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Definition of a 5MW/61.5m Wind Turbine Blade Reference Model

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Abstract

A basic structural concept of the blade design that is associated with the frequently utilized "NREL offshore 5-MW baseline wind turbine" is needed for studies involving blade structural design and blade structural design tools. The blade structural design documented in this report represents a concept that meets basic design criteria set forth by IEC standards for the onshore turbine. The design documented in this report is not a fully vetted blade design which is ready for manufacture. The intent of the structural concept described by this report is to provide a good starting point for more detailed and targeted investigations such as blade design optimization, blade design tool verification, blade materials and structures investigations, and blade design standards evaluation. This report documents the information used to create the current model as well as the analyses used to verify that the blade structural performance meets reasonable blade design criteria.

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TABLES

NOMENCLATURE

BPE	Beam Property Extraction
c	Distance from the elastic center to the mid-thickness of blade skin (thin skin)
C	Single cycle material strength
CFD	Computational Fluid Dynamics
CRP	Carbon Reinforced Polymer
DB	Double-Bias material
DLC	Design Load Case
DOE	Department of Energy
DOWEC	Dutch Offshore Wind Energy Converter
E	Young’s modulus
ECD	Extreme Coherent gust with Direction change
EI	Section stiffness; defined in Equation (2)
ETM	Extreme Turbulence Model
EWM	Extreme Wind Model
EWS	Extreme Wind Shear
FE	Finite Element
G	Shear modulus
GRP	Glass Reinforced Polymer
GUI	Graphical User Interface
LE	Leading edge
M	Bending moment
NACA	National Advisory Committee for Aeronautics
NREL	National Renewable Energy Laboratory
NTM	Normal Turbulence Model
S	Material stress
SNL	Sandia National Laboratories
TE	Trailing edge
UCS	Ultimate Compressive Strength
UD	Uni-Directional material
UTS	Ultimate Tensile Strength
ε	Strain
nu	Poisson ratio

INTRODUCTION

The NREL offshore 5MW baseline wind turbine is used extensively in studies by the wind energy research community as system that represents the current and future state of the art in an offshore HAWT system [1]. The baseline turbine concept has supported numerous investigations in topics including aerodynamics, controls, offshore dynamics and design code development.

The blades of the NREL reference turbine model are 61.5m long and weigh 17,740kg. They are described in the NREL reference turbine model by only their distributed structural properties. A basic structural layup concept for this blade is needed in studies involving blade structural design and blade structural design tools. The blade structural design presented in this report represents a concept that meets the most basic design criteria set forth by IEC standards for the onshore version of this turbine. The intent and goal of the structural concept described by this report is to provide a good starting point for more detailed and targeted investigations such as

- blade design optimization,
- blade design tool verification,
- materials and structures studies, and
- blade design standards evaluation.

While many considerations are included in the definition of the material layup in order to arrive at a reasonable design that can be used for the task listed above, the design is intentionally crude. The design is not a fully vetted blade design which is ready for commercial use.

- Material properties used in the model are representative of only generic materials.
- Safety factors for material strengths and loads are defined using a simple approach that is based on IEC [2]. Design to other standards may produce different results.
- Definition of layups is not guaranteed to be consistent with manufacturing best practices.

This report documents the information used to create the model as well as the analyses used to verify that the blade structural performance meets reasonable blade design criteria.

The blade model described here has been created using Sandia's NuMAD design tool [3]. Design loads were computed using the NREL NWTC suite of Design Codes.

APPROACH

Creation of this 5MW blade structural concept takes advantage of existing blade geometry data from the DOWEC study, a composite layup concept from the UpWind program [4] and layup and materials information from the Sandia National Laboratories 100-meter blade [5]. Analyses of the initial 61.5m model were performed in order to evaluate the blade concept with respect to some standard design load cases. A manual, iterative optimization process was used to refine the materials placement within the specified blade geometry in order to meet the stated design criteria. These analyses are documented in a later section of this report.

The current blade model went through several iterations before meeting required criteria. The initial layup is based on a scaled version of the strategy employed by the Sandia 100m-00 blade model. Changes are made based on results of aeroelastic simulations of the IEC load cases as well as buckling behavior. Following is a brief list of design philosophies used to meet each of the required criteria:

- Buckling – Aft panel foam thickness is the main driver for buckling. Also, inboard shear web thickness is set to avoid shear web buckling. Early design iterations had issues with spar cap buckling near both max chord and outboard, about 80% span. Resistance to spar cap buckling is improved by using a narrow spar cap and by ensuring adequate thickness of carbon.
- Fatigue – When fatigue damage computations indicate material failure, additional material is added in order to increase the section stiffness and reduce strains.
- Tower clearance – Early iterations of the blade design had an issue with tower strike.[i] Overall blade stiffness increases by addition of more UD carbon material to the spar cap.
- Weight – Each of the design iterations described above involve addition of material to the blade. In an effort to keep weight near the desired target, material is gradually removed from the following areas throughout the iteration process: leading edge panel foam, trailing edge reinforcement and blade root reinforcement.

The outcome of the entire design process is the blade design that is documented in this report.

Blade Geometry

The airfoils and chord schedule used in the development of 61.5 meter models in the NREL study [1] and also the UpWind study [6] were adopted from the DOWEC study [7, 8]. The reported DOWEC airfoil schedule is listed in Table 1. The TU-Delft family of airfoils was used with thickness to chord (t/c) ratios of 40.5% at maximum chord down to 21% at approximately two-thirds span. NACA 64-series airfoils were used in the final one-third blade span. No transition airfoils were reported between the root circle and airfoil at maximum chord and had to be developed for the current blade geometry.

[i] Depending on model settings, the blade definition included with the NREL 5MW reference turbine model could have an issue with tower strike during the ECD load case at rated speed. Further investigation is needed to confirm.

More detailed information on the DU family of airfoils used here can be found in the article by Timmer [9]. Use of DU airfoils for reasons other than research studies should be vetted with Delft University.

The reported NREL 5MW airfoil and chord schedule is shown in Table 2 and Table 3.

Table 1: Airfoil schedule for DOWEC 64.5m blade.

Airfoil Designation	Thickness (t/c)	Begin Radius (m)
Cylinder1	100%	1.8
Cylinder2	100%	5.98
DU40_A17	40.5%	10.15
DU35_A17	35.09%	15.00
DU30_A17	30%	20.49
DU25_A17	25%	26.79
DU21_A17	21%	34.22
NACA64_A17	18%	42.47

Table 2: NREL 5MW chord, twist, and shape distribution

RNodes (m)	AeroTwst (deg)	Chord (m)	Airfoil Table ID
2.8667	13.308	3.542	1
5.6	13.308	3.854	1
8.3333	13.308	4.167	2
11.75	13.308	4.557	3
15.85	11.48	4.652	4
19.95	10.162	4.458	4
24.05	9.011	4.249	5
28.15	7.795	4.007	6
32.25	6.544	3.748	6
36.35	5.361	3.502	7
40.45	4.188	3.256	7
44.55	3.125	3.01	8
48.65	2.319	2.764	8
52.75	1.526	2.518	8
56.1667	0.863	2.313	8
58.9	0.37	2.086	8
61.6333	0.106	1.419	8

Table 3. Translation of airfoil table name and blade profile name.

Airfoil Table ID	AeroDyn File	Blade Section Shape
3	DU40_A17.dat	DU W-405
4	DU35_A17.dat	DU W-350
5	DU30_A17.dat	DU 97-W-300
6	DU25_A17.dat	DU 91-W2-250
7	DU21_A17.dat	DU 91-W-210
8	NA64_17.dat	NACA 64-618

It is important to note that Chow [10] has created a detailed blade surface geometry that represents a 5MW wind turbine blade. Chow's geometry is based on information obtained from a variety of professional contacts. His geometry was created for the purpose of CFD analysis, thus the need for a high quality surface definition. In the current work, which focuses on structural characteristics, the overall geometry is important but details such as tip and root geometries are not as critical as they are for CFD. The blade geometry documented here is based purely on a geometry that can be determined by studying the public and readily available NREL 5MW model information, which is summarized in Table 2 and Table 3. Table 4 shows the blade station parameters used for the current blade model in NuMAD.

Table rows in bold correspond directly to aerodynamic nodes in the NREL 5MW model AeroDyn input file. Asterisks in the table indicate a need for additional explanation as follows:

- X-offset[ii] values were set in order to meet two goals: 1) center the box spar at a chordwise location which generally matches with the airfoils' maximum thickness and 2) produce a planform shape that is realistic. Smaller values for x-offset produce a swept-back leading edge, relative to the specified root diameter. A smaller root diameter would enable smaller x-offset values along the outboard blade.
- Original station information at 18.45m blade span (Table 2) implies use of the DU99-W-350 airfoil shape as well as specified values for twist and chord. A very smooth spanwise blade thickness distribution is obtained when the shape and chord at this blade span is instead determined by interpolation using adjacent stations.
- Original station information at 6.8333m blade span (Table 2) implies use of the DU99-W-405 airfoil shape as well as specified values for twist and chord. A very smooth spanwise blade thickness distribution is obtained when the shape and chord at this blade span is instead determined by interpolation using adjacent stations.
- The chord length at the blade tip in this model is arbitrary. In reality, the geometry at the blade tip would be defined in great detail. A chord length of 1.0855m is chosen here in order to be compatible with NuMAD's BPE capabilities. A pointed tip (quickly tapering chord) is not conducive to the way BPE applies forces and moments to the tip of the blade model.

[ii] The x-offset parameter in NuMAD is equivalent to pitch axis location and is also sometimes referred to as the blade reference axis.

- Aerodynamic center at each station is assumed to be located at x/c=0.275 and 0.50 for airfoil shapes and for circular shapes, respectively. Values are interpolated in the transition between circular section and airfoil section.
- NuMAD represents stacks of materials as constant thickness between one station and the next. In order to more accurately represent ply drops, intermediate stations are added to the model. Interpolated shapes in the table, indicated by shape designation *interp*, are placed in the model in order to encourage a higher resolution representation of the fabric ply drops along the span of the blade. Shapes for stations designated with *interp* have been generated by a process that uses information from four adjacent (non-*interp*) stations to come up with an intermediate shape. The following criteria are met by the interpolated shape: 1) camber line trends are preserved and 2) overall blade thickness distribution is represented as smoothly as possible.
- The indication of a "flat" trailing edge (TE) type in Table 4 is used to represent the finite trailing edge that is represented in the DU airfoil coordinate data. These airfoils are not actually "flatback" airfoils in the sense that they have had their aft surfaces spread apart in an effort to increase structural efficiency. Refer to the NuMAD User's Guide [3] for more information on the topic of airfoil trailing edge representations.

Table 4: NuMAD station parameters for the Sandia 61.5m blade.

Blade span (m)	Rotor Radius (m)	Blade Section Shape; NuMAD Airfoil File	TE Type	Twist (deg)	Chord (m)	X-offset* (-)	Aero. Center* (-)
0	1.5	circular	round	13.308	3.386	0.5	0.5
0.3	1.8	circular	round	13.308	3.386	0.5	0.5
0.4	1.9	interp	round	13.308			
0.5	2	interp	round	13.308			
0.6	2.1	interp	round	13.308			
0.7	2.2	interp	round	13.308			
0.8	2.3	interp	round	13.308			
1.3667	**2.8667**	**circular**	**round**	**13.308**	**3.386**	**0.5**	**0.5**
1.5	3	interp	round	13.308			
1.6	3.1	interp	round	13.308			
4.1	**5.6**	**interp**	**round**	**13.308**			
5.5	7	interp	round	13.308			
6.8333	**8.3333**	**interp***	**flat**	**13.308**			
9	10.5	interp	flat	13.308			
10.25	**11.75**	**DU99-W-405**	**flat**	**13.308**	**4.557**	**0.4**	**0.275**
12	13.5	interp	flat				
14.35	**15.85**	**DU99-W-350**	**flat**	**11.48**	**4.652**	**0.4**	**0.275**
17	18.5	interp	flat				
18.45	**19.95**	**interp***	**flat**	**10.162**			
20.5	22	interp	flat				
22.55	**24.05**	**DU97-W-300**	**flat**	**9.011**	**4.249**	**0.4**	**0.275**
24.6	26.1	interp	flat				
26.65	**28.15**	**DU91-W-250**	**flat**	**7.795**	**4.007**	**0.4**	**0.275**
30.75	**32.25**	**DU91-W-250**	**flat**	**6.544**	**3.748**	**0.4**	**0.275**
32	33.5	interp	flat				
34.85	**36.35**	**DU93-W-210**	**flat**	**5.361**	**3.502**	**0.4**	**0.275**
37	38.5	interp	flat				
38.95	**40.45**	**DU93-W-210**	**flat**	**4.188**	**3.256**	**0.4**	**0.275**
41	42.5	interp	sharp				
42	43.5	interp	sharp				
43.05	**44.55**	**NACA-64-618**	**sharp**	**3.125**	**3.01**	**0.4**	**0.275**
45	46.5	interp	sharp				
47.15	**48.65**	**NACA-64-618**	**sharp**	**2.319**	**2.764**	**0.4**	**0.275**
51.25	**52.75**	**NACA-64-618**	**sharp**	**1.526**	**2.518**	**0.4**	**0.275**
54.6667	**56.1667**	**NACA-64-618**	**sharp**	**0.863**	**2.313**	**0.4**	**0.275**
57.4	**58.9**	**NACA-64-618**	**sharp**	**0.37**	**2.086**	**0.4**	**0.275**
60.1333	**61.6333**	**NACA-64-618**	**sharp**	**0.106**	**1.419**	**0.4**	**0.275**
61.5	63	NACA-64-618	sharp	0	1.0855*	0.4	0.275

Table 5: Summary of material properties.

