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Blade Reliability Collaborative (BRC) Update

Josh Paquette
Blade Reliability and Materials Lead
Wind Energy Technology Dept.
Sandia National Laboratories
Joshua.Paquette@sandia.gov
(505) 844-7766

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BRC Mission

Goal:

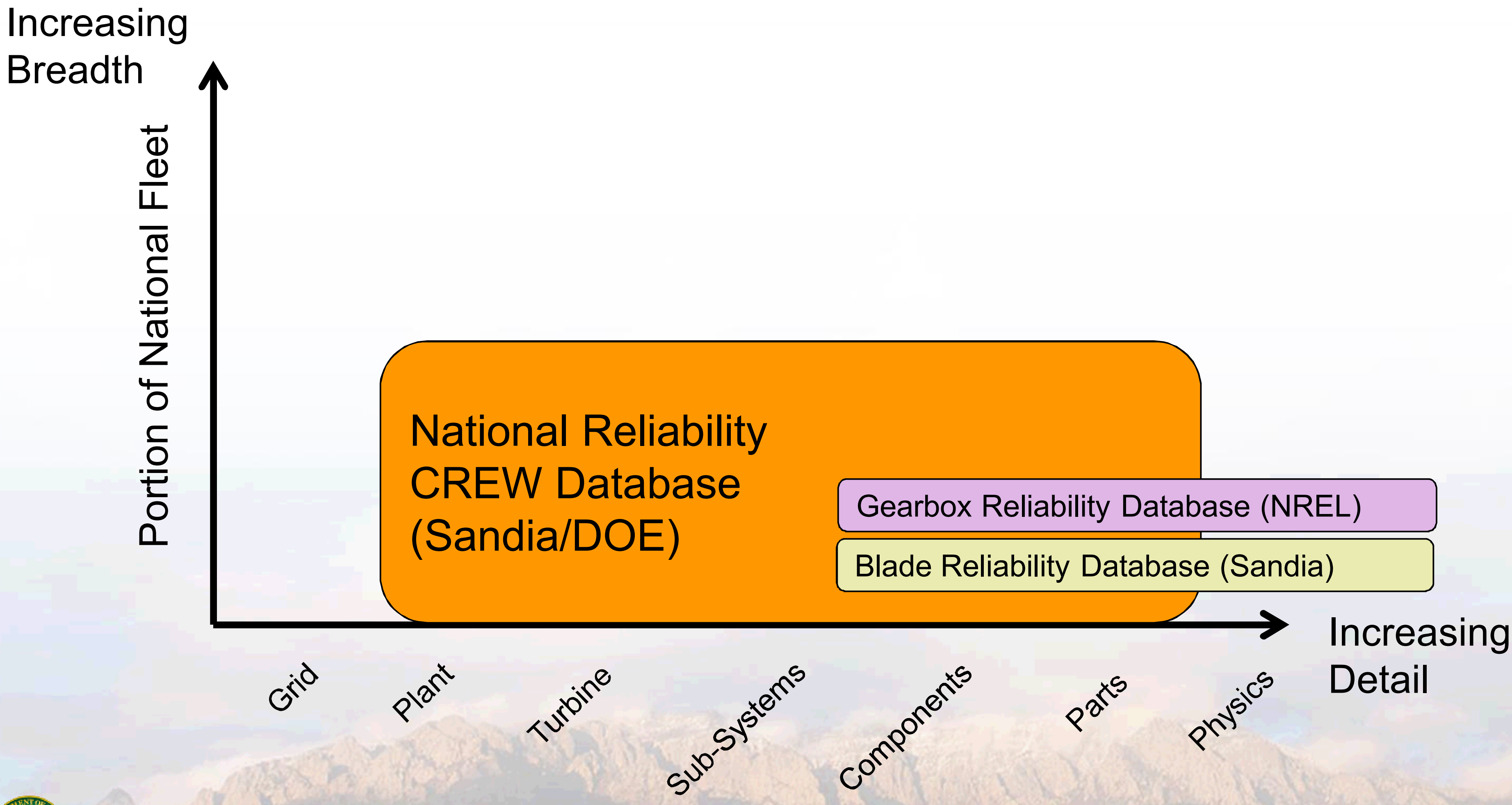
- **To develop a collaborative framework to address the issues related to the reliability of wind turbine blades as they are delivered to the field and operated for the turbine lifetime.**

Industry Value:

- **The collaborative will improve the reliability of blades delivered to the field so that remediation work before operation can be eliminated and the service lifetimes can achieve the 20 year targets that are expected by wind plant operators and financiers.**

Industry partners will be brought in for evaluation of manufacturing process through the testing of full-scale blades and the evaluation of inspection techniques. Design alternatives that are better able to avoid flaws where possible and are more readily inspected will be evaluated in conjunction with other Sandia large blade analysis programs.

