Blade Reliability Collaborative (BRC)

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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NNSA National Nuclear Security Administration
Sandia National Laboratories

BRC Mission

Problem:

- **Blade reliability issues related to manufacturing, transportation, installation, and operation can have large effects on COE as blade failures can cause extensive down time and lead to expensive repairs.**

Project Goal:

- **The BRC aims to better understand:**
  - Primary causes of premature blade failure
  - Ability of inspection methods to detect flaws and damage
  - Effects of prominent manufacturing defects on blade materials
  - Adequacy of design tools and certification testing to replicate operational life

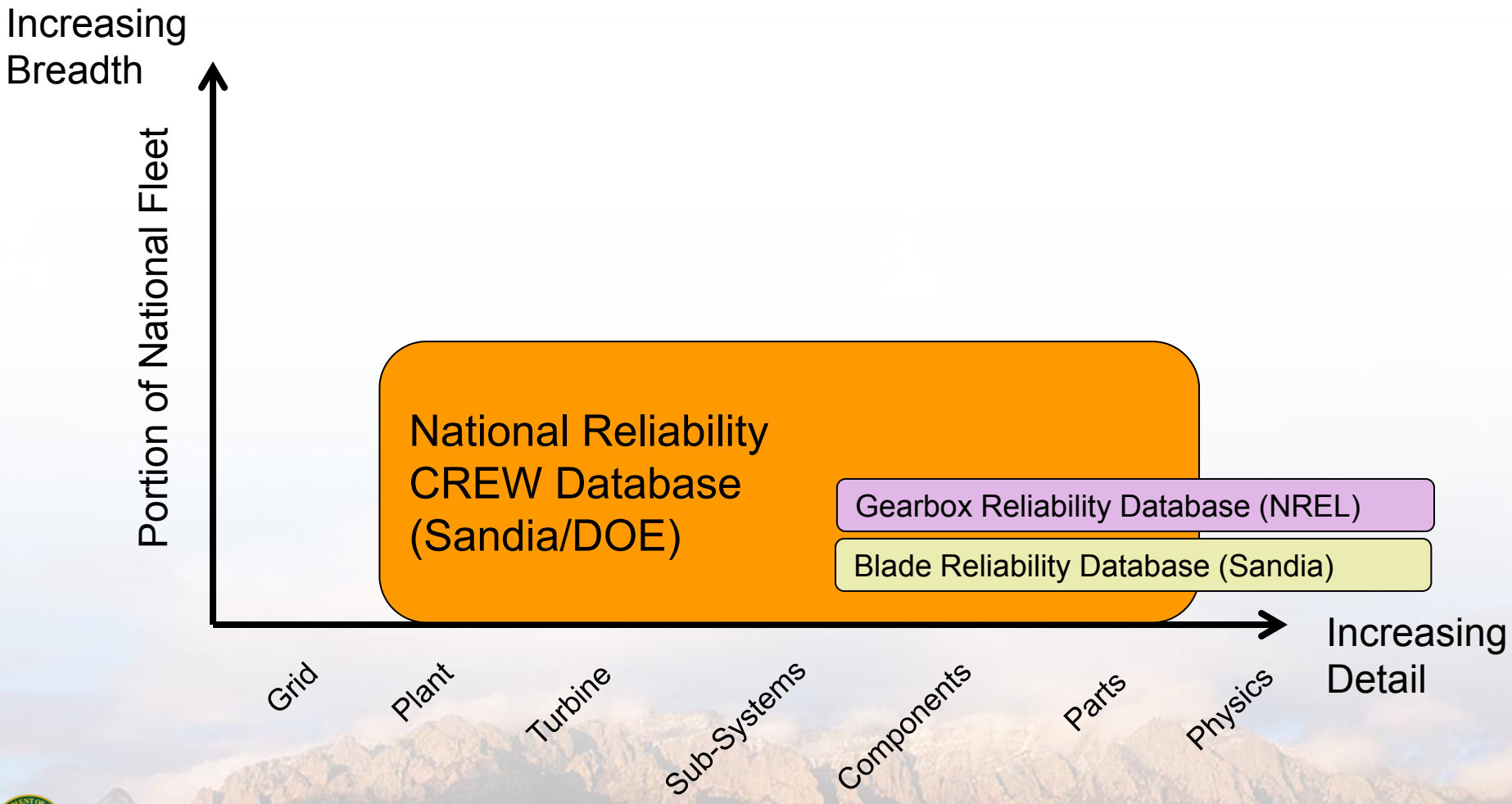
  and

  - Interface with a wide spectrum of industry, lab, and academic partners throughout the project.

In summary:

- Improve the reliability of blades delivered to the field so that remediation work before operation can be reduced and the service lifetimes can achieve the 20 year targets that are expected by wind plant operators and financiers.