	Layer Thickness	Ex	Ey	Gxy	prxy	Dens.	UTS	UCS	Reference
	[mm]	[MPa]	[MPa]	[MPa]	[-]	[kg/m3]	[MPa]	[MPa]	
Gelcoat	0.05	3440		1380	0.3	1235	-	-	from SAND2011-3779, Sandia 100-m Blade
E-LT-5500(UD)	0.47	41,800	14,000	2630	0.28	1920	972	702	from SAND2011-3779, Sandia 100-m Blade
SNL(Triax)	0.94	27,700	13,650	7200	0.39	1850	700[iii]	-	from SAND2011-3779, Sandia 100-m Blade
Saertex(DB)	1	13,600	13,300	11,800	0.49	1780	144	213	from SAND2011-3779, Sandia 100-m Blade
FOAM[iv]	1	256	256	22	0.3	200	-	-	from SAND2011-3779, Sandia 100-m Blade
Carbon(UD)[v]	0.47	114,500	8,390	5990	0.27	1220	1546	1047	Inverse CLT starting from MSU Materials Database data: MD-P2B; [±45/(0)4C]S; 55%vf; EP; Newport NB307; carbon prepreg; 85% Uni; 15%DB

Blade Tip Design

Chow [10] created a very detailed blade surface geometry to represent a 5MW wind turbine blade. The original DOWEC blade was 62.7m long with a hub radius of 1.8m. The conceptual blade created for the NREL 5MW system model is truncated at 61.5m and is placed on a hub of 1.5m. This modification is relatively simple if only BEM models are needed. Chow required a high quality surface geometry. A detailed surface geometry of the original DOWEC blade was obtained by Chow through a variety of professional contacts. The geometry was truncated and then modified using interpolation and smoothing in order to create a high quality 61.5m blade surface for CFD. Chow also worked out a method to attach the detailed DOWEC tip geometry to his truncated blade geometry. Following the Risø DTU chord schedule near the tip, the DOWEC tip was smoothly connected to the body of the NREL blade. The final tenth of meter was formed using a series of blending and smoothing operations extending the rotor radius to a full 61.5m.

[iii] The estimated strength for the triax material is set to 700 MPa by examination of similar triax materials from the SNL/MSU materials database having similarly high modulus of elasticity.

[iv] In the course of this blade design, material properties for foam were found to have a potentially significant effect on blade weight. See the Concluding Discussion at the end of this document for more discussion on the topic of foam.

[v] The UD carbon material supplements the set of materials from the 100m blade. Discussion of this material is in this report below.

This structural model does not go into detail in representing the tip geometry for the 61.5 blade.

Materials

Material properties used in this blade model are largely taken from the Sandia 100m Blade design [5] and are summarized in Table 5.

Carbon UD Properties

Material properties for a carbon unidirectional material were needed for this blade model. Newport 307 carbon unidirectional prepreg material was used for the basis for material properties. It is not uncommon to use carbon prepreg material in utility scale blades today, as the spars are typically built as part of a separate process from the blade skins.

Available test data for a combination DB & UD Newport 307, carbon prepreg material, from the SNL/MSU Materials Database [11] was used to back out equivalent properties for a 100% UD carbon using classical laminate theory (CLT). The estimation starts with a measured value for Ex taken from the SNL/MSU Database for DB/UD layup. Then, CLT is used to estimate E1, E2, G12, and NU12 of the individual UD lamina. Table 6 summarizes the information that is available from MSU Database for the mixture of DB and UD carbon.

Table 6: Available Sandia-MSU materials information describing Newport 307 [11].

	Value	Comment
Layer thickness	2.82 mm	Cell M205 Ref [11] "Recent Materials"
Ex, GPa	100.1	Mean of all values in Range V205:V240 Ref [11] "Recent Materials"
UTS, MPa	1546	Mean of all values in Range R205:R225 Ref [11] "Recent Materials"
UCS, MPa	1047	Mean of all values in Range R258:R276 Ref [11] "Recent Materials"

The measured laminate was a mixture of DB (14.8%) and UD material. The following assumptions were used to define a stack of 14.8% DB material for the inverse CLT process: 27 layers total; each layer is same thickness; 2 layers of -45 plus 2 layers of +45 subtotal 4 layers; 23 layers of Uni 0deg. Table 7 shows the combination of individual lamina properties that produce a laminate E_x of 100.1 GPa as measured by the tests.

Table 7: Lamina properties that yield equivalent laminate 14.8% DB and Ex=100.1GPa

E1, GPa	114.5	Calibrated to produce Ex of 100.1 GPa (Newport 307)
E2, GPa	E1/13.64=8.39	Ratio from Ref [12], Table 2.3
NU12	0.27	From Ref [12], Table 2.6
G12, GPa	E1/19.1=5.99	Ratio from Ref [12], Table 2.3

Advertised data from the Newport 307 webpage [13] for intermediate modulus UD carbon prepreg is summarized in Table 8. This is used as a sanity check of the properties derived from materials testing in Table 7.

Table 8: Newport 307 UD carbon prepreg, advertised mechanical properties

E1, GPa (Msi)	150.3 (21.8)
E2, GPa (Msi)	7.584 (1.1)
G12, GPa (Msi)	4.136 (0.6)
NU12	0.3
Density (kg/m^3)	1220
UTS, MPa (ksi)	2430 (353)

Where possible, this model uses data that is either directly or indirectly derived from Sandia-MSU materials testing (Table 5).

Blade Root Hardware

Blade root hardware is not included in this model.

Design Criteria

The goal of this blade design concept is to match, as closely as possible, the characteristics of the NREL 5MW reference turbine blade. The required and desired criteria for successful completion of this task are stated below.

Required Criteria

Given the blade geometry and the materials selection listed above, a layup was created to match, as well as possible, the following criteria. Highest priority is listed first:

1. Meet or exceed basic IEC design loads criteria
2. Match the overall blade mass of the reference turbine blade (17,740kg)
3. Match the spanwise *trends* of distributed properties found in the NREL 5MW reference turbine blade

Desired Criteria

A more thorough blade design optimization could take into account many more criteria, but it is likely that one of two outcomes may result: 1) the optimization problem becomes over constrained or 2) time and effort required for the optimization task increase beyond what is meant for this initial model. Given the simple goals of this reference blade design, minimal energy is put into a complete and full blade design optimization. Following are additional criteria that might be considered in creating a more refined blade layup:

1. Match the blade mode shapes and frequencies represented by the NREL 5MW distributed blade properties
2. Match the location of mass center as well as first and second blade moments of inertia for the NREL 5MW distributed blade properties
3. Match the exact values of properties found in the NREL 5MW reference turbine blade

In summary, only the *required* criteria are considered during the design of the current blade concept.

DESIGN RESULTS

Skin Layup

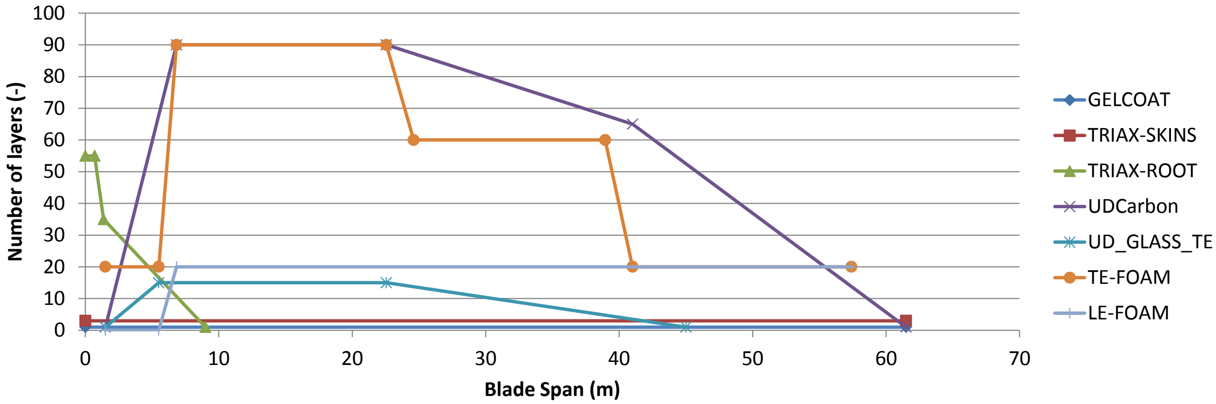


Figure 1: Schedule of layers in stacks for the SNL 61.5m blade concept.

Table 9: Mapping of stacks and materials

Stack ID	Stack name	Material
1	Gelcoat	Gelcoat
2	Triax Skins	SNL(Triax)
3	Triax Root	SNL(Triax)
4	UD Carbon	Carbon(UD)
5	UD Glass TE	E-LT-5500(UD)
6	TE Foam	Foam
7	LE Foam	Foam

Table 10: Stack usage (Stack ID) in each panel of the blade model along the blade span

Blade span (m)	TE	TE_REINF	TE_PANEL	CAP	LE_PANEL	LE
0	1,2,3,2	1,2,3,2	1,2,3,2	1,2,3,2	1,2,3,2	1,2,3,2
1.3667	1,2,3,2	1,2,3,2	1,2,3,2	1,2,3,2	1,2,3,2	1,2,3,2
1.5	1,2,3,2	1,2,3,5,6,2	1,2,3,6,2	1,2,3,4,2	1,2,3,7,2	1,2,3,2
6.8333	1,2,3,2	1,2,3,5,6,2	1,2,3,6,2	1,2,3,4,2	1,2,3,7,2	1,2,3,2
9	1,2,2	1,2,5,6,2	1,2,6,2	1,2,4,2	1,2,7,2	1,2,2
43.05	1,2,2	1,2,5,6,2	1,2,6,2	1,2,4,2	1,2,7,2	1,2,2
45	1,2,2		1,2,6,2	1,2,4,2	1,2,7,2	1,2,2
61.5	1,2,2		1,2,2	1,2,2	1,2,2	1,2,2

The following parameters are used to compute the chordwise location of the blade layup region boundaries for this model:

Table 11: Governing parameters for layup regions

LE/TE, width of region with no core	100mm
TE reinforcement width	400mm
Spar cap width	600mm

Shear Web Layup

The shear webs begin at a span of 1.3667m and end at 60.1333m.

