Large Rotor Development: Sandia 100-meter Blade Research

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WIND TURBINE BLADE MANUFACTURE 2012
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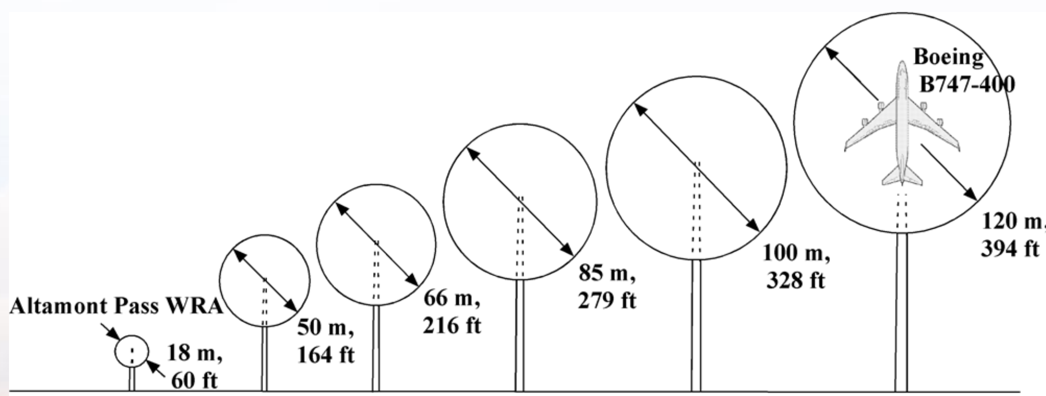
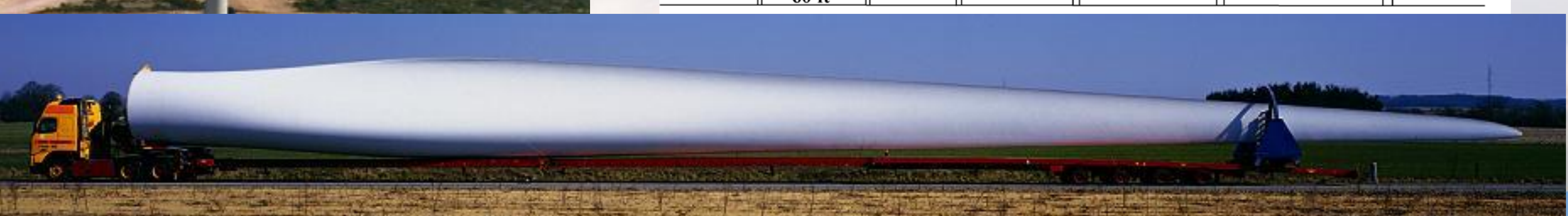
Wind Industry Trends & Challenges

- **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





Offshore Wind Energy: System Costs

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

Projected costs for shallow water offshore site

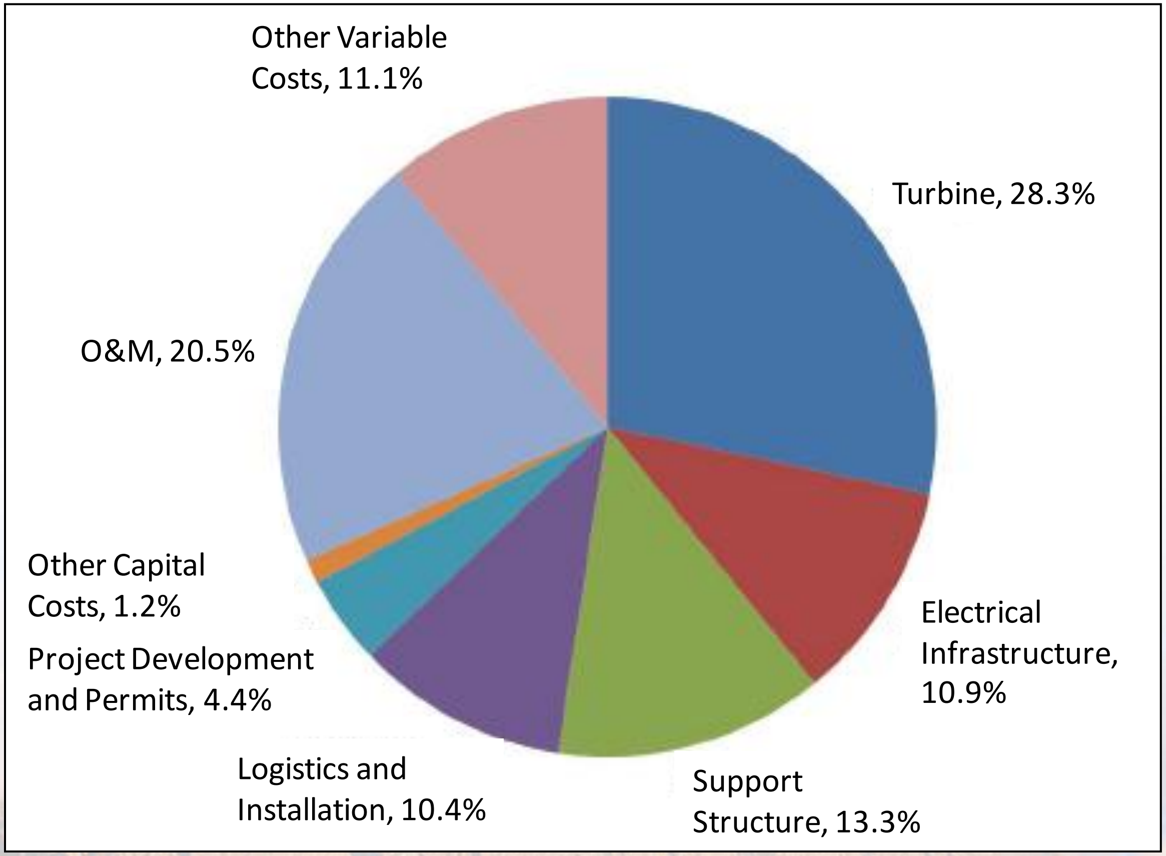


Chart Reference: Musial, W. and Ram, B., *Large-Scale Offshore Wind Power in the United States: Assessment of Opportunities and Barriers*, National Renewable Energy Laboratory, September 2010.

