Sandia Rotor Research

SMART Wind Composites Subgroup Meeting

February 17th, 2015

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Sandia National Laboratories
Outline

- Background: Personal & Sandia National Laboratories
- Wind Energy Market Trends
- Current Blade Technology Overview
- Blade Technology R&D Opportunities and Sandia Projects
  - Historical rotor programs
  - SWiFT test site
  - Blade materials and structural reliability projects
  - Advanced Manufacturing Initiative
  - Public design tools
  - Radar friendly blade
- Funding and partnerships
Personal Background

Born Minneapolis
ME from U of MN

PhD Materials
UCSB /
Wind Startup

SNL Wind

DOE Wind
Power Office
Sandia Mission Areas

- Top row: Critical to our national security, these three mission areas leverage, enhance, and advance our capabilities.

- Middle row: Strongly interdependent with NW, these four mission areas are essential to sustaining Sandia’s ability to fulfill its NW core mission.

- Bottom row: Our core mission, nuclear weapons (NW), is enabled by a strong scientific and engineering foundation.
Energy & Climate PMU

Energy Research
ARPAe, BES Chem Sciences, ASCR, CINT, Geo Bio Science, BES Material Science

Climate & Environment
Measurement & Modeling, Carbon Management, Water & Environment, and Biofuels

Nuclear Energy & Fuel Cycle

Renewable Systems & Energy Infrastructure
Renewable Energy, Energy Efficiency, Grid and Storage Systems

Transportation Energy & Systems
Vehicle Technologies, Biomass, Fuel Cells & Hydrogen Technology

Sandia National Laboratories
SNL Wind Program History

28 Years of wind turbine rotor development

Wind Program Established 1975
17m VAWT 1977

34m VAWT 1984
Composite Materials Database 1988
TT-6
QQ1-112
QQ1-435

Blade Program 1994

Advanced Manufacturing Initiative 2008

SWiFT Facility 2013
Wind Energy Market Trends
Cost of Energy Reduction

\[ \text{COE} = \text{CAPEX} (75\%) + \text{OPEX} (25\%) \]
US Wind Resource Quality Drop

Figure 29. Index of Wind Resource Quality at 80 Meters vs. Specific Power

Source: LBNL Wind Technology Market Report 2012
Capital Cost by Component

Source: NREL Cost of Wind Energy Review 2011

~ $2.5B US market for blades in 2012
Blade Cost – 40 m Blade

Total Cost at Factory

Materials 52%
Labor 41%
Equipment 7%

Labor

Preforms 17%
In-Mold 36%
Finishing 41%
Balance and Loading 6%

Material

Fabric 31%
Resin 53%
Core 13%
Coating 3%

Materials Cost $/kg

- High-end Military ~ $1000/kg
- Aerospace Industry ~ $100/kg
- Wind Industry ~ $10/kg

Source: Various product sheets from manufacturer websites
Aging Turbine Fleet

Turbine Age Distribution (North and Latin America regions)

Cumulative GW

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Source: MAKE Consulting, O&M Report 2014
Market Trends Summary

- As resource quality drops, rotors have increased
- Blade Capex is 50-50 materials and labor. Materials are already inexpensive and hard to automate
- Blade Opex – aging fleet presents repair/repowering opportunities
Current Blade Technology Overview
Blade Design Drivers

- High-cycle Fatigue ($10^7$)
- Structural Efficiency
- Lift/Drag
- Erosion & Soiling
- Acoustics
- Buckling & Torsion
- Adhesive Bonds & Stiffness (edge)
- Stiffness (flap)
- Bolt interface

Material Selection

1. Uni-directional fiber
2. Biaxial fabric - core sandwich
3. Adhesive
4. High-shear modulus core
5. Panel
6. Adhesive
7. Leading Edge
8. Trailing Edge

Source: 100m Glass Blade – SNL Report: SAND2011-3779
Manufacturing Technology

Varies from hands on to hands off depending on the process
Manufacturing Processes

40m All-glass blade summary of labor hours as a percentage of total

- Paint Prep and Paint: 22%
- Balance and Loading: 6%
- HP and LP Molds: 13%
- Infusion: 10%
- Prebond Assembly, Bonding: 12%
- Inspection, Trim, and Wet Lay-up: 11%
- T-Bolts: 2%
- Cure: 2%
- Edge Finishing: 4%
- Root Prefabs: 7%
- TE Prefabs: 0%
- Spar Caps: 7%
- Shear Webs: 4%

Current Testing Approach

Coupon testing $\rightarrow$ characteristic value $\rightarrow$ partial factors $\rightarrow$ design allowable

Tooling (molds) manufactured $\rightarrow$ 2 full-scale blades fabricated $\rightarrow$ 1 blade tested to ultimate loads $\rightarrow$ 1 blade tested for fatigue loads

Source: Montana State University Composites Group, NREL National Wind Technology Center
Blade Technology R&D Opportunities and Sandia Projects
Carbon Fiber Spars

- **Advantages:**
  - High stiffness/strength
  - Low weight

- **Challenges:**
  - Higher cost
  - Difficult to infuse
  - Sensitive to flaws

- **Sandia Research:**
  - CX-100 Blade: Demonstrated method for producing infused carbon spar

- **Industry Impact:** Carbon spars widely used on large blades

Carbon Experimental 100kW (CX-100) Blade Skin

Conventional glass – balsa blade skins

Carbon-fiberglass triaxial fabric spar cap
Aero-Structural Optimization

- Flat-Back Airfoils
  - Lower Weight
  - Increased Stiffness
  - Easier Manufacturing
  - Reduced sensitivity to surface soiling
- Embedded Root Fasteners
  - Reduced root laminate thickness
  - Allows for more fasteners, critical for large blades
- Sandia Research:
  - BSDS Project (industrial collaboration): Demonstrated aero and structural benefit
- Industry Impact: Common in current production blades
Passive Load Alleviation