Table 12: Mapping of stacks and materials in shear webs

Stack ID	Material
8	Saertex(DB)
9	Foam

Table 13: Stack usage (Stack ID) in shear webs

Blade span (m)	SW (Stack ID)	# of layers of DB per stack	Foam Thickness (mm)
1.3667	8,9,8	2	50
61.5	8,9,8	2	50

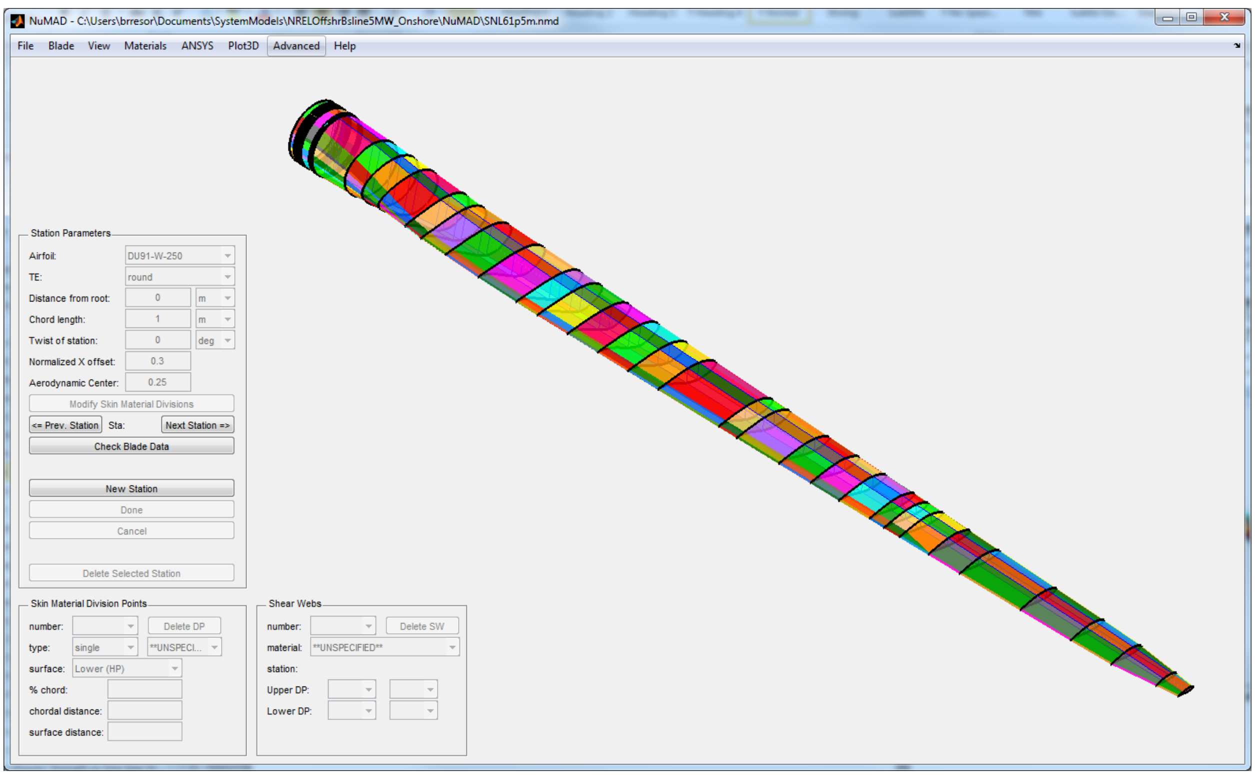


Figure 2: Model as viewed in the NuMAD GUI.

Finite Element Model Cross Sections

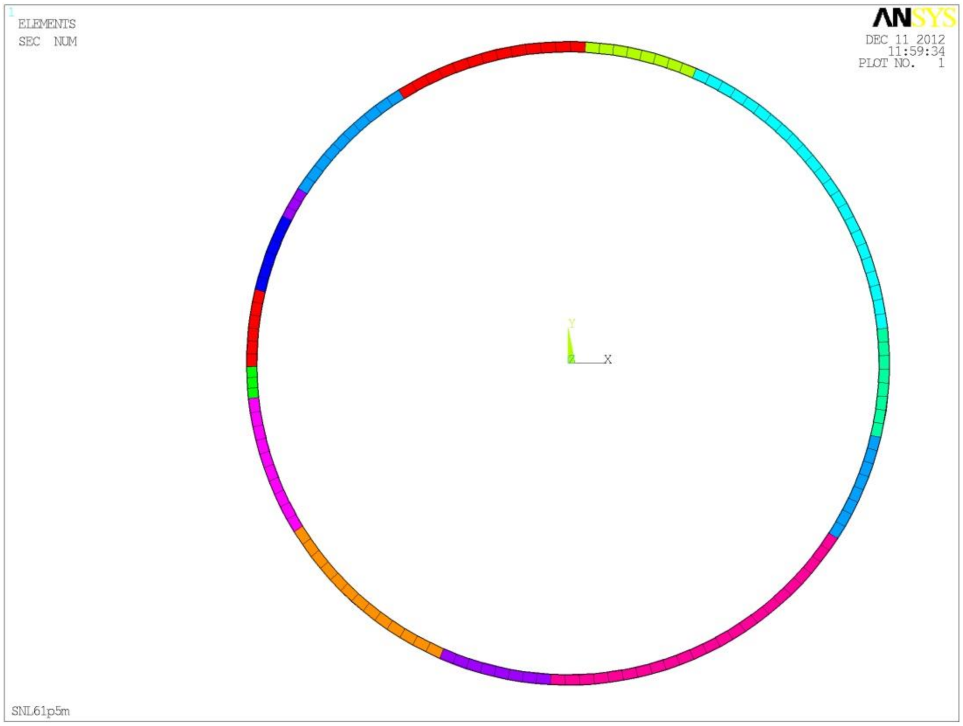


Figure 3: 0.65m span; blade root triax; circular

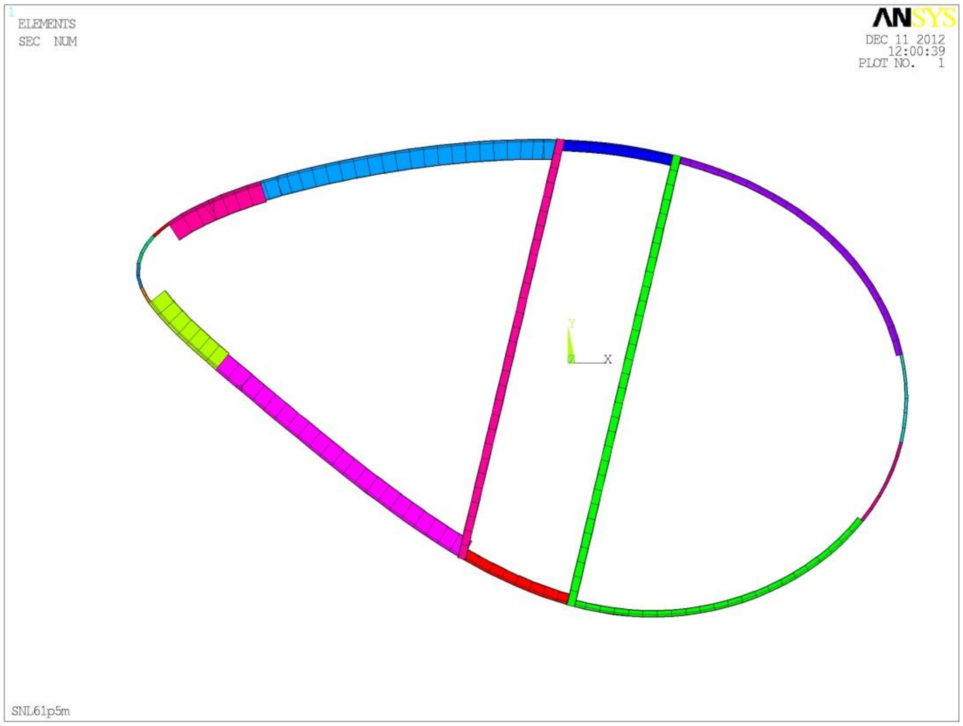


Figure 4: 6.9m span; TE reinforcement, foam, spar cap, some root reinforcement; circular/DU99-W-405 blend

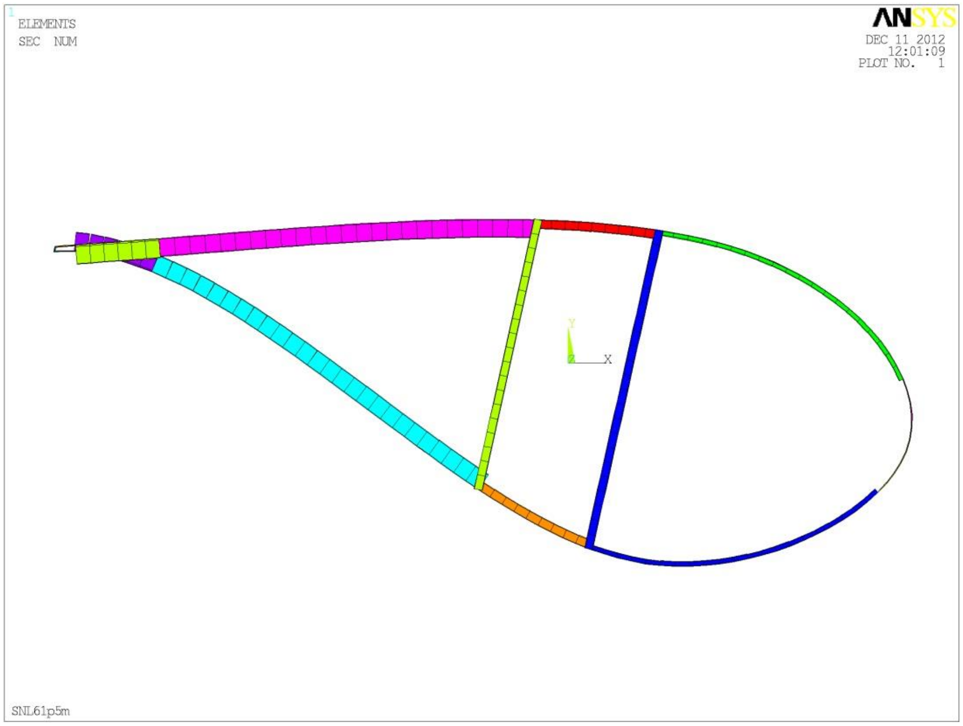


Figure 5: 12.0m span; TE reinforcement, foam, spar cap; DU99-W-405/DU99-W-350 hybrid shape

