Structural Analysis of the SNL 13m - 225k Blade

Document Number:	169.03.06.001
Document Release Version:	B
Release Date:	2016 April 26
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Client:	Sandia National Laboratories
PO Date:	20 January 2016
PO Number:	42389
Task Number:	3.B. Documentation Revision
Client POC:	Josh Paquette
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Document Approval		
Current Revision Author	A. Escalera	2016 April 22
Current Revision Checked By	A. Tran	2016 April 22
Current Revision Approved for Release By	K. Wetzel	2016 April 23

Revision History

Version	Date	Author	Changes
B	2016 April 22	A. Escalera	Updated after completion of Task 3.C.

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1. Scope of Work and Background

Wetzel Engineering, Inc. has completed the structural analysis of the Sandia 13m blade as designed. This report summarizes the analysis and results for the purpose of supporting a design assessment review by a certification agency.

Details of the geometry of the blade can be found in Appendix A

The structural design of the blade is documented in References 2. Three different structural models of the blade were built for supporting the present analysis:

- A finite element model of the full composite blade.
- An equivalent beam model consisting of finite element models of multiple spanwise sections.
- A detailed sub-model of the blade root for purposes of analyzing the root fastener structure.

The structural models for the full composite blade are described in detail in Appendix B. The material characteristics employed in the current analysis are summarized in Appendix C.

The loads used for the design and analysis of the Sandia 13m blade are provided in Reference 3. 25 different sets of distributed loads were extracted from the analysis and used for structural analysis of the blade provided in Reference3, including the tower closest approach load. Further details of the loads used in the analysis are provided in Appendix D.

The analyses and documentation are conducted and presented as per the requirements of International Electrotechnical Comission (IEC) 61400 standard for wind turbines and per Germanischer Lloyd (GL) Guidelines for the Certification of Wind Turbines Edition 2010.[4] The blade has been designed to demonstrate structural integrity with respect to the following considerations:

- Static strength analyses:
    - Ply-by-ply analysis of the fiber-reinforced structure using Puck (5) or LaRC03 (6) failure criteria for fiber failure and inter-fiber failure
    - Adhesive bond lap shear strength
    - Balsa core out-of-plane shear and compression
- Static stability (buckling), using linear (i.e., eigenbuckling) analyses
- Modal analysis
- Tower Closest Approach Deflection analysis

After completion of Task 3.C. the following modifications were performed to the blade design:

1. Reduced Aft Web length to extend from 2.2 m to 4.2 m.
2. Removed balsa core from the shell in regions between the leading edge and the main sparcap where the width of the region becomes less than 2 inches.
3. Updated root hardware weight and specifications.
4. Updated instrumentation and tip balance weight based on SNL's specifications.

WEI evaluated the static, modal and buckling results after including modifications 1-3 to identify critical changes. No significant changes in the static, modal or buckling results were observed, thus the nominal static, modal or buckling results reflect the results of the release version A of the structural analysis summary report. Modification # 4 includes a reduction of total instrumentation weight from 41.15 kg to 21.86 kg. This results in a significant change is modes, thus this report presents the updated modal analysis results for the blade design that includes modifications 1-4.

2. Results

2.1. Mass, Stiffness, Deformation, and Modal Analyses

The mass distribution of the blade was determined independently using the FEM and the equivalent beam model as well as other internal tools used for modeling the structure during design. All contributors to mass, including non-structural items such as surface finish, are included.

IEC requires the application of a safety factor to the loads for the tower clearance analysis and allows the blade maximum tip deflection to consume the full unloaded tip-tower clearance. For the 225kW turbine operating with the Sandia 13m blade, the permissible maximum tip deflection is approximately 2.436m in proximity to the tower. The original finite element analysis predicts a maximum tip deflection in proximity of the tower of 1.42m. The deformed shape for the original design is illustrated in Figure 1. The equivalent beam model under the same loading predicts a deflection of 1.45m. The stiffness distribution of the blade was taken from the equivalent beam model, as it is significantly easier to extract the results from the sectional analysis than from the full FEM.