DOE Funded Reliability Efforts



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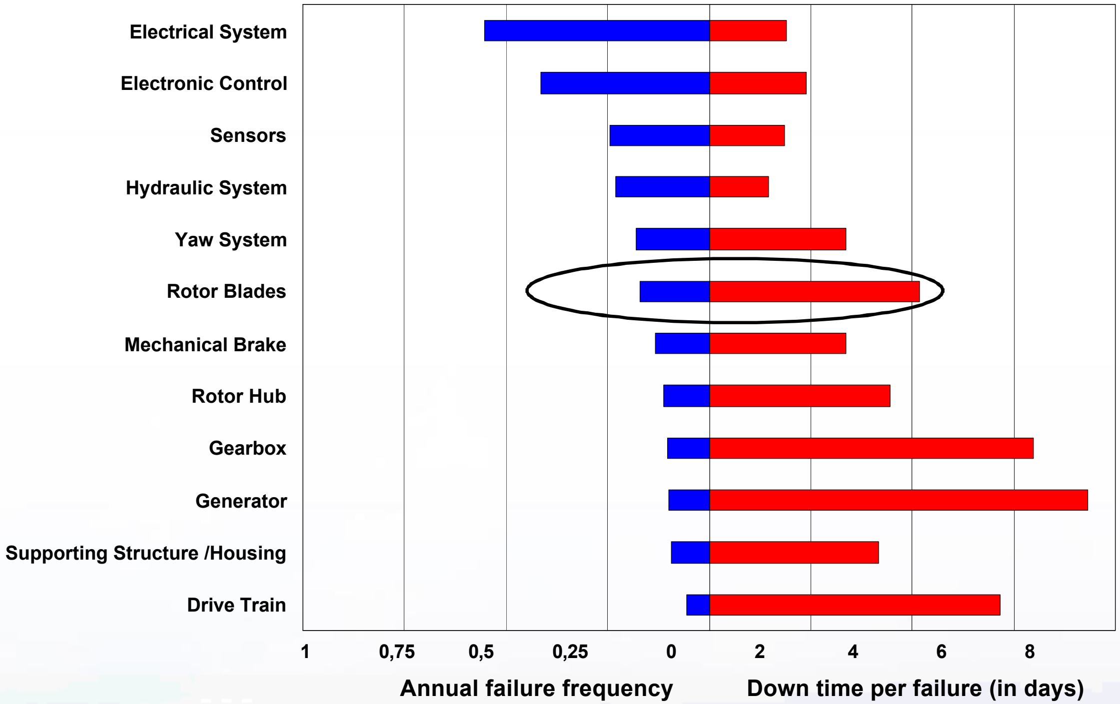
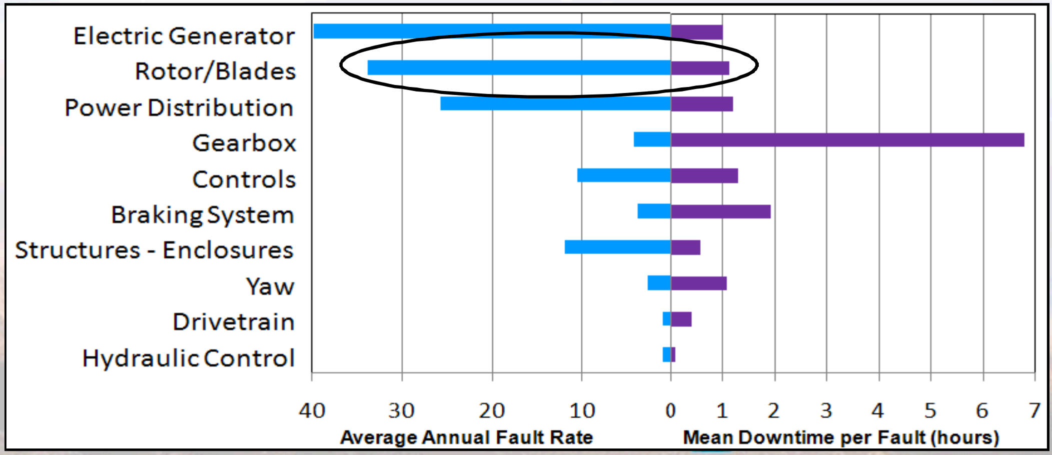
BRC Motivation

- Blades are being delivered to the site in a condition that often requires additional treatment of quality issues before they can be installed
- Rare installations need to have all the blades replaced after the discovery of a batch problem
- Blade failure can cause extensive down time and lead to expensive repairs.
- *Blade reliability issues need early attention because of the lost production and cost of significant failures*





Blades have medium failure rate, relatively high repair cost, high downtime cost. US environments may be more aggressive.

Background

Preliminary Operator Survey

- **Conducted by Roger Hill**
- **Five Plants – over 400 turbines**
- **Mostly 3+ years old**
- **About 80 blade replacements – 40 (half) at one plant**
- **Replacement times range from 2 weeks to 2 months**
- **Blade Issues Cited:**
  - Manufacturing Issues – waviness and overlaid laminates
  - Bad bonds, Delamination, and Voids
  - Trailing Edge Splits
  - Leading Edge Erosion
  - Lightning

Expert's Group Assessment

- **Experts from Industry, consulting, academia, and national labs convened to identify critical issues (few numbers)**
- **Collected expert knowledge as a basis for planning to address blade reliability needs**
- **Major Blade Reliability Issues Identified:**
  - Infusion Quality
  - Inspection Capability
  - Bonding Quality
  - Environmental Protection
  - Multiple Assembly Plants or Assembly Lines
  - Certification, Tracking and Feedback

1. Infusion (composite fabrication) Quality

Waviness

- **Complete infusion, voids**
- **Fibers moving during infusion prior to curing (waviness)**
- **Material drop off – Detailing**
- **Speed of production creates problems**
- **Scaling issues**