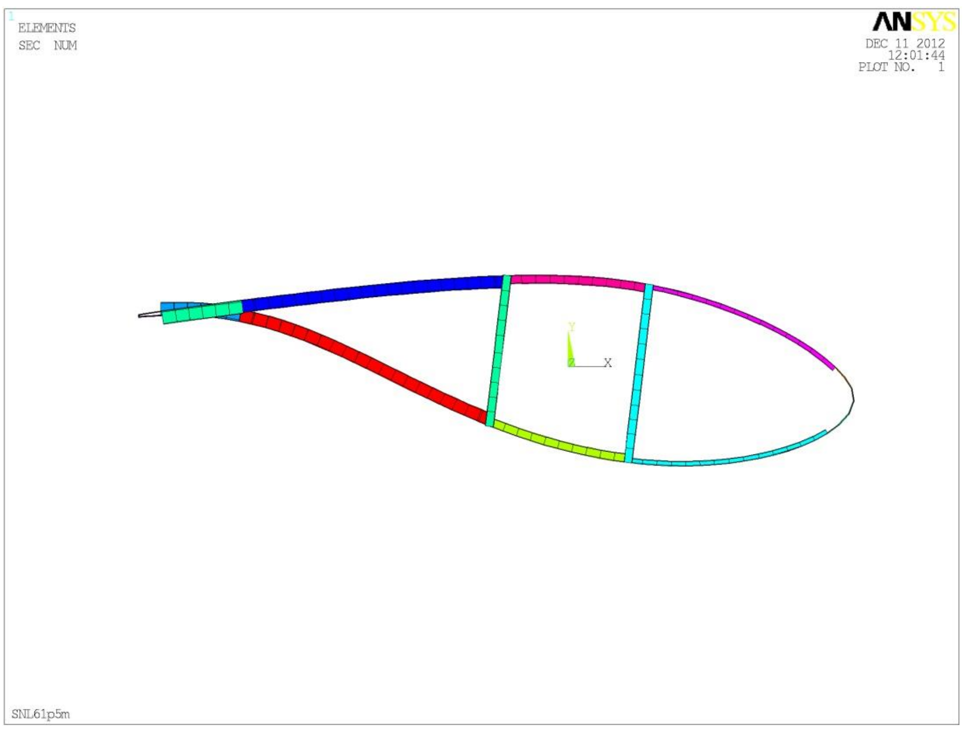


Figure 6: 30.0m span; TE reinforcement, spar cap, foam; DU91-W-250

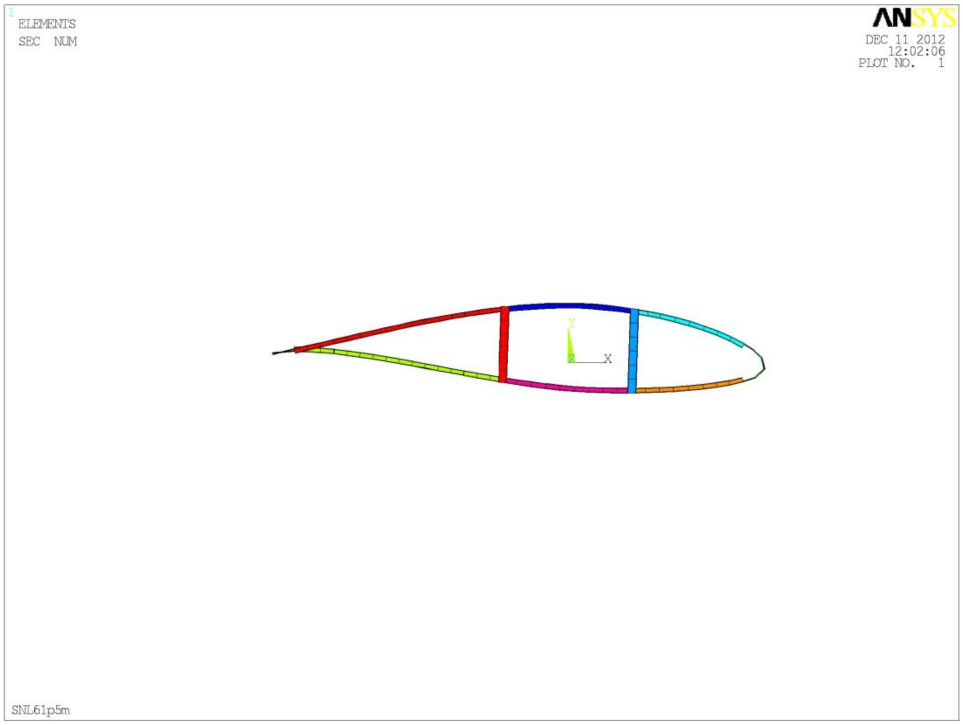


Figure 7: 50.0m span; tip skin with some spar cap and some foam; NACA 64-618

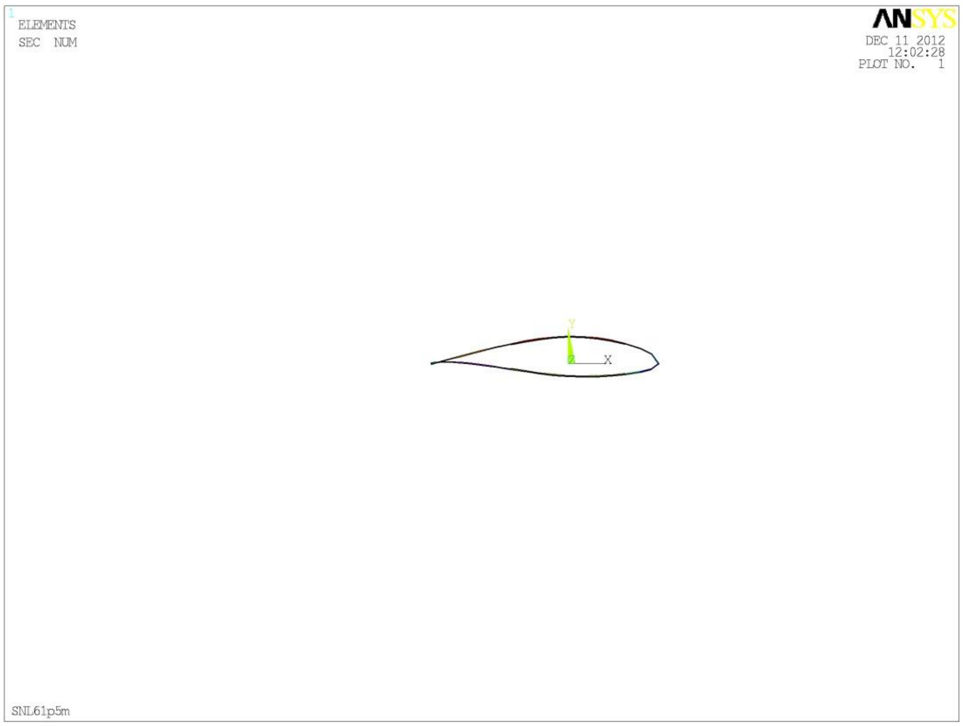


Figure 8: 61.0m span; tip skin; NACA 64-618

Discussion

Following are notable observations regarding the layup model:

- The blade inboard aft panels were made thick in order to resist buckling.
- The leading edge panels are lower in thickness than the aft panels in order to preserve weight in the blade.
- The carbon spar cap width is set relatively narrow in order to aid in its resistance to buckling.

BASIC ANALYSES

Element Size

An element size study is performed to set an adequate global element size for this model. The output metric of interest is the computed buckling load when a distributed force is applied to the model. The model was created using ANSYS Shell181 (4-node) elements. Figure 9 shows results of the element size study. Clearly, element sizes less than 0.1 meters are needed in order to adequately capture trailing edge buckling.

It is good practice to use a mesh size that yields little change in computed buckling load factors. A sufficiently accurate mesh for linear FE buckling computations can be assumed when the buckling eigenvalue does not change by more than 5% if the number of elements is doubled. [14]

Given this criterion, a global element size of 0.08m works well for this model.

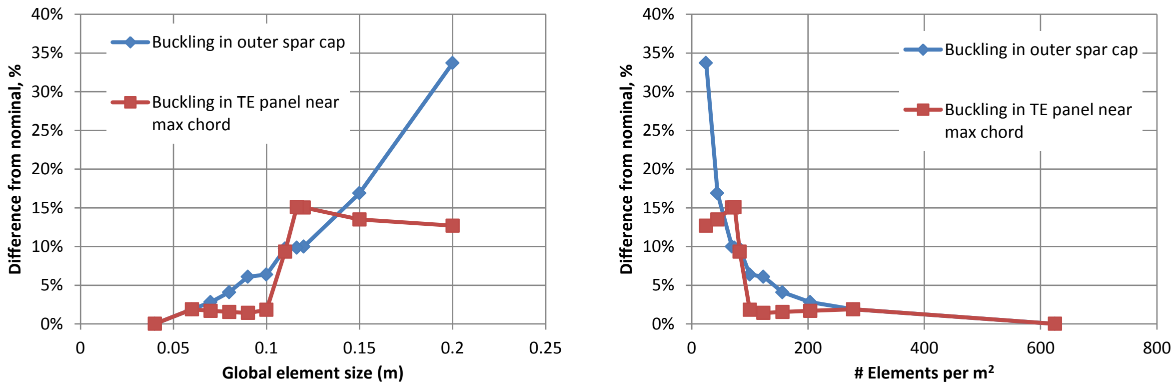


Figure 9: Variation in computed buckling load factor for two dominant modes

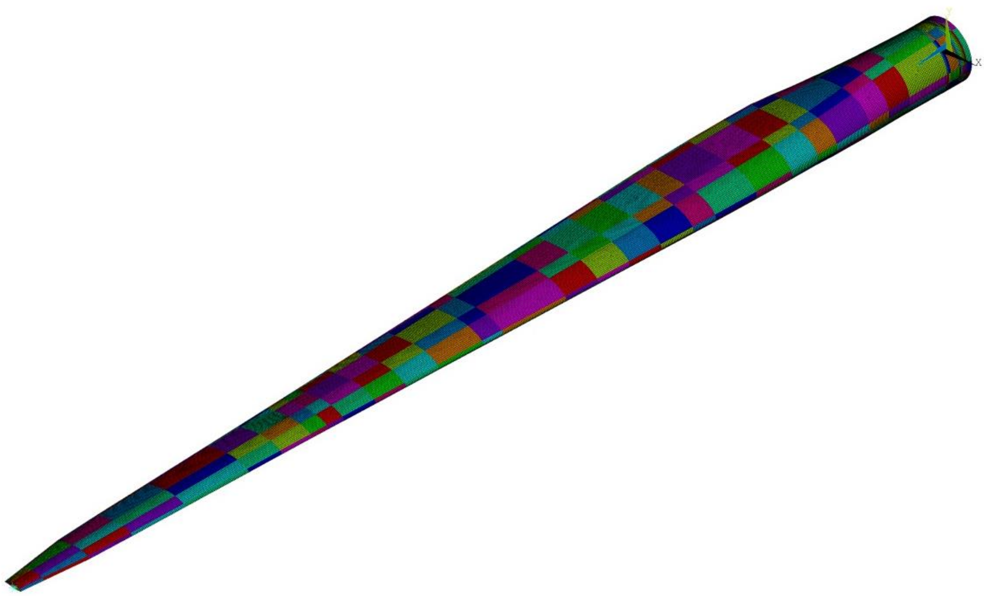


Figure 10: ANSYS FE model; global mesh size of 0.08m

Mass Properties

Required design criteria #2 for this blade model has been met according to Table 14.

Table 14: Blade model mass properties

	Required Goal	Desired Goal	FAST Output Summary	ANSYS Computed
Overall mass (kg)	17,740		16,878	17,700
Second mass moment of inertia (w.r.t. Root) ($kg\text{-}m^2$)		11,776,047	10,770,679	11,000,000
First Mass Moment of Inertia (w.r.t. Root) (kg-m)		363,231	331,598	338,086
C.M. Location (w.r.t. Root along Preconed Axis) (m)		20.475	19.648	19.102

Modal Frequencies

Table 15 summarizes the ANSYS-computed modes and frequencies for the blade model with a fixed root.

Table 15: Fixed root modal frequencies and shapes

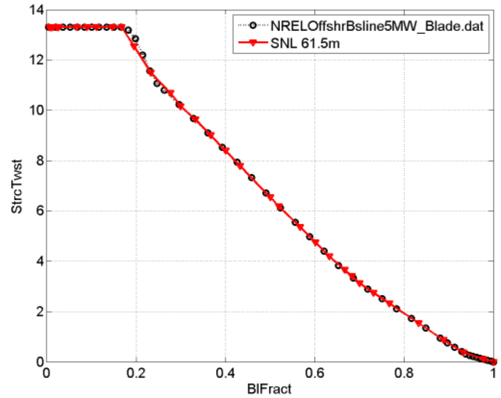
Mode #	Frequency, Hz	Description
1	0.870	1^{st} flapwise bending
2	1.06	1^{st} edgewise bending
3	2.68	2^{nd} flapwise bending
4	3.91	2^{nd} edgewise bending
5	5.57	3^{rd} flapwise bending
6	6.45	1^{st} torsion

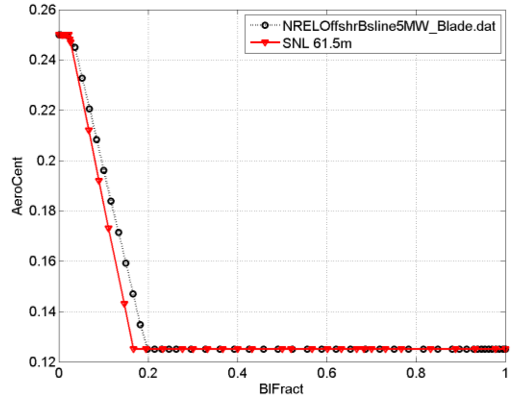
Distributed Blade Properties

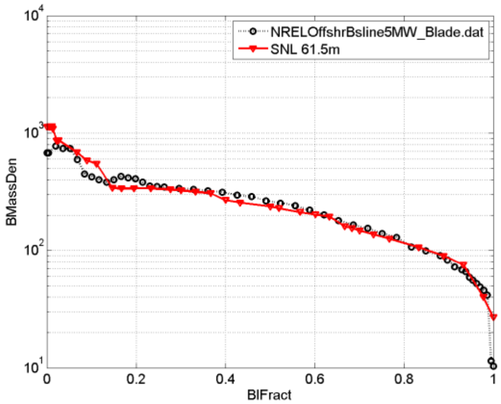
NuMAD is used to convert this blade model into the input files required for PreComp [15] sectional analysis. The computed blade properties are compared to values in Table 2-1. “Distributed Blade Structural Properties” in the NREL 5MW reference turbine report [1].

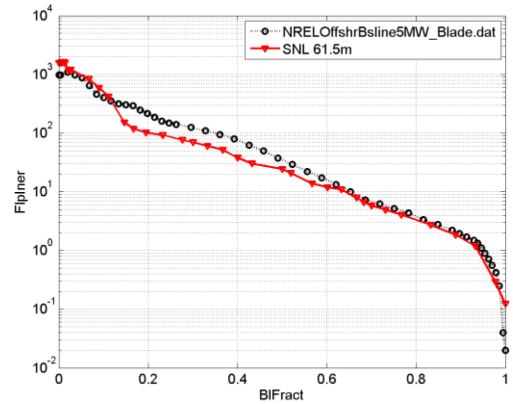
In general, there is good agreement in trends between NREL property distributions and those which are computed from the SNL 61.5m blade model. The axial stiffness of the blade is different. The SNL model is stiffer than the baseline blade properties. Additionally, the section mass centers are farther aft than initially anticipated by the NREL blade parameters.