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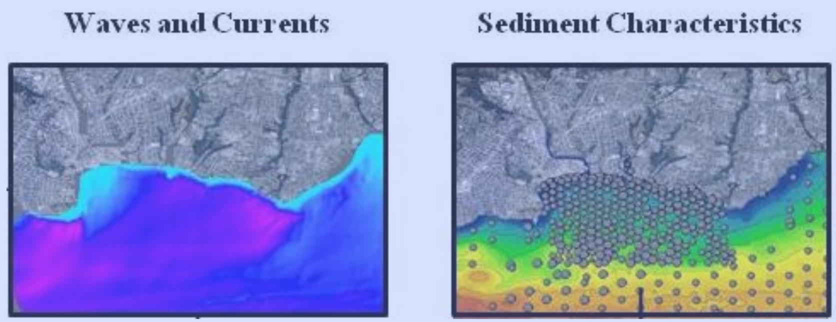
Offshore Wind @ Sandia

Addressing the challenge through research: *Identifying and mitigating technology barriers and leveraging past experiences*

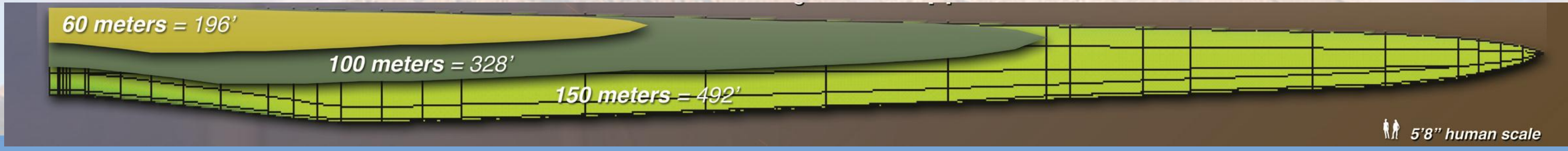


Offshore Siting Analysis

SHM/PM for O&M Process

DOE/Sandia 34 meter VAWT

Large Offshore Rotors



Large Rotor Project:
Our Goals; Approach….

- **Identify challenges** in design of future large blades
- Perform **detailed design** (layup, design standards, analysis, etc.)
  - Produce a **baseline 100-meter blade**; certification approach
  - Make these models **publicly available**
- **Targeted follow-on studies** for large blades
  - Blade weight reduction, advanced concepts
  - Aeroelasticity; power performance
  - Cost studies for large blades and large turbines

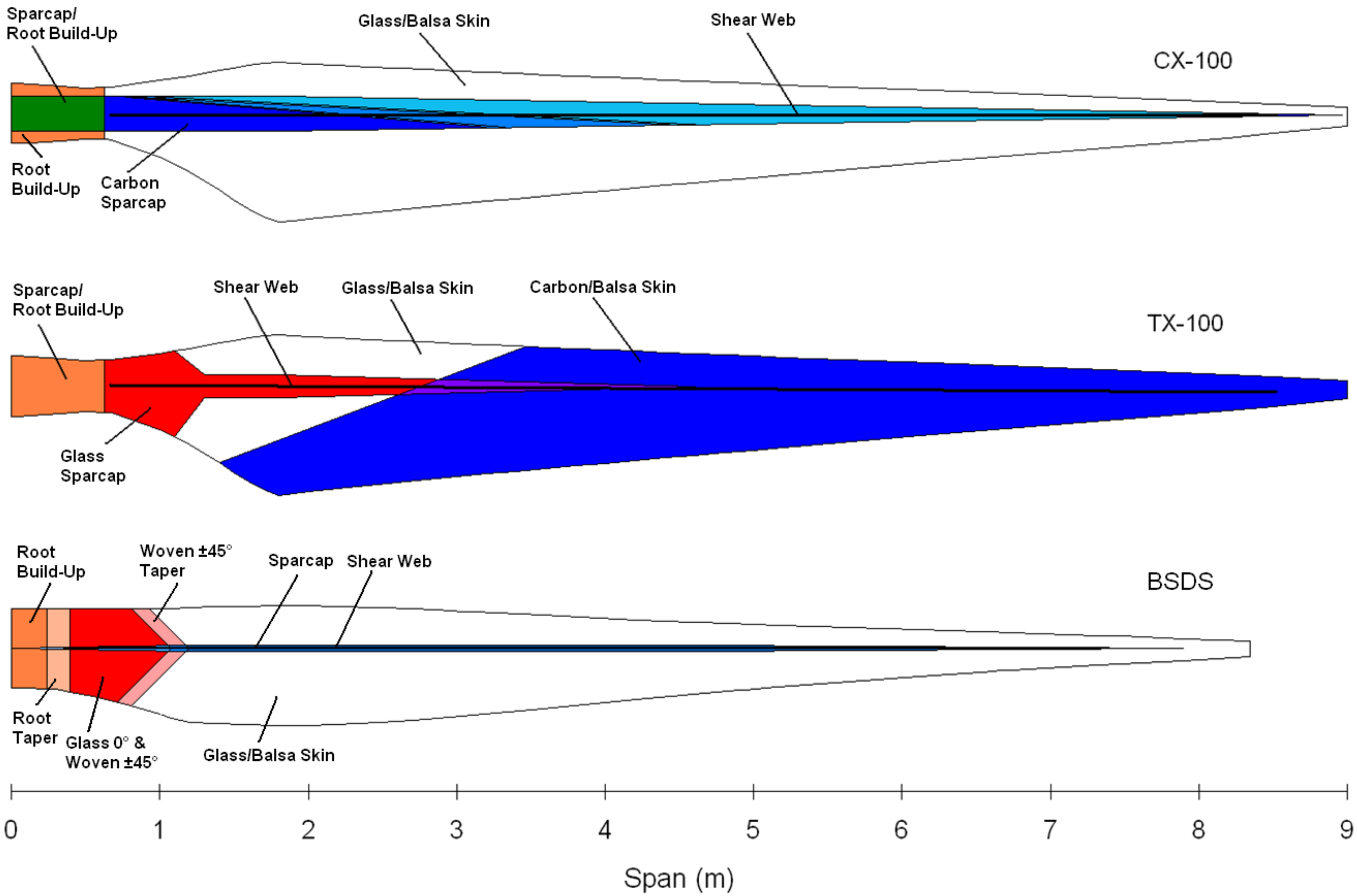
SNL Research Blade Designs:
Late 1990's to present

Research Goal

CX-100
Strategic use of carbon fiber

TX-100
Bend-twist coupling

BSDS
Flatback/thick airfoils



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 and Airfoil definitions from maximum chord outboard
  - **NREL 5MW turbine:** Used the DOWEC blade model; Turbine 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**