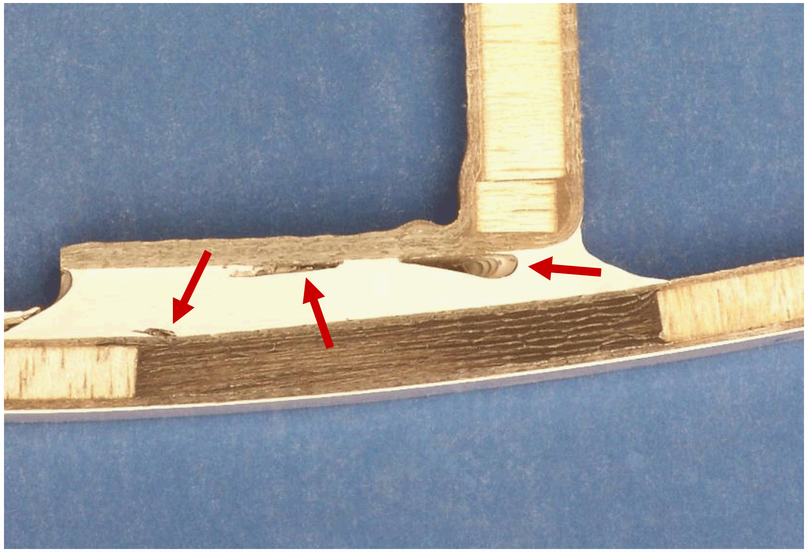
Carbon Spar Cap

Delaminations

1/2 meter

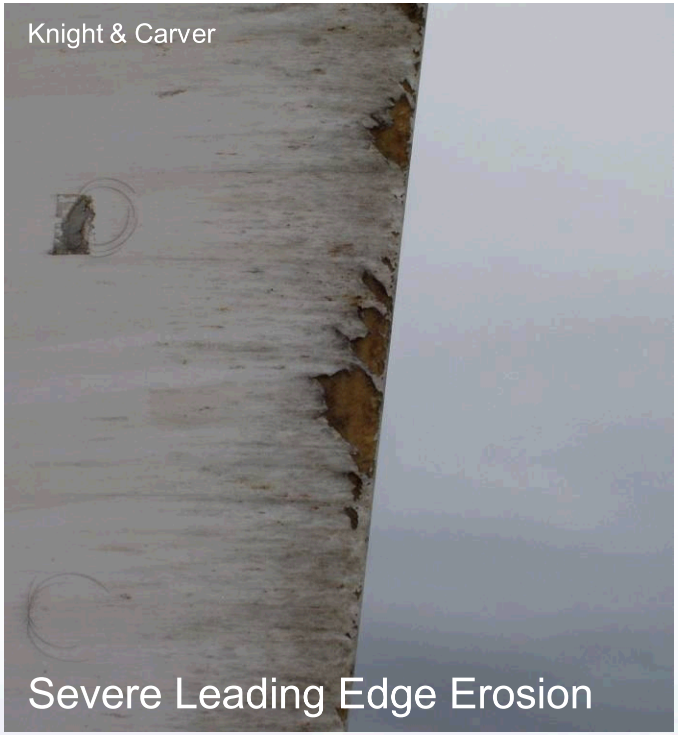
2. Bonding Quality

- **Typical Blade Bond Lines**
  - Difficult to control
  - Blind bonds
  - Scaling effects
- **Shear-Web Bonding**
- **Bond-Line Voids**
- **Bond-Line Weakness (without major voids)**
- **Commentary from a Blade Manufacturing Manager**
  - "The most difficult part of manufacturing process is trying to bond the two shells together."
  - "Trailing edge defects can grow to full blade failure."
  - "Bonding problems are the biggest issue."



Minor Voids

3. Environmental Protection



Severe Leading Edge Erosion

- **Leading edge erosion**
- **Moisture intrusion**
- **Freeze/Thaw cycling**
- **Root fastener corrosion**
- **Lightning**
  - Many blades are repaired
  - Some operators consider it manageable - when compared to other components, such as gear boxes

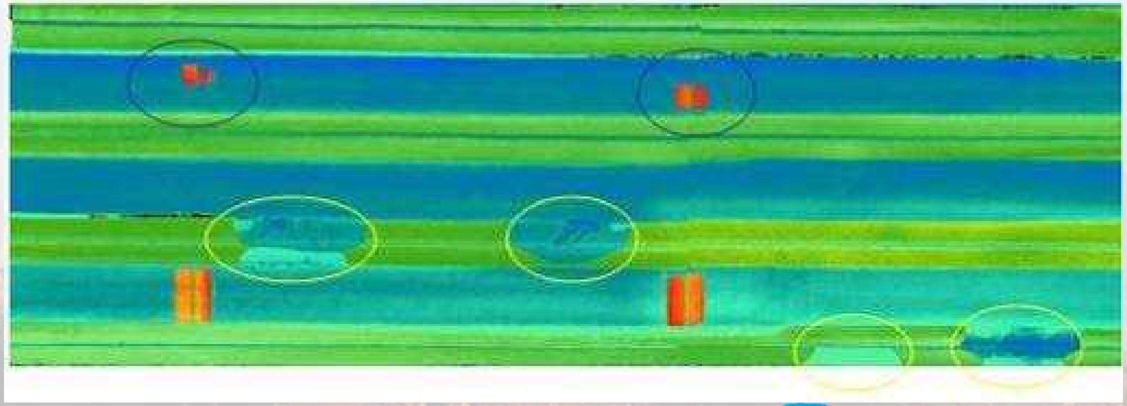
Lightning Strike

4. Inspection Capability: Factory and Field

- Existing inspection methods can detect bond line gaps and major delaminations
- Every blade manufacturer has inspection methods but some problems are still getting through
- Need to know what inspection methods are effective at finding the flaws that affect early failure.

Aircraft Example
Carbon Panel
(bonded ribs)

Phased Array UT Inspection of an Aircraft Vertical Stabilizer Specimen



5. Multiple Assembly Plants


Vientek


LM Glassfiber

- Not covered in standards
- Production start-up (infant mortality)
- Local practices and corporate cultures
- Process qualification – metrics, procedures, etc.
- Bad batches of blades
  - Lead to major plant development delays and cost overruns
  - May not be reflected in operator surveys because they are incurred before the transfer of responsibility from developer to operator



Courtesy Billy Roeseler, Boeing

BRC Tasks

- ***Blade Defect and Damage Database*** ***(PI: Tom Ashwill, SNL)*** **– Aggregate data from blade manufacturers, service companies, and operators to determine largest sources of blade unreliability**
- ***Inspection Validation*** ***(PI: Dennis Roach, SNL)*** **– Evaluate the ability of inspection techniques to accurately characterize blade defects and damage in manufacturing plants and in the field**
- ***Effects of Defects*** ***(PI: Doug Cairns, MSU)*** **– Determine how common manufacturing defects affect blade strength and service life**
- ***Analysis Validation*** ***(PI: Josh Paquette, SNL)*** **– Assess the ability of design analysis tools to find and characterize potential failure modes**
- ***Certification Testing*** ***(PI: Scott Hughes, NREL)*** **– Evaluate the ability of certification testing to uncover potential reliability issues and find innovative ways for testing to provide better insight**
- ***Standards and Partnerships*** ***(PI: Josh Paquette, SNL)*** **– Interface with international standards committees and industrial partners to identify pathways to implementing improved design, manufacture, and inspection**
  - *Partners: U-Mass. Lowell (Chris Niezrecki), EPRI (John Lindberg)*

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Blade Defect and Damage Database