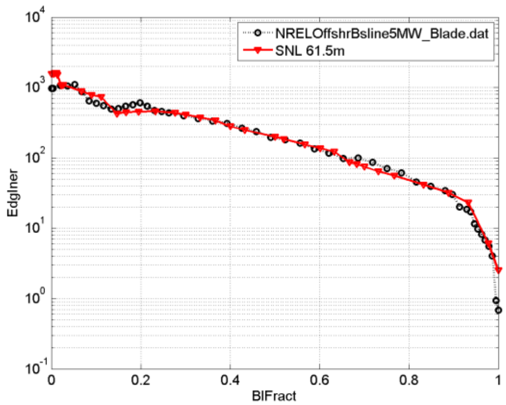
According to these analyses, required design criteria #3 has been met.

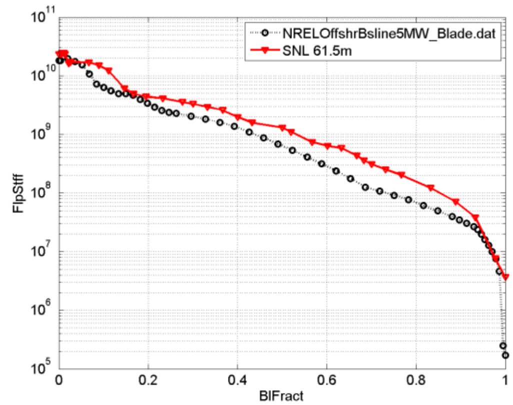

StrcTwst
BlFract
NRELOffshrBsline5MW_Blade.dat
SNL 61.5m

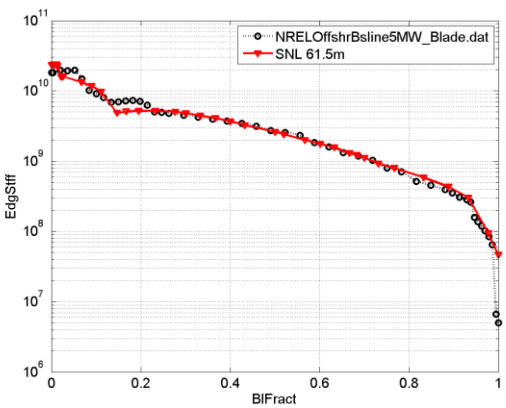

AeroCent
BlFract
NRELOffshrBsline5MW_Blade.dat
SNL 61.5m

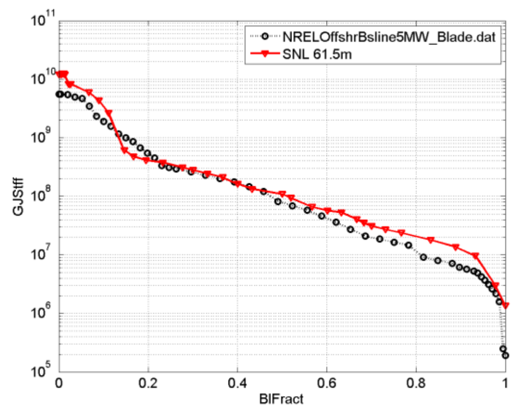

BMassDen
BlFract
NRELOffshrBsline5MW_Blade.dat
SNL 61.5m

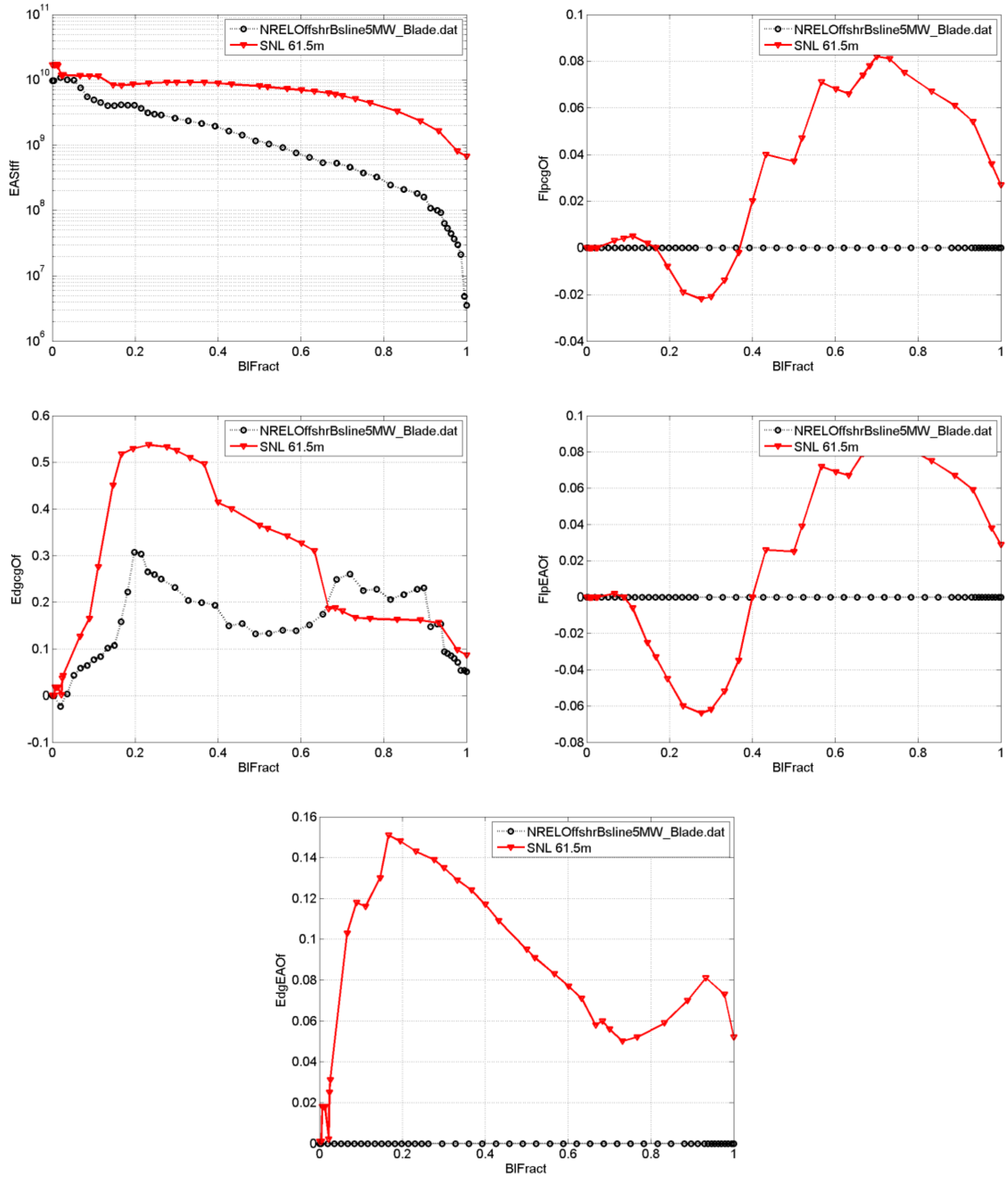

FlpIner
BlFract
NRELOffshrBsline5MW_Blade.dat
SNL 61.5m


EdgIner
BlFract
NRELOffshrBsline5MW_Blade.dat
SNL 61.5m


FlpStff
BlFract
NRELOffshrBsline5MW_Blade.dat
SNL 61.5m


EdgStff
BlFract
NRELOffshrBsline5MW_Blade.dat
SNL 61.5m


GJStff
BlFract
NRELOffshrBsline5MW_Blade.dat
SNL 61.5m



Figures 11: Distributed blade properties as computed by PreComp. All ordinates are defined as FAST blade input parameters.

