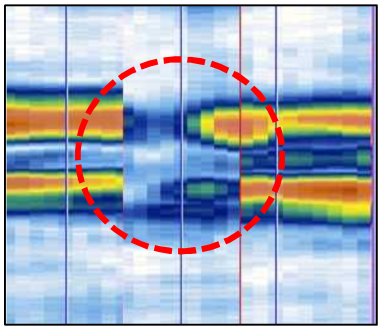
Innovative, Efficient and Effective Methods to Address Wind Blade Production and In-Service Inspection Needs

SAND2017-12079C



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Wind Blade Reliability Center

Sandia National Labs

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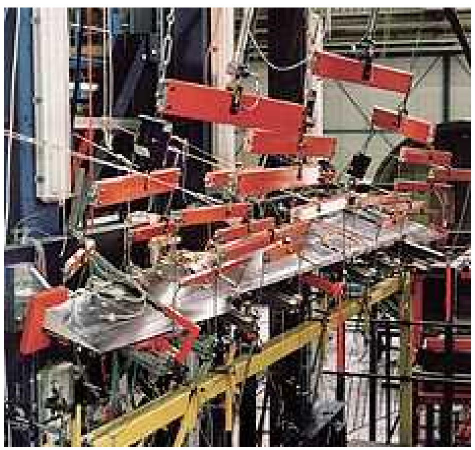
Rising Need for Wind Blade Inspections

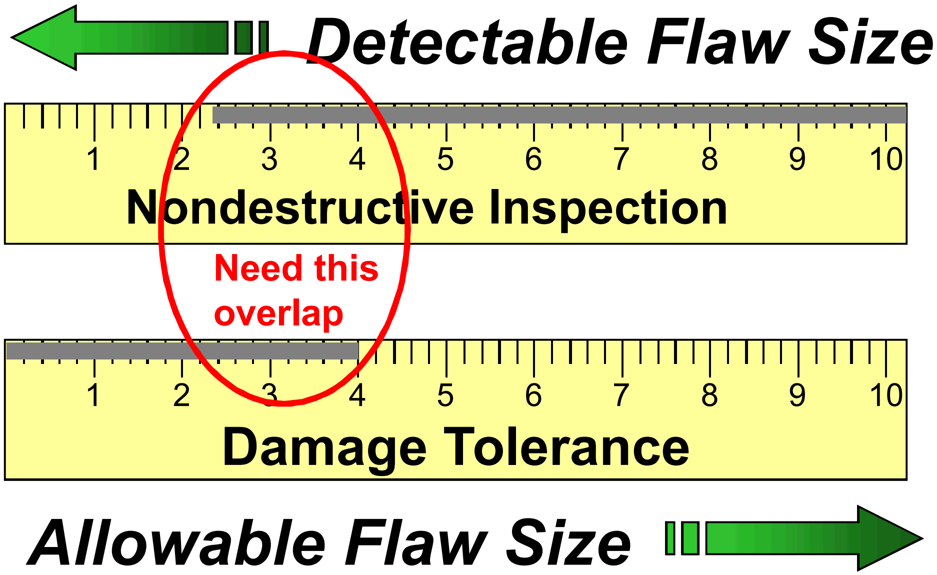
- **Rapid and steady increase in wind power installation**
- **Critical enablers to improve market competition with other electricity sources - *Dept. of Energy Wind Vision Roadmap* identifies need for continuing declines in wind power costs (blade availability) and improved reliability**
- **Increase wind farm availability and lower production costs by reducing unplanned maintenance - requires broader adoption of condition monitoring systems**
- **Better understanding of harsh environments combined with uncertainties in aging phenomena and Damage Tolerance of blades**
- **Blade maintenance is now a major issue because: 1) the number and age of wind blades in operation continues to grow, 2) larger blades have increased demand/need for more invasive repairs (vs. replacement), 3) operational loads/environment combined with seeded flaws creates the need for in-service inspections**
- **Navigant Research estimates the cumulative global revenue for wind turbine inspection services will reach nearly $6 billion annually by 2024.**

Blade Reliability Collaborative – NDI Objective

Create the ability for manufacturers to determine the quality of their product before it leaves the factory & to enhance the in-service inspection of wind blades

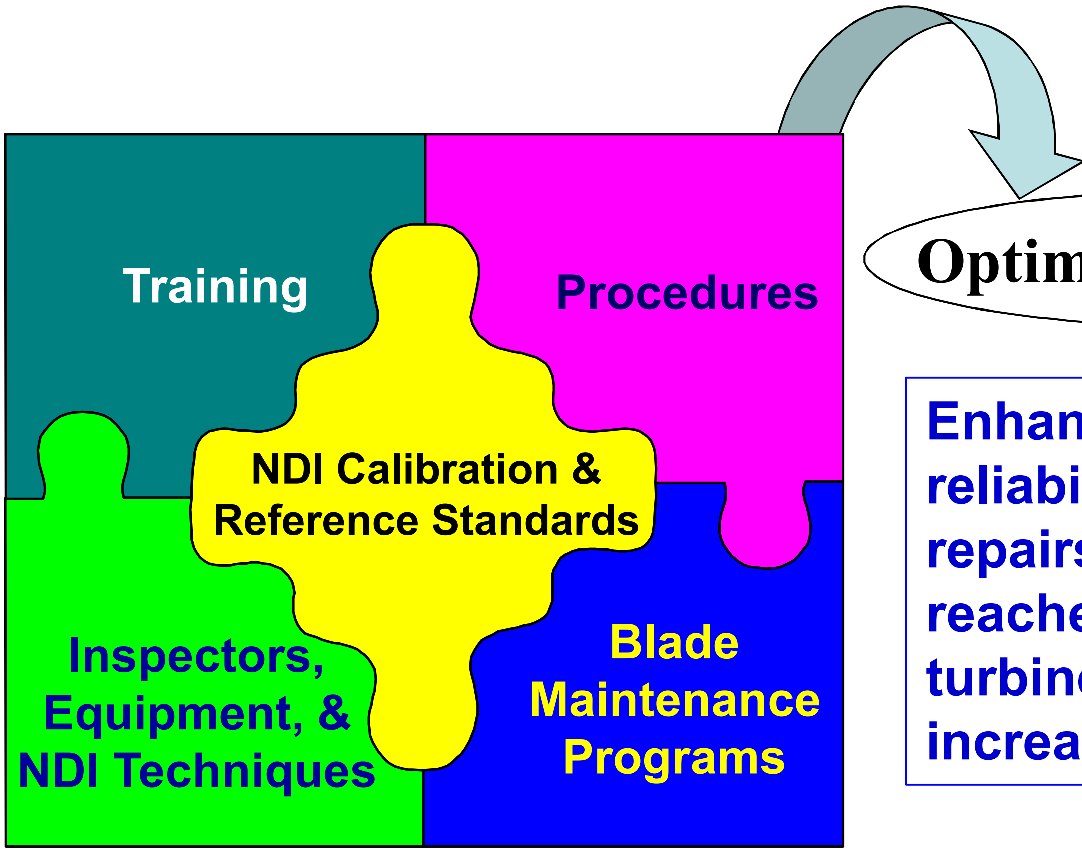


Required Relationship Between Structural Integrity and Inspection Sensitivity



Program Thrusts to Improve Wind NDI

- Use of NDI reference standards to form sound basis of comparison & ensure proper equipment set-up
- Use of material property & calibration curves (attenuation, velocity)
- Human factors – adjust procedures
- Improved flaw detection: Hybrid inspection approach - stack multiple methods which address array of flaw types (data fusion)

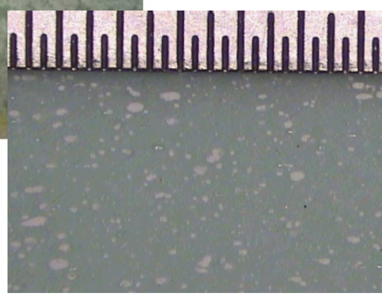


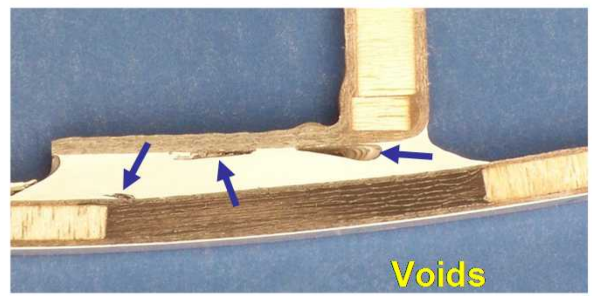
Optimized Inspections

Enhance factory reliability, facilitate repairs before $a_{critical}$ is reached, minimize turbine downtime & increase blade lifetime

Inspection Areas and Flaw Types of Interest

Flaws include: Ply Waves Delaminations, Adhesive Voids, Joint Disbonds, Snowflaking and Porosity



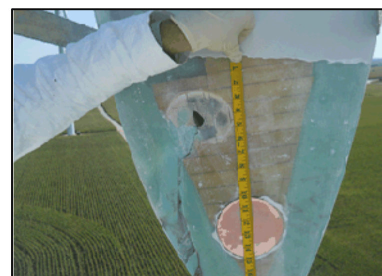


In-Service Inspection of Blades Including Wind Blade Repairs

Damage Sources -
Installation, Lightning Strike, Impact, Erosion, Overstress, Fatigue, Fabrication-Seeded, Environmental

Skin Laminate Fracture

- **In-service NDI can improve blade reliability, minimize blade downtime & extend blade life**
- **Additional access & deployment challenges**
- **Post-repair inspections**



Demand for More Extensive Wind Blade Repairs Requires Pre- and Post- Repair Inspection

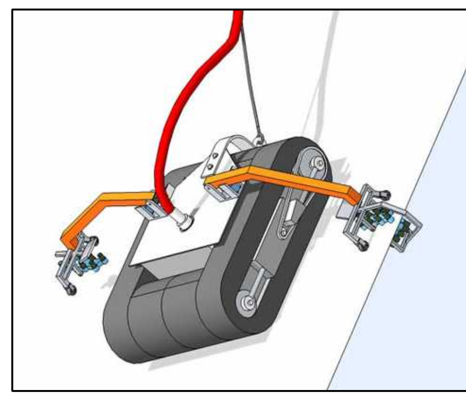
- Requires the means to conduct in-service inspections up-tower
- NDI must go beyond visual surface indications and produce deep, subsurface damage assessments
- NDI must be rapid to minimize blade downtime

