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

D. Todd Griffith, Brian Resor,
Tom Ashwill (retired)
Sandia National Laboratories

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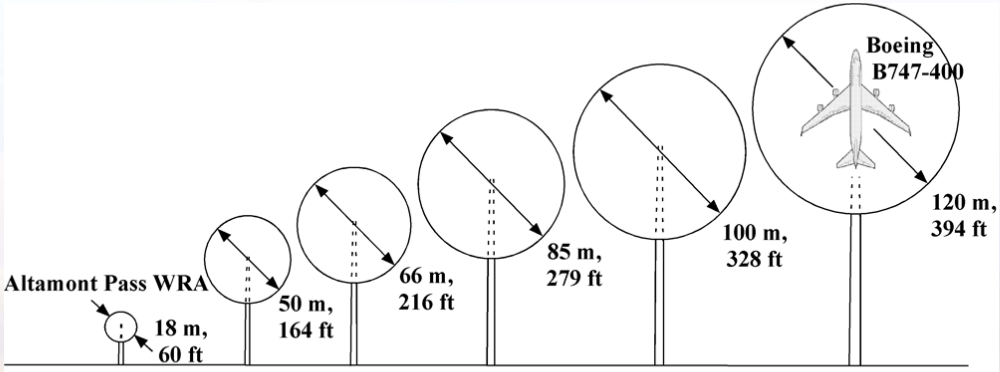
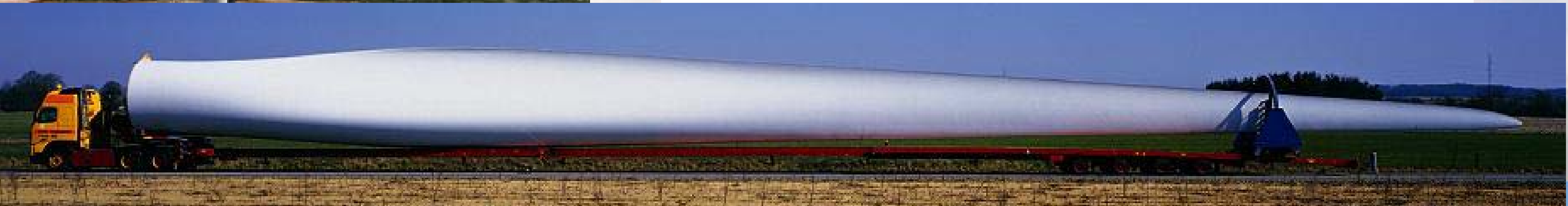
Wind Industry Trends & Challenges

- **Costs (traditional)**
  - System ~ $3/lb
  - Blades ~ $6/lb

•High-end Military ~ $1000/lb
•Aerospace Industry ~ $100/lb

- Size
  - 1.5-5.0 MW
  - Towers: 65-100 meters
  - Blades: 34-60 meters
  - Weight: 150-500 tons





Offshore Wind Energy: System Costs

- Cost of Energy (COE) reduction is key to realize US potential for offshore siting
  - Larger rotors on taller towers
  - Reduction in costs throughout system with better rotor
  - Research investments……

