DU93-W-210
24	0.667	5.019	3.633	0.375	NACA-64-618 (19%)
25	0.683	4.920	3.383	0.375	NACA-64-618 (18.5%)
26	0.732	4.621	2.735	0.375	NACA-64-618
27	0.764	4.422	2.348	0.375	NACA-64-618
28	0.846	3.925	1.380	0.375	NACA-64-618
29	0.894	3.619	0.799	0.375	NACA-64-618
30	0.943	2.824	0.280	0.375	NACA-64-618
31	0.957	2.375	0.210	0.375	NACA-64-618
32	0.972	1.836	0.140	0.375	NACA-64-618
33	0.986	1.208	0.070	0.375	NACA-64-618
34	1.000	0.100	0.000	0.375	NACA-64-618

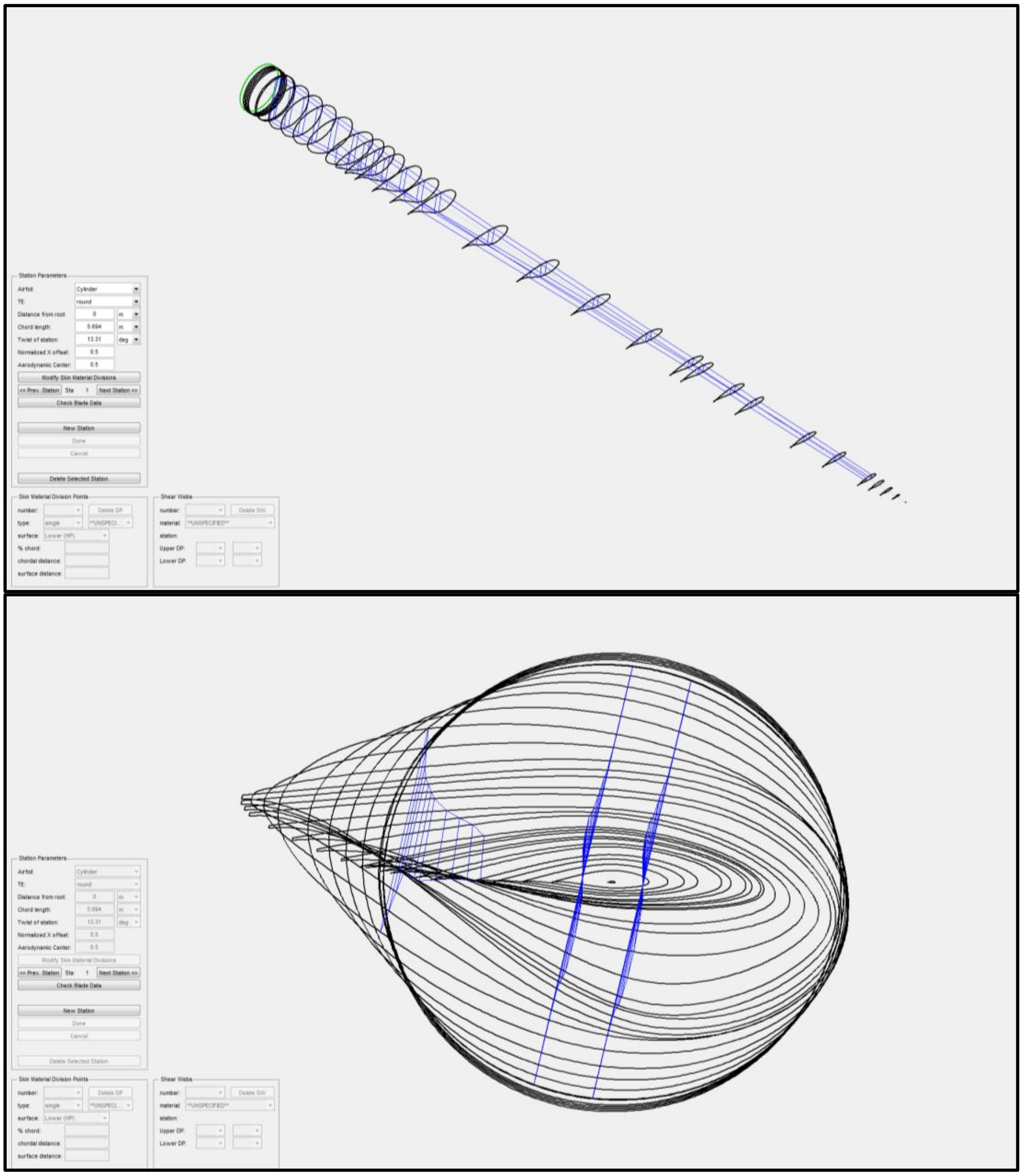


Figure 1. Two Views of the NuMAD Geometry for SNL100-01

SNL100-01 Materials

Table 2 and Table 3 list the materials and their properties for the SNL100-01 design, which were also utilized in the baseline blade. However, one new set of material properties was needed and introduced for the conceptual carbon laminate. Properties for pure unidirectional carbon laminate were 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. 8). The material tested for the database was a mixture of 85% UD and 15% DB material, and classical laminate theory (CLT) was used in an inverse manner to estimate the properties of the underlying unidirectional material for the conceptual carbon laminate as described in Reference 6. This resulted in the properties listed in Table 4 for the conceptual carbon laminate. Ultimate stress values in tension and compression were 1546 and 1047 MPa, respectively, as indicated in the Database. *For the fatigue analysis, a slope of 14 and single cycle failure stress of 1047 MPa was used in analyzing the carbon spar – the compression value was utilized to be conservative.*

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	$[\pm 45]_4$	44	13.6	13.3	0.51	11.8	144	2.16	-213	-1.80	----
SNL Triax	$[\pm 45]_2[0]_2$	---	27.7	13.65	0.39	7.2	----	----	----	----	----