- Passively sheds gust loads
- Allows for longer blades and higher energy capture
- Sandia Research:
  - TX-100 Blade: Off-axis fiber in skins to couple bend/twist
  - STAR Blade (industrial collaboration): Swept geometry to couple bend/twist
- Industry impact: Several current production and concept blades use this technology
Active Aerodynamic Control

- Quicker, more controllable response to shed gust loads
- Allows for longer blades and higher energy capture
- Possible performance enhancement
- Sandia Research:
  - SMART Blade: first full rotor with active controls
  - Utilized ailerons and patented blade displacement sensing system
- Industry Impact: Consistent industry interest, but no blades built to date
National Rotor Testbed

- Design and manufacture **sub-scale rotors** for the SWiFT turbines to emulate a modern, megawatt scale rotor.
- Enables **low-cost field testing** of new rotor technologies.
- **Public rotor** design
SWIFT Test Site

Scaled Wind Farm Test (SWiFT) Facility

Cost-effective wind plant testing facility to transition basic research to commercialization

- Lubbock, Texas
- 3 x 225 kW Turbines
- ~14 m blades
- Highly instrumented site and turbines
- Modern technology

Source: Sandia National Laboratories
Consistent high data rate and efficient research execution due to:

- High winds (7.5 m/s at 50 m) with low variability
- Narrow wind rose, which provides consistent data for chosen array configuration
- Current and historical data from unique, site-adjacent 200 m meteorological mast
- Flat terrain, which allows reduced validation uncertainty and the opportunity to add man-made terrain effects in the future

Location is in the best part of the US wind corridor—with favorable weather year-round and the most US wind installations: 12 GW and continued growth.
Open-Source Wind Turbines

*Fully documented open source hardware, developed in collaboration with Vestas*

- Solid, proven machines with collective-pitch system that allows almost any type of research to be performed
- 300 kW variable-speed generator
- AC-DC-AC full-scale convertor designed with ABB, Inc.
- Open-source controllers based on National Instruments
- Complete turbine/rotor state instrumentation including fiber-optics
Structural Reliability Program
Blade Reliability Collaborative

Improve the reliability of blades through field investigations, inspection technology, evaluating effects of defects, and improved design, analysis and certification

Many industry participants
Damage Tolerant Design

Inspection Program

+ Progressive Damage Analysis (requires a damage growth model and accurate loads data)

+ Residual Strength Analysis

= No in-service failures

Source: Doug Cairns – Montana State University
Inspection Technology

Inspection methods are need at the manufacturing plant and in the field to improve quality and reliability

- Test specimens with different flaw types and sizes
- Evaluation of non destructive inspection (NDI) methods to determine probability of flaw detection
- Operationalize methods for manufacturers and inspectors

Source: SNL – Dennis Roach – Blade Reliability Collaborative
Effects of Manufacturing Defects

- Defects in wind laminates are unique due to scale/manufacturing
- Current standards are possibly both over and under conservative in terms of flaws
- Sandia Research
  - Build, test, model coupons and sub-structures with defects
  - Develop probabilistic models of impact on blades
- Industry impact: Quantify effect on blade strength and reliability for improved standards
Testing Approach for Composites

Building Block Approach
- Complex loads
- Structural Details

- Increased number of tests
- Increased Complexity
- Non-Generic Specimen
- Generic Specimen

- Full Scale Test
- Sub-Components (spars, shells, root sections, ...)
- Elements & Details (bond line, ply drops in spar cap, ...)
- Coupons (constituents, laminae, laminates, core materials, ...)

Data Base

Structural Features

Source: Montana State University – D. Carins
Coupon Testing

Characterize static and fatigue properties of blade materials from suppliers (resins, fabrics, adhesives, cores), and laminates and structural details from blade manufacturers.

Results published in Composite Materials Database since 1989

Source: Sandia National Laboratories
Sub-Structure Testing

BoxBeam4 Event Locations, Source Amplitude by Color

- Sensors
- >50
- >60
- >70
- >80
- >90
Leading-Edge Erosion

Characterization
Measurement
Modeling

Heavy blade erosion
Insect roughness
Leading edge blade erosion

No Roughness
$k_s = 350 \mu m$

Oran W. Nicks Low Speed Wind Tunnel
Manufacturing Cost Reduction

Figure 6 Blade mass trend with respect to technology

Source: UPWIND SCALING LIMITS & COSTS REGARDING WT BLADES 2010
Advanced Manufacturing Initiative

Increased labor productivity by ~14% and reduced cycle time by ~37% while maintaining or improving part quality (preliminary results).

**Total Cost at Factory**

- **Materials**: 52%
- **Labor**: 41%
- **Equipment**: 7%

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*Iowa State University*
Blade Design Tools & System Modeling

- Design codes to analyze:
  - Structures
  - Aerodynamics
  - Control
  - Aero-servo-elastic stability
  - Manufacturing costs

- Public Tools:
  - NuMAD v.2
  - Structural blade models
  - Blade manufacturing cost model

Source: Sandia National Laboratories
Radar friendly blade

Develop a low-cost material treatment compatible with current manufacturing processes that can reduce the RCS by 20 dB

Source: Sandia National Laboratories
Funding and Partnerships

- Primary customer is Department of Energy Wind and Water Power Technologies Office
- Partnerships with industry and universities is common and instrumental to many research projects
- Various funding mechanisms exist to support partnerships as well as information sharing
Rotor Technology Integrators

wind.sandia.gov