Projected costs for shallow water offshore site

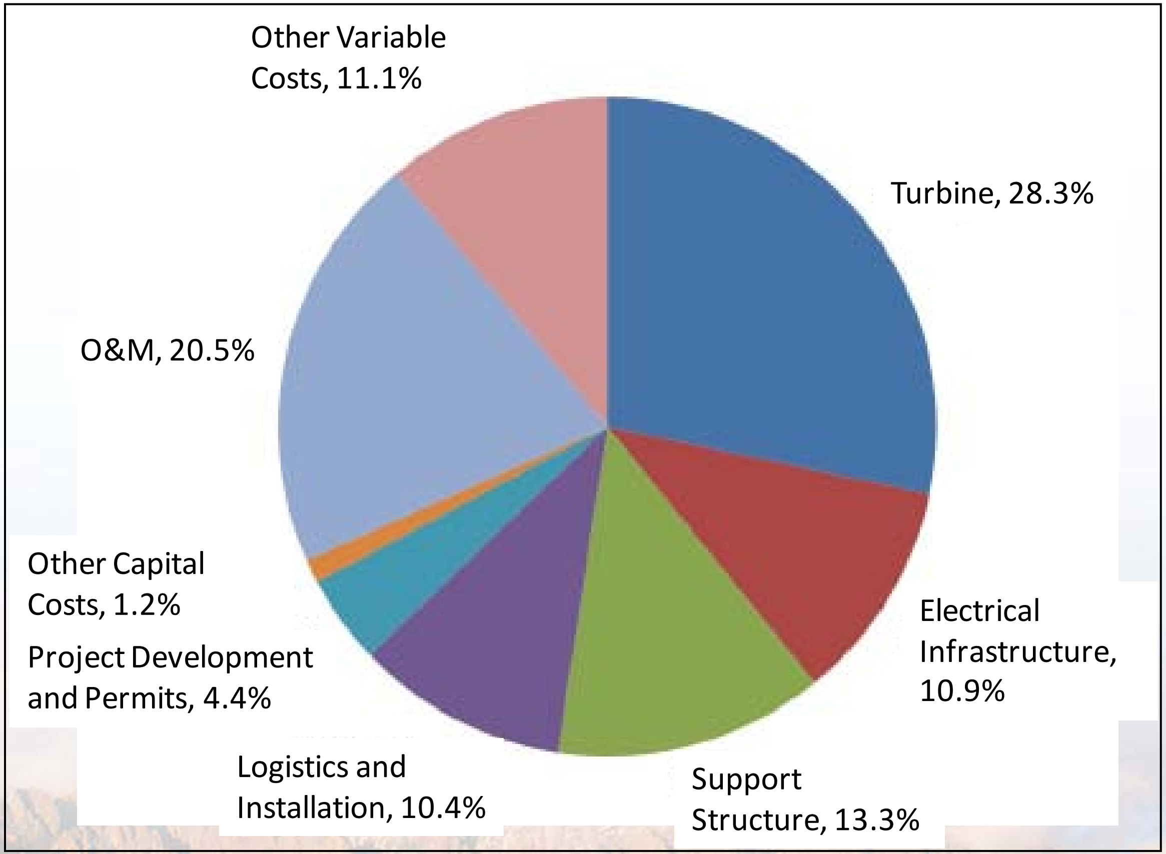


Chart Reference: Musial, W. and Ram, B., *Large-Scale Offshore Wind Power in the United States: Assessment of Opportunities and Barriers*, National Renewable Energy Laboratory, September 2010.

Our goals and approach….

- **Identify challenges** in design of future large blades
- Perform **detailed design** (layup, manufacturability, design standards, analysis) and produce a **baseline 100-meter blade**; certification approach
- Make this model (and updates) **publicly available** for use by other researchers
  - Blade weight reduction, structural innovations, aeroelasticity
  - Cost studies for large blades and large turbines
- Investigate **new design solutions** for the identified challenges/barriers and produce refined/updated 100-meter blade design models

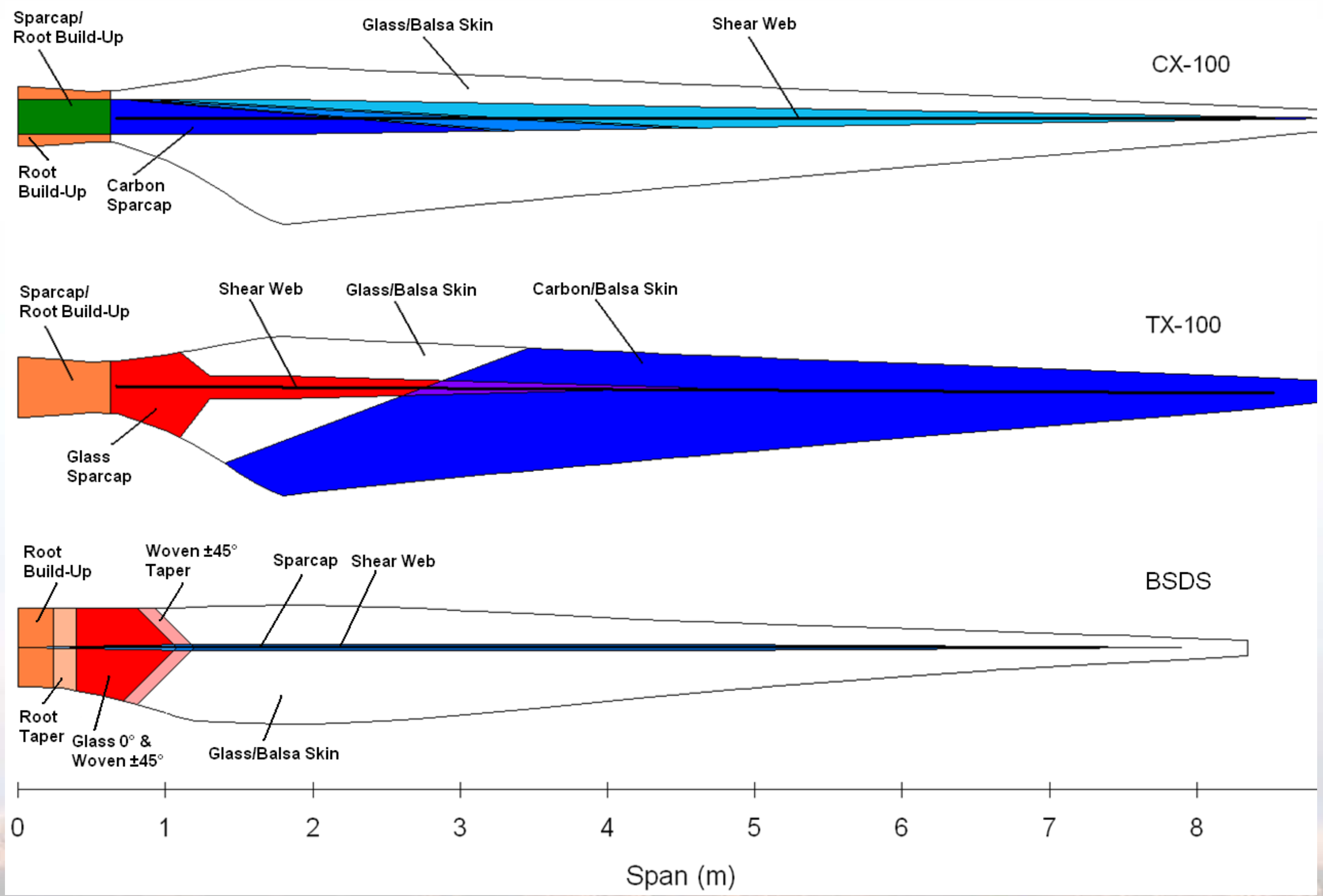
SNL Research Blade Designs: *Late 1990's to present*