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

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

Table 4. 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

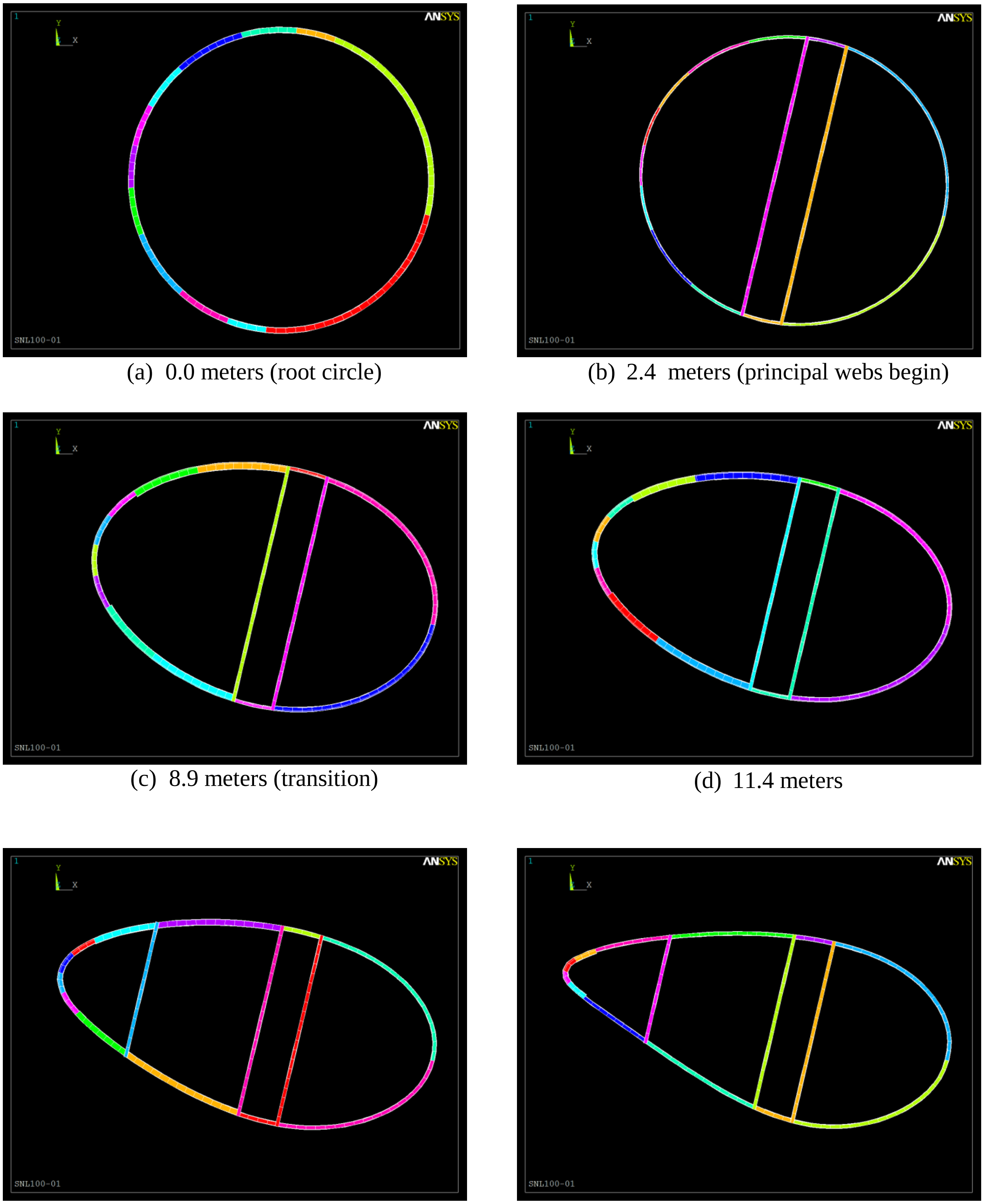
SNL100-01 Laminate Schedule

Table 5. Laminate Schedule for SNL100-01 (* indicates termination)
(this data is also provided in NuMAD.xlsx)

Station Number	Blade Span	Root Buildup	Spar Cap	TE Reinforcement	LE Panel	Aft Panel
		Triax/EP-3	Conceptual Carbon	E-LT-5500/EP-3, Foam	Foam	Foam
	(-)	(mm)	(mm)	(mm)	(mm)	(mm)
1	0.000	96				
2	0.005	77	1	1		
3	0.007	66	2	1		
4	0.009	55	2	2		
5	0.011	44	3	3		
6	0.013	39	7	4	1	1
7	0.024	35	9	4	3.5	3.5
8	0.026	31	9	5	13	13
9	0.047	31	13	5	30	100
10	0.068	31	19	5	50	100
11	0.089	20	32	5, 60	60	100
12	0.114	15	43	15, 60	60	100
13	0.146	10	69	25, 60	60	100
14	0.163	5	69	25, 60	60	60
15	0.179	1	74	25, 60	60	60
16	0.195	*	85	30, 60	60	60
17	0.222		85	25, 60	60	60
18	0.249		85	20, 60	60	60
19	0.276		80	15, 40	60	60
20	0.358		80	15, 40	60	60
21	0.439		80	8, 20	60	60
22	0.521		80	4, 10	60	60
23	0.602		75	2, 10	60	60
24	0.667		70	2, 10	60	60
25	0.683		65	2, 10	55	55
26	0.732		55	2, 10	45	45
27	0.765		40	2, 10	30	30
28	0.846		20	2, 10	15	15
29	0.895		15	2, 10	10	10
30	0.944		10	2, 10	5	5
31	0.957		10	2, 10	5	5
32	0.972		10	2, 10	5	5
33	0.986		10	2, 10	5	5
34	1.000		*	*	*	*

In addition to the detailed span-wise layup data in Table 5, the entire blade internal and external surfaces have 5 mm of triaxial material, which is unchanged from the SNL100-00 baseline blade. Extra parasitic mass is included by modeling 4 mm of epoxy resin on the internal blade surface; this value was reduced from 5 mm in the SNL100-00 baseline. The external surface includes 0.6 mm of gelcoat (surface paint), whose value is not changed from the baseline. Again, the inclusion of extra epoxy resin and surface gelcoat are included to produce a more realistic blade design weight. A final important change is that the foam thickness in all three webs was reduced to 60 mm, from a value of 80 mm in the baseline. All three shear webs consisted of the same layup for SNL100-01, 60 mm of foam sandwiched between 3 mm of double bias material (Saertex/EP-3) on the outer surfaces.