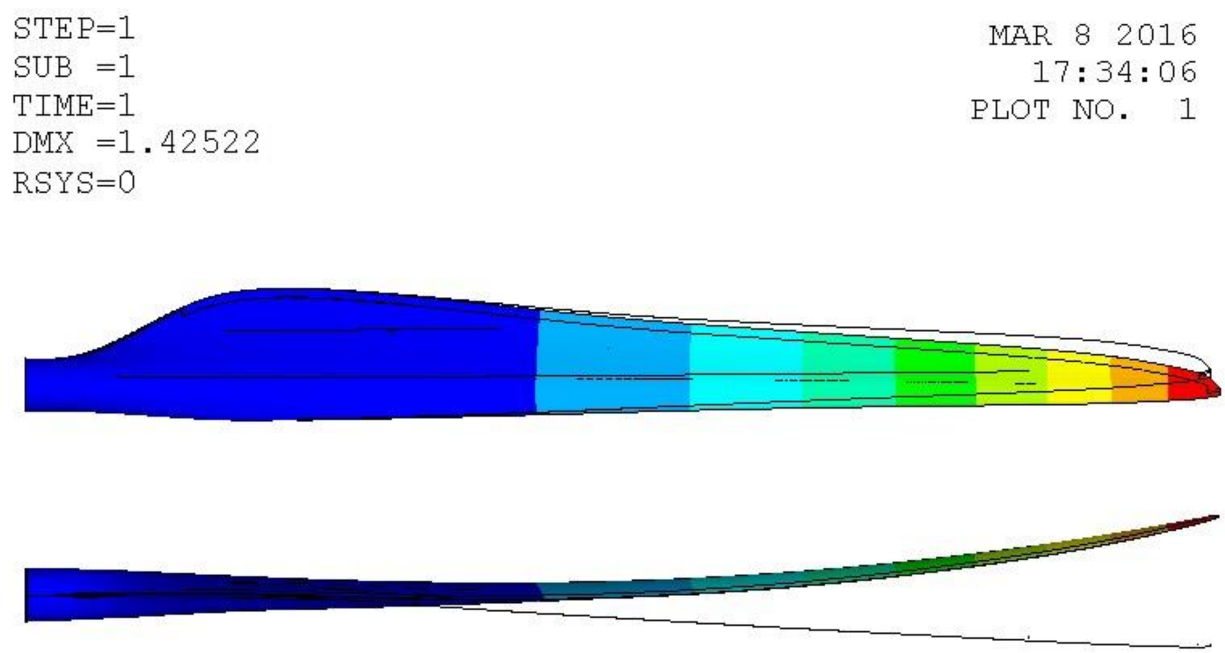


Figure 1. Deformed Shape of Blade Under Tower Closest Approach Loading

Table 1. Summary of Blade Mass and Frequency Characteristics – Without Balance Box

Blade Characteristics		
	Total Blade Mass†	537 kg
	Center of Gravity Location, zcg†	3.92 m
Natural Frequencies (Parked)		
	1st mode, 1st flatwise	2.20 Hz
	2nd mode, 1st edgewise	4.58 Hz
	3rd mode, 2nd flatwise	6.85 Hz
	4th mode, 2nd edgewise	13.44 Hz

† Including Root Inserts

Table 2. Summary of Blade Mass and Frequency Characteristics – With Instrumentation and Removable Tip

Blade Characteristics - With Instrumentation and Removable Tip		
	Total Blade Mass†	559 kg
	Center of Gravity Location, zcg†	4.12 m
Natural Frequencies (Parked)		
	1st mode, 1st flatwise	1.98 Hz
	2nd mode, 1st edgewise	4.20 Hz
	3rd mode, 2nd flatwise	6.16 Hz
	4th mode, 2nd edgewise	12.21 Hz