Research Goal

CX-100
Strategic use of carbon fiber

TX-100
Bend-twist coupling

BSDS
Flatback/thick airfoils



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Large Blade/Turbine Work Prior to this study

- Starting point needed.....
- Limited data is publicly available……no detailed layups in public domain

- However, a few "public studies" (Europe and US) provide **some data** for blades approximately 60 meters and turbines with rating of 5-6 MW
  - **DOWEC study :** Blade beam properties (span-wise stiffness and mass); Airfoil definitions (from maximum chord outboard)
  - **NREL 5MW turbine:** Used the DOWEC blade model; Includes turbine data required for a FAST model (tower, drivetrain, etc.) and controller

- **These studies were useful for upscaling to 100-meter scale to develop the initial design models, although additional information and analysis was needed for this study**

Large Blade Trends

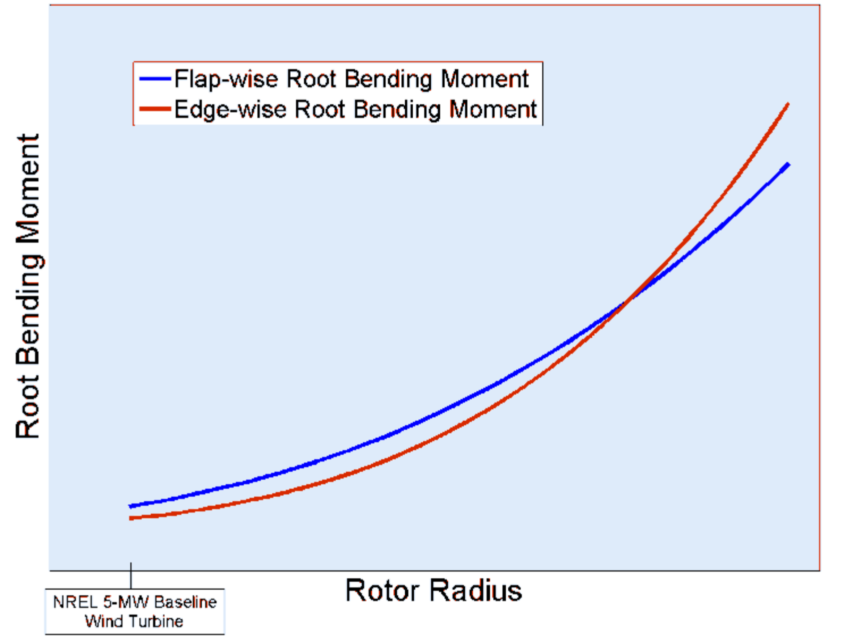
Blade Scaling and Design Drivers

Scale factor: $\alpha = \frac{Upscaled\ Length}{Baseline\ Length} = \frac{L_U}{L_B}$

Mass: $m_U = \alpha^3 \times m_B$

Rotor Power: $P_U = \alpha^2 \times P_B$

Weight growth is one of the large blade challenges. Additional challenges are explored in the detailed design & analysis process.