Cross sections are plotted for key stations along the span in Figure 2. Note that the two principal shear webs are closer in these plots, as compared to those in the SNL100-00 baseline blade in Reference 2. The thickness representation is true scale for each of the shell elements about the station. The coloring is by section number. Note that the root section is composed of multiple sections in this model although the layup properties are the same for each section of the uniform root according to Table 5. A better understanding of these plots involves interpreting them with the detailed layup schedule from either Table 5 or the NuMAD spreadsheet as a reference aid.



(a) 0.0 meters (root circle)

(b) 2.4 meters (principal webs begin)

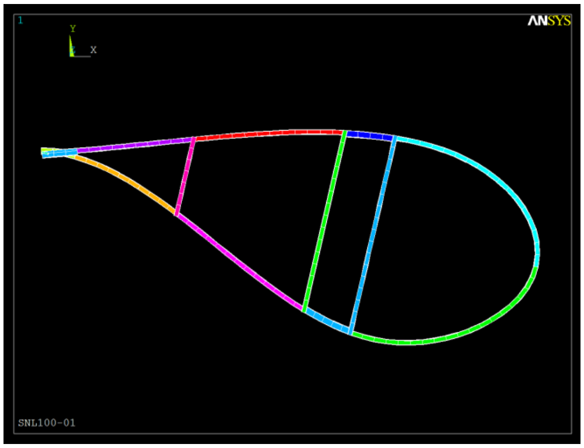
(c) 8.9 meters (transition)

(d) 11.4 meters

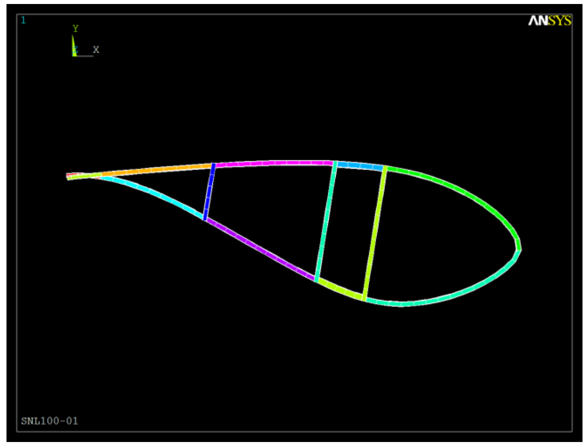
(e) 14.6 meters (third web begins)

(f) 16.3 meters

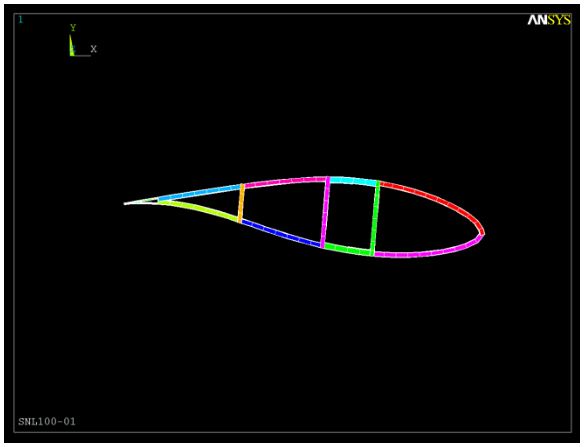
Figure 2. Selected Cross-section plots for SNL100-01



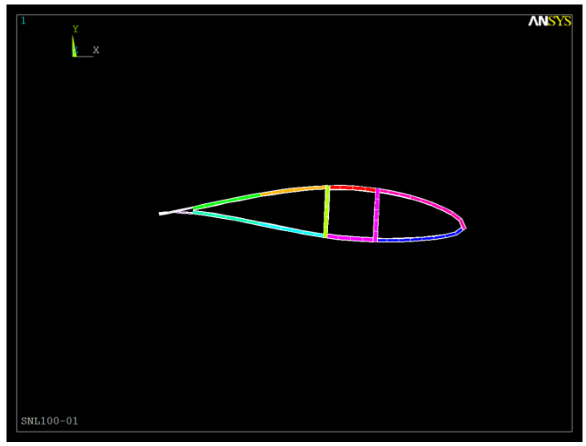
(g) 19.5 meters (maximum chord)