Table 16: Distributed blade property file for FAST

BlFract	AeroCent	StrcTwst	BMassDen	FlpStff	EdgStff	GJStff	EAStff	Alpha	FlpIner	EdgIner	PrecrvRef	PreswpRef	FlpcgOf	EdgcgOf	FlpEAOf	EdgEAOf
(-)	(-)	(deg)	(kg/m)	(Nm^2)	(Nm^2)	(Nm^2)	(N)	(-)	(kg m)	(kg m)	(m)	(m)	(m)	(m)	(m)	(m)
0.00000	0.250	13.310	1128.000	2.33800e+010	2.32300e+010	1.20900e+010	1.68800e+010	0.000	1562.000	1552.000	0.000	0.000	0.000	0.001	0.000	0.001
0.00488	0.250	13.310	1128.000	2.33800e+010	2.32300e+010	1.20900e+010	1.68800e+010	0.000	1562.000	1552.000	0.000	0.000	0.000	0.001	0.000	0.001
0.00650	0.250	13.310	1141.000	2.43700e+010	2.38300e+010	1.24800e+010	1.70800e+010	0.000	1629.000	1592.000	0.000	0.000	0.000	0.018	0.000	0.018
0.00813	0.250	13.310	1141.000	2.43700e+010	2.38300e+010	1.24800e+010	1.70800e+010	0.000	1629.000	1592.000	0.000	0.000	0.000	0.018	0.000	0.018
0.00976	0.250	13.310	1141.000	2.43700e+010	2.38300e+010	1.24800e+010	1.70800e+010	0.000	1629.000	1592.000	0.000	0.000	0.000	0.018	0.000	0.018
0.01138	0.250	13.310	1141.000	2.43700e+010	2.38300e+010	1.24800e+010	1.70800e+010	0.000	1629.000	1592.000	0.000	0.000	0.000	0.018	0.000	0.018
0.01301	0.250	13.310	1085.000	2.32100e+010	2.27000e+010	1.18900e+010	1.62400e+010	0.000	1551.000	1517.000	0.000	0.000	0.000	0.018	0.000	0.018
0.02228	0.250	13.310	859.200	1.62900e+010	1.58300e+010	8.22100e+009	1.17800e+010	0.000	1155.000	1064.000	0.000	0.000	0.000	0.002	0.000	0.002
0.02439	0.248	13.310	866.600	1.68100e+010	1.59200e+010	8.27700e+009	1.17500e+010	0.000	1203.000	1084.000	0.000	0.000	0.000	0.037	0.000	0.025
0.02602	0.247	13.310	867.800	1.71400e+010	1.59300e+010	8.28900e+009	1.18700e+010	0.000	1205.000	1084.000	0.000	0.000	0.000	0.043	0.000	0.031
0.06667	0.212	13.310	685.600	1.68800e+010	1.32200e+010	5.96100e+009	1.15000e+010	0.000	830.900	888.900	0.000	0.000	0.003	0.127	0.002	0.103
0.08943	0.192	13.310	582.400	1.49400e+010	1.17500e+010	4.32200e+009	1.14400e+010	0.000	586.300	781.000	0.000	0.000	0.004	0.165	0.000	0.118
0.11106	0.173	13.310	548.100	1.22400e+010	9.69000e+009	2.63500e+009	1.13500e+010	0.000	421.400	734.800	0.000	0.000	0.005	0.276	-0.006	0.116
0.14634	0.143	13.310	340.500	6.12200e+009	4.83500e+009	6.06600e+008	8.35100e+009	0.000	151.000	424.500	0.000	0.000	0.002	0.451	-0.025	0.130
0.16667	0.125	13.310	337.300	4.90800e+009	5.06900e+009	4.77200e+008	8.17700e+009	0.000	119.200	444.100	0.000	0.000	0.000	0.517	-0.033	0.151
0.19512	0.125	12.530	336.300	4.39000e+009	5.15800e+009	4.13600e+008	8.49600e+009	0.000	102.300	452.700	0.000	0.000	-0.008	0.529	-0.045	0.148
0.23333	0.125	11.480	336.300	4.10100e+009	5.21000e+009	3.74500e+008	8.86700e+009	0.000	91.790	457.500	0.000	0.000	-0.019	0.537	-0.060	0.143
0.27642	0.125	10.680	330.200	3.56400e+009	5.02500e+009	3.10000e+008	9.11500e+009	0.000	76.330	433.400	0.000	0.000	-0.022	0.533	-0.064	0.139
0.30000	0.125	10.160	324.900	3.31400e+009	4.80700e+009	2.81700e+008	9.16800e+009	0.000	69.560	410.400	0.000	0.000	-0.021	0.525	-0.062	0.135
0.33333	0.125	9.630	316.000	2.94400e+009	4.44100e+009	2.43000e+008	9.17800e+009	0.000	60.140	373.900	0.000	0.000	-0.014	0.510	-0.052	0.129
0.36667	0.125	9.010	307.100	2.59900e+009	4.10800e+009	2.11400e+008	9.16900e+009	0.000	51.810	340.700	0.000	0.000	-0.002	0.496	-0.035	0.124
0.40000	0.125	8.400	268.200	1.98100e+009	3.67100e+009	1.62600e+008	8.83600e+009	0.000	38.010	278.700	0.000	0.000	0.020	0.414	0.000	0.117
0.43333	0.125	7.790	255.400	1.58700e+009	3.23400e+009	1.33900e+008	8.50600e+009	0.000	30.150	247.300	0.000	0.000	0.040	0.400	0.026	0.109
0.50000	0.125	6.540	237.100	1.30100e+009	2.59900e+009	1.09800e+008	7.98600e+009	0.000	24.480	199.100	0.000	0.000	0.037	0.365	0.025	0.095
0.52033	0.125	6.180	229.300	1.10300e+009	2.40100e+009	9.38600e+007	7.76700e+009	0.000	20.690	184.500	0.000	0.000	0.047	0.358	0.039	0.091
0.56667	0.125	5.360	212.200	7.37700e+008	2.00000e+009	6.60400e+007	7.29100e+009	0.000	13.820	154.400	0.000	0.000	0.071	0.342	0.072	0.083
0.60163	0.125	4.750	202.400	6.38900e+008	1.76100e+009	5.72400e+007	6.95900e+009	0.000	11.930	136.300	0.000	0.000	0.068	0.326	0.069	0.077
0.63333	0.125	4.190	194.500	5.84300e+008	1.56400e+009	5.29400e+007	6.70300e+009	0.000	10.900	121.500	0.000	0.000	0.066	0.310	0.067	0.071
0.66667	0.125	3.660	159.700	4.35800e+008	1.29500e+009	4.04900e+007	6.29300e+009	0.000	7.907	86.160	0.000	0.000	0.074	0.186	0.079	0.058
0.68293	0.125	3.400	153.800	3.62100e+008	1.21700e+009	3.52500e+007	5.99700e+009	0.000	6.652	80.830	0.000	0.000	0.078	0.188	0.086	0.060
0.70000	0.125	3.130	147.500	3.09600e+008	1.11000e+009	3.11600e+007	5.69300e+009	0.000	5.755	74.450	0.000	0.000	0.082	0.181	0.091	0.056
0.73171	0.125	2.740	136.400	2.54100e+008	9.22700e+008	2.71700e+007	5.09700e+009	0.000	4.852	63.690	0.000	0.000	0.081	0.167	0.089	0.050
0.76667	0.125	2.320	125.600	2.03400e+008	7.95900e+008	2.38700e+007	4.45400e+009	0.000	4.042	55.320	0.000	0.000	0.075	0.165	0.083	0.052
0.83333	0.125	1.530	105.700	1.22000e+008	5.82300e+008	1.78500e+007	3.28000e+009	0.000	2.700	41.360	0.000	0.000	0.067	0.163	0.075	0.059
0.88894	0.125	0.860	89.560	7.09800e+007	4.32000e+008	1.35300e+007	2.34100e+009	0.000	1.831	31.660	0.000	0.000	0.061	0.162	0.067	0.070
0.93333	0.125	0.370	75.460	3.81400e+007	3.02900e+008	9.57600e+006	1.63700e+009	0.000	1.186	22.960	0.000	0.000	0.054	0.156	0.059	0.081
0.97772	0.125	0.110	40.250	7.69700e+006	9.48600e+007	3.00500e+006	8.08800e+008	0.000	0.294	6.112	0.000	0.000	0.036	0.098	0.038	0.073
1.00000	0.125	0.000	26.980	3.66600e+006	4.69000e+007	1.35800e+006	6.76000e+008	0.000	0.123	2.514	0.000	0.000	0.027	0.087	0.029	0.052

```
--------------------- BLADE MODE SHAPES ---------------------------------------
0.117967        BldFl1Sh(2) - Flap mode 1, coeff of x^2
1.9594          BldFl1Sh(3) -            , coeff of x^3
-3.01419        BldFl1Sh(4) -            , coeff of x^4
3.41643         BldFl1Sh(5) -            , coeff of x^5
-1.47961        BldFl1Sh(6) -            , coeff of x^6
-1.30218        BldFl2Sh(2) - Flap mode 2, coeff of x^2
3.93682         BldFl2Sh(3) -            , coeff of x^3
-18.1759        BldFl2Sh(4) -            , coeff of x^4
29.0697         BldFl2Sh(5) -            , coeff of x^5
-12.5284        BldFl2Sh(6) -            , coeff of x^6
0.441793        BldEdgSh(2) - Edge mode 1, coeff of x^2
2.62532         BldEdgSh(3) -            , coeff of x^3
-4.47955        BldEdgSh(4) -            , coeff of x^4
3.62767         BldEdgSh(5) -            , coeff of x^5
-1.21524        BldEdgSh(6) -            , coeff of x^6
```

SIMULATION AND ANALYSIS OF DESIGN LOAD CASES

Required design criteria #1 calls for an extensive set of aeroelastic simulations to evaluate the loads experienced by this blade during design-driving scenarios. This blade is analyzed under the assumption that it is for onshore use. FAST [16] and AeroDyn [17] are used to perform the aeroelastic simulations. TurbSim [18] and IECWind [19] are used to generate wind input files for the simulations. Computed responses from the simulations are processed using Matlab. Response waveforms used as input for fatigue analyses are processed using Crunch [20], for rainflow cycle counting.

An automated process, managed by Matlab, has been created to manage all the IEC DLC simulations, analyses and results discussed in this section.

Design load cases (DLC's) are specified by the IEC Design Standard for wind turbines [2]. The goal in each case is to evaluate the turbine response with respect to the following failure modes:

- analysis of ultimate strength;
- analysis of fatigue failure;
- stability analysis (buckling, etc.);
- critical deflection analysis (mechanical interference between blade and tower, etc.).

The full set of required design load cases includes power production (with and without faults), startup, shutdown (emergency and normal), parked configuration (with and without faults), transport and erection. Since this is a conceptual blade model for use only as a research subject, only the DLC's listed in Table 17 are examined. These load cases have proven to be the most likely design drivers for the majority of turbine blades. Table 18 summarizes the important input parameters for the IEC aeroelastic simulations.

Table 17: IEC DLC's used in design of this blade model

DLC 1.2 (NTM)	Fatigue damage evaluation during normal power production in normal turbulence
DLC 1.3 (ETM)	Ultimate loads evaluation during normal power production in extreme turbulence
DLC 1.4 (ECD)	Ultimate loads evaluation during normal power production with an extreme coherence gust with change in wind direction
DLC 1.5 (EWS)	Ultimate loads evaluation during normal power production with the presence of extreme wind shear
DLC 6.1 (EWM50)	Ultimate loads evaluation while in a parked configuration during a 50-year extreme steady wind event
DLC 6.3 (EWM01)	Ultimate loads evaluation while in a parked configuration during a 1-year extreme steady wind event with extreme yaw misalignment

Table 18: Important input parameters for IEC analyses

V_{in}	3 m/s
V_{out}	25 m/s
V_{rated}	11.4 m/s
IEC Class	I
Turbulence Class	B
Vref	50 m/s [IEC 6.2, Table 1]
Specified structural damping ratio for blades in FAST (All Modes)	1.5%[vi]
Component Class	2[vii]
Average wind speed	0.2*Vref=10m/s [IEC 6.3.1.1]
V_{50}	1.4*Vref=70 m/s
V_1	0.8*V_{50}=56 m/s
Mean wind speeds for turbulent wind simulations	5, 7, 9, 11, 13, 15, 17, 19, 21, 23m/s
Turbulence model	Kaimal
Aeroelastic simulation usable record length	600 seconds (turbulent) 100 seconds (steady)
Number of turbulent aeroelastic simulations at each wind speed	6
Turbine design life	20 years

Table 19: Spanwise location of simulated blade gages

Blade Gage Name	Span Location (m)
RootM	0
Spn1ML	1.3667
Spn2ML	4.100
Spn3ML	6.8333
Spn4ML	10.25
Spn5ML	14.35
Spn6ML	18.45
Spn7ML	22.55

[vi] The NREL reference turbine document calls for structural damping of 0.477465% for all blade modes. However, using this value in the simulations for extreme wind in a parked configuration resulted in structural instability. Determination of the correct approach for modeling such behavior should be investigated as part of future work. For the current work, damping values were increased to 1.5% for all modes.
[vii] Component Class 2 is used to refer to "non fail-safe" structural components whose failures may lead to the failure of a major part of a wind turbine.

Simulation of IEC DLC 1.0 Power Production

DLC 1.1 NTM Ultimate Strength for Extrapolated Extreme Event (NTM)

Simulation of this load case was not performed as part of this work. Barone et.al. were able to perform this simulation on the NREL 5MW turbine in a land-based installation [21]. The work determined that the raw computed values for DLC 1.1 out-of-plane blade tip deflection and flapwise blade root bending moment were approximately 10m and 18,000 kN-m, respectively. In this case, these computed loads do not drive the design of this blade.

DLC 1.2 NTM Fatigue During Normal Operation (NTM)

These simulations were performed using FAST and AeroDyn with TurbSim providing the three-dimensional full-field wind data with normal turbulence.

All normal settings were used in the aeroelastic simulation (i.e. NREL 5MW reference turbine inputs files used as-is). One hour of power generation is simulated at each wind speed in the operational range of the turbine, evenly spaced every 2 m/s.

DLC 1.3 NTM Ultimate Strength During Extreme Turbulence (ETM)

These simulations were performed using FAST and AeroDyn with TurbSim providing the three-dimensional full-field wind data with extreme turbulence.

All normal settings were used in the aeroelastic simulation (i.e. NREL 5MW reference turbine inputs files used as-is). One hour of power generation is simulated at each wind speed in the operational range of the turbine, evenly spaced every 2 m/s.

DLC 1.4 NTM Ultimate Strength During Coherent Gust with Direction Change (ECD)

These simulations were performed using FAST and AeroDyn with IECWind providing the hub-height wind data for a Class IB turbine.

All normal settings were used in the aeroelastic simulation (i.e. NREL 5MW reference turbine inputs files used as-is). Wind speeds of rated, 2m/s above rated and 2m/s below rated, including wind changes in both directions, were analyzed.

DLC 1.5 NTM Ultimate Strength in Extreme Wind Shear (EWS)

These simulations were performed using FAST and AeroDyn with IECWind providing the hub-height wind data for a Class IB turbine.

All normal settings were used in the aeroelastic simulation (i.e. NREL 5MW reference turbine inputs files used as-is). Steady wind with positive and negative vertical shear were analyzed every 2 m/s throughout the operational range of the turbine.

Simulation of IEC DLC 6.0 Parked Turbine

One of the standard IEC test cases is to model the turbine in high winds when the turbine is parked. There are several ways to model a parked rotor, depending on the design of the turbine system. This work uses the following assumptions regarding the parked configuration:

- This turbine uses full-span pitch so blades are feathered (pitch angle 90-degrees).
- It is assumed that this turbine's HSS brake is engaged for a parked configuration so rotor rotation is fixed at zero.
- The turbine drivetrain model is active so that basic drivetrain dynamics are included in the model response.
- Computation of inflow factors is turned off in AeroDyn because the rotor is stationary.

DLC 6.1 Ultimate Strength in Fifty Year Wind

These simulations were performed using FAST and AeroDyn with IECWind providing the hub-height wind data for a Class IB turbine.

Normal settings were used in the aeroelastic simulation (i.e. NREL 5MW reference turbine inputs files used as-is), with only modifications for parked configuration as described above. Yaw misalignment angles of -15 through 15 degrees, in 5 degree increments were simulated.

DLC 6.3 Ultimate Strength in One Year Wind With Extreme Yaw Misalignment

These simulations were performed using FAST and AeroDyn with IECWind providing the hub-height wind data for a Class IB turbine.

Normal settings were used in the aeroelastic simulation (i.e. NREL 5MW reference turbine inputs files used as-is), with only modifications for parked configuration as described above. Yaw misalignment angles of -30 through 30 degrees, in 5 degree increments, were simulated.