Initial Large Blade Trend Studies

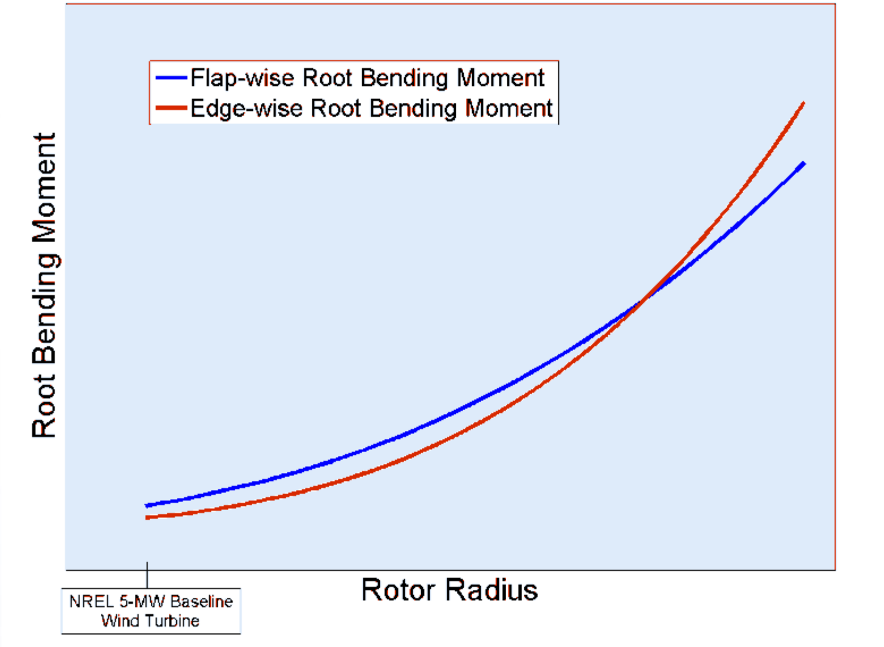
Blade Scaling and Design Drivers

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

$$\text{Mass: } m_U = \alpha^3 \times m_B$$

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

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



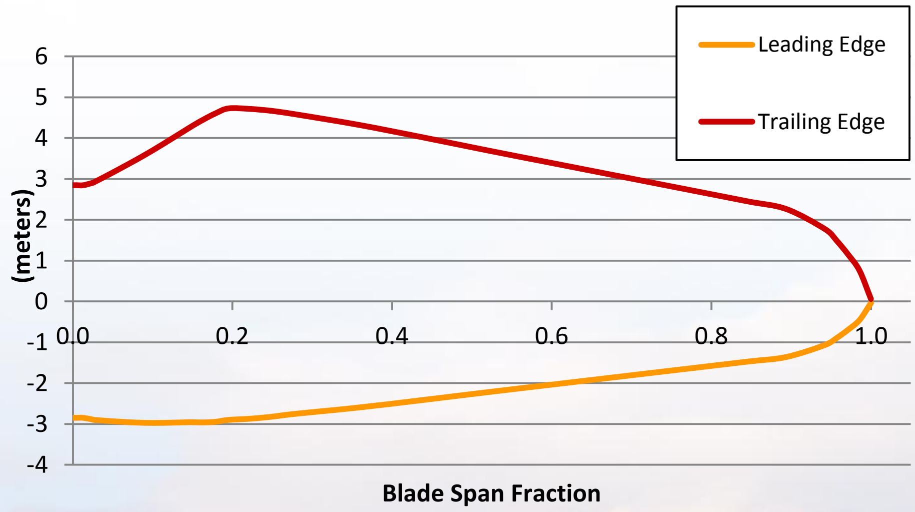
Root Bending Moments:

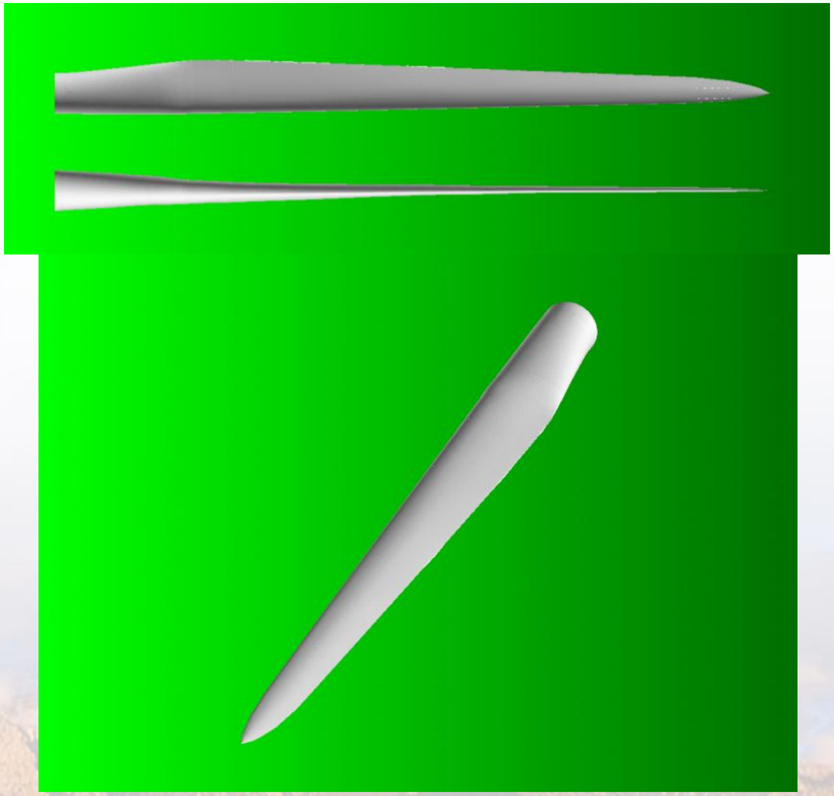
$$\text{Due to Aerodynamic Forces: } M_U^A = \alpha^3 \times M_U^A$$