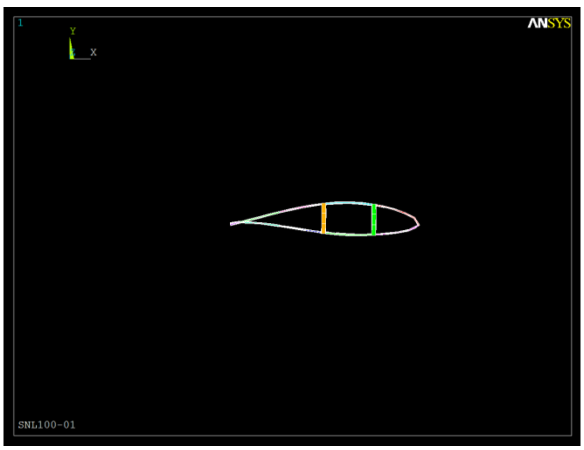
(h) 35.8 meters



(i) 60.2 meters (third web ends)



(j) 73.2 meters



(k) 94.3 meters (principal webs end)

(l) 97.2 meters

Figure 2. Selected Cross-section plots for SNL100-01 (cont'd)

SNL100-01 Bill of Materials Analysis

For the six materials used in this design, which are listed in Table 2, Table 3 and Table 4, their contribution to the total blade weight was calculated using PreComp [13] by omitting one material/laminate at a time. Based on using the FAST code, the total blade weight is 73,995 kg. This analysis was performed for individual laminates and also the traditional bill of materials summary. The bill of materials summary is provided first in Table 6. Here quantities of dry fibers and resin are assessed separately, with the exception of the carbon prepreg material. The resin weight includes only the infused resin, which includes the parasitic resin, but not the resin in the prepreg. The change to carbon spar has a significant effect on the bill of materials as the carbon prepreg replaces a large fraction of uni-directional glass in the baseline SNL100-00 design. Foam core requirements increase slightly in an absolute sense, although their percentage of the total blade weight increases significantly.

Table 6. Bill of Materials for SNL100-01

Material	Description	Mass (kg)	Percent Blade Mass
E-LT-5500	Uni-directional Fiberglass	10,924	14.8%
Saertex	Double Bias Fiberglass	9,368	12.7%
Carbon Prepreg	Conceptual Laminate	10,094	13.6%
EP-3	Infused Resin	26,723	36.1%
Foam	Foam Core	15,948	21.6%
Gelcoat	Coating	927	1.3%

Table 7 provides an analysis of the laminate usage in the design along with total mass and percentage of total blade mass. This provides an assessment of material usage in the various blade components. The table shows that only 2.8% of the blade weight is composed of uni-directional glass laminates used in trailing edge reinforcement. The carbon spar caps are 13.6% of the blade weight. By far, the largest contributor to blade weight are the triaxial laminates in the root buildup and skins with 47.3% of the blade weight. The extra (parasitic) resin accounts for 5,495 kg of the blade weight while the gelcoat accounts for 927 kg. In total, the inclusion of extra resin and gelcoat comprise 8.7% of the total blade weight. The three shear webs were found to total 9,435 kg or 12.8% of the total blade weight. Note that due to numerical errors, a small summation error results in the weight totals for both Table 6 and Table 7 to be 11 kg short of the total blade weight of 73,995 kg (this is less than a 0.02% error).

Table 7. Materials Usage Summary for SNL100-01

Material	Usage/Location	Mass (kg)	Percent Blade Mass
E-LT-5500/EP-3	trailing edge	2,059	2.8%
Carbon Prepreg	Spar cap	10,094	13.6%
SNL Triax/EP-3	Root build-up, internal & external surfaces	35,014	47.3%
Foam	Core panels, shear webs	15,948	21.6%
Resin (parasitic)	extra weight (interior surface)	5,495	7.4%
Saertex/EP-3	Shear webs	4,447	6.0%
Gelcoat	Coating	927	1.3%

SNL100-01 Span-wise Properties

Blade span-wise properties were calculated using the PreComp [13] as implemented within the NuMAD v2.0 Matlab-based graphical user interface. Table 8 lists the blade span-wise properties including flap- and edge-wise EI, EA, GJ, and mass distributions. Additional span-wise information (e.g. airfoil and chord schedules) can be found above or in the file package for SN100-01. The data in Table 8 is also found in the FAST blade input file as described in Table 12.