DOE Funded Reliability Efforts



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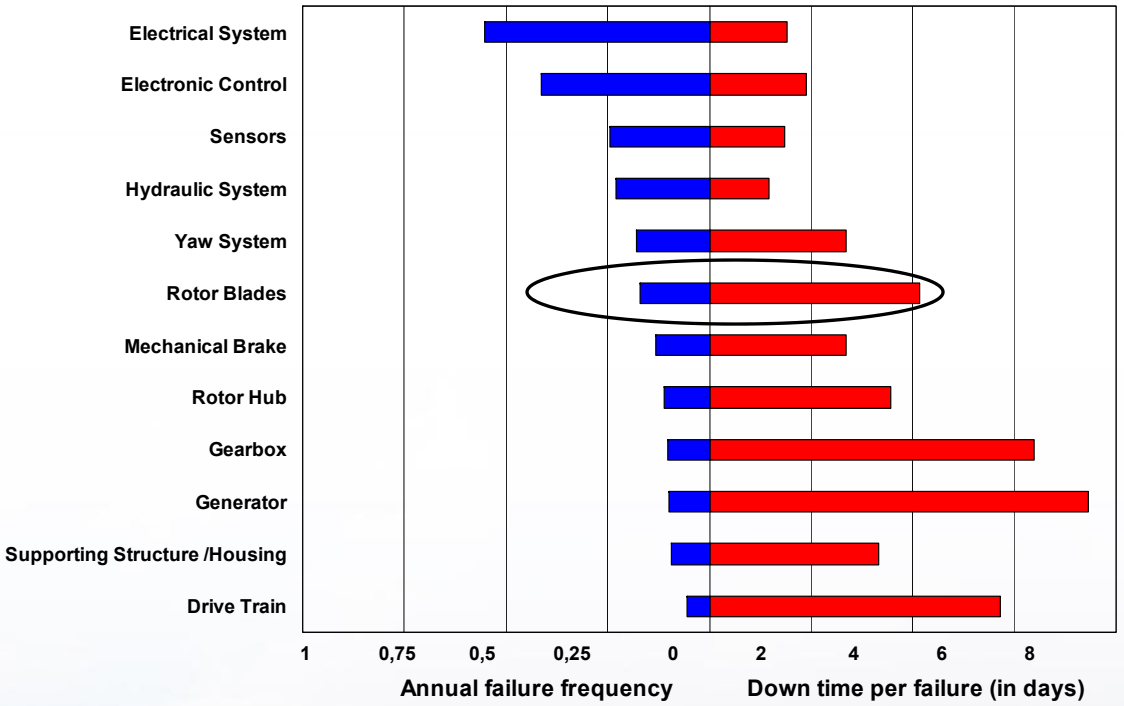
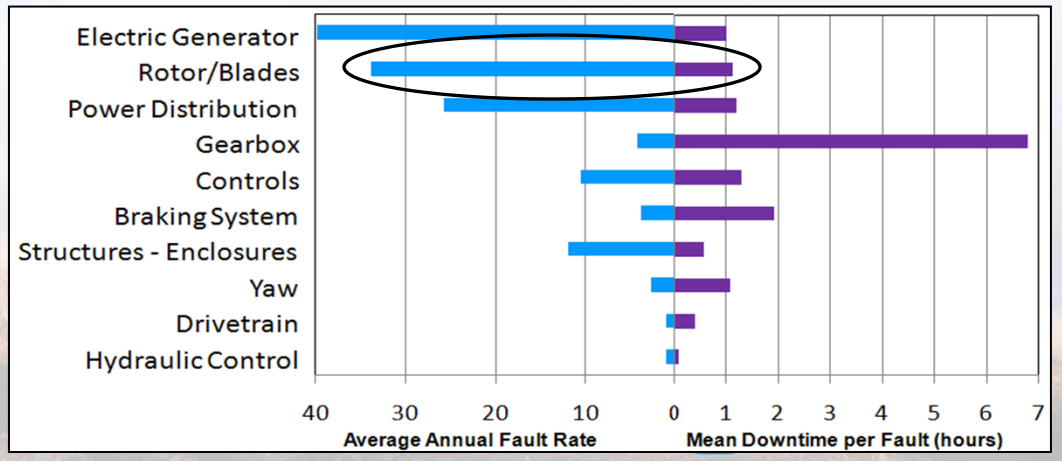
BRC Motivation