Severe Growth of Fiber Fracture

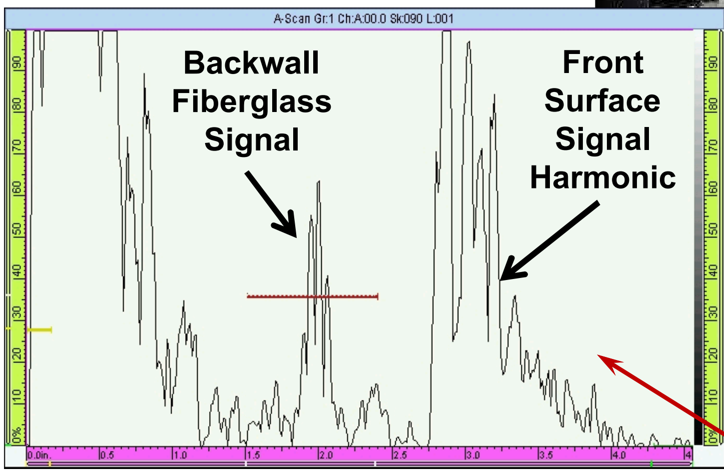
Scarfed Blade Repair Process

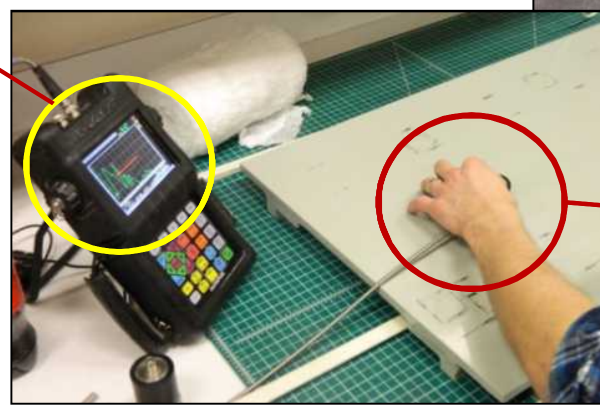
Lightning Strike Damage

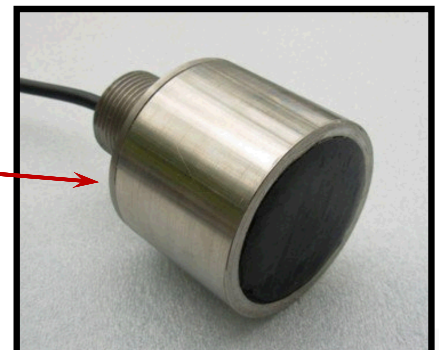
Drone- and Robot-Deployed NDI Systems



Overcome Inspection Challenges

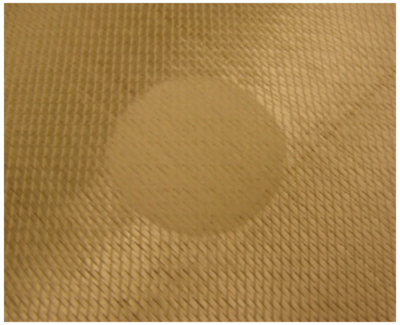




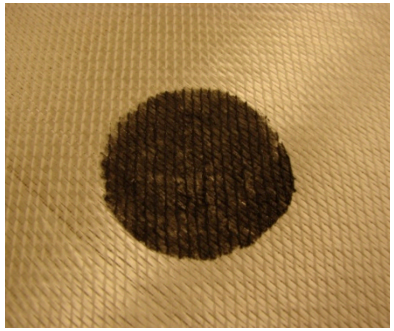


Want to make NDI easier, quicker, more reliable and more sensitive

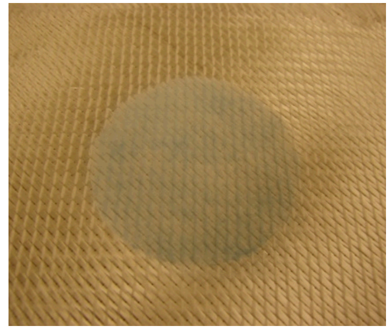
Different Flaw Types Engineered into NDI Performance Assessment Specimens



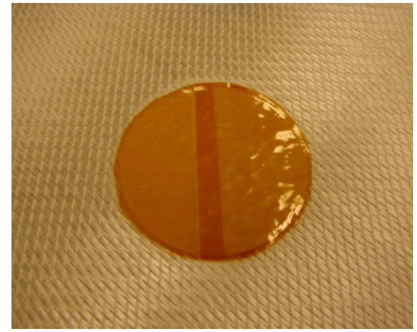
Glass Beads



Grease



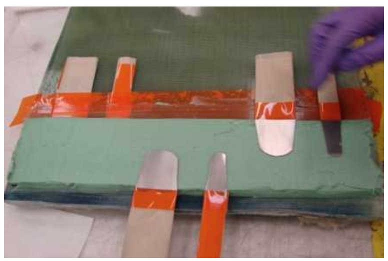
Mold Release



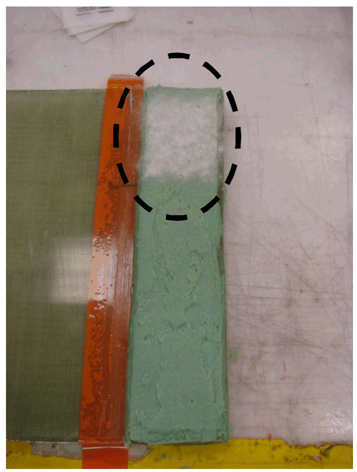
Pillow Insert

Materials inserted into multiple layers

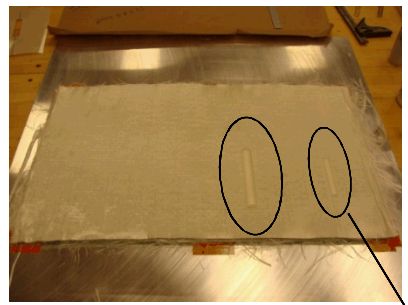
Voids in bond joint



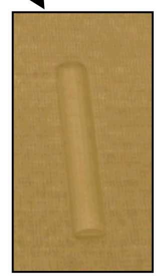
Pull tabs in bond joint

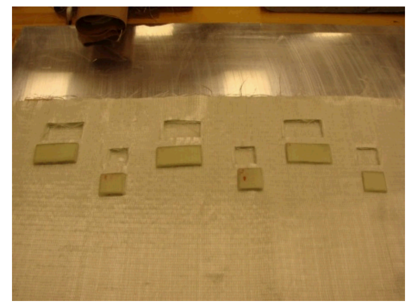


Glass beads In bond joint



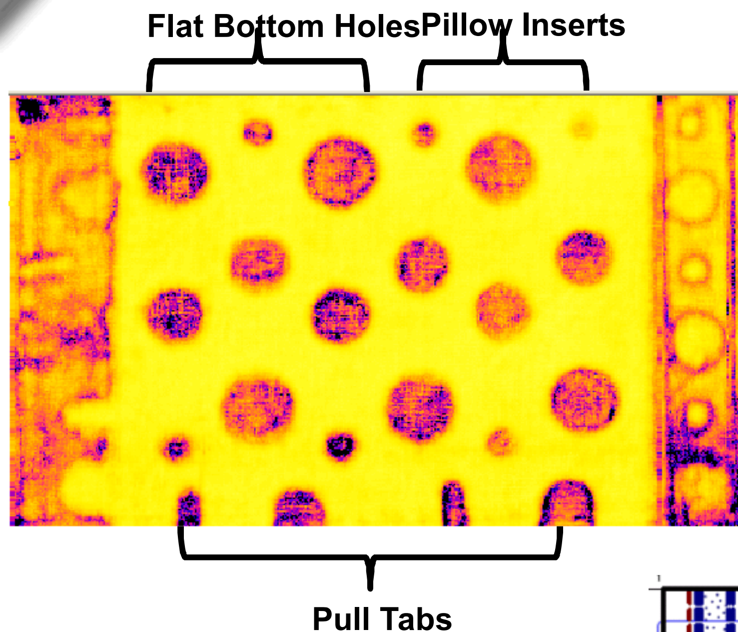
Waviness produced by pre-cured resin rods