Root Bending Moments:

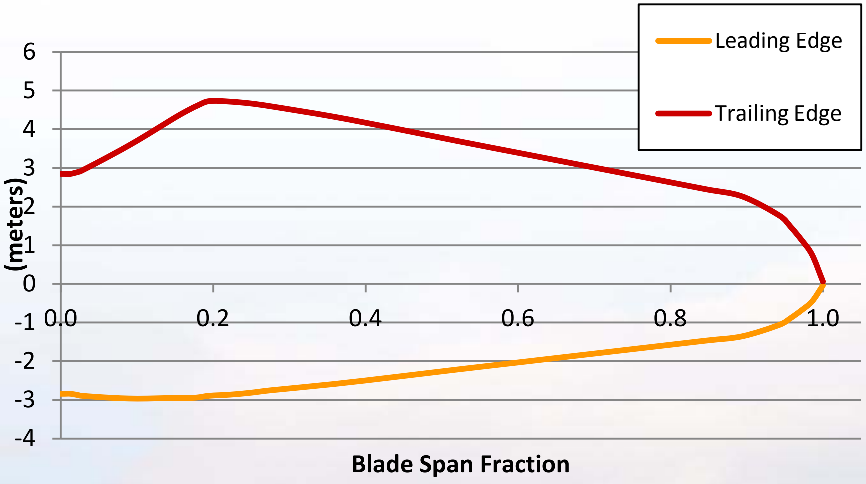
Due to Aerodynamic Forces: $M_U^A = \alpha^3 \times M_U^A$

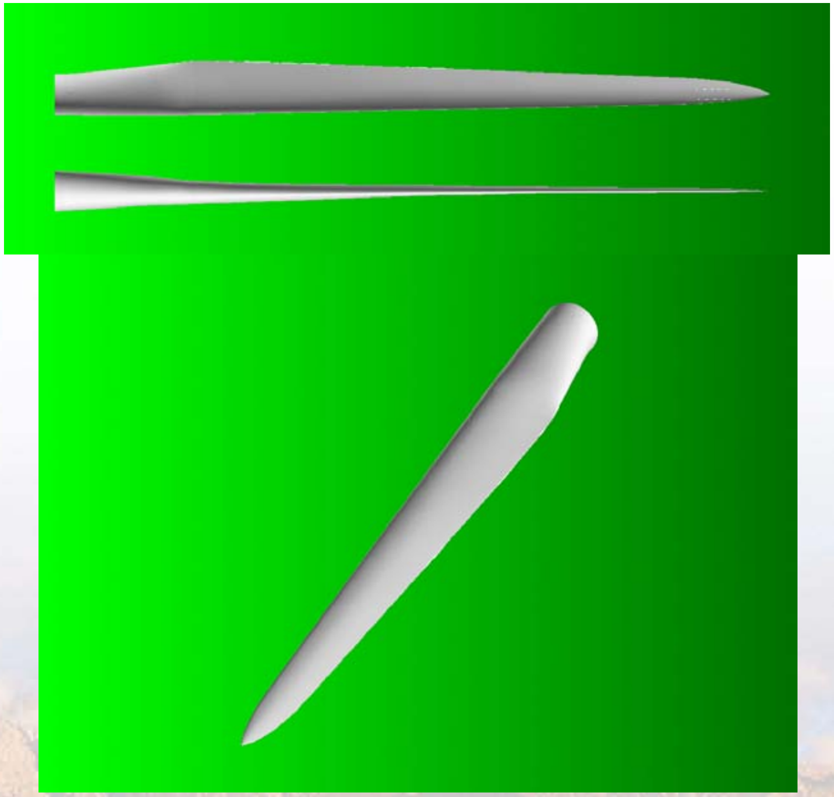
Due to Gravitational Forces: $M_U^G = \alpha^4 \times M_B^G$

SNL100-00 External Geometry

The airfoil shapes inboard of maximum chord were produced by interpolation.

Otherwise, this baseline SNL100-00 designed uses a scaled-up chord distribution and outboard airfoil shapes from DOWEC; same twist as well





Design Loads and Safety Factors

Acceptance of the design to blade design standards is a key element of the work; certification process using IEC and GL specifications; Class IB siting

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

Safety factors for materials and loads included for buckling, strength, deflection, and fatigue analyses