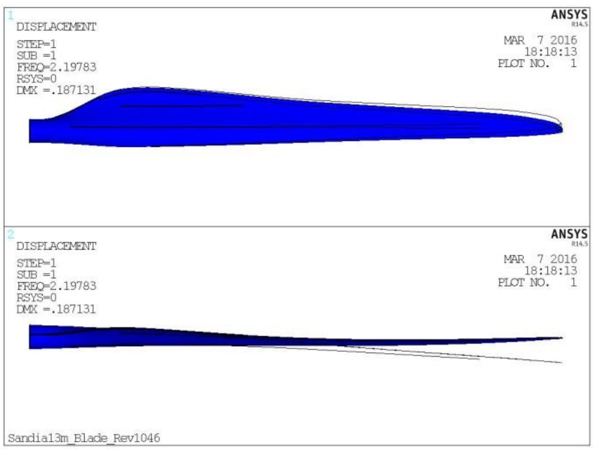
† Including Root Inserts

Table 3. Summary of Blade Distributed Structural Characteristics

Spanwise Station (along s-curve)	Spanwise Station (along pitch-axis)	Edgewise Stiffness	Flapwise Stiffness	Torsional Stiffness	Structural twist	Mass per unit length
s [m]	z [m]	EI_{edge} [Nm^2]	EI_{flap} [Nm^2]	GJ [Nm^2]	ϕ [°]	dm/dz [kg/m]
0.000	0.000	1.01E+08	1.01E+08	5.18E+07	0.00	339.37
0.125	0.125	1.01E+08	1.01E+08	5.18E+07	0.00	339.37
0.250	0.250	1.01E+08	1.01E+08	5.18E+07	0.00	237.10
0.670	0.670	2.74E+07	2.01E+07	6.90E+06	13.30	50.92
0.850	0.850	2.35E+07	1.75E+07	6.88E+06	14.48	47.39
1.525	1.525	3.12E+07	1.36E+07	6.89E+06	15.63	52.15
2.200	2.200	3.65E+07	1.04E+07	5.43E+06	15.89	53.21
2.605	2.605	3.66E+07	8.88E+06	4.53E+06	15.84	52.73
3.482	3.481	3.13E+07	6.10E+06	2.98E+06	14.67	49.87
4.443	4.441	2.43E+07	4.24E+06	1.84E+06	12.52	44.97
5.458	5.455	1.77E+07	2.75E+06	1.18E+06	10.22	38.81
6.115	6.112	1.43E+07	2.13E+06	8.73E+05	9.16	35.44
7.023	7.019	1.08E+07	1.53E+06	6.14E+05	8.02	31.36
7.542	7.537	9.31E+06	1.22E+06	5.23E+05	7.47	29.02
8.054	8.049	8.04E+06	9.88E+05	4.45E+05	7.02	26.76
8.950	8.944	6.13E+06	6.36E+05	3.31E+05	6.49	22.94
9.518	9.511	5.12E+06	4.59E+05	2.76E+05	6.17	20.63
10.402	10.394	3.52E+06	2.38E+05	1.85E+05	5.87	17.01
11.184	11.176	1.54E+06	1.04E+05	1.19E+05	5.94	13.56
11.650	11.641	1.05E+06	5.15E+04	8.56E+04	6.00	11.74
12.125	12.116	4.79E+05	2.01E+04	3.42E+04	5.99	9.92
12.460	12.451	2.61E+05	8.97E+03	1.74E+04	5.86	8.51
12.738	12.728	9.08E+04	3.08E+03	5.22E+03	5.58	7.01
12.865	12.855	2.83E+04	9.52E+02	1.28E+03	5.29	6.00
12.947	12.937	1.54E+03	5.36E+01	1.85E-01	4.84	2.00
13.000	12.990	1.65E+02	5.69E+00	8.77E-02	4.52	0.89

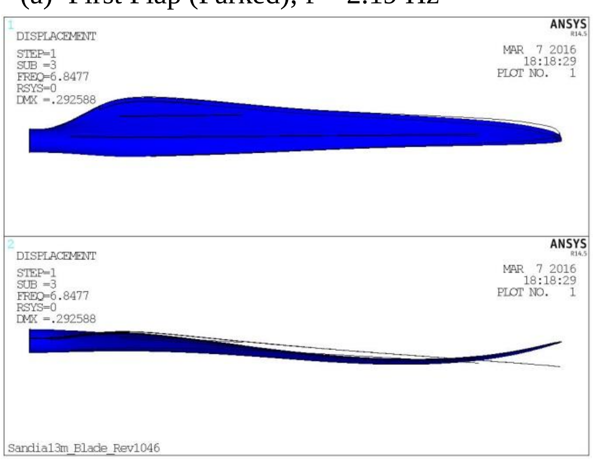
Notes: Distributed mass includes root inserts but not root studs

A modal analysis was conducted using ANSYS FEM software and an equivalent beam model to determine the natural frequencies and mode shapes. The first four modes of the model without instrumentation and the removable tip are illustrated in Figure 2. The fundamental first natural flapwise frequency of this model 2.19Hz. The estimated first natural flapwise frequency calculated by using the differential scalar between parked and rotating frequencies according to the equivalent beam model is 2.48Hz, which is positioned below the 3P blade passage frequency of 2.6Hz at rated shaft speed of 52rpm. The other modes are sufficiently outside of the 4P, 6P, and 9P blade passage frequencies, with a minimum 8% margin with respect to 9P. Tables 1-2 present the mass and frequency characteristics for the blade itself and for the blade with instrumentation and the additional weight of a removable tip. The addition of instrumentation and a removable tip reduce the fundamental first natural flapwise frequency by 10% and the fundamental first natural edgewise frequency by 8%, placing the rotating frequencies sufficiently outside of 3P, 4P, 6P and 9P blade passage frequencies. However, as a result of the additional weight, the rotating first natural edgewise frequency falls right below 5P.

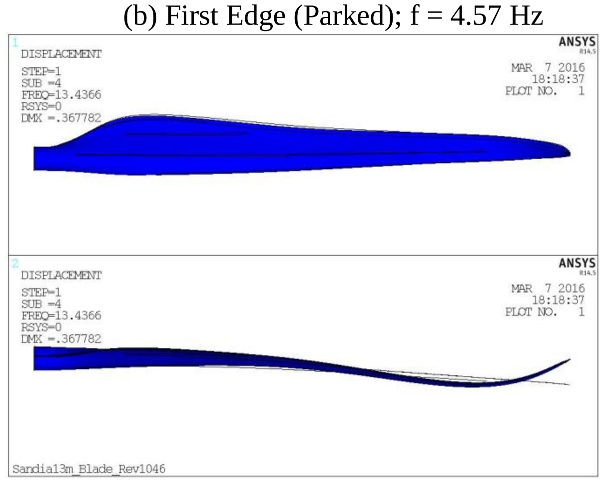


(a) First Flap (Parked); f = 2.19 Hz

(b) First Edge (Parked); f = 4.57 Hz



(c) Second Flap (Parked); f = 6.85 Hz



(d) Second Edge (Parked); f = 13.44 Hz

Figure 2. Static Mode Shapes, Sandia 13m Blade (no instrumentation or removable tip weight)