- 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

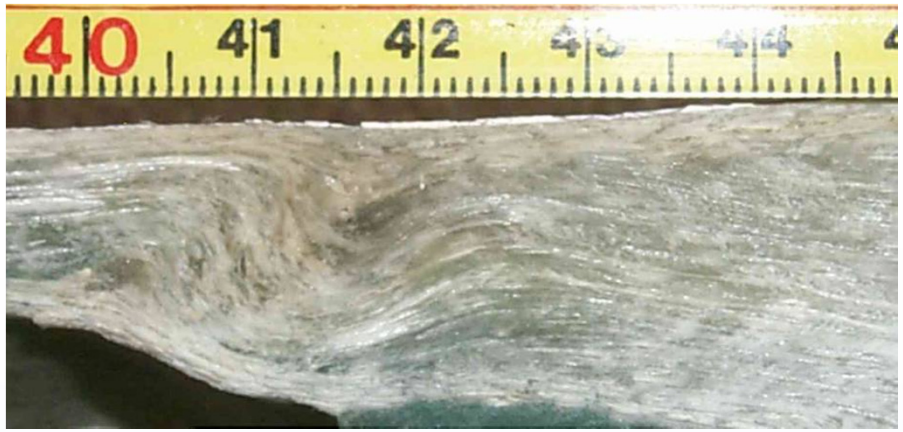
Preliminary Operator Survey

- **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

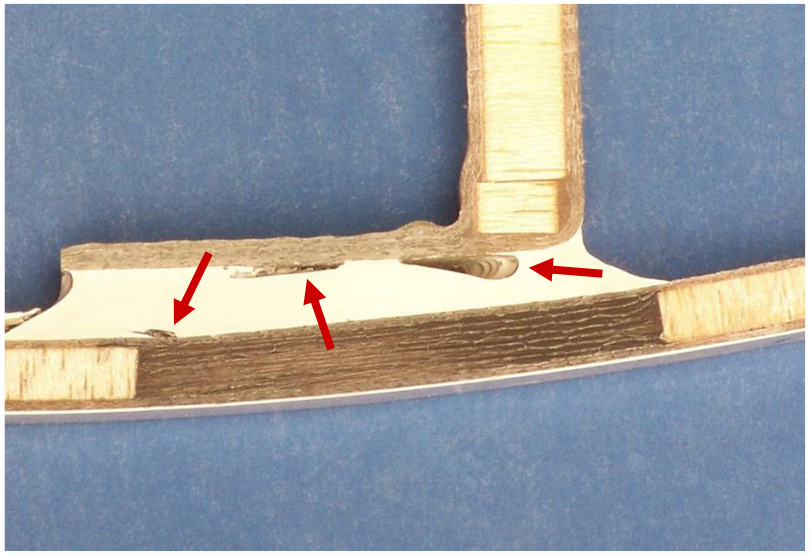
Carbon Spar Cap

Delaminations

1/2 meter

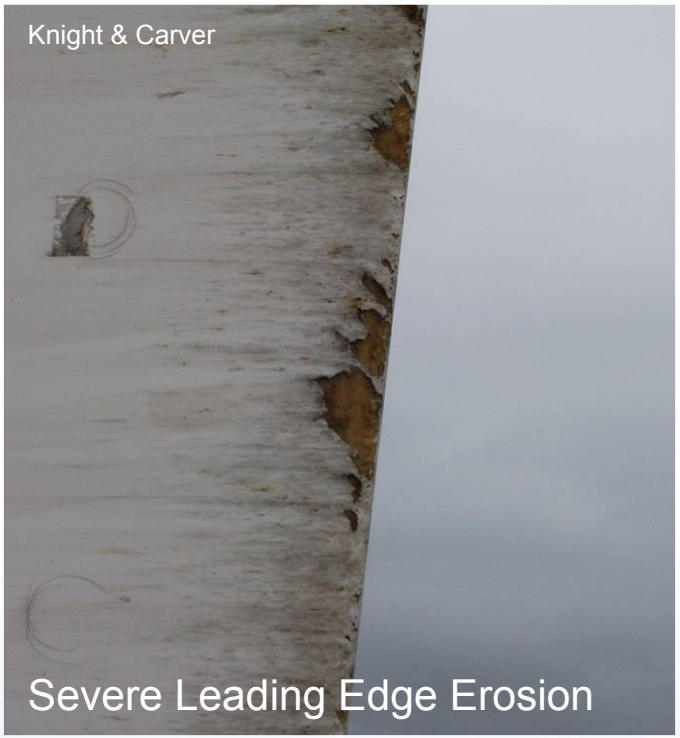
2. Bonding Quality

- **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



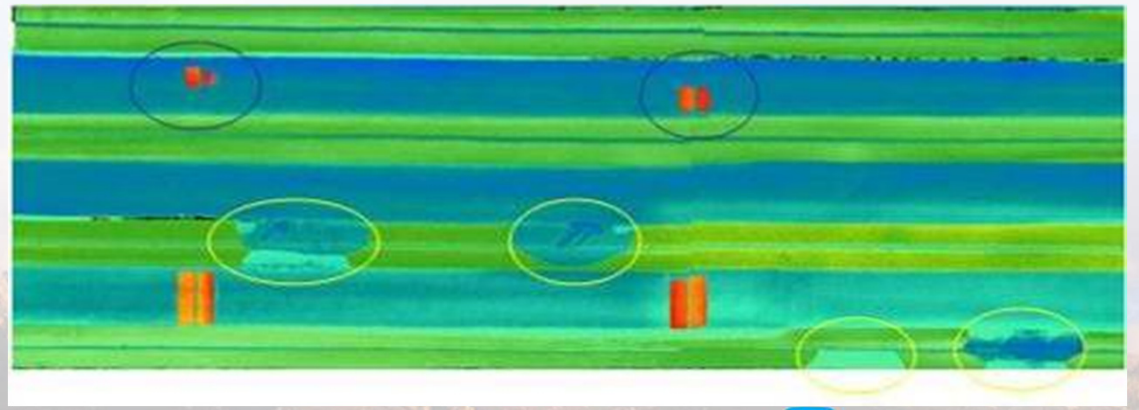
- **Leading edge erosion**
- **Moisture intrusion**
- **Freeze/Thaw cycling**
- **Root fastener corrosion**
- **Lightning**
  - Many blades are repaired
  - Some operators consider it manageable - when compared to other components, such as gear boxes