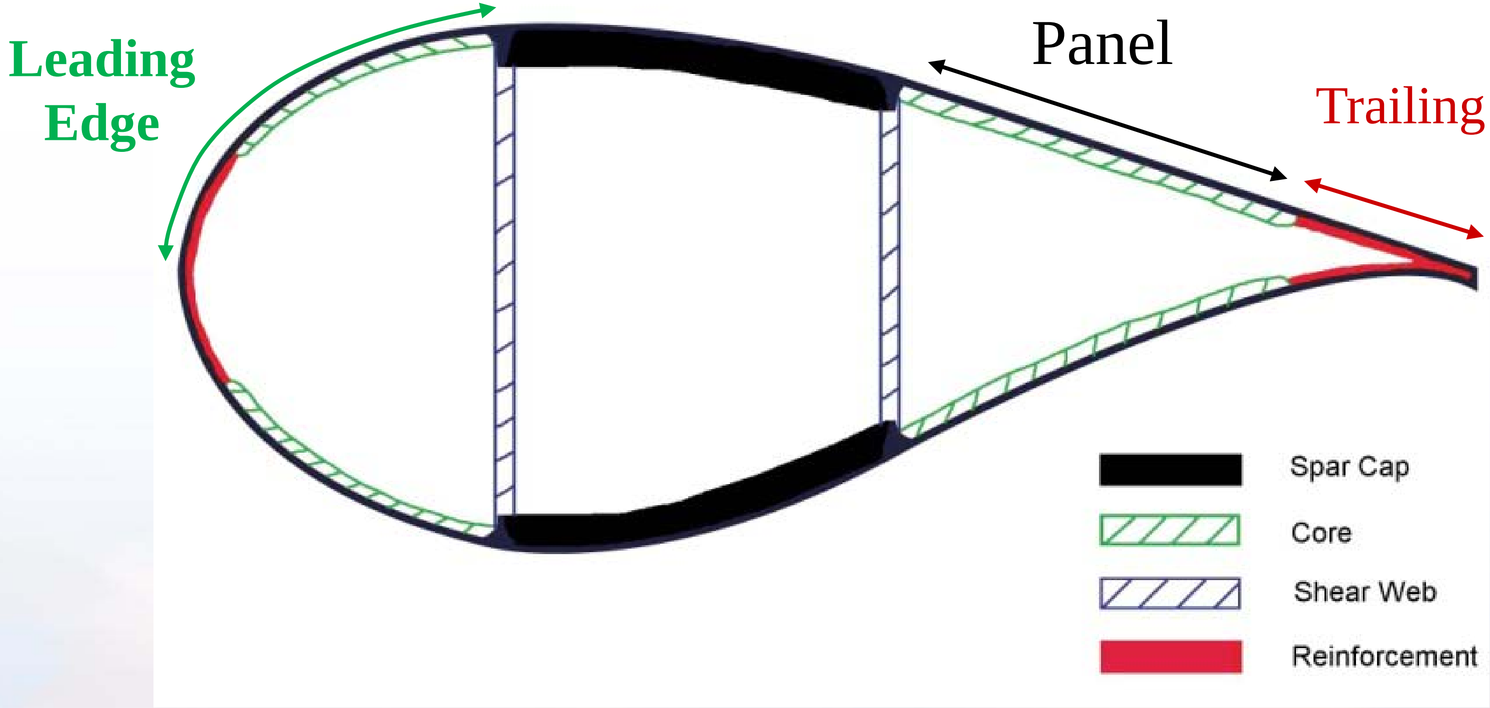
SNL100-00: Design Constraints and Assumptions

- All-glass materials
  - **no carbon**
- Typical or traditional manufacturing
  - **Ply-dropping, parasitic resin mass**
- Typical geometry and architecture
  - **No flatbacks**
  - **Initially two shear web design**

- ……….all these assumptions led to a baseline design that we've termed SNL100-00;

Which is **not formally optimized for weight**, but is designed to work and reduce weight as much as possible despite the lack of inclusion of any blade innovations.

Initial Design: Use of Two Shear Webs



Two shear webs not acceptable due to buckling failure and high weight

SNL100-00 Design:
Summary of Analyses

Key design information in the Sandia Blade Design Scorecard:

Blade specs, summary of analysis margins, and bill of materials

Analysis summary

1) **Strains:** good margins in both the spar cap and trailing edge

2) **Tip deflection:** acceptable for the assumed overhang distance, and modest tilt and precone angles. The smallest clearance margins were found for extreme operating conditions as opposed to extreme parked conditions

3) **Buckling:** satisfied by addition of a third shear web + reinforcements

4) **Fatigue:** expected life was calculated to be 1290 years (GL slope b=10). Edge-wise (gravitational) loading was the driver for fatigue life