2.2. Static Strength

Static stresses in the blade were determined using the FEA results for loading under all of the 24 Polar Load Sets. Material allowable strengths used for design purposes were adjusted by the combined safety factors as required by GL (summarized in Appendix C). For the glass fiber-reinforced materials, the strength was assessed on a ply-by-ply basis. Unidirectional glass fabrics and multi-axial glass fabrics were analyzed for FF and IFF using the LaRC03 criteria.[6] Homogeneous materials, including the adhesives and the balsa core, were analyzed using a Maximum Stress criteria with respect to the applicable component of stress. All materials exhibit positive margins, as summarized in Table 4.

Table 4. Summary of Static Stress Results, All Materials

	Location	Material	Failure Mode	Reserve Margins
Stress	Shell	E-Glass DB	+/-45 Fiber Failure +/-45 Interfiber Failure	37% 38%
	Shell	E-Glass UD	0 Fiber Failure 0 Interfiber Failure	37% 38%
	Main Girder	E-Glass UD	0 Fiber Failure 0 Interfiber Failure	68% 33%
	Trailing Edge Girder	E-Glass UD	0 Fiber Failure 0 Interfiber Failure	165% 217%
	Main Web	Glass - Double Bias	+/-45 Fiber Failure +/-45 Interfiber Failure	166% 238%
	Aft Web	Glass - Double Bias	+/-45 Fiber Failure +/-45 Interfiber Failure	198% 127%
	Shell	Balsa	Out-of-plane Compression	9486%
Shear	Main Web	Glass Glass-Balsa	ILSS at Glass-Glass Interface ILSS at Glass-Core Interface	8802% 8802%
	Aft Web	Glass Glass-Balsa	ILSS at Glass-Glass Interface ILSS at Glass-Core Interface	4073% 4073%

2.3. Adhesive Bond Strength

Lap shear stresses of the adhesive bonds between the pressure and suction surfaces of the blade (at the trailing edge and leading edge), as well as between the webs and the inner skin, have been analyzed. Germanischer Lloyd provides a characteristic lap shear strength for adhesive bonds of 7MPa, a value GL indicates may be used without further verification.[4] Material specifications agreed upon by Sandia in Reference 7 denote a characteristic lap shear strength of 7MPa. GL also prescribes combined safety factors for lap shear strength that multiply to 2.23 for post-cured bonds.[4] This results in an allowable lap shear strength for design calculations of 3.14MPa. The reserve margins shown in Figure 3 are against the 7MPa strength, less the safety factors. The average lap shear in the bond peaks at 2.64MPa. The adhesive lap shear results have been averaged across the bond width.