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

SNL100-00 *External Geometry*

- The inboard airfoils 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

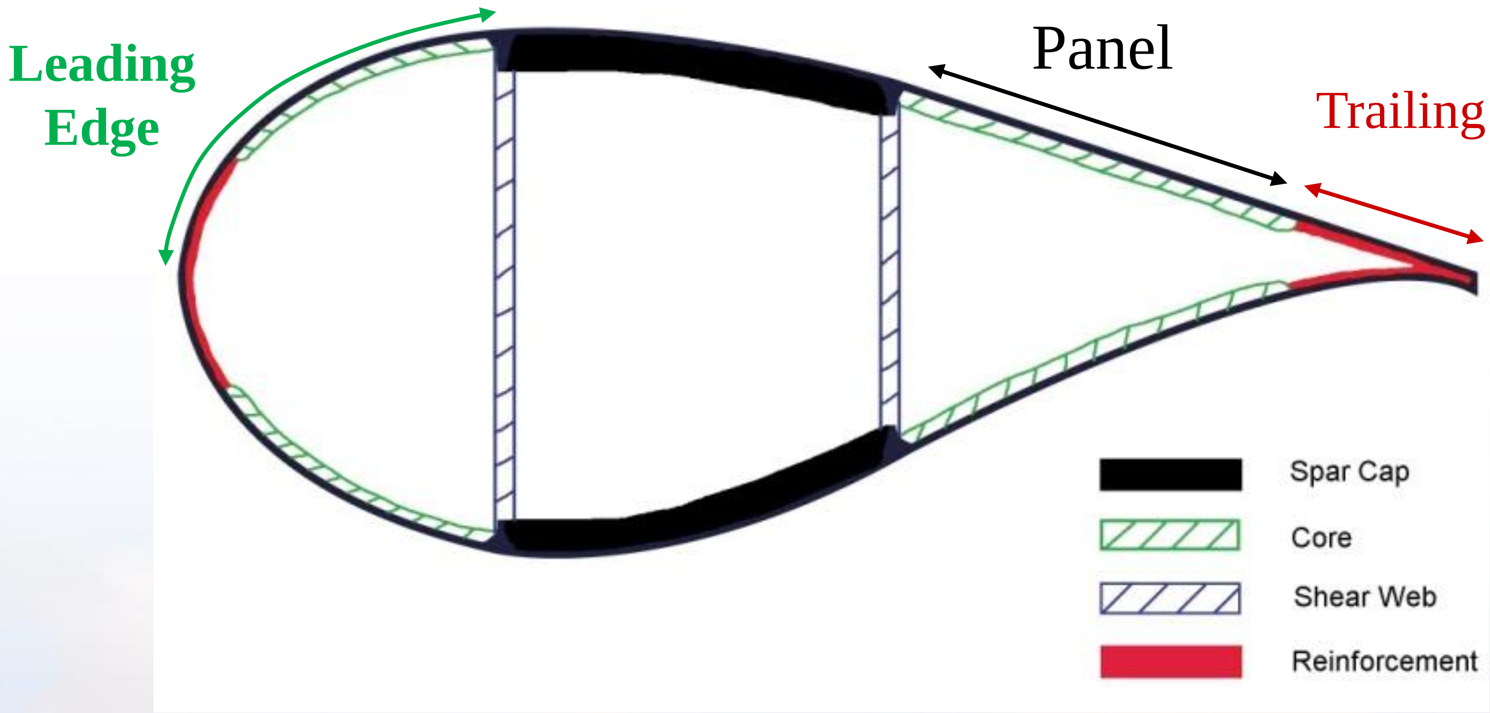
SNL100-00: Design Constraints and Assumptions

- 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.

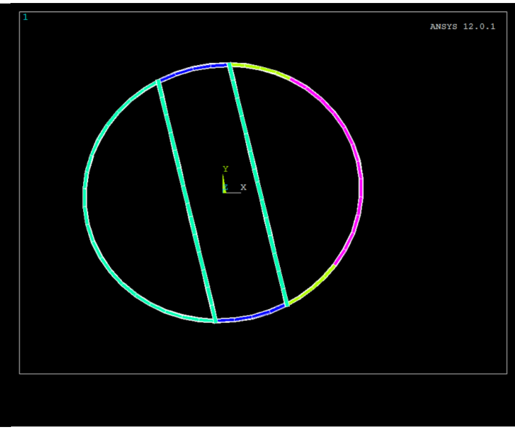
Initial SNL100-00 Design:
Two Shear Web Architecture



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

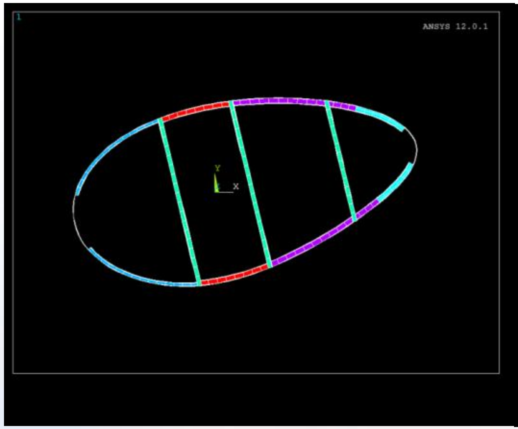
SN100-00: Layup

(a) 0.0 meters (root circle)

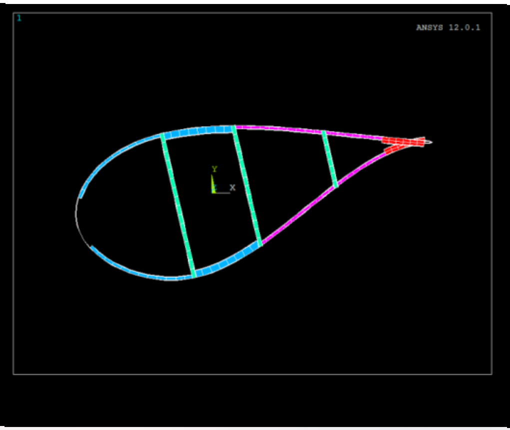


(b) 2.4 meters (shear webs begin)

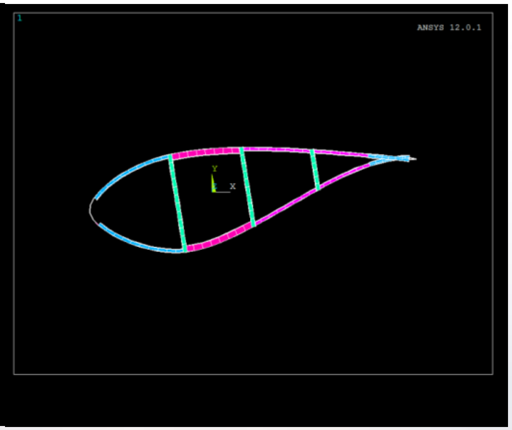
(c) 8.9 meters(transition)



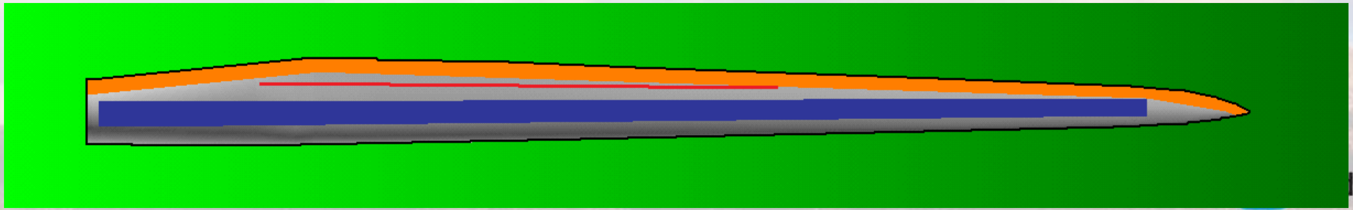
(d) 14.6 meters (third web begins)