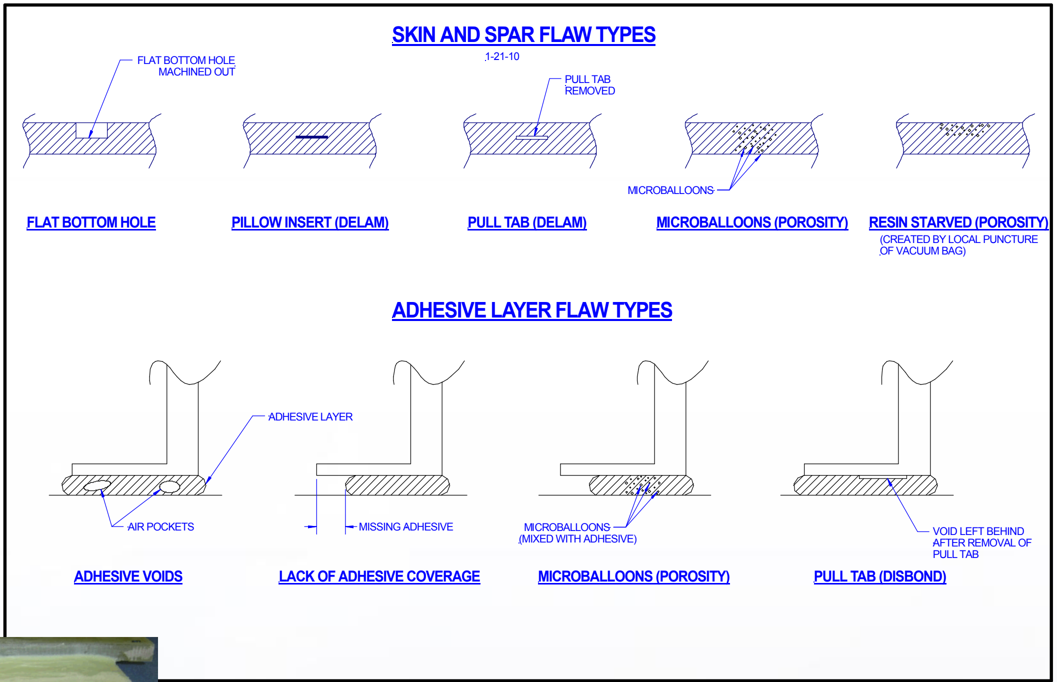
- **Work with manufacturers to understand plant and under-warranty issues**
- **Survey wind farm owners/operators**
- **Collect and analyze repair information from blade service companies**
- **Summarize data from NREL certification tests**
- **Create a blade failure mode database**
- **Involves Sandia, NREL, and subcontractors in a comprehensive effort**

- **Data Collection and NDAs**
  - Partner will disclose Inspection and repair reports
  - Sandia will only disclose summary aggregated information
- **NDA Status**
  - 3rd Party Blade Companies:
    2 completed, 3 in process
  - Owner / Operators:
    1 completed, 1 in process, 2 in discussion
- ***More partners welcome!!!***

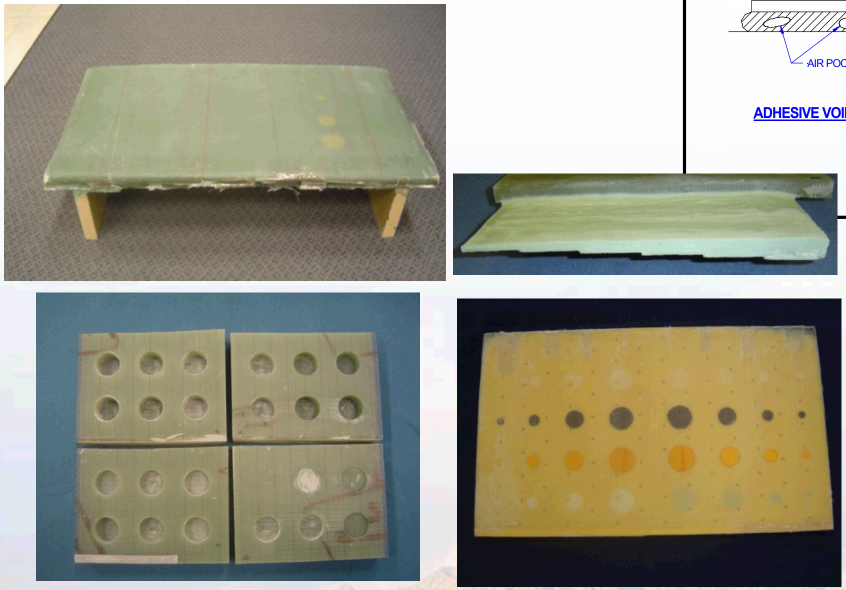
Identify causes of early field failures and unreliability

Inspection Validation

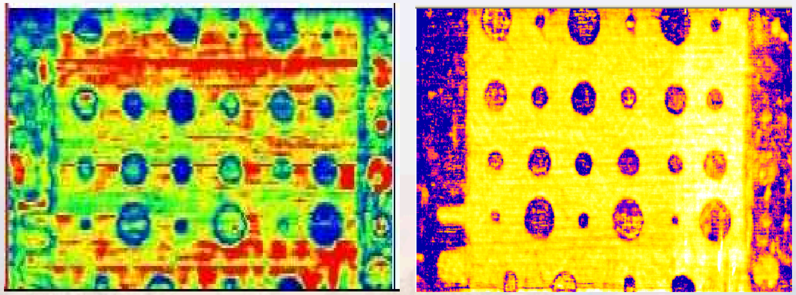
- Build representative samples with known flaws
- Establish baseline NDI results
- Bring in vendors to validate their capabilities (current list of over 20 participants)
- Research conducted by Sandia's Aviation Assurance NDT Validation Center (AANC)