Analysis of Ultimate Strength

Strain in the skin of the blade is estimated using the following relationship,

$$\varepsilon = \frac{Mc}{EI} \tag{1}$$

The section stiffness, EI, includes effects of multiple materials and the blade cross section shape. It is defined as follows

$$\begin{aligned} Flapwise, EI &= \iint E(x,y)x^2 dxdy \\ Edgewise, EI &= \iint E(x,y)y^2 dxdy \end{aligned} \tag{2}$$

Where x and y are the flap and edgewise coordinates of the differential area elements, respectively, with respect to the section elastic center. The flapwise and edgewise stiffnesses of this blade are computed using PreComp and are plotted in Figures 11.

The distance, c, is assumed here to be the half height of the airfoil (flapwise c) or the distance from the blade reference axis (i.e. pitch axis; defined by NuMAD x-offset) to the blade trailing edge (edgewise c). This definition of edgewise c assumes colocation of the blade reference axis and the elastic axis of the section. This assumption is not true for this blade, but because the elastic axis is located slightly aft of the blade reference axis for much of the blade, it is a conservative assumption. Flap and edge c values are plotted in Figure 12.

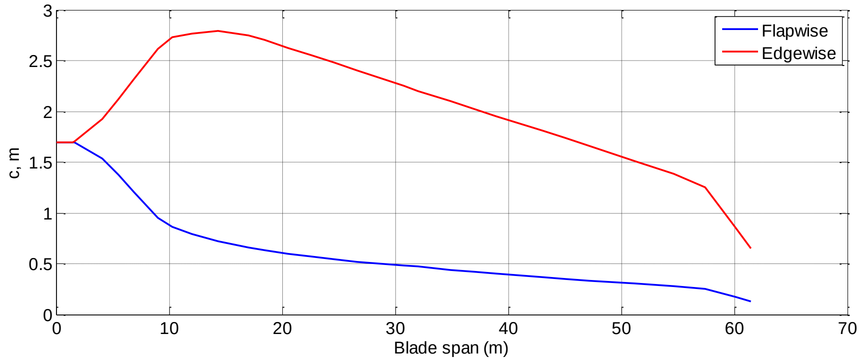


Figure 12: Distributions of skin distance from neutral axes, c

It is important to note that edge and flap loadings are analyzed separately in this blade design. A more thorough approach would involve computing the combined loading effects of flap and edge moments, and axial forces at each blade gage location. The combined load states could then be used to compute strains.

Finally, stress is proportional to strain,

$$S = E\varepsilon \tag{3}$$

Table 20: Safety factors used in evaluation of ultimate strength (IEC 7.6.2)

Partial safety factor for loads, γ_f	1.35	Do not use for DLC 1.1
Partial safety factor for materials, γ_m	1.3	Rupture from exceeding tensile or compression strength
Partial safety factors for consequences of failure, γ_n	1.0	Component class 2
Total safety factor	1.755	

Table 21: Computed maximum flapwise strain values

DLC Name	Max Flapwise Strain (micro-strain)	Channel	Simulation
IECDLC1p2NTM[viii]	1979	Spn4MLyb1	11 m/s avg wind
IECDLC1p3ETM	2291	Spn4MLyb1	19 m/s avg wind
IECDLC1p4ECD	2479	Spn4MLyb1	Negative gust at rated speed
IECDLC1p5EWS	1678	Spn4MLyb1	+11 m/s
IECDLC6p1EWM50	2911	Spn4MLyb1	+15 degree yaw misalignment
IECDLC6p3EWM01	1931	Spn4MLyb1	+20 degree yaw misalignment

[viii] Ultimate loads analysis of DLC 1.2 is not required. The maximum strains are shown here purely for informational purposes.

Table 22: Computed maximum edgewise strain values

DLC Name	Max Edgewise Strain (micro-strain)	Channel	Simulation
IECDLC1p2NTM[viii]	1504	Spn4MLxb1	23 m/s avg wind
IECDLC1p3ETM	1811	Spn4MLxb1	23 m/s avg wind
IECDLC1p4ECD	1421	Spn4MLxb1	Negative gust at rated speed
IECDLC1p5EWS	883	Spn4MLxb1	+3 m/s
IECDLC6p1EWM50	2048	Spn4MLxb1	-15 degree yaw misalignment
IECDLC6p3EWM01	1289	Spn4MLxb1	-15 degree yaw misalignment

The maximum strains observed in these simulations are 2911 and 2048 microstrain in the flap and edge direction, respectively. Maximum stresses in Table 23 are estimated with multiplication of strains by the elastic moduli in Table 5 and by the total safety factor from Table 20.

None of the materials exceed their maximum allowable stress.

Table 23: Computed ultimate stresses

	Max Flapwise Stress (including s.f.) (MPa)	Max Edgewise Stress (including s.f.) (MPa)
E-LT-5500(UD)	214	150
SNL(Triax)		100
Carbon(UD)	585	

Analysis of Fatigue Failure

Fatigue analysis is performed in the same manner as is documented in Appendix A of the Sandia 100m blade report, Reference [5]. A simple two-parameter fatigue model is used for this investigation. Rain flow cycle accumulation rates from the collection of aeroelastic simulations are scaled according to a Rayleigh wind distribution with average as noted in Table 18 and 20-years of operation with 100% availability. Important material properties for the fatigue damage analysis are summarized in Table 24. Stresses used in the fatigue analysis include the total safety factor from Table 25. The end result of the analysis is a series of Miner's fatigue damage ratios shown in Table 26. Ratios of greater than 1.0 indicated fatigue failure.

Table 24: Material properties for fatigue analysis.

	b[ix]	C (MPa)	E
E-LT-5500(UD)	10	1000	See Table 5
Carbon(UD)	14	1546	See Table 5
SNLTriax	10	700	See Table 5

[ix] To promote simplicity, the fatigue slope parameter, b, is set to 10 (GRP) or 14 (CRP) for all materials for these analyses. This choice is consistent with GL standards for computation of fatigue damage in epoxy-laminate [GL 5.5.4.(13)] or carbon/epoxy laminate [GL 5.5.5.(6)]

The quality of fatigue test data has a large effect on the safety factors which are used in the fatigue damage analysis. Regarding material safety factors for fatigue,

> *"The partial safety factor for materials shall be at least 1.5 provided that the SN curve is based on 50 % survival probability and coefficient of variation < 15 %. For components with large coefficient of variation for fatigue strength, i.e. 15 % to 20 % (such as for many components made of composites, for example reinforced concrete or fiber composites), the partial safety factor γ_m must be increased accordingly and at least to 1.7. For fiber composites, the strength distribution shall be established from test data for the actual material. The 95 % survival probability with a confidence level of 95% shall be used as a basis for the SN-curve. In that case γ_m may be taken as 1.2. The same approach may be used for other materials."* From Reference [2].

Table 25: Safety factors used in evaluation of fatigue damage (IEC 7.6.3)

Partial safety factor for loads, γ_f	1.0	
Partial safety factor for materials, γ_m	1.7	Assuming adequate SN curve data
Partial safety factor for materials, γ_m	1.2	Assuming great SN curve data
Partial safety factors for consequences of failure, γ_n	1.15	Component class 2
Total safety factor	1.38	Assuming great SN curve data

Table 26: Miner's fatigue damage results.

	E-LT-5500(UD)	Carbon(UD)	SNL(Triax)
RootMxb1 (edgewise)	6.90E-09		1.36E-07
Spn1MLxb1	8.82E-08		1.73E-06
Spn2MLxb1	5.26E-07		1.03E-05
Spn3MLxb1	1.96E-05		3.86E-04
Spn4MLxb1	**1.22E-02**		**2.40E-01**
Spn5MLxb1	1.31E-03		2.58E-02
Spn6MLxb1	2.01E-04		3.95E-03
Spn7MLxb1	4.10E-05		8.06E-04
RootMyb1 (flapwise)		4.06E-08	7.55E-07
Spn1MLyb1		8.00E-06	3.49E-05
Spn2MLyb1		4.56E-07	4.41E-06
Spn3MLyb1		4.32E-07	4.16E-06
Spn4MLyb1		**3.31E-04**	4.65E-04
Spn5MLyb1		4.46E-05	1.06E-04
Spn6MLyb1		1.40E-05	4.45E-05
Spn7MLyb1		8.61E-06	3.07E-05

The largest damage fraction is found in the trailing edge triaxial material at 10.25m (Spn4MLyb1). These values are calculated based on a twenty year lifetime. Simple extrapolation shows material at this location surviving for 20/0.240=83 years.

Stability Analysis (Buckling)

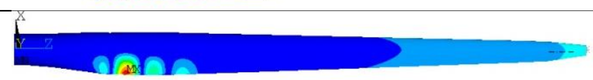
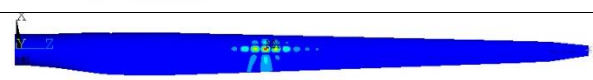
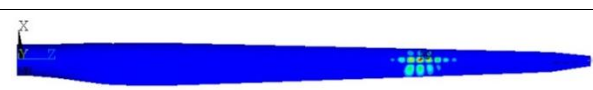
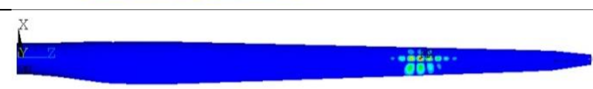
Table 27: Safety factors used in evaluation of buckling loads (IEC 7.6.4)

Partial safety factor for loads, γ_f	1.35	Do not use for DLC 1.1
Partial safety factor for materials, γ_m	1.2	Global buckling of curved shells, such as blades
Partial safety factors for consequences of failure, γ_n	1.0	Component class 2
Total safety factor	1.62	

Table 28: Maximum computed flapwise blade root bending moments

DLC Name	Max Flapwise Root Bending Moment (kN-m)	Channel	Simulation
IECDLC1p2NTM	15,310	RootMyb2	15 m/s average wind
IECDLC1p3ETM	17,990	RootMyb3	19 m/s average wind
IECDLC1p4ECD	18,120	RootMyb1	Negative gust at rated speed
IECDLC1p5EWS	13,360	RootMyb2	+11 m/s
IECDLC6p1EWM50	22,740	RootMyb1	+15 degree yaw misalignment
IECDLC6p3EWM01	15,630	RootMyb1	+20 degree yaw misalignment

Table 29: Buckling modes and load factors for load cases with highest root moments

Load case		Load factor	Buckled mode shape
IECDLC6p1EWM50	+15 degree yaw misalignment	1.64	
		1.68	
		1.88	
IECDLC1p4ECD	Negative gust at rated speed	1.63	
IECDLC1p3ETM	19 m/s average wind	1.95	

Using the distributed aerodynamic loads from the aeroelastic simulation exhibiting the highest root bending moment, in this case DLC 6.1, a lowest buckling factor of 1.64 is computed. In addition, the loads associated with negative gust at rated speed also bring on a buckling mode at

1.63 in the outboard spar cap. The load factor requirement from in Table 27 has been met. See Table 29 for a summary of dominant mode shapes for the three largest computed blade loads.

Critical Deflection Analysis

FAST computes the out-of-plane deflection of the blade tip for all simulations. A summary of maximum deflections is found in Table 32. Table 31 summarizes other important information regarding computation of tower clearance. The tower radius information used here is taken from the ADAMS-specific input associated with the NREL 5MW reference turbine.

Table 30: Safety factors used in evaluation of tower clearance (IEC 7.6.5)

Partial safety factor for loads, γ_f	1.35	Do not use for DLC 1.1
Partial safety factor for materials, γ_m	1.1	
Partial safety factors for consequences of failure, γ_n	1.0	Component class 2
Total safety factor	1.485	

Table 31: Allowable OoP tip deflection parameters

Tower height (m)	87.6	FAST model input
Tower-to-shaft (m)	1.96256	FAST model input
Shaft tilt (deg)	5	FAST model input
Shaft horizontal length (m)	5.0191	FAST model input
Precone (deg)	2.5	FAST model input
Rotor radius (m)	62.5	FAST model input
Tower base radius (m)	3.000	ADAMS-specific input
Tower top radius (m)	1.935	ADAMS-specific input
Tower radius @ blade tip (m)	2.660	Computed
Nominal tower clearance (m)	13.16	Computed
Available clearance (m)	10.50	Computed

Allowable tower clearance, including safety factor, is computed as follows:

$$10.50\text{m}/1.485 = 7.07\text{m}$$

Tower clearance criteria is met by this blade design.