(e) 19.5 meters (max chord)



(f) 35.8 meters



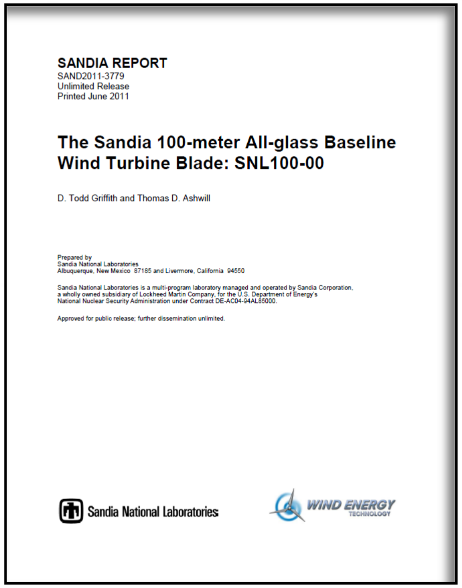
SNL100-00: Design Overview

Design Performance Review

- Fatigue — 1290 year fatigue life
- Maximum Strain — 48.2% margin
- Tip deflection — 1.77m clearance
- Buckling — 6.3% margin
- Flutter — 1.2-1.3x max speed

3-Blade Upwind Rotor

- Land based and off-shore installations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The Sandia 100-meter All-glass Baseline Wind Turbine Blade: SNL100-00

D. Todd Griffith and Thomas D. Ashwill

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WIND ENERGY TECHNOLOGY

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

Material	Description	Mass (kg)	Percent Blade Mass
E-LT-5500	Uni-axial Fiberglass	37,647	32.5%
Saertex	Double Bias Fiberglass	10,045	8.7%
EP-3	Resin	51,718	44.7%
Foam	Foam	15,333	13.3%
Gelcoat	Coating	920	0.8%

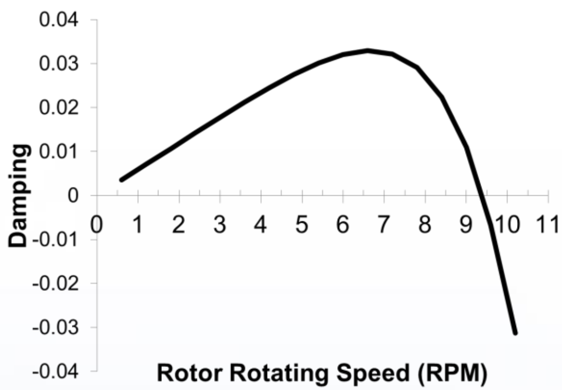
Max operating speed: 7.44 RPM
Cut in/out wind speed: 3.0/25.0 m/s

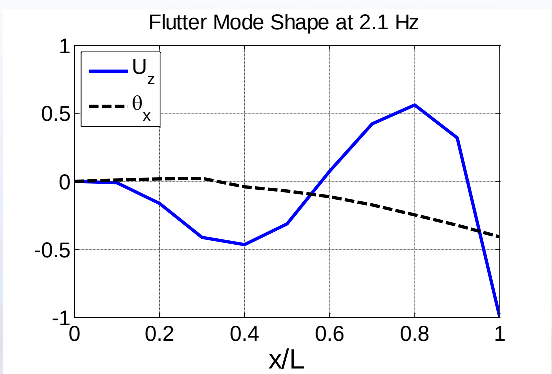
SNL100 Follow-on Projects

1. Sandia Flutter Study
2. Altair/Sandia CFD Study
3. Sandia Blade Manufacturing Cost Model
4. Carbon Design Studies
5. Future Work

(1) Sandia Flutter Parameter Study

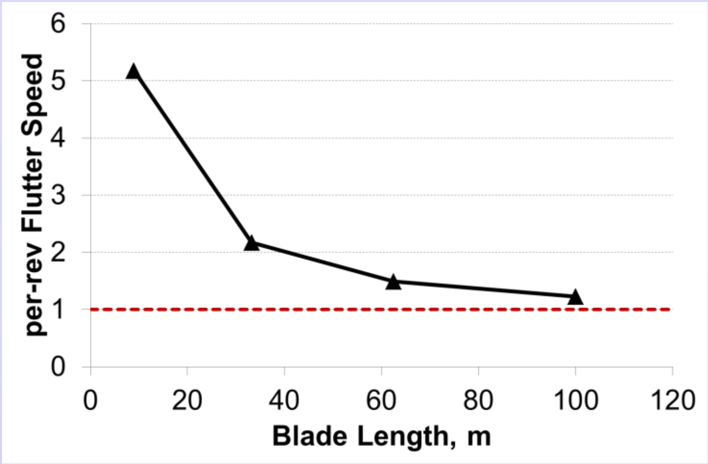
- **Resor, Owens, and Griffith. "Aeroelastic Instability of Very Large Wind Turbine Blades." Scientific Poster Paper; EWEA Annual Event, Copenhagen, Denmark, April 2012.**

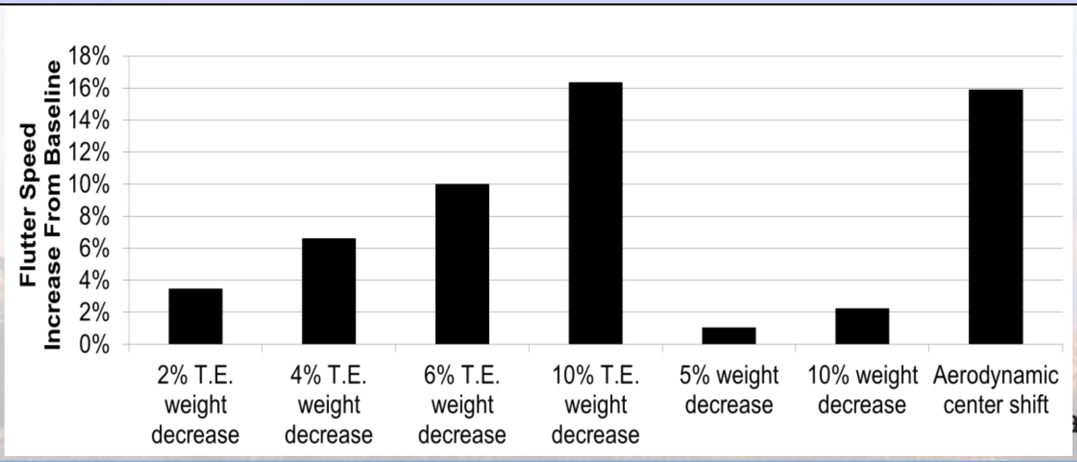




Data shown are from classical flutter analyses:

- **SNL CX-100; 9-meter experimental blade**
- **WindPact 33.25-meter 1.5MW concept blade**
- **SNL 61.5-meter blade (preliminary design)**
- **SNL100-00 Baseline Blade**

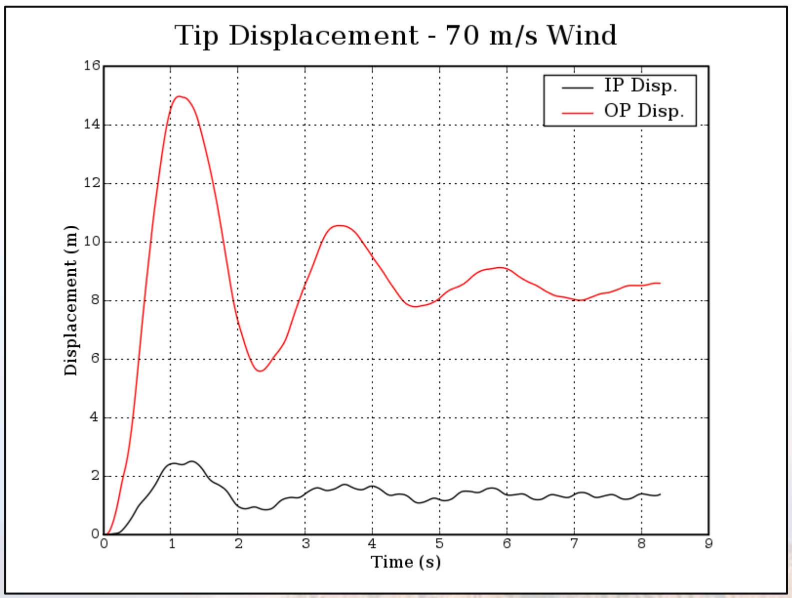


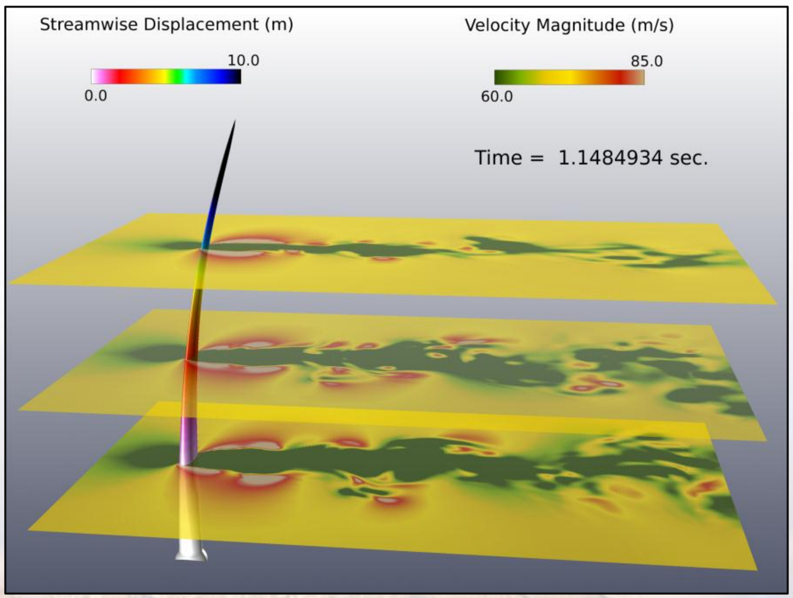


(2) High-fidelity CFD Analysis of SNL100-00

Fully coupled fluid/structure interaction model of Sandia's 100m blade has been developed using *AcuSolve*

- *AcuSolve* CFD solution validated against existing tools
  - Good agreement with WT_Perf for all quantities
  - Some curious results when comparing *AcuSolve* and WT_Perf to FAST
  - Model extended to handle wind gusts and blade flutter simulations





Corson, D., Griffith, D.T, et al, "Investigating Aeroelastic Performance of Multi-MegaWatt Wind Turbine Rotors Using CFD," AIAA Structures, Structural Dynamics and Materials Conference, Honolulu, HI, April 23-26 2012, AIAA2012-1827.

HyperWorks

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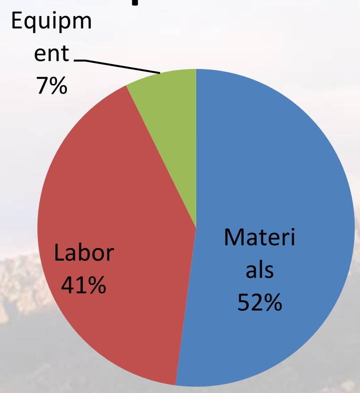
(3.1) Sandia Blade Manufacturing Cost Model: Approach

- **Components of the Model:**
  - Materials, Labor, Capital Equipment
- **Input the design characteristics**
  - Geometry and BOM from blade design software (NuMAD)
  - Materials cost based on weight or area
  - Labor scaled based on geometry associated with the subtask
  - Capital equipment scaled from typical on-shore blades
- ***Two principal questions:***
  - ***Trends in principal cost components for larger blades?***
  - ***Cost trade-offs for SNL100 meter design variants?***

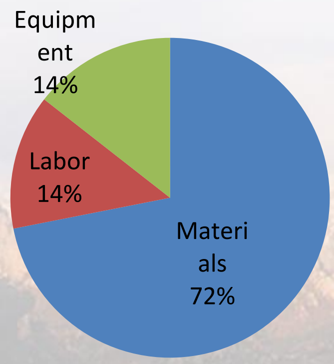
(3.2) Sandia Blade Manufacturing Cost Model: Total Cost

- **Examples: labor scaling factor for subtasks based on component length, surface area, total ply length, bond line length, etc.**
- **Plans to document this soon, including SNL100-01 carbon blade studies**
- **Initial feedback has been positive and constructive**
- **Material costs become a much greater driver of overall manufacturing costs**
  - Materials: 3rd power, Labor: 1.5, Equipment: 2.09, Overall: 2.7
  - Weight reduction reduces the cost of both materials and labor