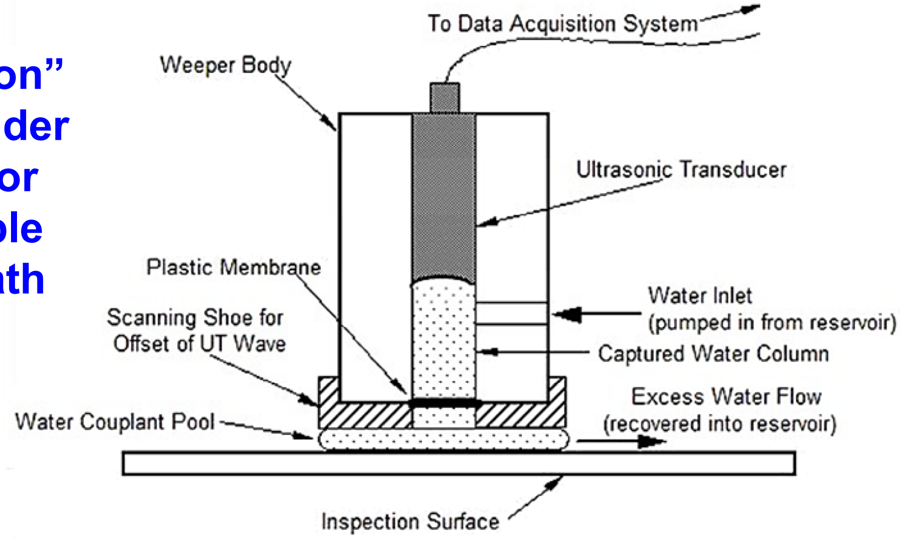


Dry fabric areas

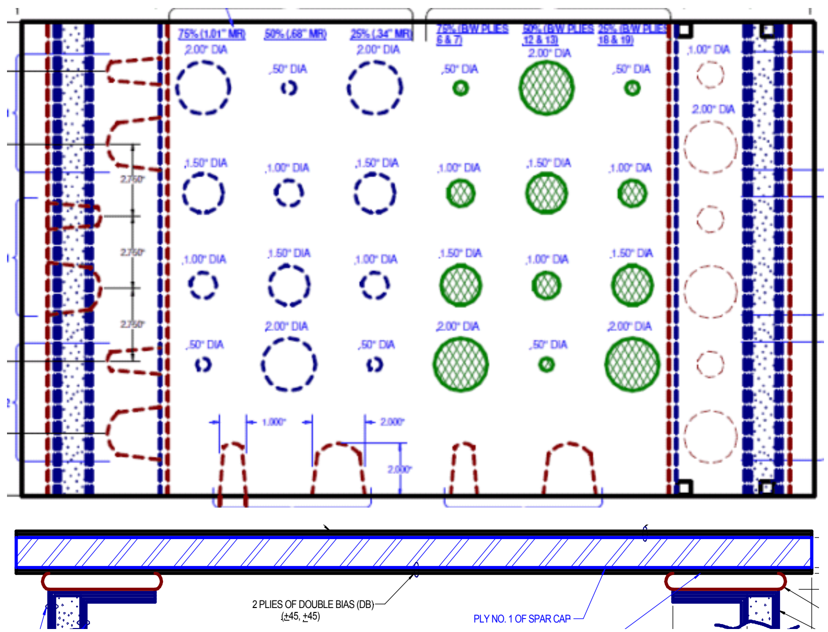
MAUS P-E UT with Focused Probe (1 MHz/2”) and Adjustable Water Path



New “Immersion” Probe Holder Allows for Adjustable Water Path



REF-STD-6-202-250-SNL-1



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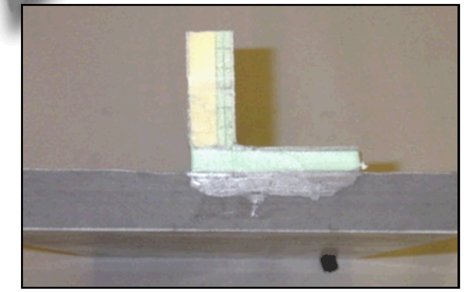
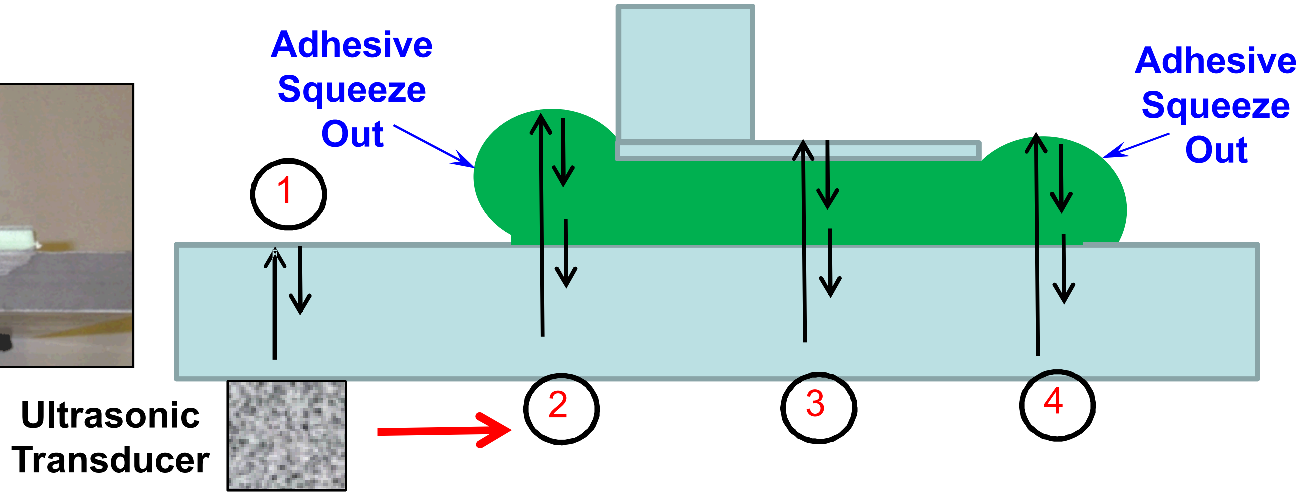
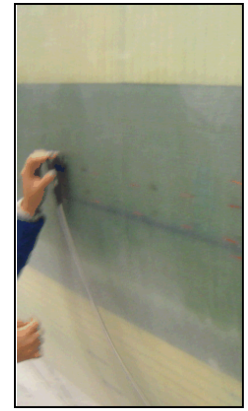
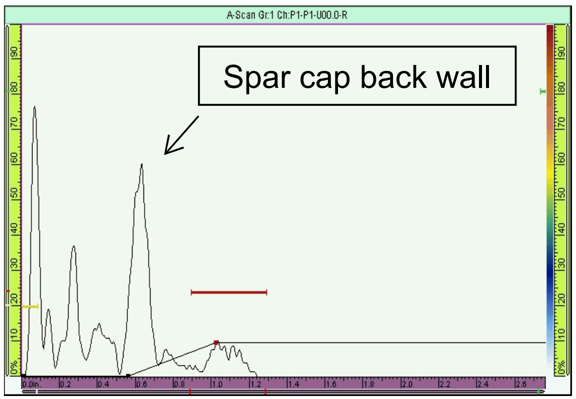
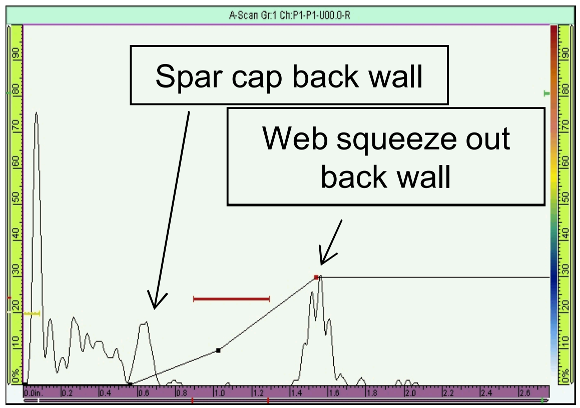
Pulse-Echo Inspection of Bond Joint