Table 32: Maximum computed out-of-plane deflections

DLC Name	Max OoP Deflection (m)	Channel	Simulation
IECDLC1p2NTM	4.72	OoPDefl2	15 m/s
IECDLC1p3ETM	5.58	OoPDefl3	19 m/s
IECDLC1p4ECD	6.03	OoPDefl2	Negative gust at rated speed
IECDLC1p5EWS	4.24	OoPDefl2	+11 m/s
IECDLC6p1EWM50	0.06	OoPDefl3	+10 degree yaw misalignment
IECDLC6p3EWM01	0.11	OoPDefl1	-30 degree yaw misalignment

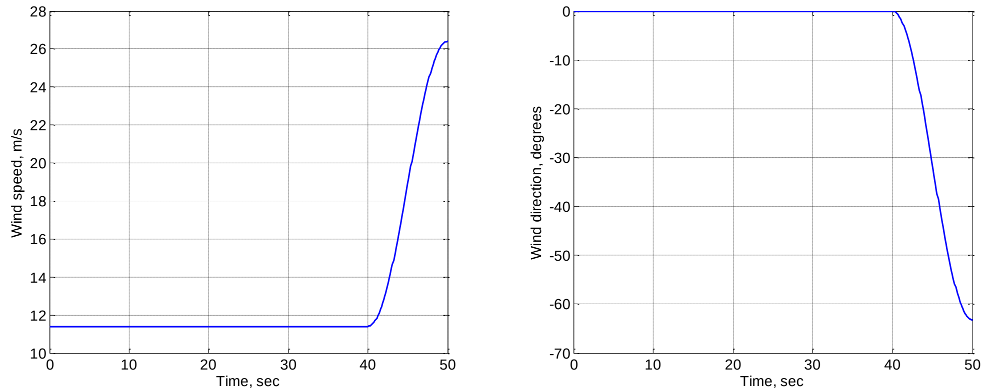


Figure 13. ECD-R wind speed and direction associated with the analysis performed here.

SUMMARY DISCUSSION

Several lessons were learned in the course of performing this work. This blade model is meant to be a simple structural representation that is used to support design tools development activities, so further effort was not directed into solving the follow-on issues that have been discovered. They are discussed here in order to lay the groundwork for future investigations that may use this model.

Full Optimization. Many manual iterations were performed on the design of the blade in order to meet the basic criteria set forth. The iterative process is not too time-consuming, compared to efforts in the past. However, it can be difficult to decide when to stop perfecting the model. For example, this model actually has allowance for less spar cap material because tower clearance has been met with extra margin. It is likely that in the future, the analysis process used to design this blade can be automated and managed by a purposely design optimization routine. In this case, it is likely that a much more optimal blade design will be found.

Material Properties. The material properties used in this model are based off of generic values that were also used for the Sandia 100m blade concept. Perhaps an obvious point, in the course of work on both blades it has become obvious that the designs are sensitive to material properties. Future work may uncover better mechanical properties and associated materials that can be used to produce a new baseline design for this blade.

Foam Properties. Of particular importance to the weight of this blade is the foam. The foam accounts for 21% of this overall blade mass. The author discovered during the course of this work that materials manufacturers offer a wide range of foam densities. The density used here is 200 kg/m^3 but densities as low as 50-60 kg/m^3 are also offered. It is likely that a lighter foam could be used in this model. However, as the density of foam decreases, so does the Young's modulus and shear modulus. A thorough blade designer would pursue studies of the various types of core material at the core thicknesses being used in their blade. The goal would be to avoid core material that is soft enough to allow buckling of face plates into the foam. This type of buckling mode is not predicted by the shell element modeling approach used by NuMAD so it's recommended to design with stiff enough core materials as not to allow it.

Safety Factors. All safety factors are listed in this report so that the reader can know exactly what was used. Choice of safety factors may vary quite a lot depending on the chosen standard or organizational best practices. Obviously, the final Blade Design Scorecard parameters, especially blade weight, are greatly affected by these choices.

BLADE MODEL FILES

The following files are contained in the SNL 61.5m blade model folder, *SNL61p5m:*

NuMAD Files

NuMAD.xlsx --Microsoft Excel® workbook containing information for creation of the blade model through the "File->XLS-2-NMD…" option in NuMAD. The following two files are created as part of this process:

- SNL61p5m.nmd -- The NuMAD blade model data file. This file is for use with NuMAD v2.0.
- MatDBsi.txt -- The NuMAD material data file.

shell7.src -- Output from NuMAD. This file contains the APDL commands that are used directly by ANSYS to create the shell element model using the command string "/INPUT,shell7,src" at the ANSYS command input.

ANSYS Macro Files

The following are ANSYS macro files that are used in conjunction with the model

- zAirfoil.mac, zFlatback.mac, zSmoothe.mac -- These are ANSYS macro files that are required to execute the commands found in the *shell7.src* file. These macros must remain in the same folder as the shell7 file when the ANSYS input execution is performed.
- BOM.mac – Determines the mass of each material in the ANSYS blade model
- Buckle.mac – performs steps required for linear buckling analysis
- Make_nlist.mac – creates file named *NLIST.lis*; this file is used to map aerodynamic forces from AeroDyn output to the FE nodes.

Matlab Scripts

The following scripts assume that the user is running the latest version of source files in the Sandia NuMAD Toolbox.

- makeForces2Ansys.m – read AeroDyn information and compute forces for application to the blade FE model; produces file *forces.forces*.
- compareBaseAndPreComp.m – Plot comparison of blade properties in *FASTBlade_precomp.dat* and *NRELOffshrBsline5MW_Blade.dat*.

Other Files

Forces.forces – file containing the aerodynamic forces on the blade as computed by AeroDyn. Used by makeforces2ansys.m to create forces.src
Forces.src – used by *buckle.mac* to apply forces to all blade skin nodes
FASTBlade_precomp.dat – Section properties as computed by PreComp; FAST blade file format

‘Airfoils’ Folder

Following is a list of the airfoil shape files in the NuMAD *airfoils* folder in the blade model files package:

DU91-W-250.txt
DU93-W-210.txt
DU97-W-300.txt
DU99-W-350.txt
DU99-W-405.txt
Interp_000400.txt
Interp_000500.txt
Interp_000600.txt
Interp_000700.txt
Interp_000800.txt
Interp_001367.txt
Interp_001500.txt
Interp_001600.txt
Interp_004100.txt
Interp_005500.txt
Interp_006833.txt
Interp_007000.txt
Interp_009000.txt
Interp_012000.txt
Interp_012300.txt
Interp_017000.txt
Interp_018450.txt
Interp_020500.txt
Interp_022000.txt
Interp_024600.txt
Interp_027000.txt
Interp_032000.txt
Interp_032800.txt
Interp_037000.txt
Interp_041000.txt
Interp_042000.txt
Interp_045000.txt
Interp_047000.txt
Interp_052000.txt
Interp_055000.txt
Interp_058000.txt
NACA-64-618.txt
circular.txt

SUMMARY: BLADE DESIGN SCORECARD

Table 33: Blade parameters

Parameter	**Value**
Blade Designation	SNL61p5-00
Wind Speed Class	IB
Blade Length (m)	61.5
Blade Weight (kg)	17,700
Span-wise CG location (m)	19.102
# shear webs	2 (box spar)
Maximum chord (m)	4.652 (23.3% span)
Lowest fixed base natural frequency (Hz)	0.870 (ANSYS FE)
Control	Variable speed; collective pitch
Special notes:	Designed to basic IEC req's

Table 34: Blade design performance metrics summary analysis

	Design Load Condition (DLC) designation	**Metrics**	**Notes/method**
Fatigue	NTM	Critical location: Inboard (edge-wise): 83yrs at 17% span	Two-parameter fatigue model used; Miner's rule; FAST
Ultimate	Parked EWM50; blades feathered; +15 degree yaw misalignment	Max strain 2911 micro-strain; Max stress 585 MPa Allowable stress 1546 MPa Max/allowable 38%	17% blade span (flapwise); strain computed using M*c/EI; FAST
Tip Deflection	ECD-R	Computed 6.03m Allowable 7.07m	FAST
Buckling	Parked EWM50; blades feathered; +15 degree yaw misalignment & ECD negative gust operating at rated speed	Min load factor 1.64 & 1.63 Allowable 1.62	ANSYS linear buckling; distributed load from AeroDyn
Flutter	--	Flutter margin estimate 1.55 (2rd flap bending)	NuMAD Classical Flutter (see SAND2012-7028)

Table 35: Blade bill of materials

Material	Mass (kg)	% Blade mass
E-LT-5500 Uni fiber	2,439	13.8%
Saertex DB fiber	2,811	15.9%
Foam	3,855	21.8%
Gelcoat	29	0.2%
Total Resin	5,481	31.0%
Newport 307 Prepreg (incl. resin)	3,085	17.4%

REFERENCES

1. Jonkman, J., Butterfield, S., Musial, W., and Scott, G. "Definition of a 5-MW Reference Wind Turbine for Offshore System Development," National Renewable Energy Laboratory: NREL/TP-500-38060, 2009.

2. *IEC 61400-1 Ed.3: Wind turbines - Part 1: Design requirements*, International Electrotechnical Committee, 2005.

3. Berg, J., Resor, B. R., Owens, B. C., and Laird, D. *Numerical Manufacturing and Design Tool (NuMAD) for Wind Turbine Blades*. (v2.0) http://energy.sandia.gov/?page_id=2238.

4. Nijssen, R. "WMC5MW laminate lay-out of reference blade for WP 3: UPWIND WMC5MW laminate data, Rev. 1." Knowledge Centre Wind turbine Materials and Constructions, 2007.

5. Griffith, D. T., and Ashwill, T. D. "The Sandia 100-meter All-glass Baseline Wind Turbine Blade: SNL100-00," Sandia National Laboratories: SAND2011-3779, 2011.

6. "The UpWind Project," http://www.upwind.eu. Accessed on October 18, 2012.

7. Kooijman, H. J. T., Lindenburg, C., Winkelaar, D., and van der Hooft, E. L. "DOWEC 6 MW Pre-Design: Aero-elastic modeling of the DOWEC 6 MW pre-design in PHATAS," Energy Research Center of the Netherlands: ECN-CX--01-135, DOWEC 10046_009, 2003.

8. Lindenburg, C. "Aeroelastic Modeling of the LMH64-5 Blade," Energy Research Center of the Netherlands: DOWEC-02-KL-083/0, DOWEC 10083_001, 2002.

9. Timmer, W. A., and van Rooij, R. P. J. O. M. "Summary of the Delft University wind turbine dedicated airfoils," *Journal of Solar Energy Engineering-Transactions of the Asme* Vol. 125, No. 4, 2003, pp. 488-496.doi: Doi 10.1115/1.1626129

10. Chow, R. "Computational Investigations of Inboard Flow Separation and Mitigation Techniques on Multi-Megawatt Wind Turbines," *Aeronautical Engineering*. Vol. PhD., University of California-Davis, 2011.

11. "DOE/MSU Composite Material Fatigue Database: May 29, 2012 Update," http://energy.sandia.gov/?page_id=3057#COMPOSITES. Accessed on October 12, 2012.

12. Daniel, I. M., and Ishai, O. *Engineering Mechanics of Composite Materials*: Oxford University Press, 1994.

13. "Newport 307 Product Data Sheet," Newport Adhesives and Composites, Inc.: PL.NB307.071510, 2010.

14. *Guideline for the certification of wind turbines*, Germanischer Lloyd, 2010.

15. Damiani, R., and Bir, G. S. *NWTC Design Codes PreComp*. (v1.00.03) http://wind.nrel.gov/designcodes/preprocessors/precomp. July 2012.

16. Jonkman, J. *NWTC Design Codes FAST*. (v7.01a) http://wind.nrel.gov/designcodes/simulators/fast/. December 3, 2012.

17. Laino, D. J., Jonkman, B., and Nguyen, K. *NWTC Design Codes AeroDyn*. (v13.00.01a) http://wind.nrel.gov/designcodes/simulators/aerodyn/. February 21, 2012.

18. Kelley, N., and Jonkman, B. *NWTC Design Codes TurbSim*. (v1.06.00) http://wind.nrel.gov/designcodes/preprocessors/turbsim/. September 25, 2012.

19. Buhl, M. *NWTC Design Codes IECWind*. (v5.01.02) http://wind.nrel.gov/designcodes/preprocessors/iecwind. October 8, 2012.

20. Buhl, M. *NWTC Design Codes Crunch*. (v3.00.00) http://wind.nrel.gov/designcodes/postprocessors/crunch/. April 6, 2007.

21. Barone, M., Paquette, J., Resor, B., and Manuel, L. "Decades of Wind Turbine Load Simulation," *50th AIAA Aerospace Sciences Meeting*. Nashville, TN, 2012.

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