40m All-Glass Blade Cost Components

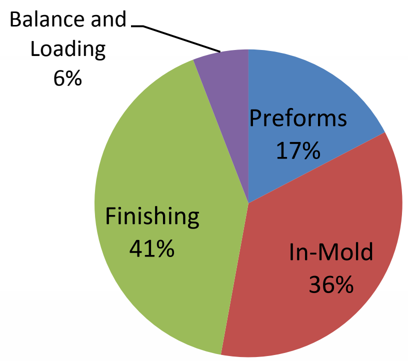


100m All-Glass Blade Cost Components

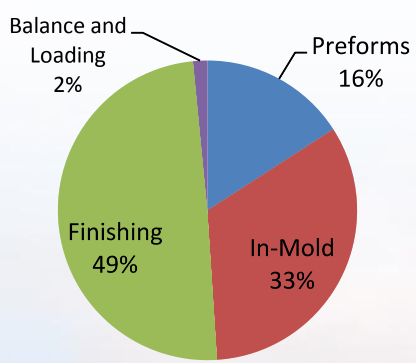


(3.3) Sandia Blade Manufacturing Cost Model: Labor

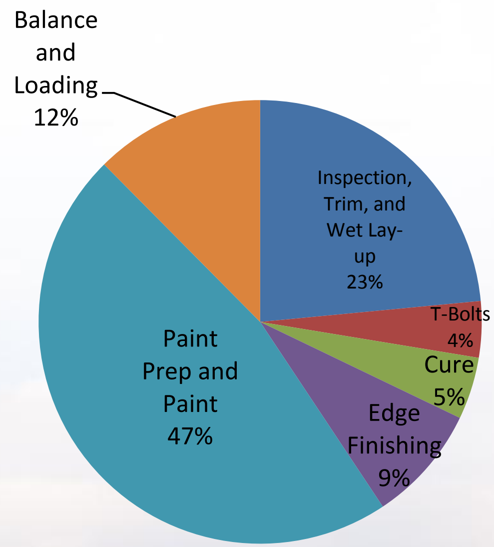
40m All-Glass Blade Aggregate Labor Hour Components



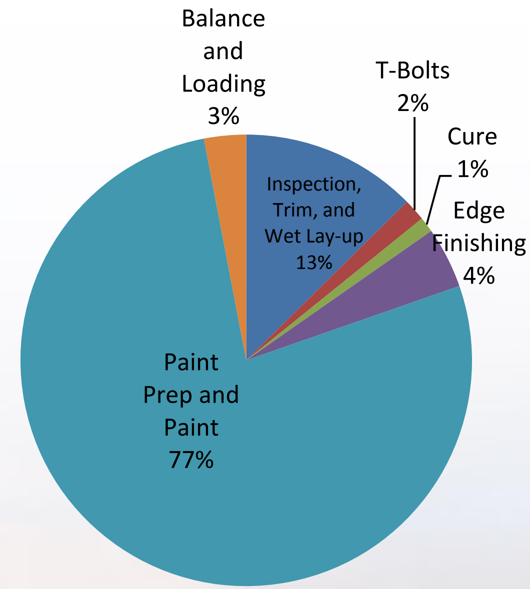
100m All-Glass Blade Aggregate Labor Hour Components



40m All-Glass Blade Finishing Labor-Hours as a Percentage of Total



100m All-Glass Blade Finishing Labor-Hours as a Percentage of Total

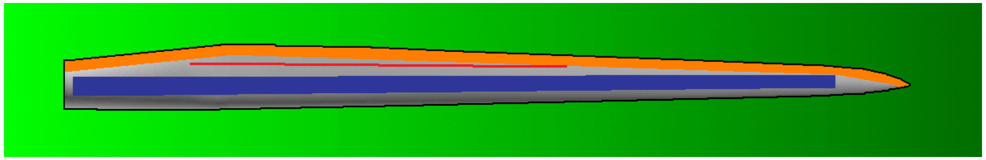


Manufacturing operations related to blade surface area become a much larger driver of labor costs (skin lay-up and finishing operations like painting and sanding)

(4.1) Carbon Design Studies

Conceptual carbon laminate introduced into Baseline SNL100-00 Blade

- ***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**
4. **Case Study #4: Reduce spar width and replace with carbon; reduce TE reinforcement dimensions**

(4.2) Carbon Design Studies

Design Scorecard Comparison: Performance and Weight

	SNL100-00 Baseline**	Case Study #1	Case Study #2	Case Study #3	Case Study #4
	All-glass baseline blade	Carbon Spar Cap	Carbon Trailing Edge Reinforcement	Carbon Spar Cap plus Foam	Carbon Spar width and TE reduction
Max Deflection (m)	11.9	10.3	12.0	10.3	12.7
Fatigue Lifetime (years)	1000	N/A	N/A	281	72
Governing location for fatigue lifetime	15% span edge-wise	N/A	N/A	*15% span flap-wise*	*11% span flap-wise*
Lowest Buckling Frequency	2.365	0.614	2.332	2.391	2.158
Blade Mass (kg)	114,197	82,336	108,897	93,494	78,699
Span-wise CG (m)	33.6	31.0	32.1	34.0	31.3

(4.3) Carbon Design Studies

Design Scorecard Comparison: Bill of Materials

	SNL100-00 Baseline		Case Study #4
	All-glass baseline blade		Carbon Spar width and TE reduction
Blade Mass (kg)	114,197		78,699
Span-wise CG (m)	33.6		31.3
E-LT-5500 Uni-axial Glass Fiber (kg)	39,394		13,894
Saertex Double-bias Glass Fiber (kg)	10,546		10,623
Foam (kg)	15,068		16,798
Gelcoat (kg)	927		927
Total Infused Resin (kg)	53,857		32,234
Newport 307 Carbon Fiber Prepreg (kg)	0		8,586

(4.4) Carbon Design Studies

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
- **For Case Study #4, reduced carbon spar width and TE reduction**
  - further weight reduction, buckling satisfied, flap-wise fatigue driven, chord-wise CG forward = greater flutter margin

- **Will finalize the updated design "SNL100-01" in near future**
  - Cost-performance tradeoffs
  - Updated 13.2 MW Turbine model with SNL100-01 blades
  - Both blade and turbine to be publicly available