5) **Flutter:** flutter speed estimated to be close to maximum operating speed

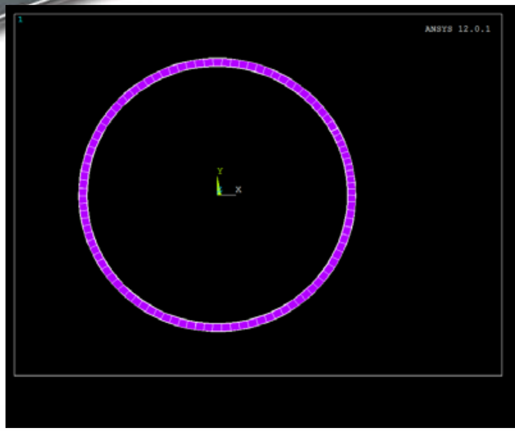
SNL100-00 Design: Strain and Deflection

FAST Simulations of SNL13.2-00-Land turbine

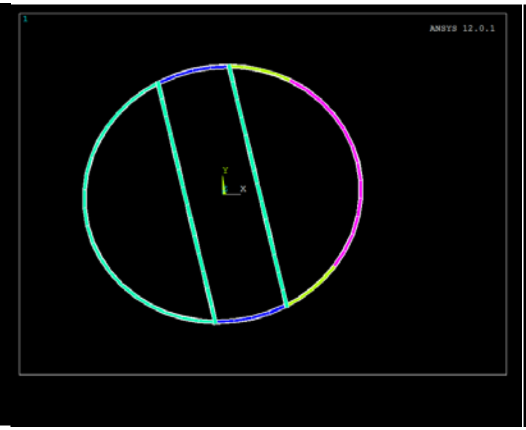
Machine	Load Case	Flap-wise	Edge-wise	Tip Defl
		(kN-m)	(kN-m)	(m)
13.2 MW	ECD+R	67,410	47,220	10.1
13.2 MW	ECD-R	74,810	52,460	11.9
13.2 MW	NWPR	49,250	48,600	7.3
13.2 MW	EWM50 (0^o pitch)	110,700	17,300	12.3
13.2 MW	EWM01 (0^o pitch)	73,300	11,320	8.2
13.2 MW	EWSV+R	58,440	47,260	8.6
13.2 MW	EWSH-R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

All within allowable, even for the initial two shear web design

SN100-00: Layup

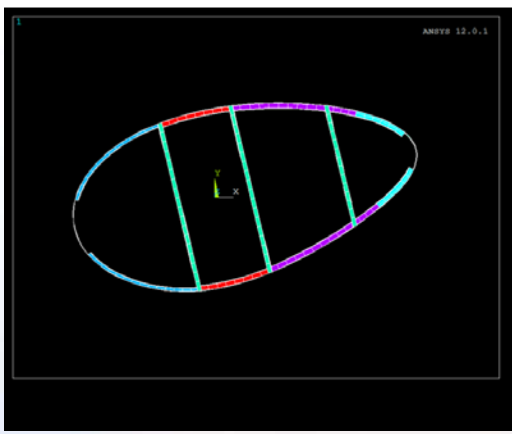


(a) 0.0 meters (root circle)

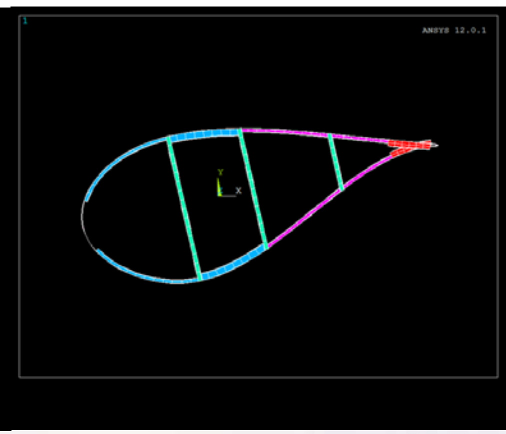


(b) 2.4 meters (shear webs begin)

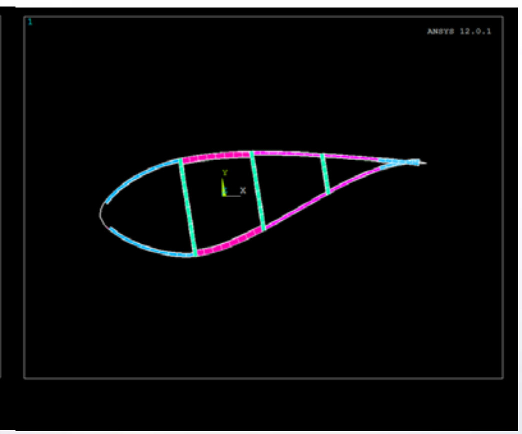
(c) 8.9 meters(transition)



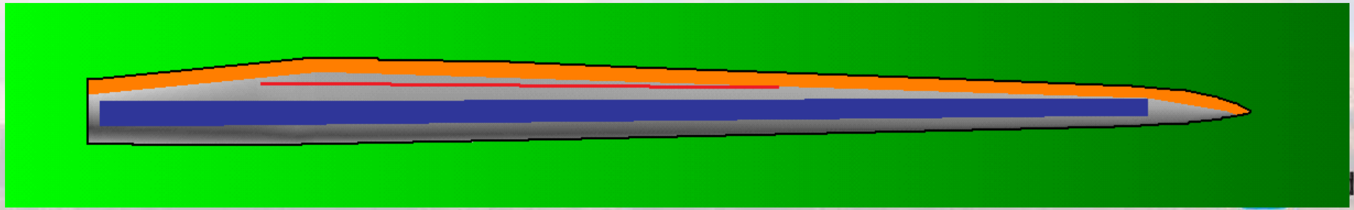
(d) 14.6 meters (third web begins)



(e) 19.5 meters (max chord)