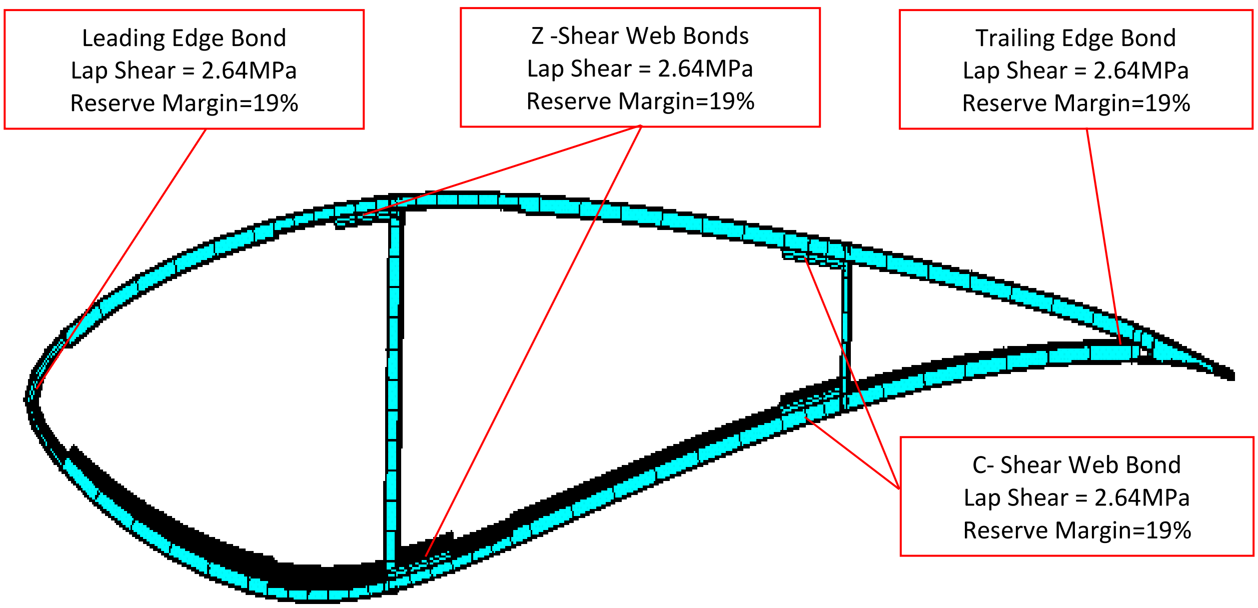


Figure 3. Adhesive Bond Lap Shear Strength Analysis of the Sandia 13m Blade

2.4. Static Stability (Buckling)

WEI subjects the blade to a linear analysis to determine the eigenvalue based on the following:

- For regions in the main spar cap or inboard/outboard of the main girder centerline
  Minimum Eigen Value = 1.35*1.1*1.1*1.25*1.1 = 2.25
- For sandwich core regions = 1.35*1.1*1.1*1.25 = 2.04

As shown below, for the linear analyses, all load sets satisfy the 2.25 minimum eigenvalue requirement for regions in and next to the main spar cap and the 2.04 minimum eigenvalue for sandwich core regions.

Table 5. Summary of Buckling Results for the Sandia 13m Blade

	Linear Analysis - In main girder or inboard/outboard of the main girder centerline		Linear Analysis - Everywhere else in the blade	
Design Load	Buckling Load Factor	Margin of Safety	Buckling Load Factor	Margin of Safety
0	N/A	N/A	13.31	504%
15	N/A	N/A	6.91	214%
30	4.48	99%	4.48	103%
45	3.16	40%	3.16	43%
60	2.50	11%	2.50	13%
75	2.26	1%	N/A	N/A
90	2.29	2%	N/A	N/A
105	2.79	24%	N/A	N/A
120	3.94	75%	N/A	N/A
135	N/A	N/A	5.84	165%
150	N/A	N/A	7.10	222%
165	N/A	N/A	10.57	380%
180	N/A	N/A	12.41	463%
195	N/A	N/A	8.33	278%
210	5.98	166%	5.98	171%
225	4.43	97%	4.43	101%
240	3.77	68%	3.77	71%
255	3.51	56%	3.51	59%
270	3.68	63%	3.68	67%
285	4.46	98%	4.456	102%
300	6.23	177%	6.232	183%
315	N/A	N/A	9.991	353%
330	N/A	N/A	20.317	822%
345	N/A	N/A	24.85	1027%

3. References

1. Wetzel Engineering, Inc., 3D CAD Model 169.02.01.001, Revision A1, Sandia 13 m Blade Loft, 4 February 2016.
2. Wetzel Engineering, Inc., Document 169.05.02.001, Revision B, Sandia 13m Blade Aero+Structure Design Summary, 22 April 2016.
3. Wetzel Engineering, Inc., Document 169.06.02.05, Revision A, Ultimate Loads Sandia 13m Blade, 9 March 2016.
4. Germanischer Lloyd, Guideline for the Certification of Wind Turbines, Edition 2010.
5. Wetzel Engineering, Inc., Report 98.05.03.001, Puck Failure Criteria, 02 November 2012.
6. Wetzel Engineering, Inc., Report 98.05.03.002, LaRC03 Failure Criteria, 02 November 2012.
7. Wetzel Engineering, Inc., Report 169.03.03.001, Revision A, Sandia 13m Blade Materials and Test Standards, 2 February 2016.

A. Appendix A: Geometry of the Sandia 13m Blade

Key details of the blade geometry are summarized in Table 6. Reference 1 contains the three-dimensional CAD models of the blade surface geometry. Further details of the blade geometry can be found in Reference 2, the Aero-Structural summary for the blade.

Table 6. Summary of Key Geometry of the Sandia 13m Blade

General Geometry		
	Blade Length	13.000 m
	Position of Largest Chord, LC-L*	2.605 m
	Length of Largest Chord, LC-C	1.473 m
	Position of 96% Length, L96%-L*	12.46 m
	Length of L96%-L Chord, L96%-C	0.375 m
Blade Root Geometry		
	Outer Diameter	0.578 m
	Inner Diameter	0.450 m
	Wall Thickness	0.070 m
	Fastener Type	Embeds
	Bolt Circle Diameter	0.508 m
	Bolt Count	24
	Bolt Size	M24
Shear Web Geometry		
	Number of Webs	2
	Start of Web 1, SW1-L1*	1.000 m
	Chordwise Location of Web 1 at start, SW1-CP1**	0.013 m
	End of Web 1, SW1-L2*	11.000 m
	Chordwise Location of Web 1 at end, SW1-CP2**	0.013 m
	Start of Web 2, SW2-L1*	2200 m
	Chordwise Location of Web 2 at start, SW2-CP1**	0.550 m
	End of Web 2, SW2-L2*	4200 m
	Chordwise Location of Web 2 at end, SW2-CP2**	0.550 m