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

- **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

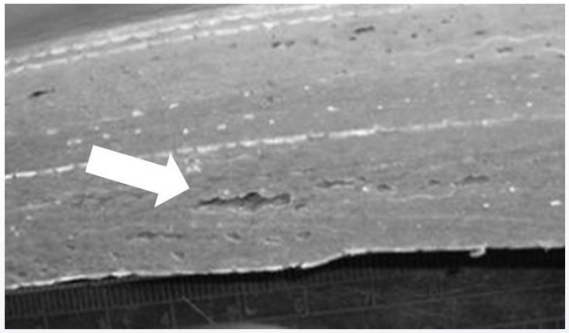
Courtesy Billy Roeseler, Boeing

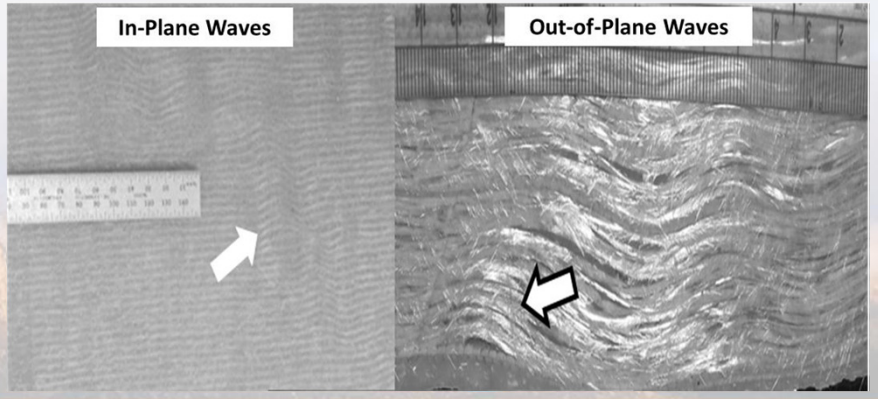
BRC Tasks

- ***Blade Defect and Damage Database*** – Aggregate data from blade manufacturers, service companies, and operators to determine largest sources of blade unreliability
- ***Inspection Validation*** – Evaluate the ability of inspection techniques to accurately characterize blade defects and damage in manufacturing plants and in the field
- ***Effects of Defects*** – Determine how common manufacturing defects affect blade strength and service life
- ***Analysis Validation*** – Assess the ability of design analysis tools to find and characterize potential failure modes
- ***Certification Testing*** – Evaluate the ability of certification testing to uncover potential reliability issues and find innovative ways for testing to provide better insight
- ***Standards and Partnerships*** – Interface with international standards committees and industrial partners to identify pathways to implementing improved design, manufacture, and inspection

Blade Defect and Damage Database

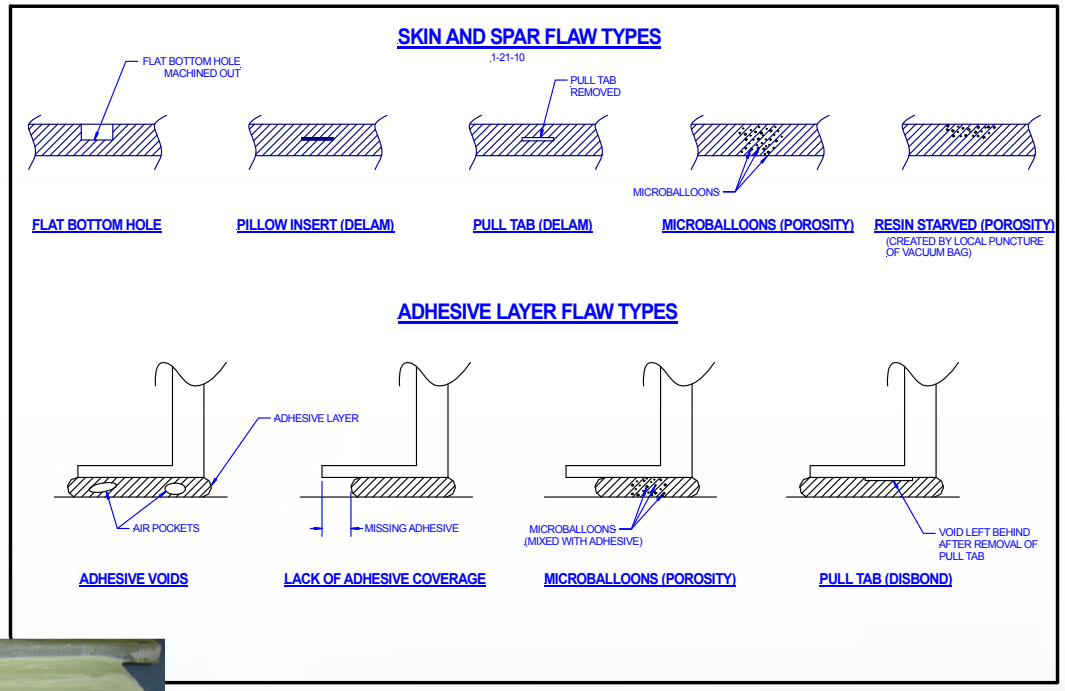
- Work with manufacturers to understand plant and under-warranty issues
- Survey wind farm owners/operators
- Collect and analyze repair information from blade service companies
- Summarize data from NREL certification tests
- Found prevalence of in-plane and out-of-plane waves, porosity, bonding problems in *inspected blades*
- Found large amount of leading edge erosion and lightening damage in *blade inspection and repair reports*
- ***More partners welcome!!!***



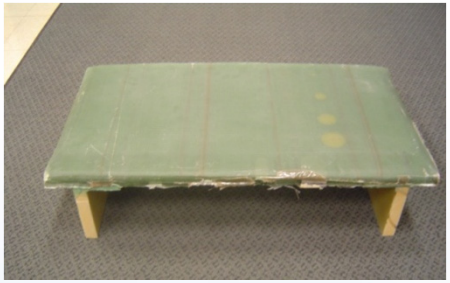


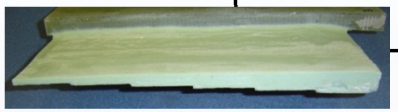
Inspection Validation

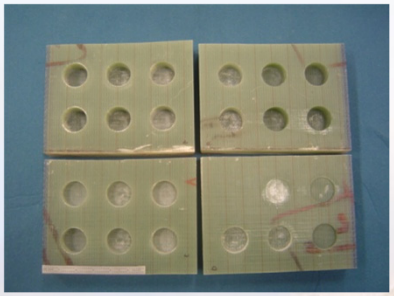
- Build representative samples with known flaws
- Establish baseline NDI results
- Vendor inspections to validate product capabilities (current list of over 20 participants)
- Research conducted by Sandia's Aviation Assurance NDT Validation Center (AANC)