(f) 35.8 meters



SNL100-00 Design Summary

1. A 100-meter wind turbine blade is possible using all-glass materials
   - However, quite heavy (~114,000 kg with 3.3 scaling factor) and not cost-effective
   - Application of innovation and optimization is needed – the SNL100-00 model is made publicly available along with its associated 13.2 MW turbine model
2. The detailed design and analysis process demonstrated that many design drivers are challenged
   - especially fatigue life (edge-wise), flutter, buckling and deflection

Large Blade Research Needs

- Innovations for weight and load reduction
- Evaluation of design code suitability for analysis of large-scale machines
  - Large deflection behavior
  - Spatial variation of inflow across the rotor
- Anti-buckling and flutter mitigation strategies
- Aerodynamics and power optimization: aerodynamic twist, chord schedule, and tip speed ratio
- Transportation and manufacturing

Revisit SNL Research Blade Innovations……

Research Goal

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Strategic use of carbon fiber

TX-100
Bend-twist coupling

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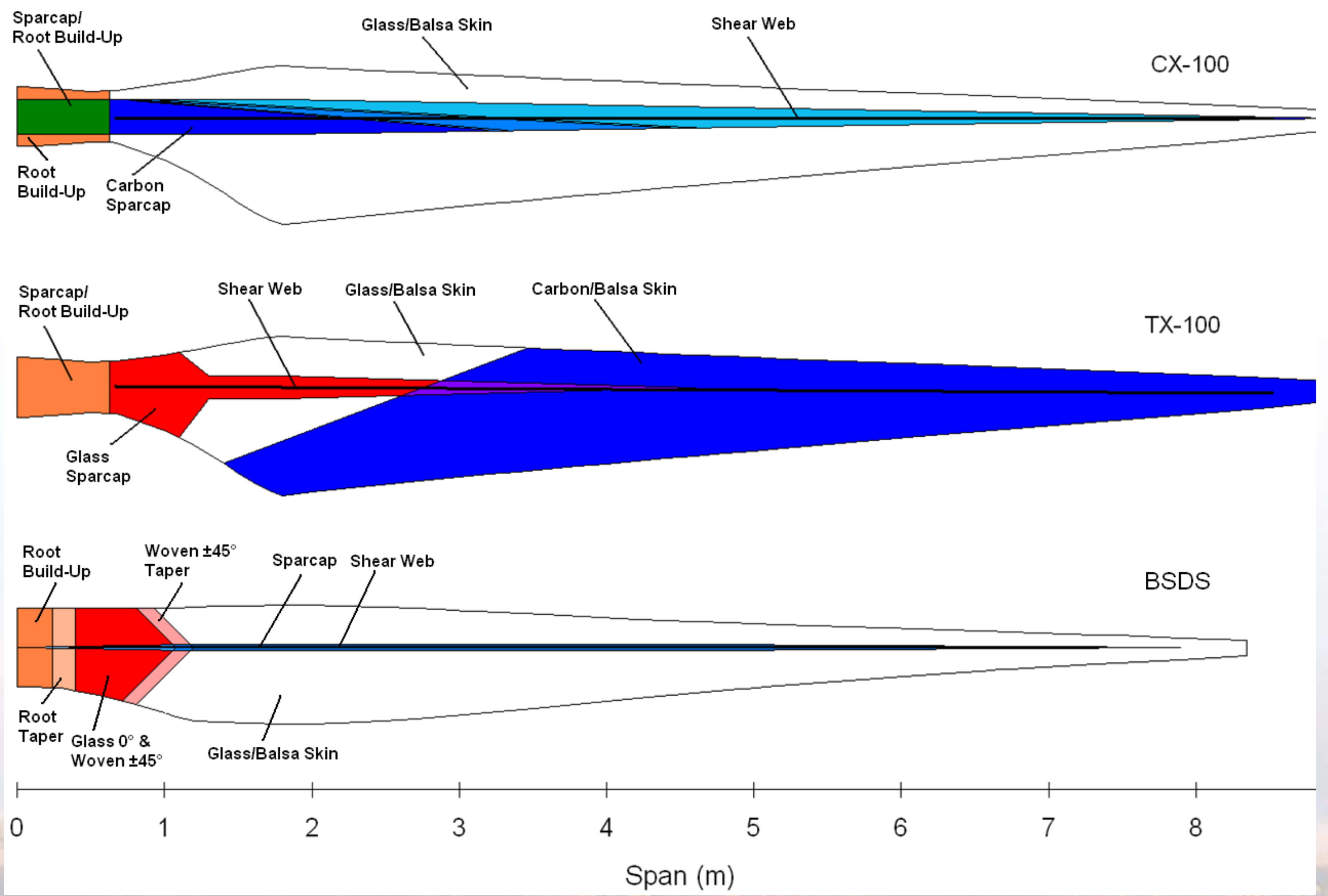


Carbon Parameter Studies (1)

Conceptual carbon laminate introduced into Baseline

- ***Initial studies: replace uni-directional glass in either spar cap or trailing edge reinforcement with carbon***