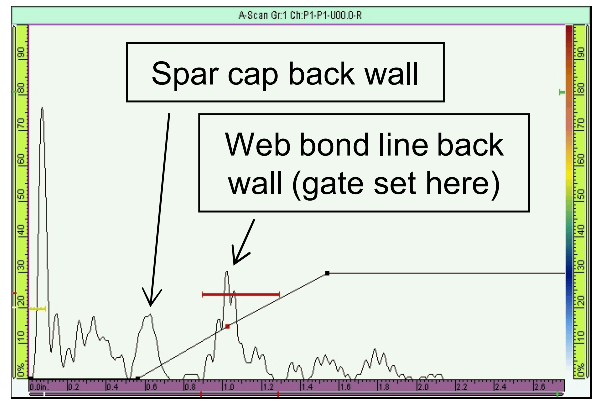










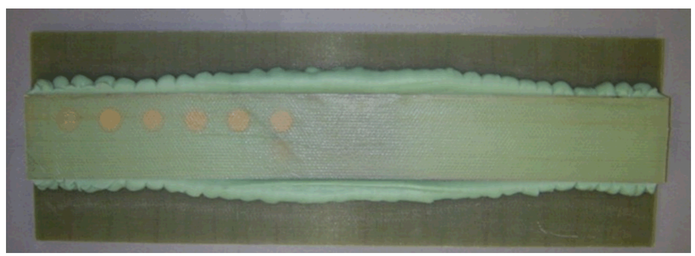


Spar Cap - 1

Web Squeeze Out- & 2 4

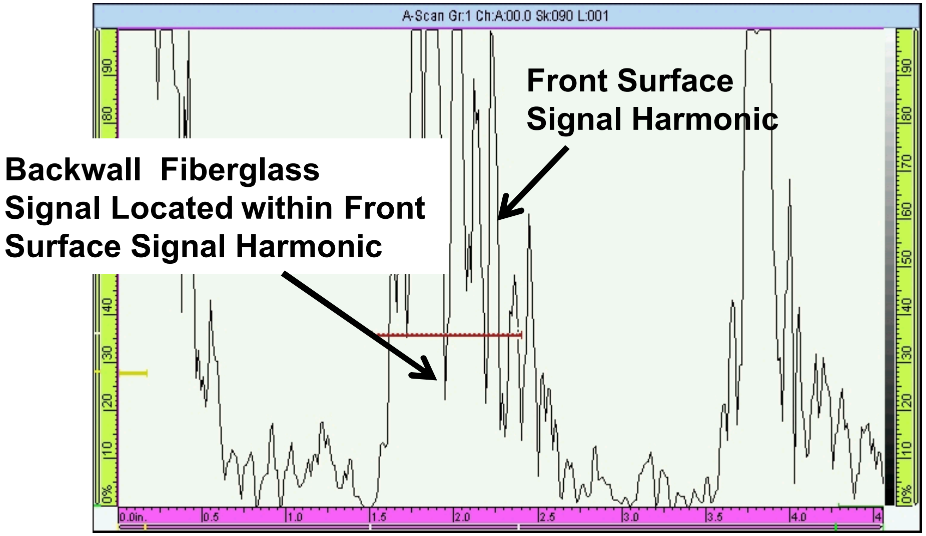
Web Bond Line- 3

A-Scan Signals

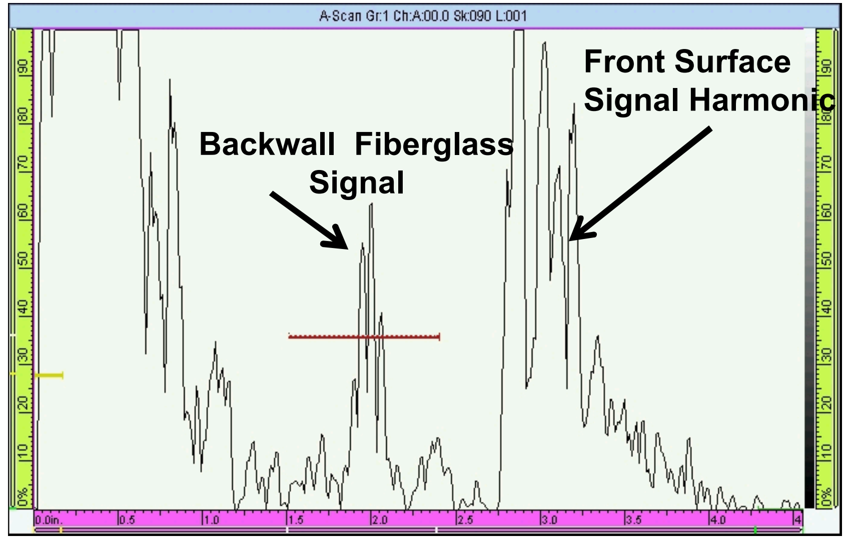


Design of Delay Lines to Avoid Signal Interference

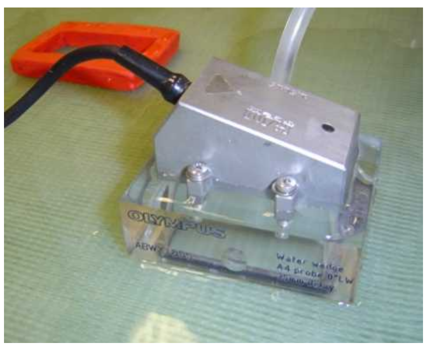
Water Box Signal Analysis - 25mm compared to 40mm; Moves harmonic return signal outside area of interest.



25mm Delay



40mm Delay



1.5 MHz Phased Array UT Probe

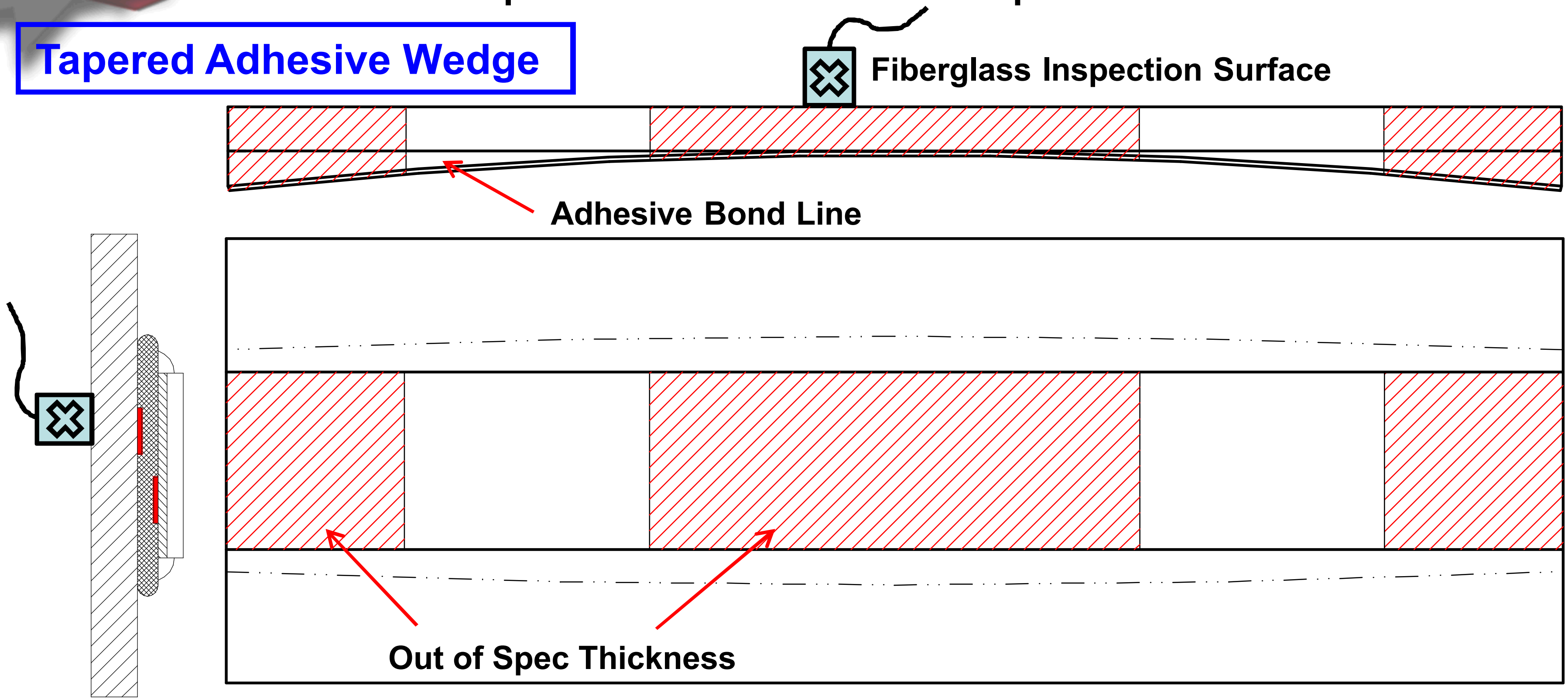
Sandia has focused on a sealed couplant box that:

- Adjusts to slight curvature in surfaces
- Eliminates water flow to open box
- Maximizes signal strength
- Accommodates necessary standoffs for signal clarity
- Easily saves scanned images for reference using a wheel encoder

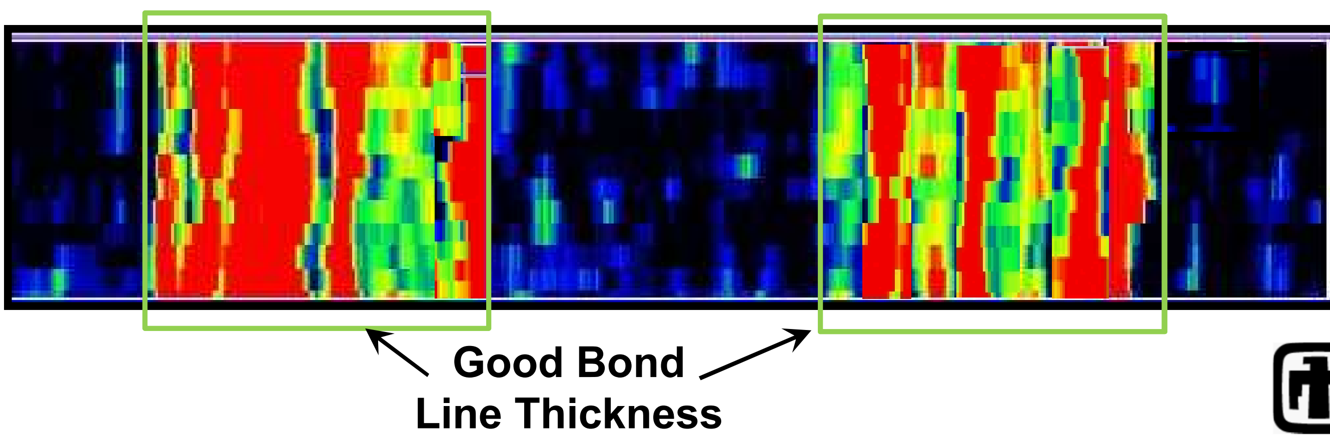
Adhesive Thickness Measurements with Phased Array UT

Develop and assess methods to inspect bond line thickness

Tapered Adhesive Wedge



Phased Array UT Results



An Experiment to Assess Flaw Detection Performance in Wind Turbine Blades (POD)

Purpose

- Generate industry-wide performance curves to quantify:
  - how well current inspection techniques are able to reliably find flaws in wind turbine blades (industry baseline)
  - the degree of improvements possible through integrating more advanced NDI techniques and procedures.

Expected Results - evaluate performance attributes

1) accuracy & sensitivity (hits, misses, false calls, sizing)
2) versatility, portability, complexity, inspection time (human factors)
3) produce guideline documents to improve inspections
4) introduce advanced NDI where needed

Ensure representative blade construction and materials

Wind Blade NDI Probability of Detection Experiment

- Blind experiment: type, location and size of flaws are not know by inspector
- Statistically relevant flaw distribution – Probability of Detection (POD)
- Used to analytically determine the performance of NDI techniques – hits, misses, false-calls, flaw sizing, human factors, procedures

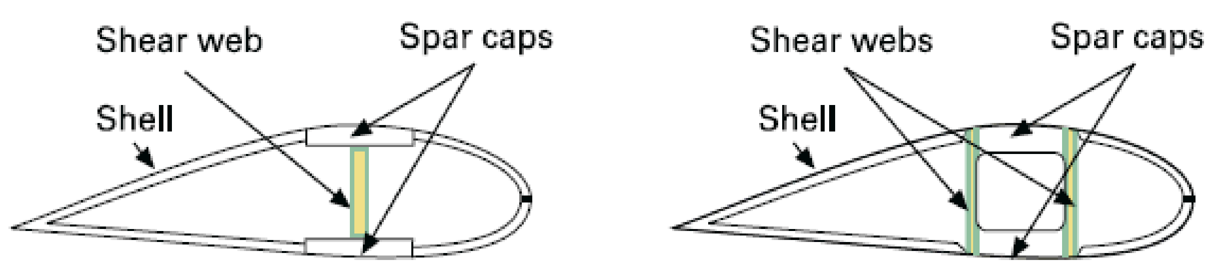
Experimental Design Parameters

- Representative design and manufacturing
- Various parts of blade such as spar cap, bonded joints, leading and trailing edge
- Statistically valid POD (number, size of flaws and inspection area)
- Random flaw location
- Maximum of two days to perform experiment
- Deployment

Fabrication Considerations

- Realistic, random flaw locations
- Portable sample set
- Range of thickness
- Material types (fiberglass and adhesives)