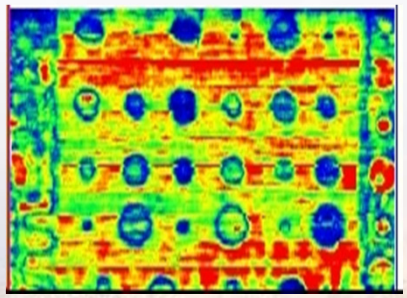
Methods for Producing Common Flaws

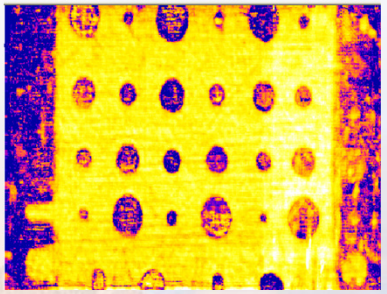






Manufactured Flawed Specimens

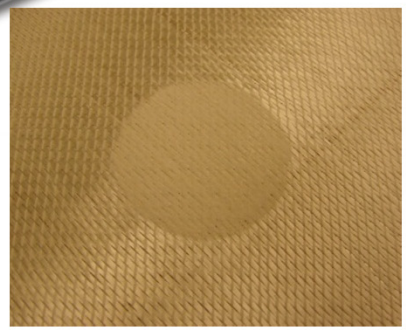




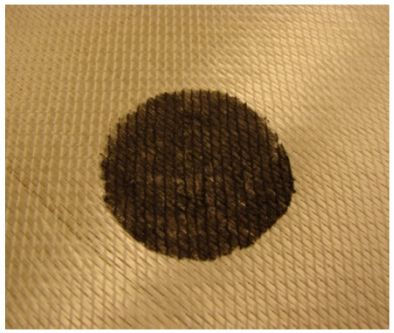
Sample NDI Results

Create Probability of Detection (POD) curves for inspection techniques

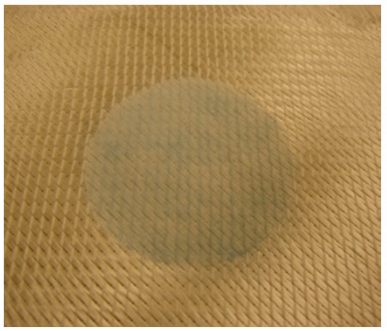
Inspection Validation: Flaw Creation



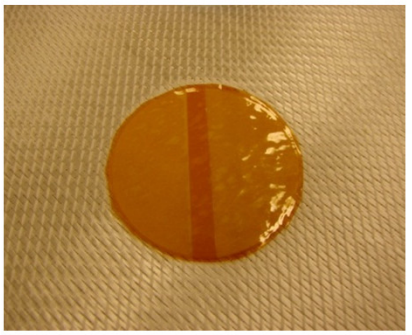
Glass Beads



Grease

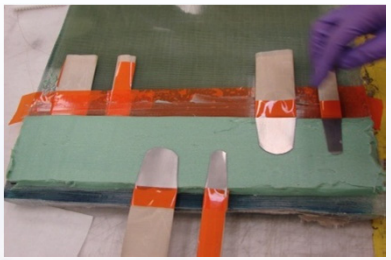


Mold Release

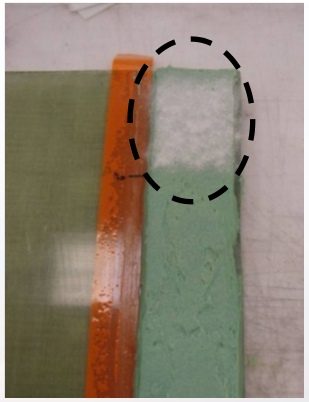


Pillow Insert

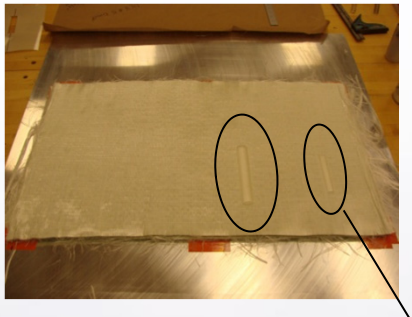
Voids in bond joint



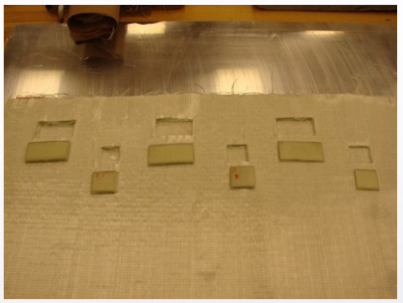
Pull tabs in bond joint



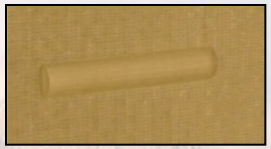
Glass beads In bond joint

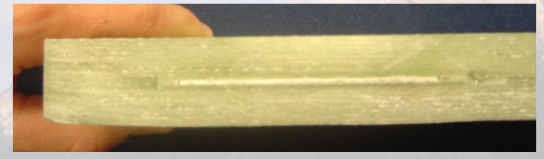


Waviness produced by pre-cured resin rods



Dry fabric areas





Single ply of dry fabric

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Inspection Validation: NDI Partners

OLYMPUS

PHYSICAL ACOUSTICS CORPORATION

TOSHIBA
Leading Innovation

Thermal Wave Imaging

Sonatest

Resodyn CORPORATION

DANTEC DYNAMICS

IOWA STATE

MISTRAS GROUP, INC.