- **SNL100-00: Baseline All-glass Blade**

1. **Case Study #1: All carbon spar cap**
2. **Case Study #2: All carbon trailing edge**
3. **Case Study #3: All carbon spar cap with foam**

Carbon Parameter Studies (2)

Design Scorecard Comparison: Performance and Weight

	SNL100-00 Baseline**	Case Study #1	Case Study #2	Case Study #3
	All-glass baseline blade	Carbon Spar Cap	Carbon Trailing Edge Reinforcement	Carbon Spar Cap plus Foam
Max Deflection (m)	11.9	10.3	12.0	10.3
Fatigue Lifetime (years)	1000	N/A	N/A	281
Governing location for fatigue lifetime	15% span edge-wise	N/A	N/A	*15% span flap-wise*
Lowest Buckling Frequency	2.365	0.614	2.332	2.391
Blade Mass (kg)	114,197	82,336	108,897	93,494
Span-wise CG Location (m)	33.6	31.0	32.1	34.0

Carbon Parameter Studies (3)

Design Scorecard Comparison: Bill of Materials

	SNL100-00 Baseline	Case Study #1	Case Study #2	Case Study #3
	All-glass baseline blade	Carbon Spar Cap	Carbon Trailing Edge Reinforcement	Carbon Spar Cap plus Foam
Blade Mass (kg)	114,197	82,336	108,897	93,494
Span-wise CG (m)	33.6	31.0	32.1	34.0
E-LT-5500 Uni-axial Glass Fiber (kg)	39,394	16,079	34,952	16,079
Saertex Double-bias Glass Fiber (kg)	10,546	10,546	10,546	10,546
Foam (kg)	15,068	15,068	15,917	26,600
Gelcoat (kg)	927	927	927	927
Total Infused Resin (kg)	53,857	33,996	50,072	33,996
Newport 307 Carbon Fiber Prepreg (kg)	0	10,208	1,902	10,208

Carbon Parameter Studies (4)

Observations: Comparison with SNL100-00 Baseline

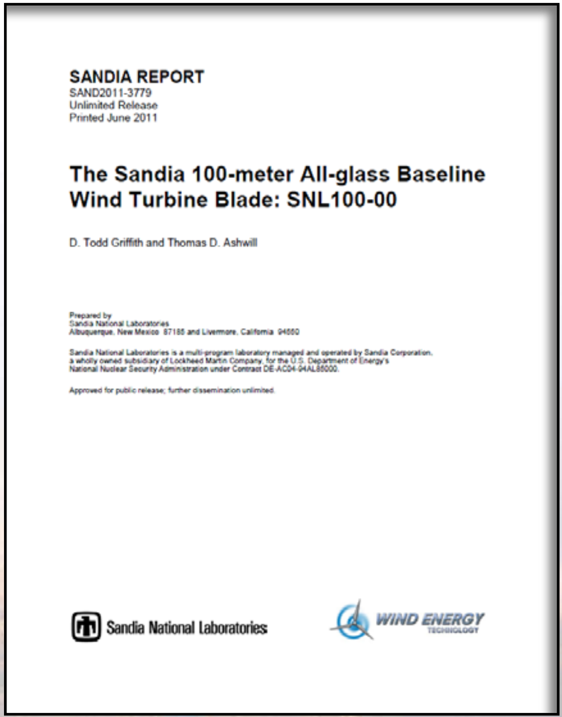
- **For Case Study #1, all carbon spar cap:**
  - buckling of the thinner spar cap
- **For Case Study #2, all carbon trailing edge (reduced width):**
  - small decrease in blade weight; important for flutter
- **For Case Study #3, all carbon spar cap with foam:**
  - Large weight reduction; flap-wise fatigue became driver

- **These initial parameters studies guide an optimal usage of carbon compared to Baseline**
- **Additional work is needed to develop an updated design ("SNL100-01")**
  - Cost-performance tradeoffs
  - Complete certification analyses
  - Updated 13.2 MW Turbine model with SNL100-01 blades

Resources, Model Files

Model files on Project Website (both blade and turbine)
www.energy.sandia.gov/?page_id=7334
www.sandia.gov/wind

SNL100-00 Blade: detailed layup (NuMAD), ANSYS input
SNL13.2-00-Land Turbine: FAST turbine, controller, IECWind, Modes



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The Sandia 100-meter All-glass Baseline Wind Turbine Blade: SNL100-00

D. Todd Griffith and Thomas D. Ashwill

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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WIND ENERGY TECHNOLOGY

Design Scorecard

D.T. Griffith, "Sandia Large Rotor Design Scorecard (SNL100-00)", Sandia National Laboratories Technical Report, December 2011, SAND2011-9112P.

References:

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

Resor, B., Owens, B, Griffith, D.T., "Aeroelastic Instability of Very Large Wind Turbine Blades," EWEA Annual Event Scientific Track, Copenhagen, Denmark, April 16-19, 2012.