Specimens designs applicable to various blade construction



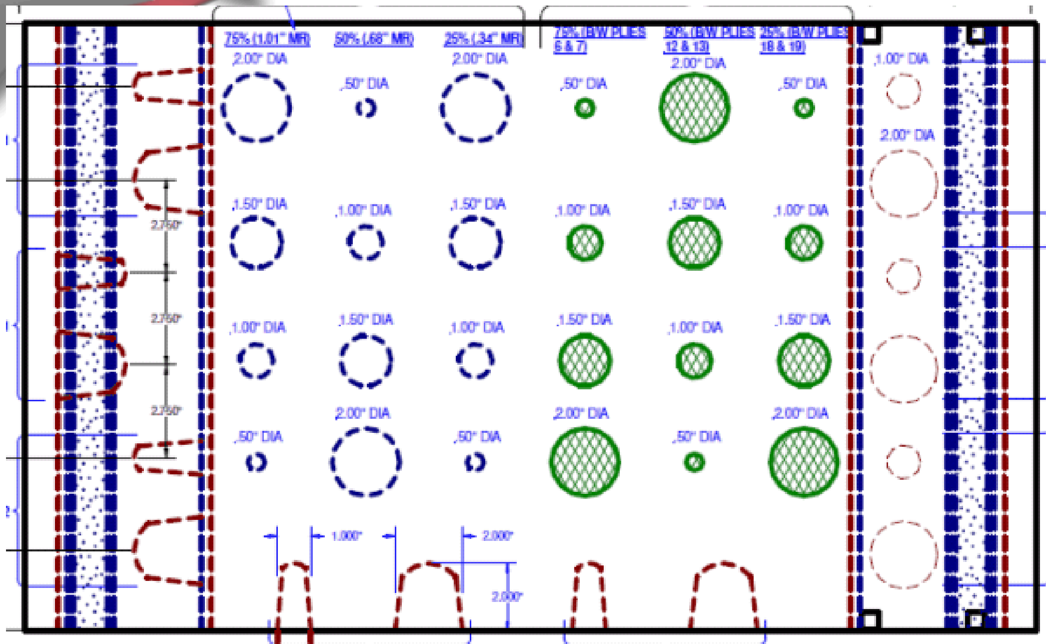
Spar Caps & Shear Web

Box Beam

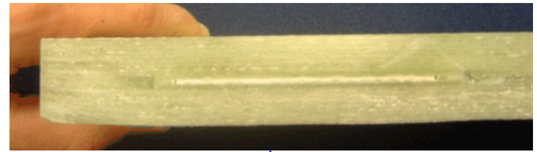
Implementation of Wind POD Experiment

- 11 POD specimens with spar cap and shear web geometry
- Thickness ranges from 8 Plies (0.45” thick laminate, 0.85” thick with adhesive bond line) to 32 Plies (1.80” thick laminate, 2.20” thick with adhesive bond line)
- All panels painted with wind turbine blade paint (match inspection surface)

WIND POD Specimens Used for NDI Comparison

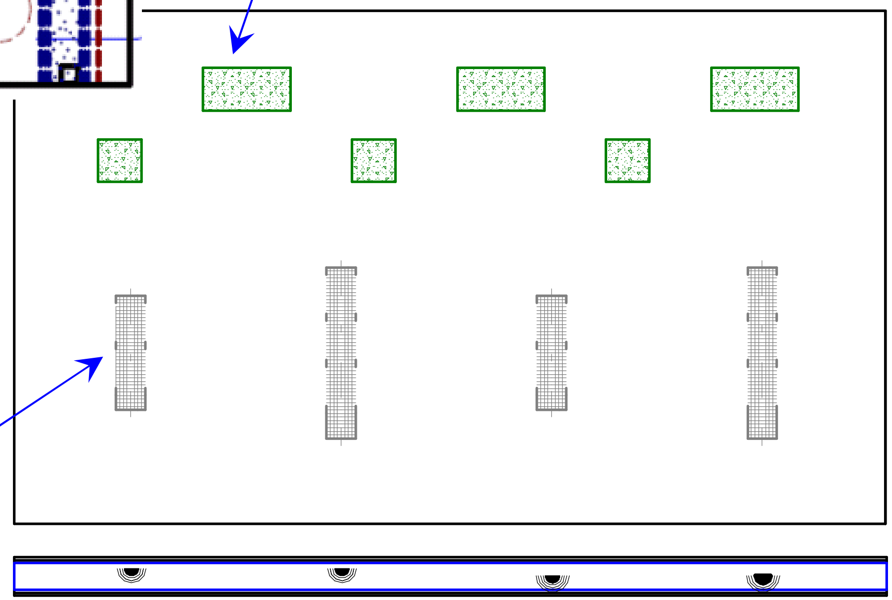


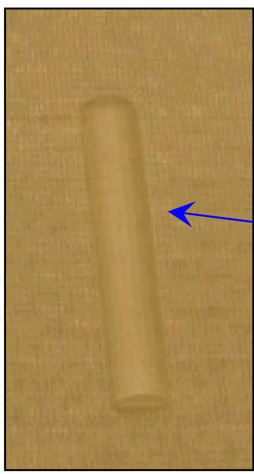
REF-STD-2-127-173-SNL-1



Dry Fiber Areas

REF-STD-4-135-SNL-1 (wrinkles & dry areas)





Resin Rod Induced Waves

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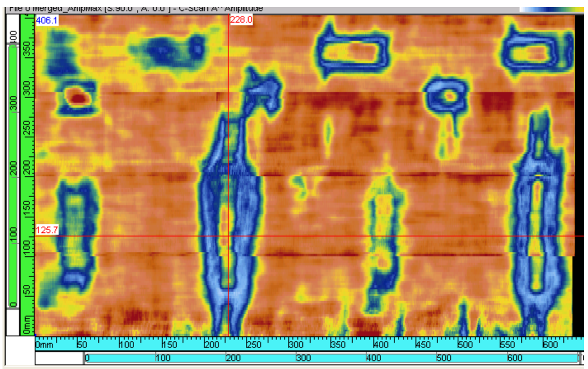
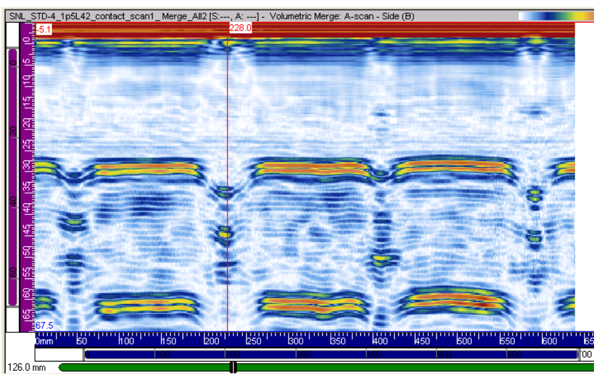
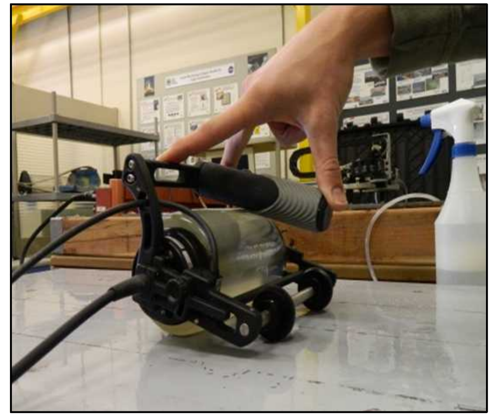
Phased Array UT – Display and Deployment