BOEING

VISTA ENGINEERING TECHNOLOGIES

EVISIVE
MICROWAVE NDE TECHNOLOGY

MOVIMED
custom imaging solutions

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Inspection Validation: Probability of Detection (POD) Experiment

First design iteration of POD experiment 2012 (12 to 18 samples)

→

Review Committee

NREL
UpWind
DOE
Clipper
LM Wind Power
Gamesa
Molded Fiberglass
SNL
TPI Composites
GE – Global Research
Vestas
Sandia

→

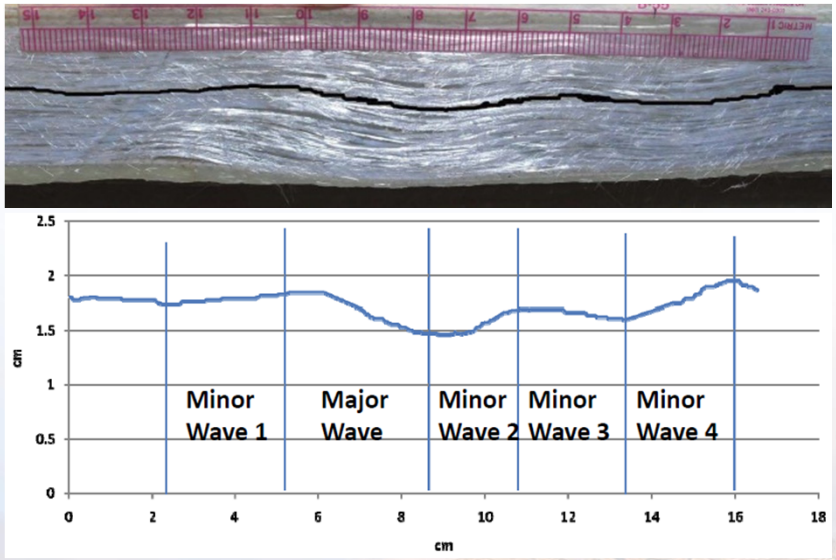
Second iteration incorporating review committee's suggestions

Ensure representative blade construction and materials

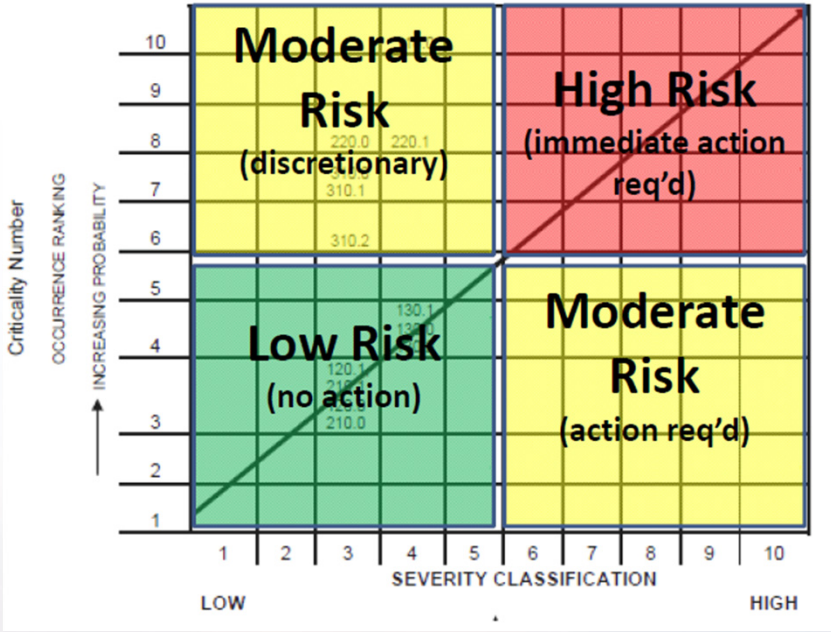
NREL
tpi
UPWIND SOLUTIONS
Gamesa
Clipper
Vestas
U.S. DEPARTMENT OF ENERGY
LM WIND POWER
GE Global Research
Sandia National Laboratories