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

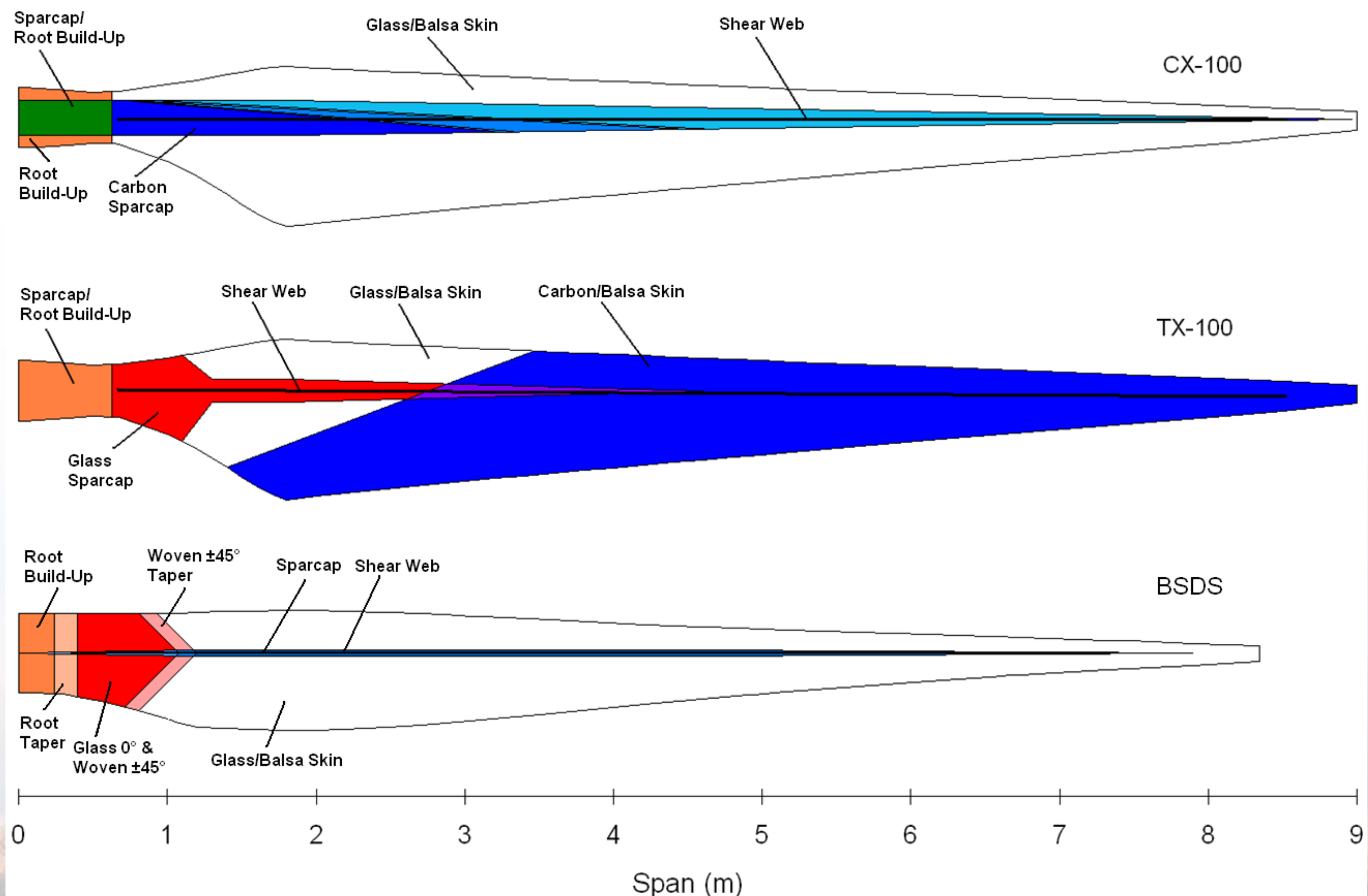
Revisit SNL Research Blade Innovations……

<u>Research Goal</u>

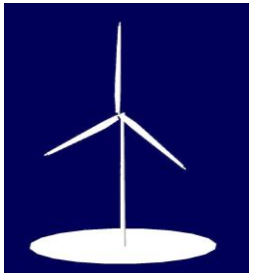
CX-100
Strategic use of carbon fiber

TX-100
Bend-twist coupling

BSDS
Flatback/thick airfoils



Resources, Model Files



Model files on Project Website (both blade and turbine)

- www.sandia.gov/wind
- www.energy.sandia.gov/?page_id=7334

SNL100-00 Blade: detailed layup (NuMAD), ANSYS input

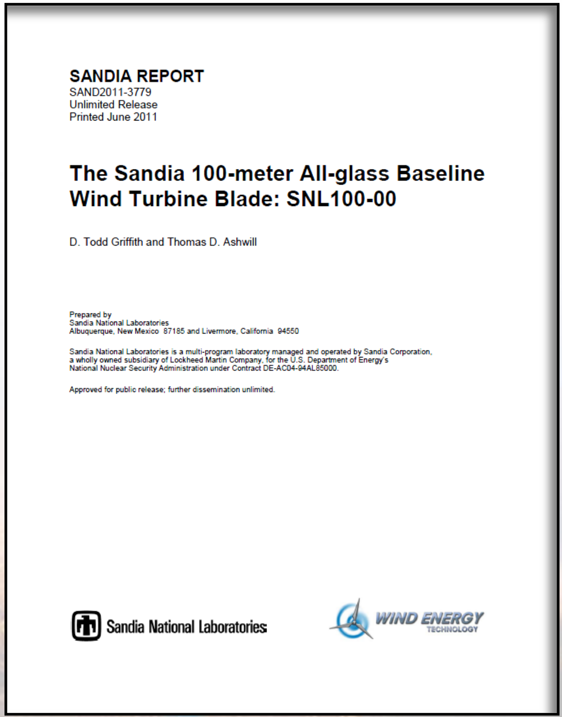
SNL13.2-00-Land Turbine: FAST turbine, controller, IECWind, Modes

References:

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

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

Griffith, D. T., Resor, B.R., "Challenges and Opportunities in Large Offshore Rotor Development: Sandia 100-meter Blade Research," AWEA WindPower 2012 (Scientific Track), Atlanta, GA, June 1, 2012.



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WIND ENERGY TECHNOLOGY

Backup

Sandia Classical Flutter Capability

- **SNL legacy capability (Lobitz, Wind Energy 2007) utilized MSC.Nastran and Fortran to set up and solve the classical flutter problem.**

$$[M + M_a(\Omega)]\{\ddot{u}\} + [C_C(\Omega) + C_a(\omega,\Omega)]\{\dot{u}\} + [K(u_0,\Omega) + K_{tc} + K_{cs}(\Omega) + K_a(\omega,\Omega)]\{u\} = 0$$

  - Requires numerous manual iterations to find the flutter speed

- **A new Matlab based tool has been developed in 2012**
  - Starting point: Emulate all assumptions of the legacy Lobitz tool
  - Continued development and verification: automated iterations, higher fidelity modeling assumptions

Matrix	Description
M, C, K	Conventional matrices (with centrifugal stiffening)
$M_a(\Omega)$, $C_a(\omega, \Omega)$, $K_a(\omega, \Omega)$	Aeroelastic matrices
$C_C(\Omega)$	Coriolis
$K_{cs}(\Omega)$	Centrifugal softening
K_{tc}	Bend-twist coupling