Table 8. SNL100-01 Span-wise Properties

Station Number	Span Fraction	mass_den	flp_stff	edge_stff	tor_stff	axial_stff	flp_iner	edge_iner
(-)	(-)	(kg/m)	(N-m^2)	(N-m^2)	(N)	(N-m^2)	(kg-m)	(kg-m)
1	0	3620	2.11E+11	2.08E+11	1.09E+11	5.31E+10	14340	14140
2	0.005	2997	1.76E+11	1.73E+11	9.00E+10	4.40E+10	11930	11800
3	0.007	2622	1.53E+11	1.51E+11	7.82E+10	3.85E+10	10350	10340
4	0.009	2256	1.30E+11	1.30E+11	6.66E+10	3.31E+10	8797	8933
5	0.011	1894	1.09E+11	1.10E+11	5.52E+10	2.79E+10	7297	7530
6	0.013	1739	1.03E+11	1.00E+11	5.00E+10	2.61E+10	6626	6905
7	0.024	1857	9.66E+10	9.48E+10	4.57E+10	2.55E+10	6523	6589
8	0.026	1757	8.92E+10	8.85E+10	4.19E+10	2.37E+10	6115	6229
9	0.047	1859	8.54E+10	9.30E+10	4.05E+10	2.43E+10	6005	6864
10	0.068	1891	8.31E+10	9.82E+10	3.91E+10	2.53E+10	5567	7411
11	0.089	1589	7.00E+10	7.81E+10	2.79E+10	2.20E+10	4120	6450
12	0.114	1463	6.01E+10	7.96E+10	2.14E+10	2.22E+10	3118	6367
13	0.146	1100	4.92E+10	5.78E+10	8.54E+09	2.02E+10	1794	4809
14	0.163	1005	4.22E+10	5.60E+10	6.91E+09	1.97E+10	1401	4592
15	0.179	980.1	3.79E+10	5.39E+10	5.35E+09	2.03E+10	1166	4467
16	0.195	979.2	3.65E+10	5.47E+10	4.12E+09	2.22E+10	1004	4424
17	0.222	948.2	3.16E+10	4.99E+10	3.58E+09	2.18E+10	858.9	4144
18	0.249	912.1	2.71E+10	4.39E+10	2.98E+09	2.14E+10	717.9	3759
19	0.276	862.3	2.20E+10	3.79E+10	2.51E+09	2.01E+10	589.1	3327
20	0.358	796.2	1.48E+10	3.16E+10	1.61E+09	1.96E+10	373.2	2702
21	0.439	714.3	9.65E+09	2.20E+10	1.04E+09	1.87E+10	232	1959
22	0.520	645.5	6.24E+09	1.56E+10	6.56E+08	1.81E+10	144	1424
23	0.602	579.6	3.98E+09	1.13E+10	4.13E+08	1.67E+10	89.65	1050
24	0.667	516.3	2.54E+09	8.92E+09	2.70E+08	1.55E+10	56.79	808
25	0.683	489.7	2.17E+09	8.36E+09	2.41E+08	1.45E+10	49	742.7
26	0.732	431.8	1.56E+09	6.90E+09	1.91E+08	1.26E+10	36.08	587.3
27	0.764	369.4	1.12E+09	5.92E+09	1.71E+08	9.84E+09	28.33	479.8
28	0.846	281.3	5.15E+08	4.00E+09	1.21E+08	6.05E+09	16.48	311.1
29	0.894	247.8	3.50E+08	3.12E+09	9.49E+07	4.99E+09	12.17	238.7
30	0.943	188.7	1.47E+08	1.56E+09	4.51E+07	3.65E+09	5.415	114.6
31	0.957	141.1	8.49E+07	9.16E+08	2.63E+07	3.00E+09	2.939	65.1
32	0.972	109.1	3.80E+07	4.23E+08	1.17E+07	2.32E+09	1.31	30.03
33	0.986	71.77	1.00E+07	1.20E+08	3.07E+06	1.53E+09	0.344	8.523
34	1.000	5.941	5.78E+03	6.19E+04	2.22E+03	1.26E+08	0.001	0.004