Effects of Defects: Flaw Characterization

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



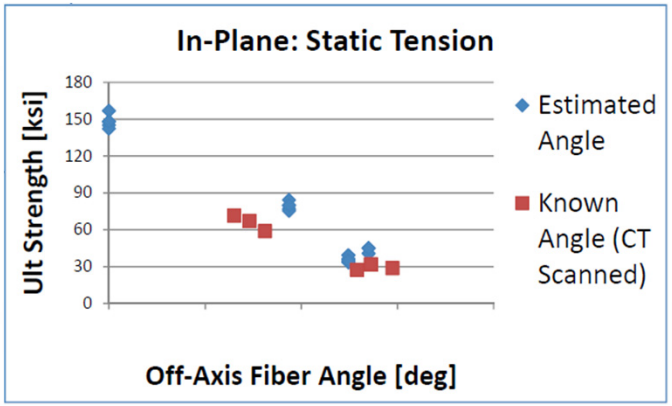
Manufactured Flawed Specimens



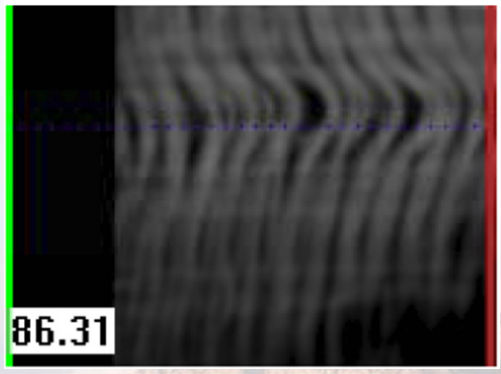
Criticality/Severity Matrix

Effects of Defects: Flawed Coupon Testing

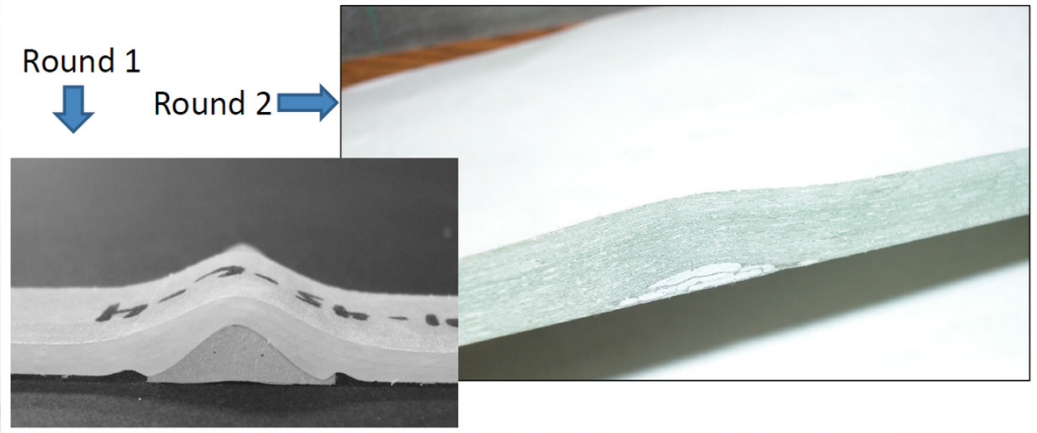
- **Produce flawed coupon samples**
  - In-plane waves
  - Out-of-plane waves
  - Porosity
  - Bondlines
- **Flaw characterization using high-fidelity inspection**
- **Tension, compression, and shear testing**



Effect on Tensile Strength



In-Plane Waviness Specimen



Out-of-Plane Waviness Specimen

Trey Riddle, PhD. Student, MSU

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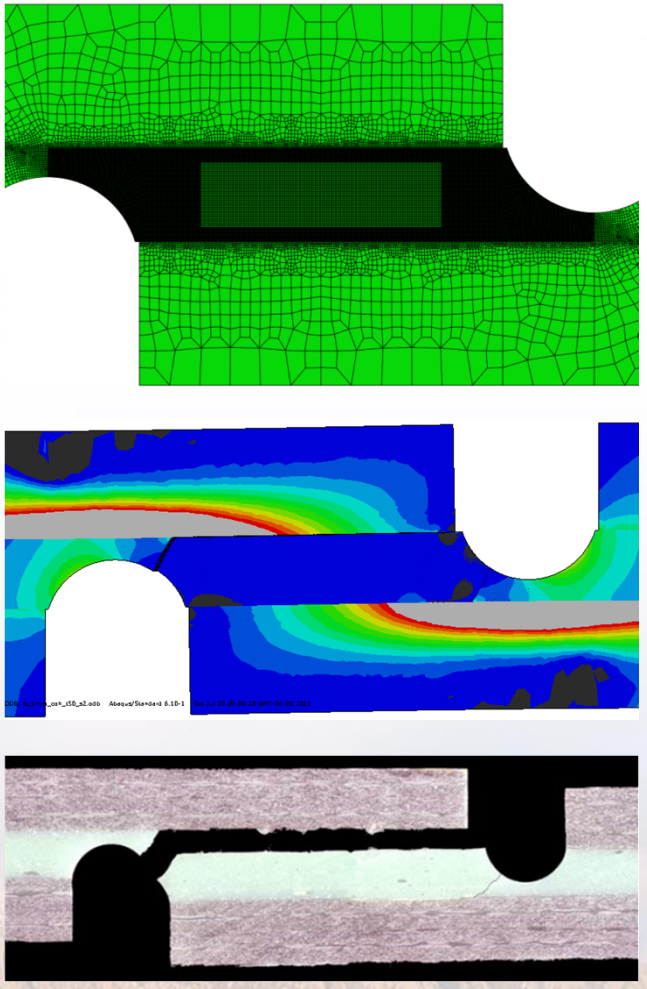
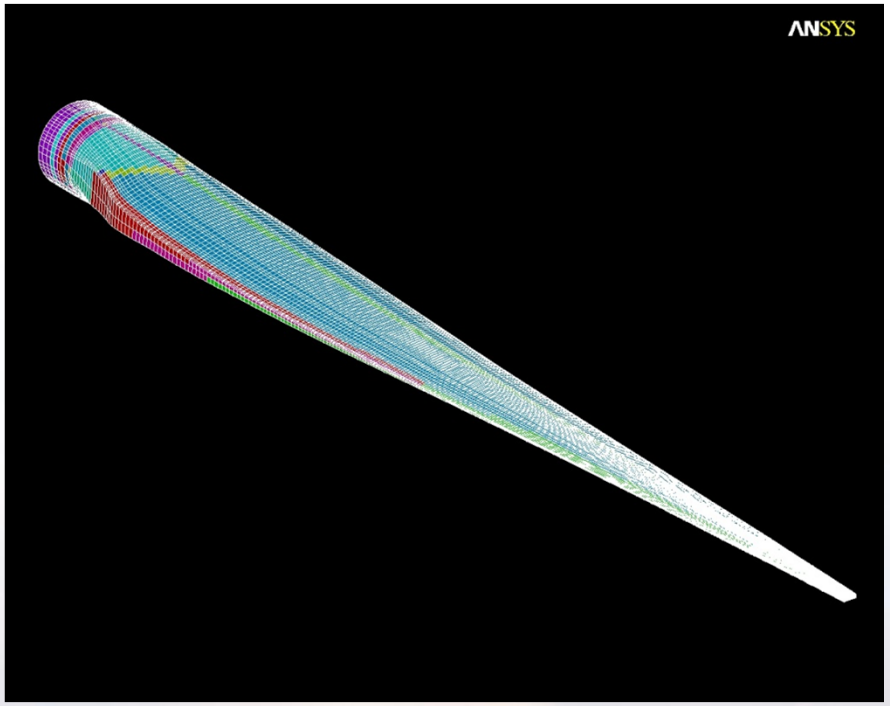
Effects of Defects: Analysis