* spanwise station along the arclength of the blade

** measured from centerline to aft surface of web, towards leading edge

The following is a summary of the key characteristics of the blade construction:

- The blade is constructed of E-glass infused with epoxy resin and includes ~160 kg/m^3 (dry) balsa wood as core for sandwich constructions.
- The primary load-carrying components include two spar caps embedded between the inner and outer blade shells.
- The spar caps are constructed of unidirectional E-glass fabric infused with epoxy resin. The spar caps will be laid as dry glass layers between in between the outer and inner shell layers and co-infused.
- The trailing edge of the blade is reinforced with a separate spar cap that is composed of unidirectional E-glass fabric. This girder will be laid as dry glass layers between in between the outer and inner shell layers and co-infused.
- All structural components of the blade are fabricated using a vacuum-assisted resin infusion process (VARIM).
- The skin of the blade is constructed using a combination of unidirectional and double-bias (±45º) E-glass fabrics.
- Loads are transferred from the central spar to the root of the blade by tapering down the thickness of the spar caps towards the root while increasing the thickness of the skin glass material in the shell. This occurs primarily in the transition region of the blade between the cylindrical root and the location of the maximum chord.
- The blade root is comprised of 24 count M24 embeds, attached to embedded female inserts with outer diameter equal to 36mm. Adhesive bond line is 5mm thick between the metallic inserts and the glass root.

B. Appendix B. Description of the Finite Element Model

B.1. Finite Element Mesh

A detailed finite element model of the Sandia 13m blade was produced using the ANSYS commercial finite element software, version 14.5.7. The geometry of the blade is taken from Reference 1. The main shells were meshed using 4-node layered shell elements (SHELL181). The trailing edge was meshed with 8-node bricks (SOLID185) so that the adhesive bonds could be modeled. The FEM consists of a total of 82821 elements and 79210 nodes. The blade was meshed with a nominal element size of 10mm from the root to blade station 7010 at which point the nominal element size is increased to 20mm for the remainder of the blade. Figure 4 provides an overview of the FEM model used for analysis. The blade was divided circumferentially into 22 regions, as summarized in Table 7.

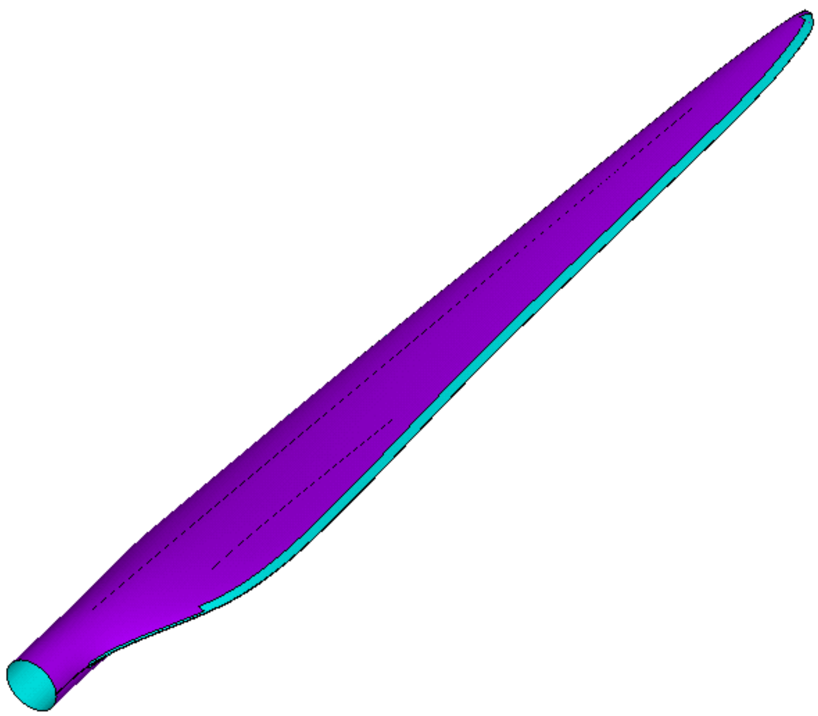


Figure 4. Finite Element Model of the WEI11.65-100K-B Blade

Table 7. Summary of Main Shell Regions for Laminate Definition

Region		Description
Pressure Surface	Suction Surface	
1	22	Skin + Trailing Edge Tape + Adhesive
2	21	Skin + Trailing Edge Tape + Adhesive
3	20	Skin + Trailing Edge Tape + Balsa Core
4	19	Skin + Balsa Core (between Aft Web and Trailing Edge Tape)
5	18	Skin + Balsa Core + Aft Web Bond Strip
6	17	Skin + Balsa Core (between Aft Web Bond Strip and Main Spar Cap)
7	16	Skin + Spar Cap (aft of Main Web) - no bond
8	15	Skin + Spar Cap (aft of Main Web) - bond strip*
9	14	Skin + Spar Cap (fore of Main Web) - no bond
10	13	Skin + Balsa Core (between Spar Cap and Leading Edge Bond Strip)
11	12	Skin + Leading Edge Bond Strip + Adhesive