3. SANDIA LARGE ROTOR DESIGN SCORECARD (SNL100-01)

Design scorecard summary for updated SNL100-01 100-meter blade. Significant design changes from the baseline SNL100-00 blade (see report SAND2011-3779) include: (1) entire spar cap is replaced with carbon, (2) width of spar reduced by 50% with both principal shear webs moved accordingly, (3) root build-up was thinned, (4) trailing edge reinforcements were significantly reduced in thickness (50%) and width (50%), (5) shear web foam core reduced in all three webs (25% reduction), (6) parasitic resin thickness reduced from 5mm to 4 mm.

Table 9. Design Scorecard: Blade Parameters

Parameter	Value
Blade Designation (name)	SNL100-01
Design Wind Speed Class	IB
Blade Length (m)	100
Blade Weight (kg)	73,995
Span-wise CG location (m)	33.1
# shear webs	3
Maximum chord (m)	7.628 (19.5% span)
Lowest fixed base natural frequency (Hz)	0.49 Hz (NuMAD/ANSYS)
Control	Variable speed; collective pitch
Special notes:	Updated design with carbon spar cap starting with SNL100-00 baseline design; 7.2% of blade weight is parasitic/extra weight (resin)

Table 10. Design Scorecard: Blade Design Performance Metrics Summary

Analysis	Design Load Condition (DLC) designation	Metrics	Notes/method
Fatigue	Turbulent Inflow (NTM) (4 to 24 m/s)	202 years fatigue life at 50% span in spar 570 years fatigue life at 15% span in spar 1260 years fatigue life at 24% span in TE	MSU/DOE Database provided single cycle failure values and GL was referenced for slope values (10 for glass and 14 for carbon); Miner's Rule calculation
Ultimate	EWM50; 0 degree pitch with 15 degree yaw error	Max strain = 3525 micro-strain Allowable strain = 5139 micro-strain Max/allowable = 68.6%	At 2% span (near root); flap-wise; FAST
Deflection	ECD-R	Max (10.48 m) vs. allowable (13.67 m); Clearance = 3.19 m = 23.3%	FAST, NuMAD/ANSYS
Buckling	EWM50; 0 degree pitch with 15 degree yaw error	Min load factor (2.077) vs. allowable (2.042); near root to 10 meters span-wise)	Linear, ANSYS
Flutter	--	Flutter margin 1.84 (@ 13.7 RPM)	Sandia NuMAD-based Flutter Tool (BLAST); updated tool since SNL100-00 calculations

Table 11. Design Scorecard: Blade Design Bill of Materials

Material	Description	Mass (kg)	Percent Blade Mass
E-LT-5500	Uni-axial Fiberglass	10,924	14.8%
Saertex	Double Bias Fiberglass	9,368	12.7%
Carbon Prepreg	Conceptual Laminate	10,094	13.6%
EP-3	Epoxy Resin (total)	26,723	36.1%
Foam	Foam core	15,948	21.6%
Gelcoat	Coating	927	1.3%

A few observations are made on the blade parameters and analysis of the Design Scorecard for SNL100-01.