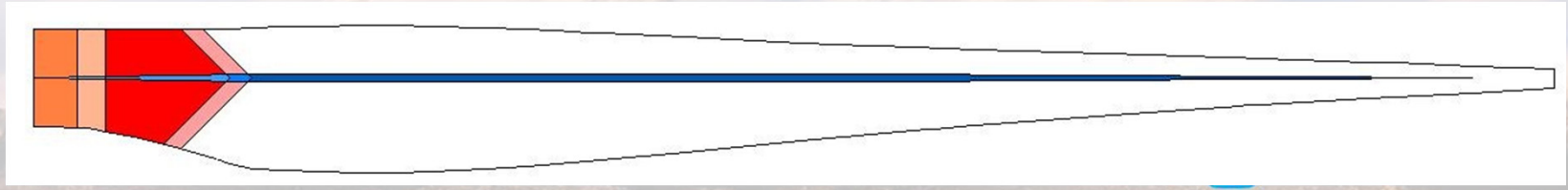
- **Progressive Damage Modeling underway**
  - Binary material property degradation model
  - Abaqus user subroutine for failure criteria
  - 2D mesh generated utilizing four layers of a quadrilateral, plane stress shell element
- **Adhesive Bond Line Modeling**
  - Current analysis tool uses the Cohesive Zone Model (CZM)
  - Useful for strength predictions, evaluating crack propagation
  - Cohesive elements are placed within FE mesh between continuum elements (bulk material



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**
- **Test Specimen: BSDS Subscale Blade**
  - Glass and carbon spar versions
  - Fiber waviness, porosity, delaminations, dis-bonds
  - Ply Drops, Bondlines, Material Transition
- **Block Fatigue Loading**
- **Inspection before, during, and after testing**





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

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Upcoming Activities

- **Blade Defect and Damage Database**
  - Collect further data on leading edge erosion
- **Inspection Validation**
  - Complete round-robin testing on NDI Feedback Specimens with “advanced” NDI methods
  - Complete analysis of inspection results with NDI comparisons
  - Complete first design iteration of POD experiment set including experimental protocol, deployment and manufacturing
  - Interface with OEMs, operators and designers during POD review process

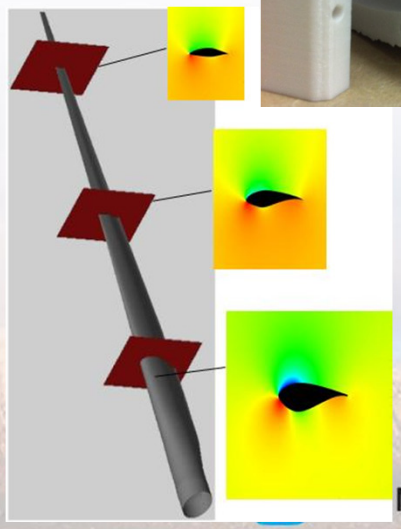
Upcoming Activities *(cont.)*

- **Effects of Defects**
  - Final round of testing including thick laminates and complex & combined flaws
  - CZM and DDM modeling
  - Probabilistic modeling of effects of defects on full-blade model using HPC resources
- **Analysis Validation**
  - Finalize test blade design with flaws
  - Manufacture and inspect test blades
  - Begin analysis of blade models
- **Certification Testing**
  - Perform proof and fatigue test on specimen

Upcoming Activities *(cont.)*

Leading Edge Erosion Study

- **1: Data Gathering and Erosion Profile Characterization (Sandia, Owner, OEM)**
  - Analyze collected wind farm data to determine effect of erosion on performance
  - Obtain leading edge surface reliefs from turbines with eroded leading edges
- **2: Wind Tunnel Testing (Texas A&M)**
  - Characterize and parameterize leading edge roughness
  - Design and test blade section wind tunnel model (based on actual blade airfoil shape) with removable leading edge*
- **3: Aerodynamic Modeling (UC-Davis)**
  - Identify roughness-induced boundary layer transition model and implement transition model into a 2D CFD code
  - Build model for rotor performance with LE erosion
  - Quantify LE erosion impact on cost of energy



* Wind tunnel model will be designed to fit in Virginia Tech aeroacoustic wind tunnel for future noise measurement campaigns.

Accomplishments

- **Participation in the collaborative has grown to over 40 representatives of academia, labs, and industry, including blade designers, blade manufacturers, blade service companies, turbine OEM's, and turbine owner/operators.**
  - EPRI, U-Mass Lowell, TPI Composites, MFG, Rope Partners, EDPR, Vestas, Gamesa, GE, Dantec Dynamics, Laser Technology Inc. and many others.
- **Construction of a blade reliability database which includes blade failure data.**
- **Development of blade-specific NDI inspection panels, with inspection of those panels by over 20 NDI manufactures.**
- **Significant characterization, modeling, and mechanical testing of blade specimens with fiber waviness, porosity, and defective bondlines.**