*** The model includes a Z web, in which the bond strip is fore of Main Web in the Suction Side and aft of the Main Web in the Pressure Side.**

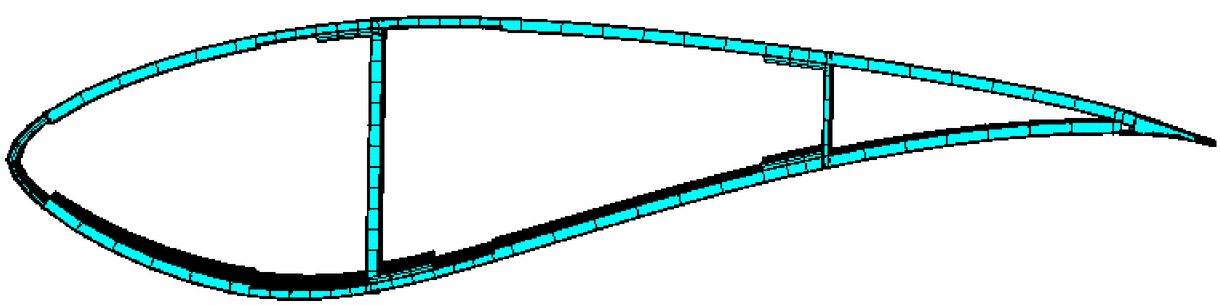


Figure 5. Finite Element Model Detail

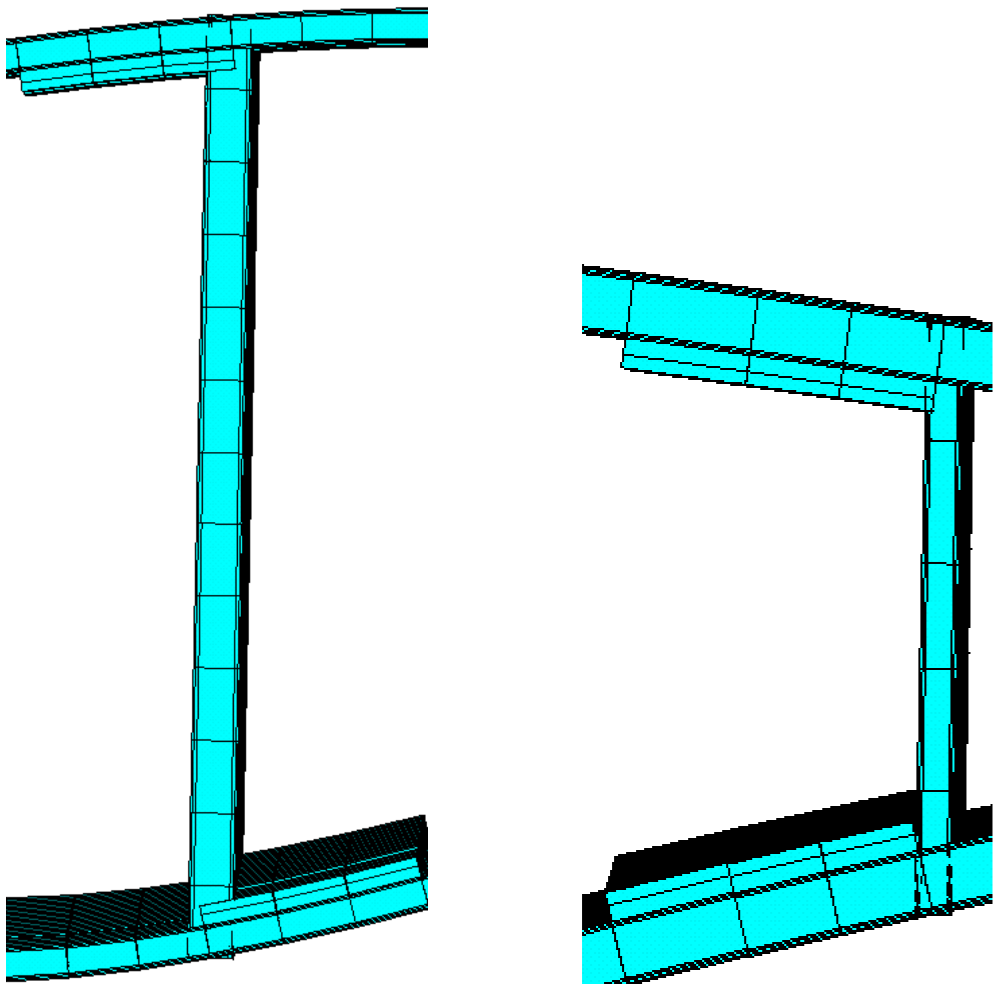


Figure 6. FEM Detail – Left: Main Z Web; Right: Aft C Web

B.2. Equivalent Beam Model

WEI complements the full blade FEA with an equivalent beam model tool. We utilized an in-house blade section analysis tool to analyze the blade structure at multiple, distinct spanwise sections. Each section contour is divided into a number of regions (20 in the present study), and the laminate structure in each region is defined. The code meshes the cross-section of the laminated structure with nine-node two-dimensional elements. The output from the blade section model are 4x4 beam-equivalent stiffness and compliance matrices (including axial tension, edgewise bending, flapwise bending, and torsional degrees of freedom) and the 6x6 inertial matrix. These matrices can be used to construct an equivalent beam model of the blade suitable for dynamic simulations. If sectional loads are provided, the program will also calculate full strain fields on all elements and find the maximum strain values for all components for all materials. WEI finds exceptional agreement between this model and the full FEA, generally within 1-2% in strain estimation. Similarly, modal and deflection analyses are in agreement between the FEA and equivalent beam models.

C. Appendix C. Materials

Material properties used in the present analysis are as per agreement with NPS, which can provide separate documentation to support the properties employed. Reference 7 provides the agreed upon material specifications.

The material models employed in the present analysis have reduced characteristic strengths for static strength analyses. These factors are given by γ_{ma}=2.205 for R_{11} and γ_{IFF}=1.688 for R_{12} and R_{22}.