Methods for Producing Common Flaws



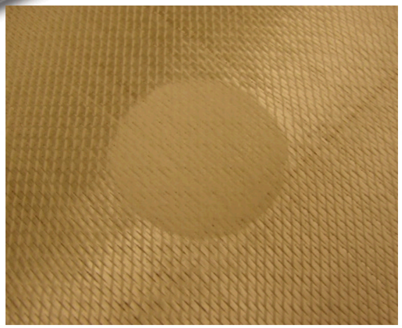
Manufactured Flawed Specimens



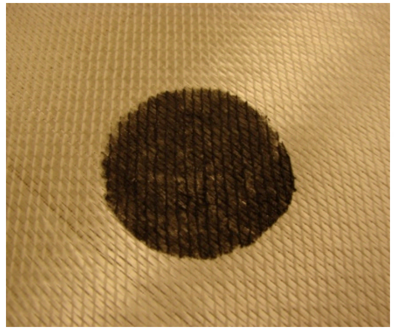
Sample NDI Results

Create Probability of Detection (POD) curves for inspection techniques

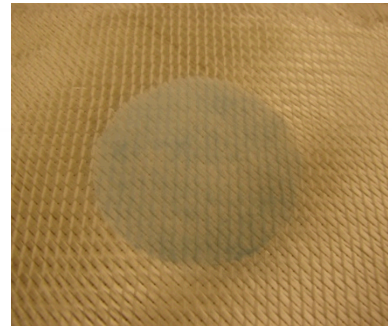
Inspection Validation: Flaw Creation



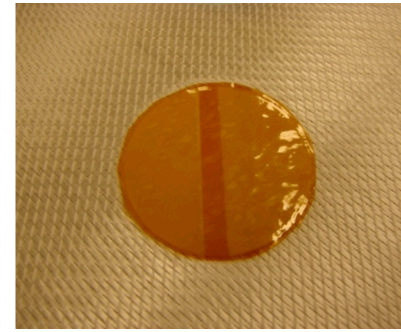
Glass Beads



Grease



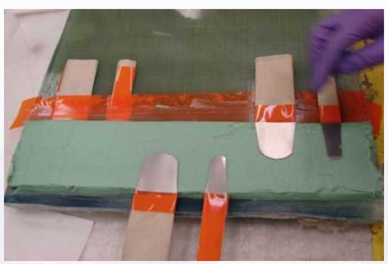
Mold Release



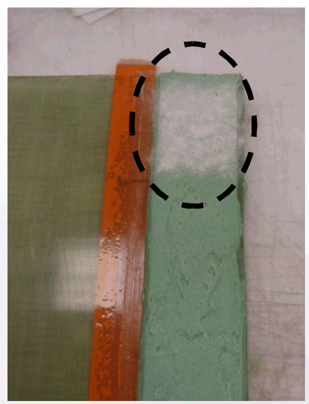
Pillow Insert

Materials inserted into multiple layers

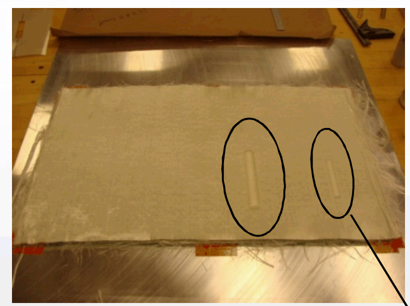
Voids in bond joint

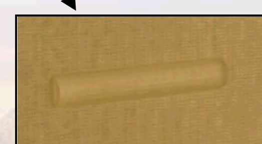


Pull tabs in bond joint

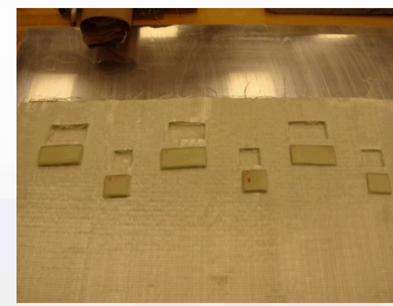


Glass beads In bond joint





Waviness produced by pre-cured resin rods



Dry fabric areas

Single ply of dry fabric

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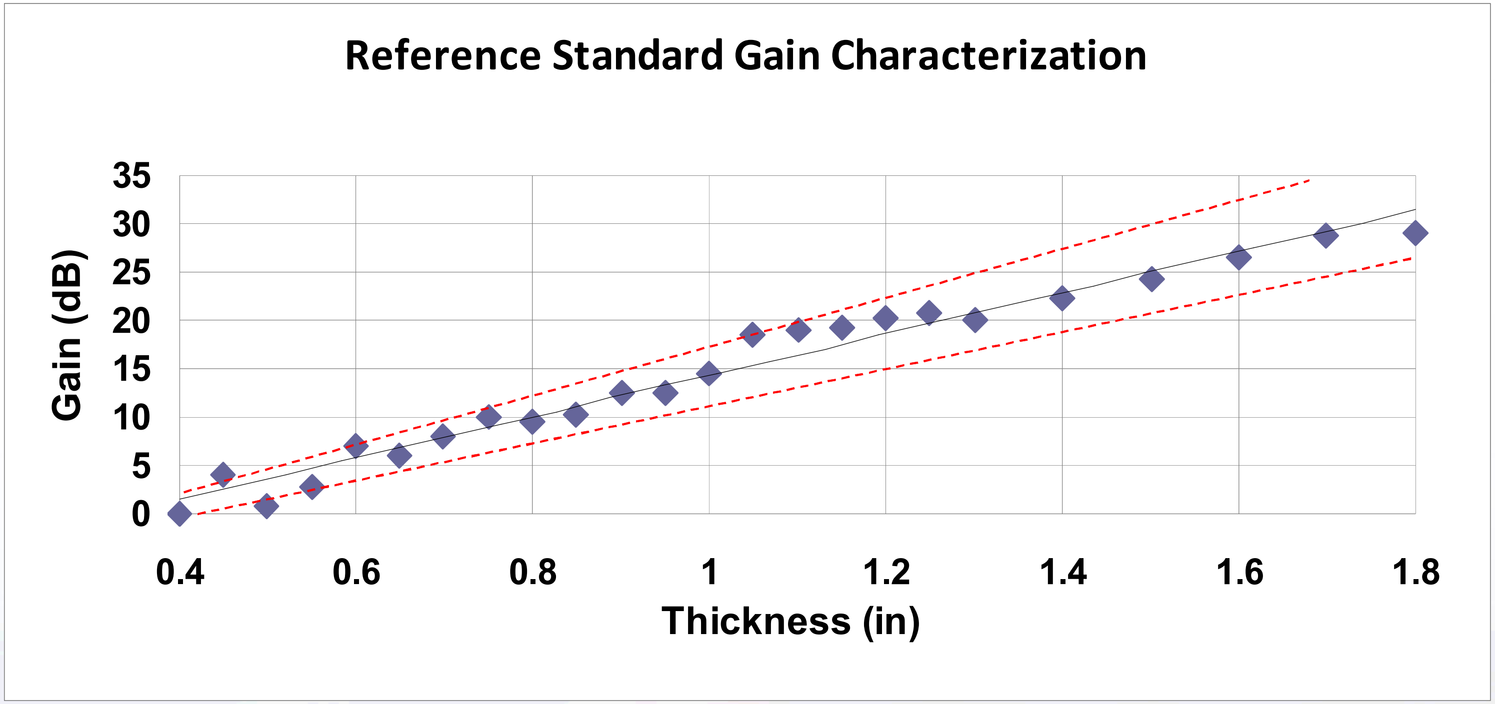
Inspection Validation:
Impact on Manufacturing Floor Inspection