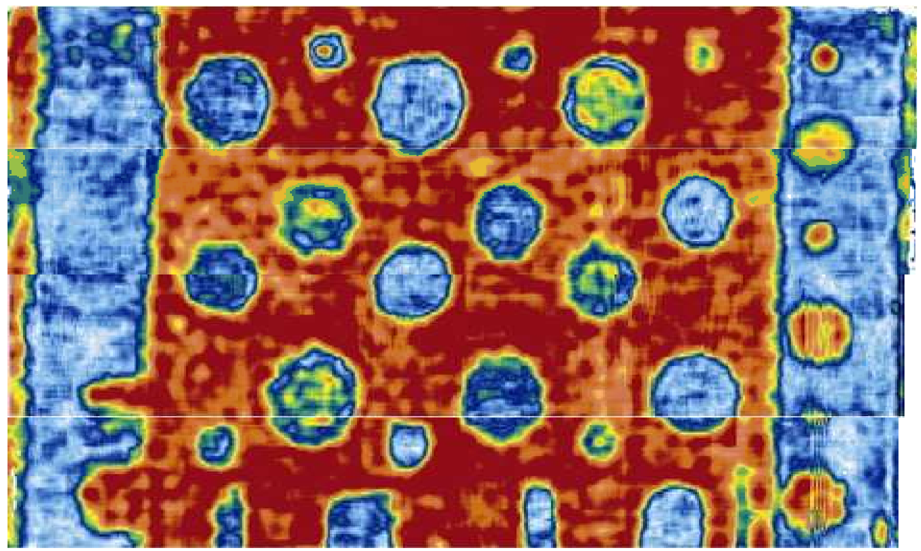




GE Phased Array UT RotoArray



Sonatest RapidScan 2



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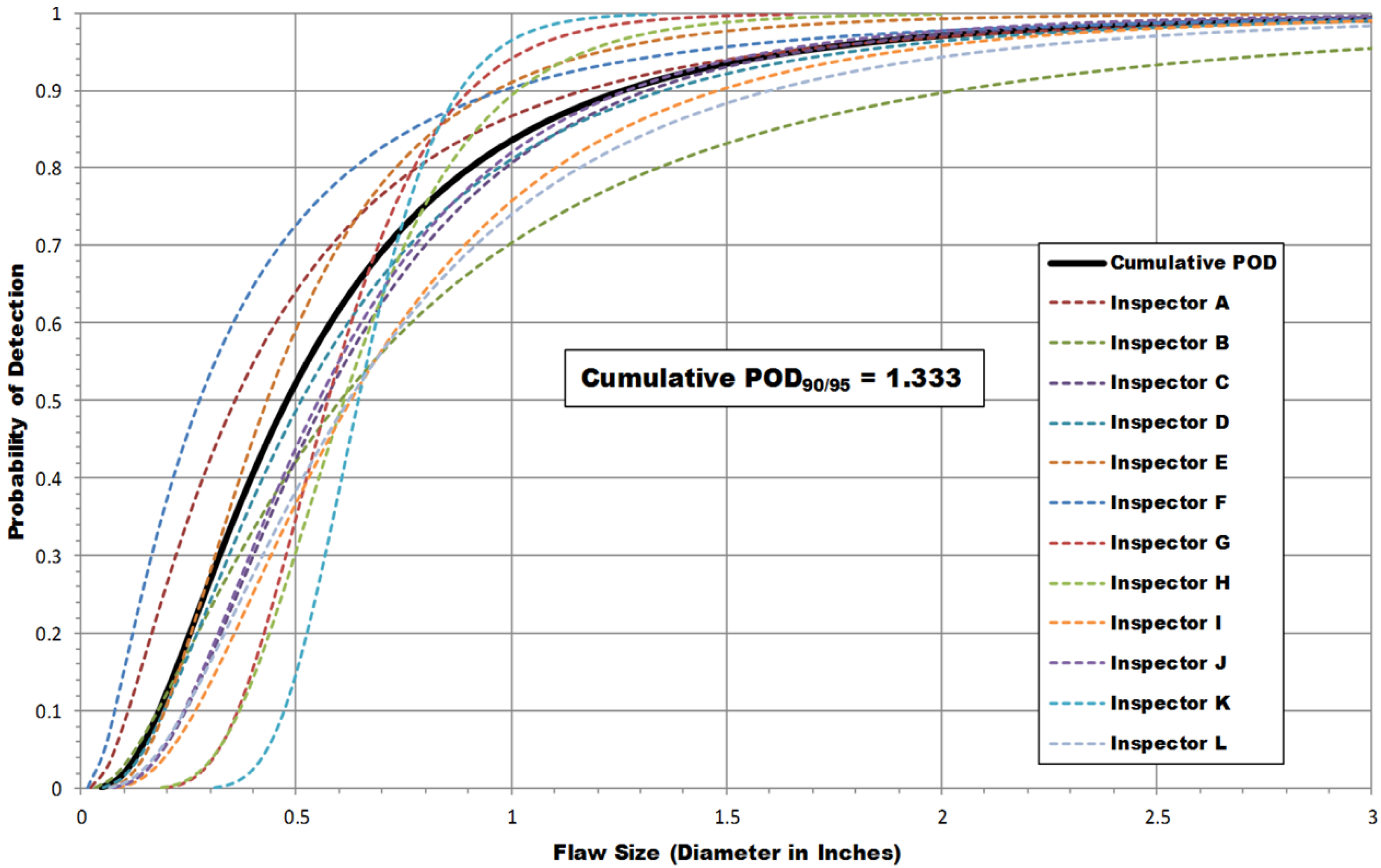
Wind Blade Flaw Detection Experiment – Individual Inspector and Cumulative POD Comparison

All Panels - Spar Cap with Shear Web and Box Spar Construction Types



Conventional Single Element Pulse-Echo Ultrasonic Inspection Method

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Wind Blade Flaw Detection Experiment – Various NDI Performance Attributes Evaluated

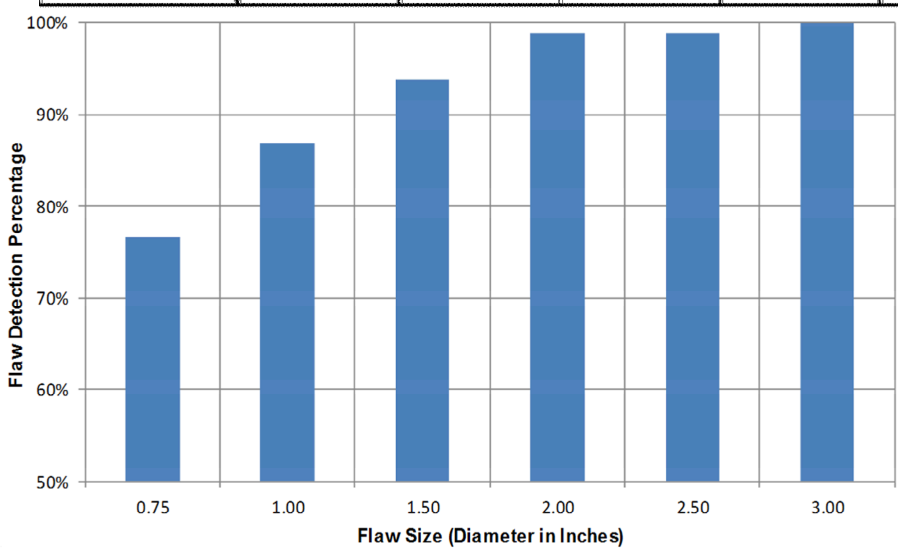
Overall Flaw Detection Percentage & Accuracy in Determining Flaw Size All Panels - 12 Inspectors - All Flaws (CT & CG)							
Accuracy in Sizing the Flaws That Were Detected (1546 Total Flaws Detected)						Flaw Detection Percentage (1704 Total Flaws)	
Flaw Size	5 (100%)	4 (76%-99%)	3 (51%-75%)	2 (25%-50%)	1 (< 25%)	Flaw Size	Percent Detected
0.75	42%	18%	16%	10%	15%	0.75	74%
1.00	35%	32%	19%	9%	6%	1.00	83%
1.50	24%	40%	19%	10%	7%	1.50	93%
2.00	22%	47%	16%	10%	4%	2.00	97%
2.50	20%	46%	22%	9%	4%	2.50	99%
3.00	16%	52%	13%	8%	12%	3.00	99%
Overall Sizing Performance	26%	40%	18%	10%	7%	Overall Flaw Detection	91%

Spar Cap with Shear Web and Box Spar Construction Types

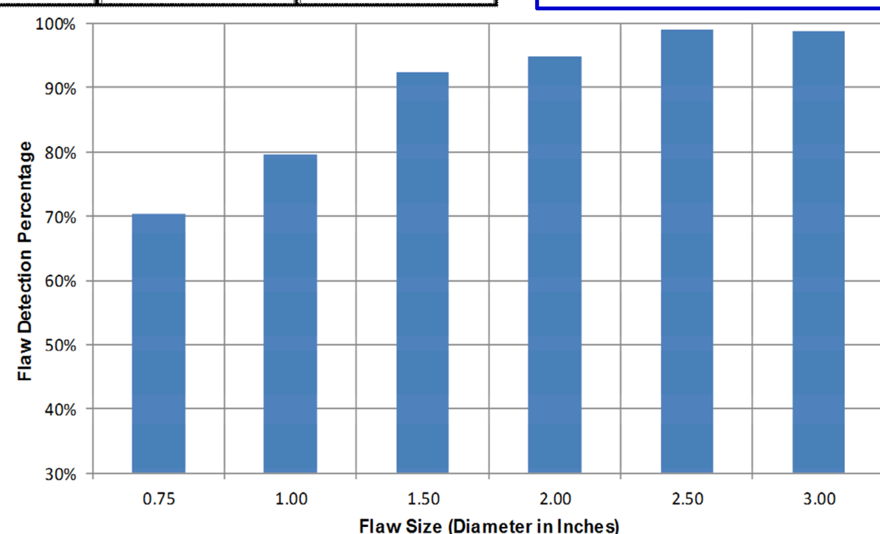
$POD_{90/95} = 1.334$

Spar Cap with Shear Web Construction Types

$POD_{90/95} = 1.208$



All Panels - Constant Thickness Flaws



All Panels - Complex Geometry Flaws

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Wind Blade Flaw Detection Experiment – Improvements Produced by Use of Advanced NDI

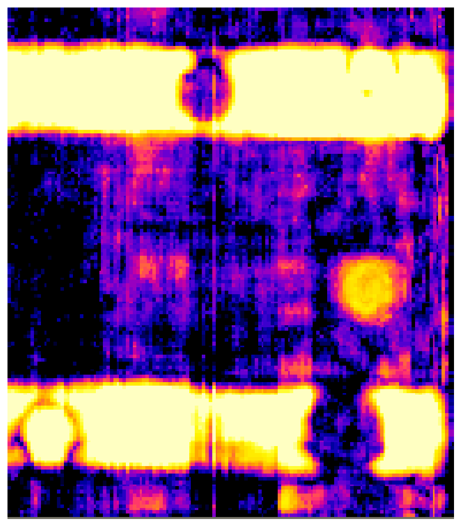
All Panels, All Flaw Types – Conventional NDI

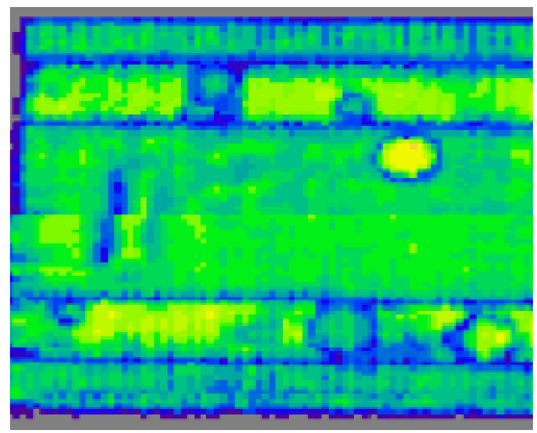
$POD_{90/95} = 1.333$

All Panels, All Flaw Types – Advanced NDI (sample)