As per GL, the multi-axial fiber-reinforced materials are analyzed on a first-ply failure basis, ply-by-ply. As such, each ply is analyzed as an oriented unidirectional. The strength characteristics of the unidirectional glass are used for this analysis. However, we are employing the LaRC03 criteria for analyzing the multi-axial materials. Reference 6 provides details regarding LaRC03 criteria. It uses the fracture toughness of the composite to improve the failure prediction of the matrix-dominated failure modes. As of publication of this report, NPS has not yet performed testing for fracture toughness. Therefore, we have employed a procedure to use the LaRC03 criteria to back out the fracture toughness[6].

Table 8. Fracture Toughness Values for Glass used in Analysis

Parameter	Unfactored	Factored per GL	Units
Mode 1 Fracture Toughness, G_{IC}	200	48	J/m^2
Mode 2 Fracture Toughness, G_{IIC}	800	170	J/m^2
Fracture Plane Angle	46	46	Degrees

D. Appendix D. Loads

25 different sets of distributed loads were extracted from the Blade Loads Analysis (Reference 3) and used for structural analysis of the blade. For each of those sets, the maximum load at each spanwise station across the 3 blades was found. The resultant maximum distributed polar load set for each of the load sets is plotted in Reference 2. The design loads are labeled according to the orientation of the polar load relative to the leading edge and represent polar loads of 15° intervals.

The loads are applied to the FEM as discrete point loads applied to a number of nodes at each station, shown in Figure 7. The loads are distributed uniformly across all of the spar cap nodes at each station.

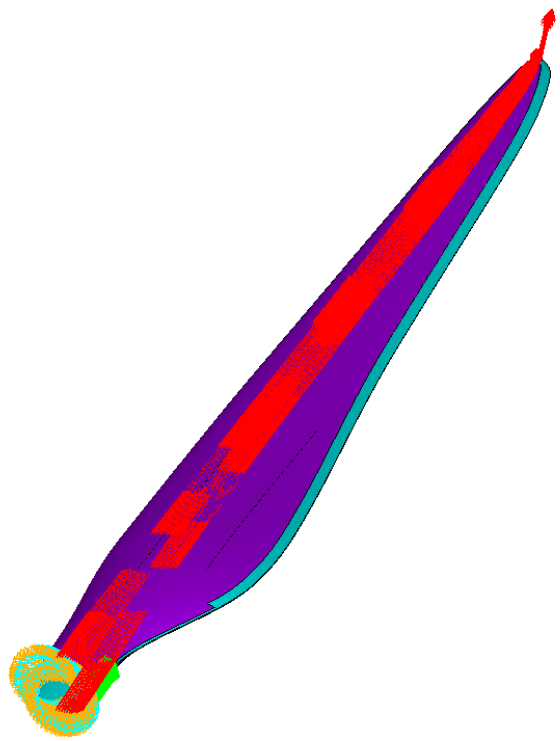


Figure 7. Application of Point Loads to the FEM