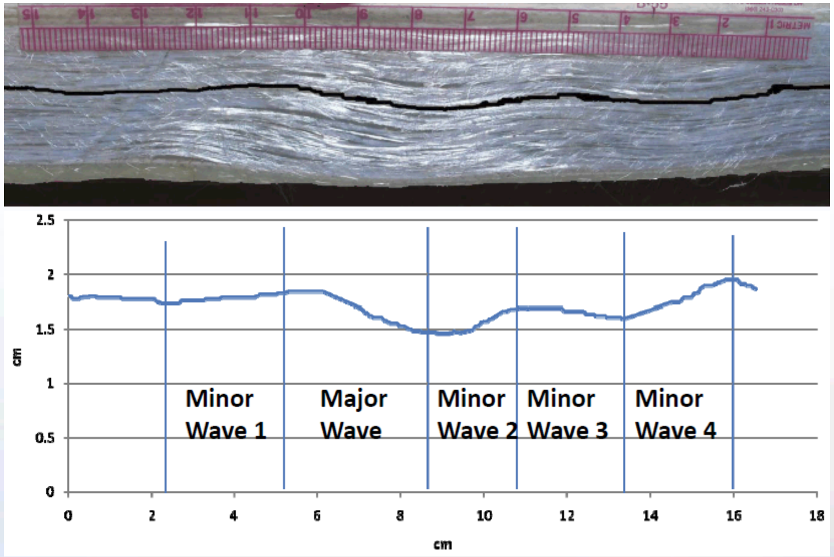


Response calibration curve that can be used for QA – family of curves could produce an envelope of acceptable attenuation levels

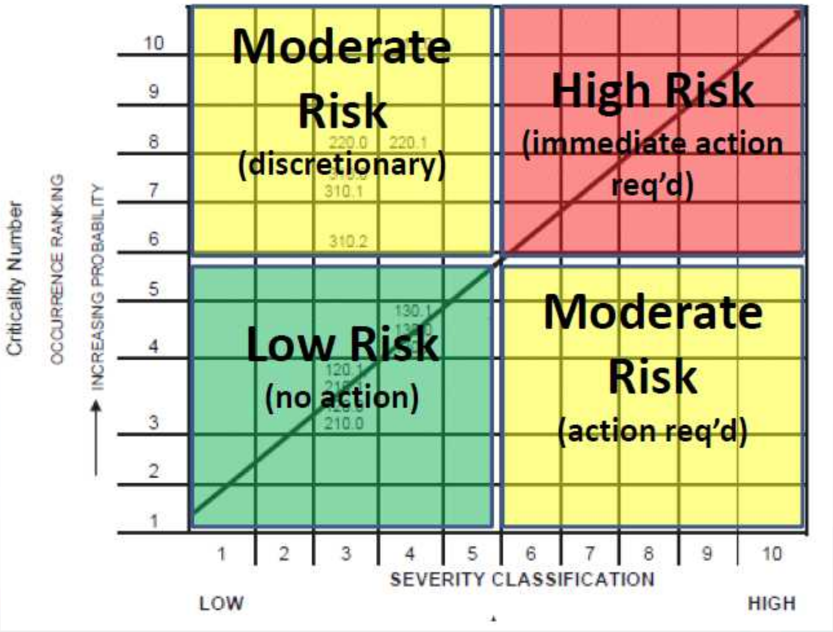
Viability of Test Specimens – quantification of velocity, attenuation, and Signal-to-Noise

Effects of Defects: Flaw Characterization

- Collection of flawed samples
- Parameterization of geometries
- Development of flaw criticality/severity classification



Manufactured Flawed Specimens

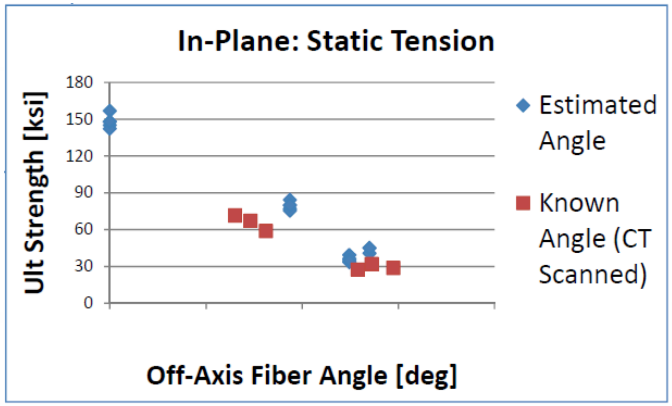


Criticality/Severity Matrix

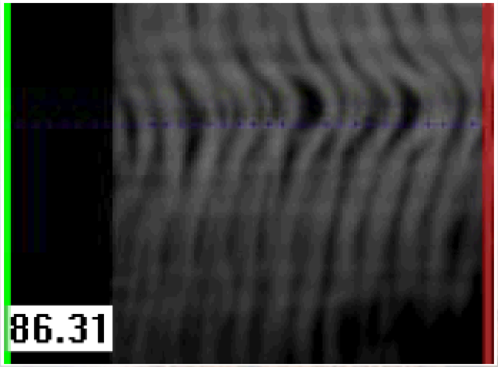
White paper, "Wind Turbine Composite Blade Manufacturing: The Need for Understanding Defect Origins, Prevalence, Implications and Reliability" June 2010

Effects of Defects: Coupon Testing

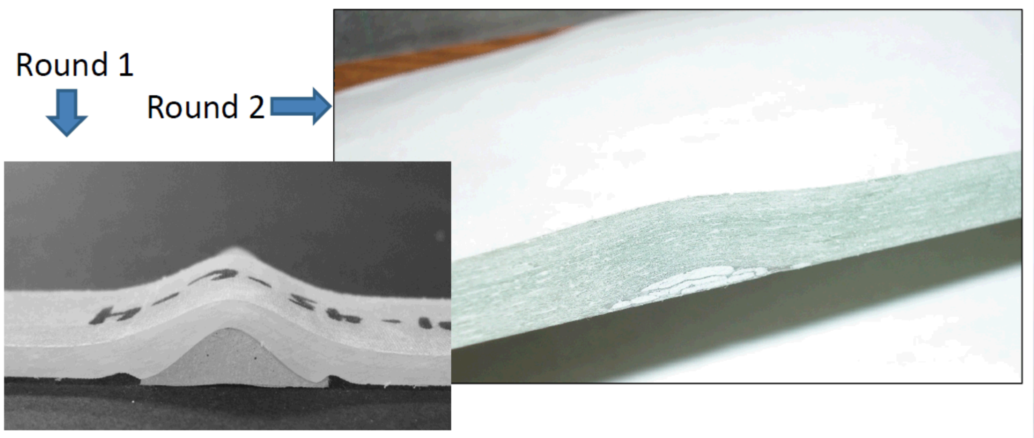
- Completed as-built flaw characterization and testing of remaining Round 1 Test Specimen
- First iteration Flaw Criticality Analysis completed
- Framework for Probabilistic Reliability Protocol Developed
- Manufacturing procedures finalized for Round 2 testing
    - Improved Out-of-Plane waves and thicker laminates