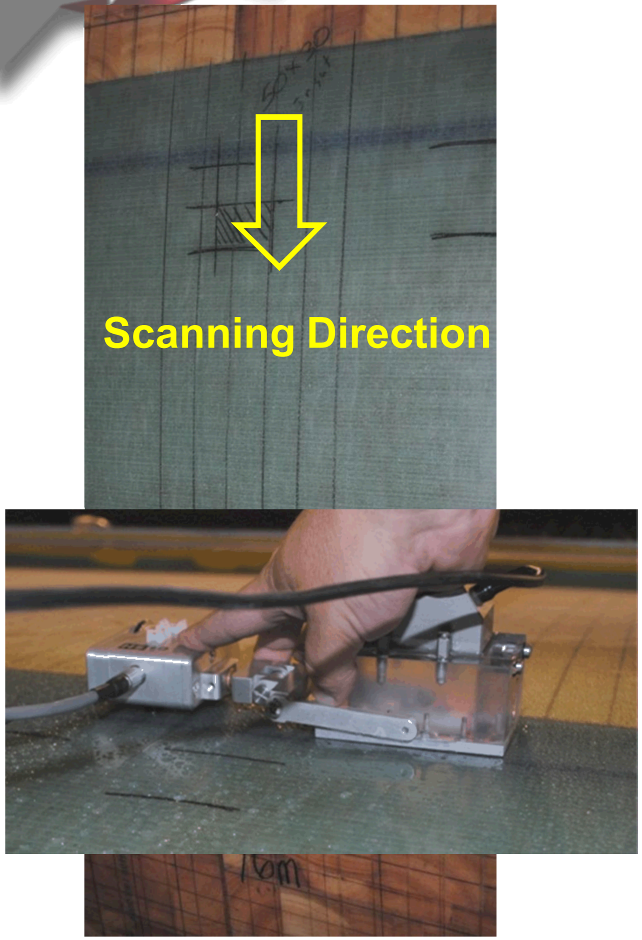
$POD_{90/95} = 1.105$

C-scan images produced by single-element ultrasonic scanner systems – easier to interpret data

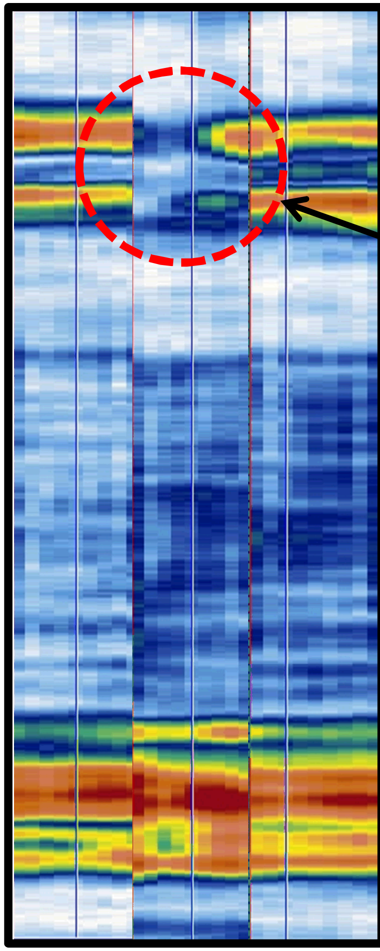




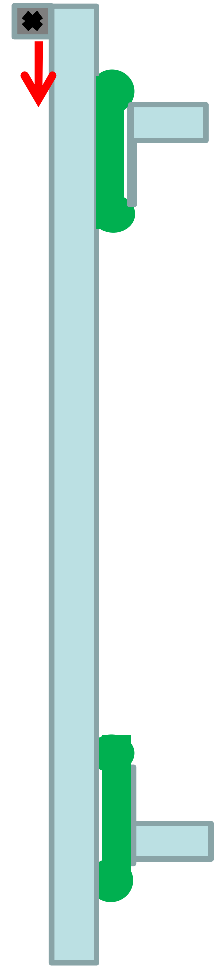
On-Blade Phased Array UT Inspections



16 Meter Station on Fiberglass Spar Cap Blade



Vertical Strip C-Scan Image Showing Adhesive Void in Upper Bond Line



Spar Cap Cross Section Schematic Showing the Spar Cap, Adhesive Bond Line and Shear Webs

Sealed water box and 1.5L16 Phased Array probe was used to detect missing adhesive in bond lines

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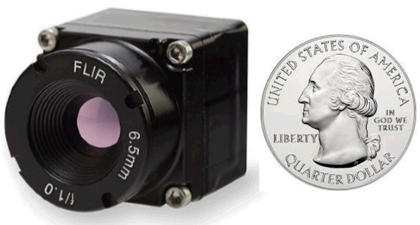
Wind Blade In-Service Inspection – Drone-Deployed NDI System

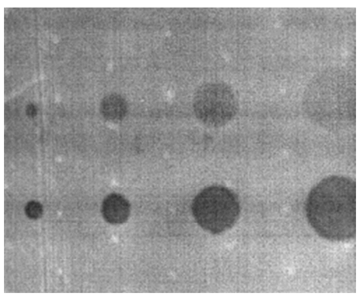
SKYSPECS

Thermography Inspection of Subsurface Flaws



Flir IR Camera (15 g)

(320 X 256 pixels)

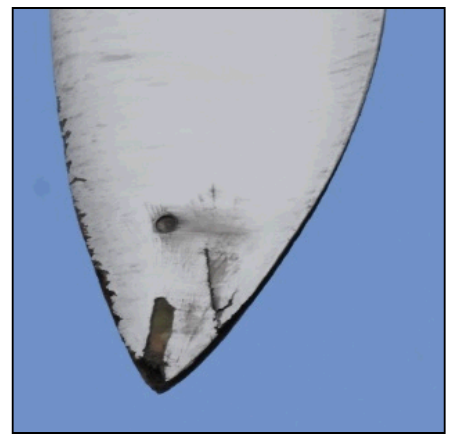


LiDAR and GPS Sensors & Computer for Automated Drone Controls

LiPo Batteries (2.3 Kg)

Visual Inspection of Surface Flaws

Digital Camera (450 g)



Drone Empty Weight = 10 lbs. (4.5 Kg)
Max Payload = 20 lbs. (9 Kg)

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Wind Blade In-Service Inspection – Drone-Deployed NDI System

SKYSPECS

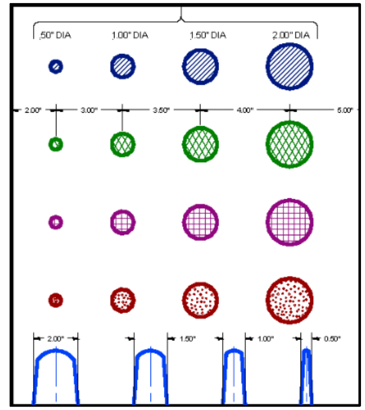
Thermal Wave Imaging

Solar Radiation Thermography

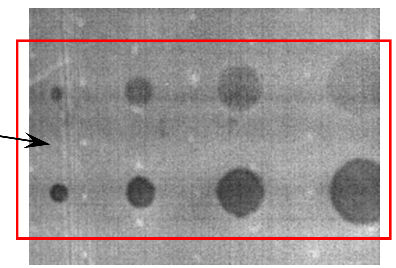
Heating: Blades Facing Sun

Cooling: Blades Facing Away from Sun

Foam Core with Fiberglass Skin

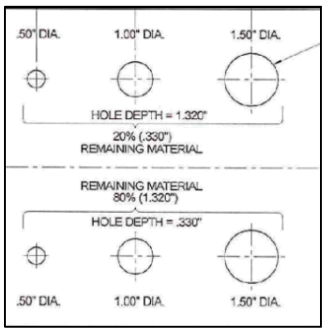


IR Images of Engineered Damage

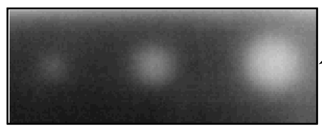


Heating Duration: 60s

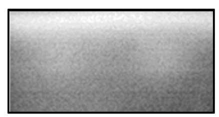
Thick Fiberglass Spar Cap



.330" Deep Flaws Clearly Visible



.660" Deep Flaws Barely Visible



Heating Duration: 120s

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Wind Blade In-Service Inspection – Drone-Deployed NDI System

Thermal Wave Imaging

SKYSPECS

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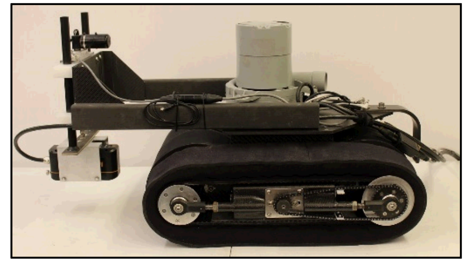
Wind Blade In-Service Inspection – Robot-Deployed NDI System



- Automated, remotely-controlled with wireless data transfer to ground station
- Includes Phased Array Ultrasonics for full-penetration damage detection
- Combined with high-fidelity visual inspection using deployed camera
- Real-time health assessment – allows for immediate repairs during a single maintenance stop and rapid return-to-service
- Benefits are escalated for off-shore applications
- Avoid more extensive repairs and even catastrophic blade failures (replacement)

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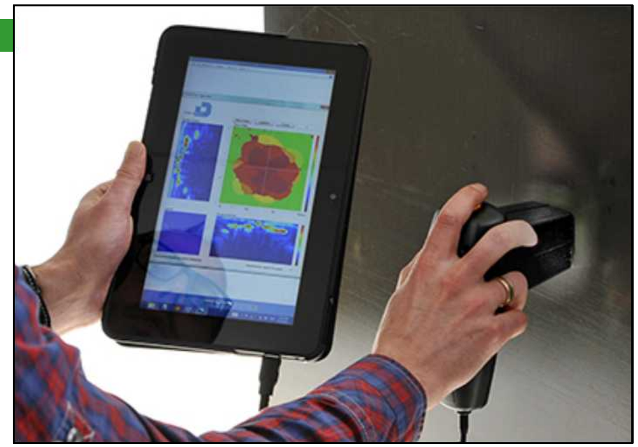
ICM INTERNATIONAL CLIMBING MACHINES