- The blade weight was computed based on the FAST turbine model with a value of 73,995 kg. The mass scaling factor for this design is about 2.6 in comparison to UpWind 5MW model as noted in Reference 2. The same comparison for the all-glass SNL100-00 baseline blade yielded a mass scaling factor of 3.33 as documented in Reference 2.
- The parasitic weight was a bit larger by percentage for SNL100-01. This could be given an additional look within manufacturing considerations as this parasitic mass is over 7% of the total blade weight and potentially more than 7% of the blade cost of materials.
- The fatigue properties for the carbon in this study had a lower single cycle failure stress than for the uni-directional glass as the compression properties were used to be conservative in the fatigue life calculation. However, the slope parameter for carbon was better than for the uni- glass as indicated above. Fatigue properties for candidate carbon materials should be given a close look along with cost and modulus data. Note that in Table 10 the fatigue life estimates noted are the locations with lowest fatigue life.
- In this analysis, the goal fatigue life in the design was 10 times the service life of 20 years, which is of course 200 years. This value was chosen simply to more conservative, although the life estimates can be quite sensitive to design changes. Although a more refined analysis may be prudent for higher fidelity design analyses or other purposes, following this established approach (used for both SNL100-00 and SNL100-01) reduces or eliminates errors in the fatigue life estimate due to uncertainty in method of calculation so that design variants can be compared.
- The Extreme Coherent gust with Direction change at rated speed (ECD-R) was again the driving case for deflection, which is of course an operating case. However, the SNL100-01 design is stiffer having greater margin on tip-tower clearance.
- In this design, yaw errors were considered for the 50-year occurrence wind cases and slightly higher loads were found for these cases.
- Buckling design was driven by the EWM50 load for this design as well, which includes the yaw error condition. Due to root thinning and web thinning in this design, the lowest frequency buckling modes occurred inboard and in the webs. Higher margins on buckling were present in the outboard spar and along the trailing edge.
- Two key factors in the buckling analysis that were changed in the design analysis for SNL100-01 included: (1) a distributed nodal force for the “EWM50 load case with yaw error” was applied in ANSYS to all the blade external surface nodes, which replaced the span-wise point loads approach, and (2) the blade was modeled using 4 node shell elements instead of 8 node shells. Initial studies indicate that the distributed load results in a larger value for the buckling frequency (higher computed buckling capacity) than the point loads approach. The effect of the element type on the buckling solution was reduced through mesh convergence studies. However, this is not to say that both of these along with additional buckling studies could be conducted to further investigate modeling issues associated with buckling solutions for large blades, including an assessment of through the thickness layering design solutions and their accuracy.
- The reported flutter speed was estimated using a new flutter tool under development at Sandia.

4. DESCRIPTION OF ARCHIVED BLADE MODEL FILES FOR SNL100-01

The blade model file package for SNL100-01 includes both the NuMAD [10, 11] blade design files and input files for ANSYS [14] generated by NuMAD. The blade was designed using NuMAD (version 2.0) and analyzed using ANSYS (version 14.0). Table 1 provides a summary of the available model files. Please note that the *.mac files, which are distributed with NuMAD, are also included in this blade file package for convenience as they are needed when reading the *.src files into ANSYS.

Table 12. SNL100-01 Blade Model Files Summary

Filename	Usage	Description
NuMAD.xlsx	Primary input file for Matlab-based NuMAD Code (NuMAD v2.0)	Spreadsheet blade model data including detailed blade geometry, materials, and layup information
SNL100-01.nmd	NuMAD model file	Produced using NuMAD v2.0 with input from NuMAD.xlsx spreadsheet
MatDBsi.txt	NuMAD materials database	Contains material/laminate property information
SNL100-01_FASTBlade_precomp.dat	Can be used with SNL13.2MW FAST turbine model for aeroelastic simulations and design loads analysis	FAST blade file for SNL100-01; Produced using NuMAD v2.0
"airfoils" folder	NuMAD airfoil geometry coordinates	Contains a set of files with coordinates for blade cross section geometries
"docs" folder	documentation	Contains associated documents including most of the references to this report
SNL100-01.src	NuMAD output file; ANSYS model input file	Text file formatted for input to ANSYS to generate a finite element model
master.db	ANSYS database file	Created using SNL100-01.src input to ANSYS
SNL100-01.p3d	Blade external geometry file	Plot 3D file format

The NuMAD input files are useful to investigate blade re-design efforts (e.g. changes in material selection and placement or changes in geometry). NuMAD can produce two types of input files for ANSYS, which include the text input file (*.src) and the ANSYS database file (*.db). A complete set of files for NuMAD and ANSYS is included so that the blade data can be verified by reproduction and also so that modified design solutions can be compared with the provided carbon SNL100-01 design.

The provided files should provide multiple paths for verification of blade model data. For example, SNL100-01.src can be read directly into ANSYS to produce the SNL100-01 finite element model (e.g. "/input, SNL100-01, src").

5. REFERENCES

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