Effect on Tensile Strength



In-Plane Waviness Specimen



Out-of-Plane Waviness Specimen

Trey Riddle, PhD. Student, MSU

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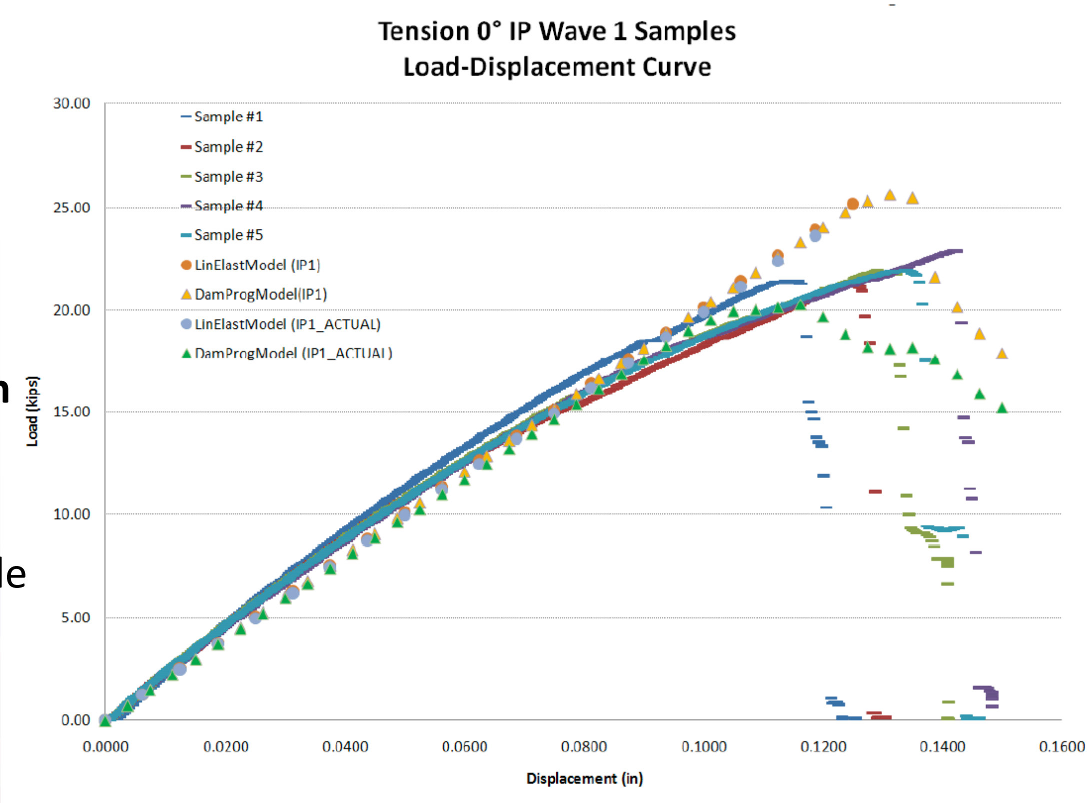
Effects of Defects: Analysis

- **Progressive Damage Modeling underway**
  - Binary material property degradation model
  - Abaqus user subroutine for failure criteria
  - 2D mesh generated utilizing four layers of a quadrilateral, plane stress shell element
- **Reasonable correlations between physical testing and initial modeling efforts**
  - Comparison of load-displacement curves acceptable
  - Best correlation with wave patterns of actual as-tested determined by CT scanning
- **Comprehensive update available soon (Sandia Website)**



Jared Nelson, PhD. Student, MSU

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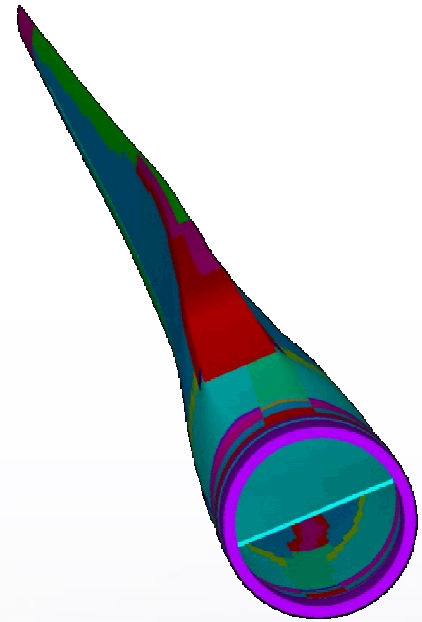
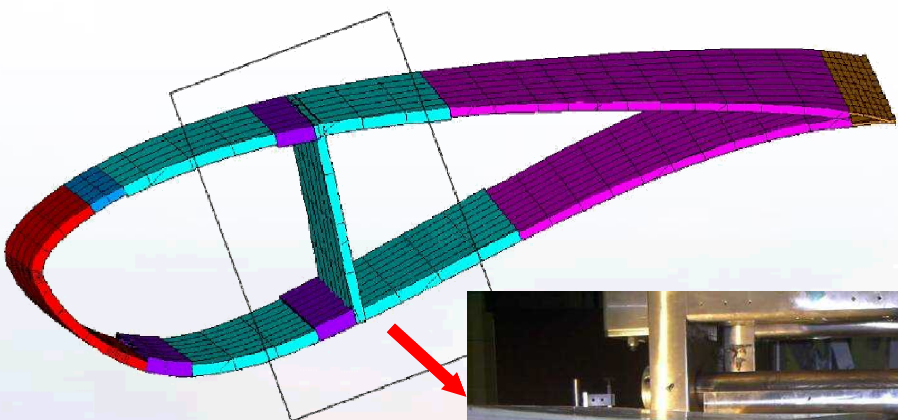
Analysis Validation

- **Exercise composite modeling codes and assess ability to accurately model ultimate and fatigue strength in blades**
- **Validate through highly instrumented laboratory testing to determine first failure and damage progression**
- **Create the ability for the analysis to have be a predictive tool for evaluating blade design capacity – including details**





Analysis Validation: Test Specimen Design

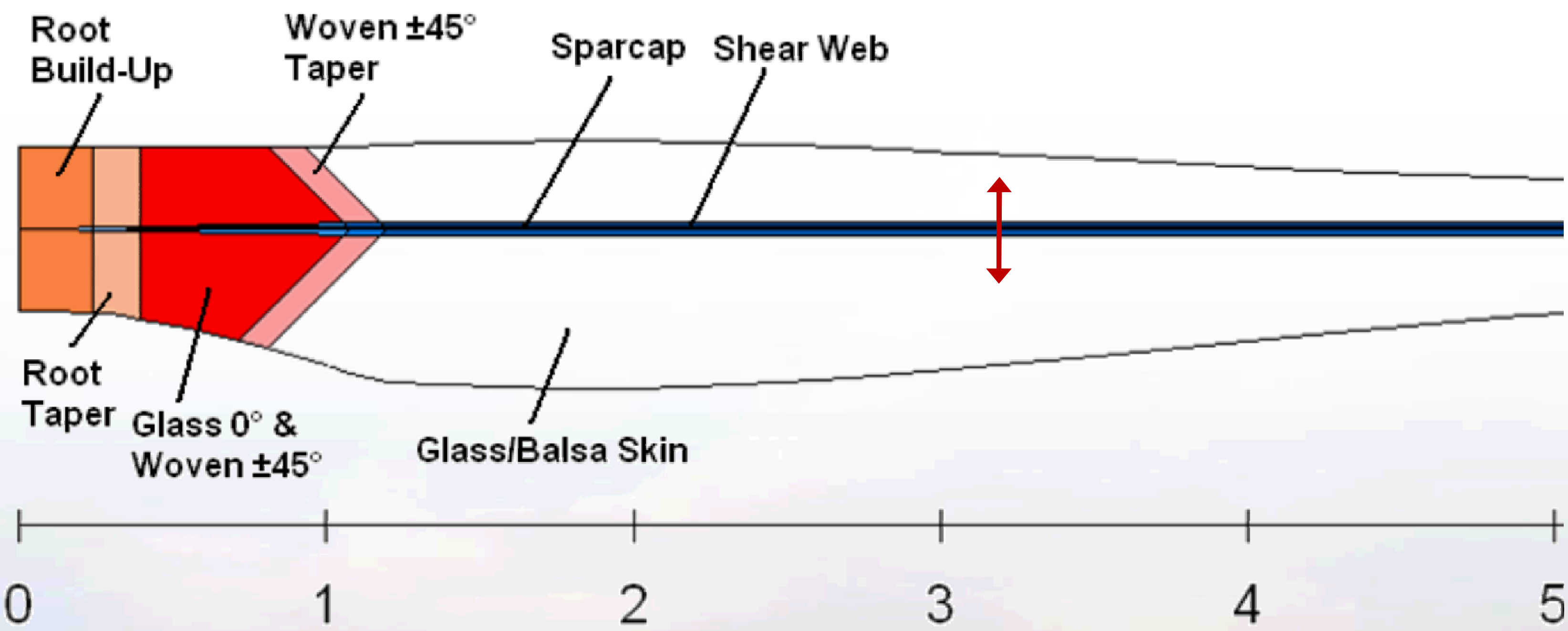
Features of Interest

- **Materials**
  - Glass, Carbon, Core
- **Structural Elements:**
  - Spar, Shear Web, Sandwich Panels, Trailing Edge
- **Details:**
  - Ply Drops, Bondlines, Material Transition
- **Defects and Damage**
  - Delaminations, Waves, Disbonds, Porosity
- **Loading**
  - Static, Fatigue
- **Other Considerations**
  - Load Introduction, Defect and Damage Repair, Instrumentation and Inspection Techniques

Current Specimen Plan

- **Modified BSDS 9m Blade**
  - Replace carbon spar with glass
  - Manufacture partial blade
  - Possible modification to mold for sharp trialing edge
- **Advantages**
  - Access to molds
  - Large amount of previous test data
  - Well known behavior
  - Relatively cheap to build specimens
  - Straightforward load introduction
- **Testing**
  - Proof-Fatigue
  - Stop for defect inspection
  - Patch defects with excessive growth

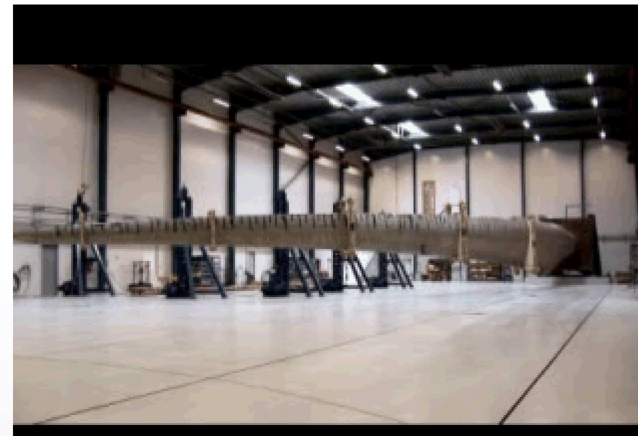
Analysis Validation: Test Specimen Design



Certification Testing - NREL

- **Heavily instrumented blades subjected to certification tests**
  - Good blades
  - Pre-damaged blades
- **Evaluate how the test works the critical areas and failure modes**
- **Develop improvements to certification testing**
- **NREL element of the program**

LM Glassfiber



LM Glassfiber

- **Full-scale blade testing: Fatigue tests reveal hidden flaws**
  - Production blades
  - Detailed inspection
  - Typical manufacturing quality resulting capability

Upcoming Activities

- **Blade Defect and Damage Database (SNL)**
  - Keep pursuing the NDAs
  - Collect more data from current contributors
  - Need 5 to 6 participating companies
  - Continue analysis
  - Draft report
- **Inspection Validation (SNL)**
  - Conduct round-robin testing on NDI Feedback specimens with "advanced" NDI methods
  - Complete analysis of inspection results with NDI comparisons (sensitivity, repeatability, coverage, adaptability, deployment, cost, etc.)
  - Produce a statistically-valid, Probability of Flaw Detection (POD) study to quantitatively evaluate the ability of advanced NDI to find hidden flaws in turbine blades; implement study

Upcoming Activities (cont.)

- **Effects of Defects (MSU)**
  - Manufacture and statically test Round 2 specimen
  - Attempt to acquire more as-built flaw data from partners
  - Research and select a probabilistic reliability methods suitable for wind turbine composites
  - Refine criticality analysis algorithm and expand to include probabilistic methods, damage progression analysis and probability of detection criteria as developed by D. Roach at Sandia (if available)
- **Analysis Validation (SNL)**
  - Finalize specimen design with flaws
  - Finish identifying analysis partners
  - Place contract for specimen manufacture
  - Build/analyze models of specimen
  - Characterize and inspect specimen
- **Certification Testing (NREL)**
  - Publish white paper on certification testing needs
  - Perform proof and fatigue test on specimen

Thank You!