Robot with On-Board NDI System and Camera(s) for Real-Time Assessments

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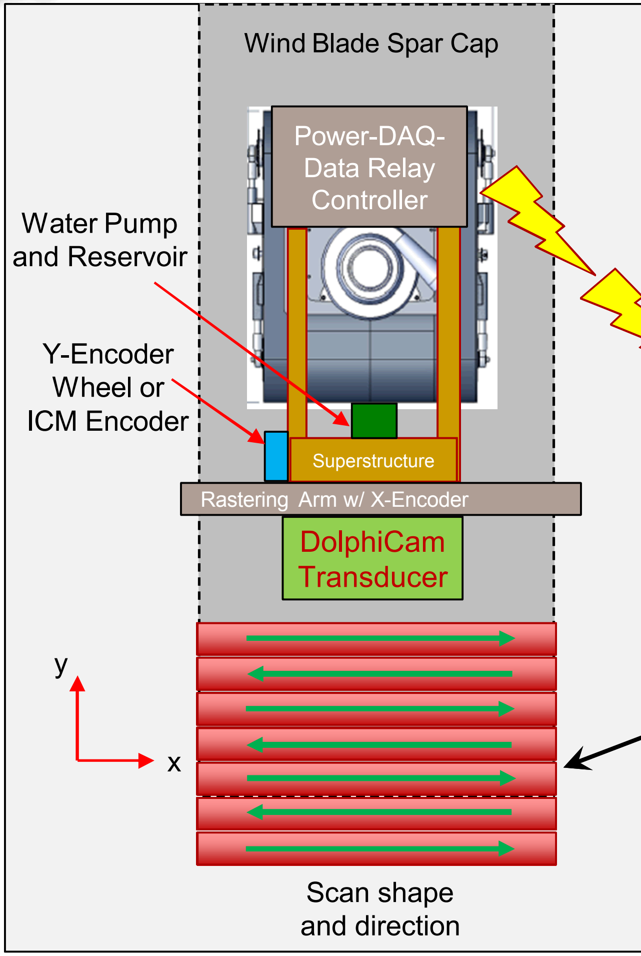
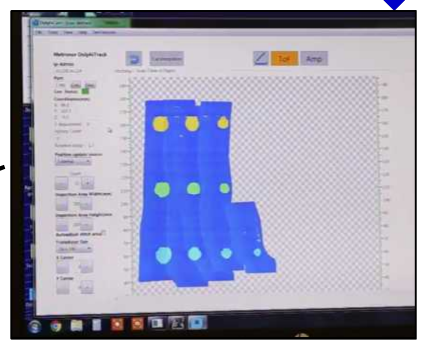
Wind Blade In-Service Inspection – Robot-Deployed NDI System

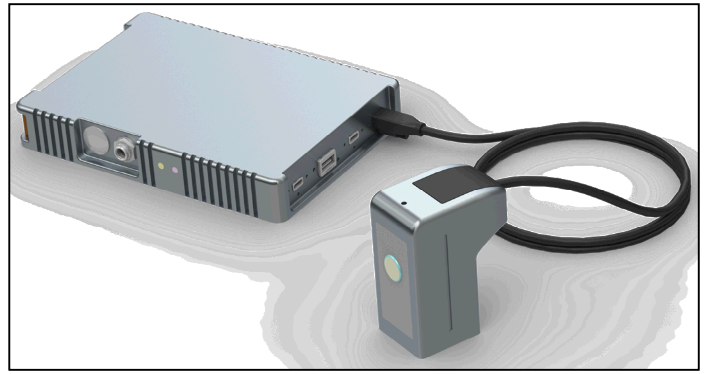


Real-Time Wireless Data Transmission

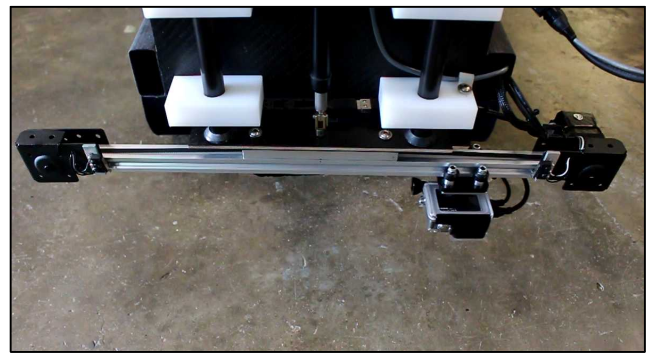
Laptop



Inspection Image



Low-Frequency Dolphi-Cam UT Imaging System with DAQ Box for Power and Real-Time Data Transfer



Raster Scanner on Robot

Robot increments in small Y step and then rastering arm on robot moves DolphiCam head in the X-direction. Repeat this process to produce a 2-D C-scan.

Wind Blade In-Service Inspection –
Robot-Deployed NDI System

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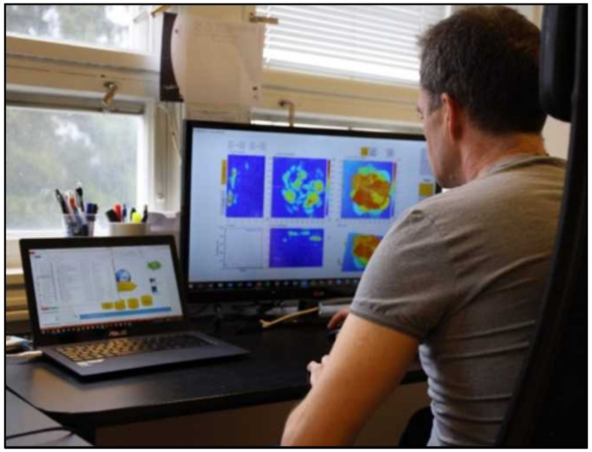
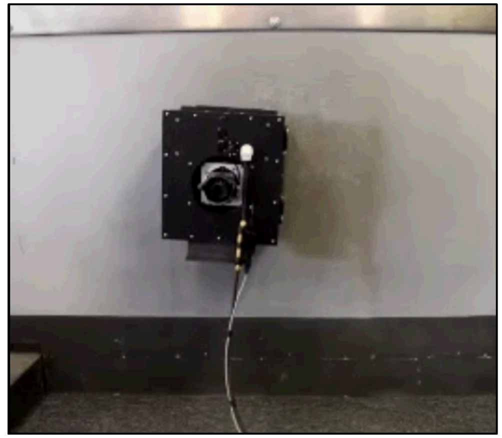
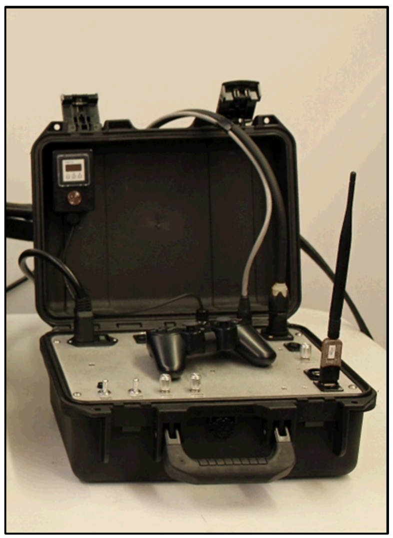
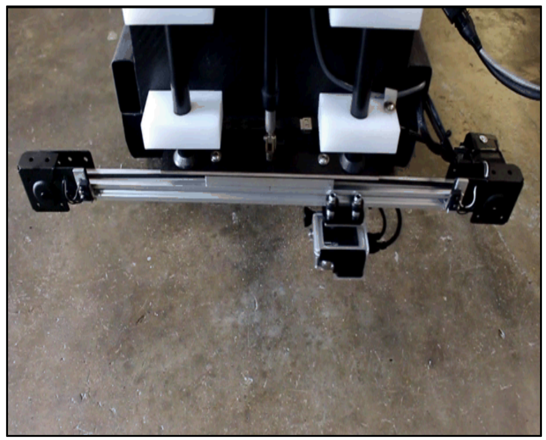


Ground Workstation – Data Acquisition & Analysis Plus Control of Robot

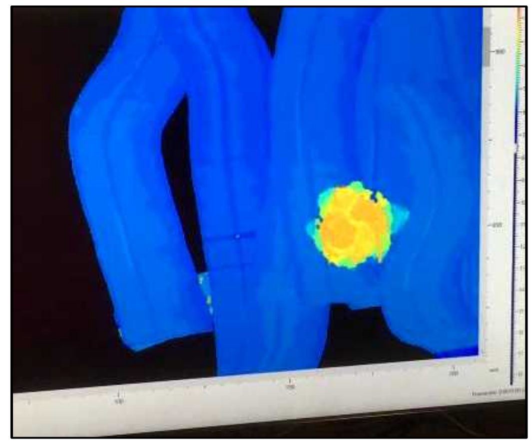


Robot Crawling on Vertical Surface





Raster Scan of Area



C-Scan Inspection Image

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ON-GROUND ⟵ ⟶ ON-BLADE

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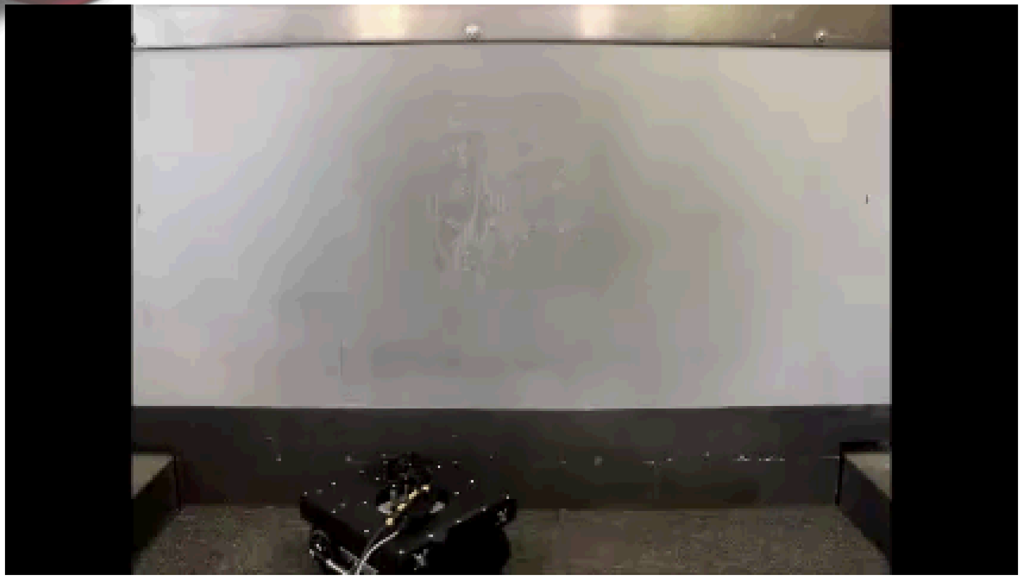
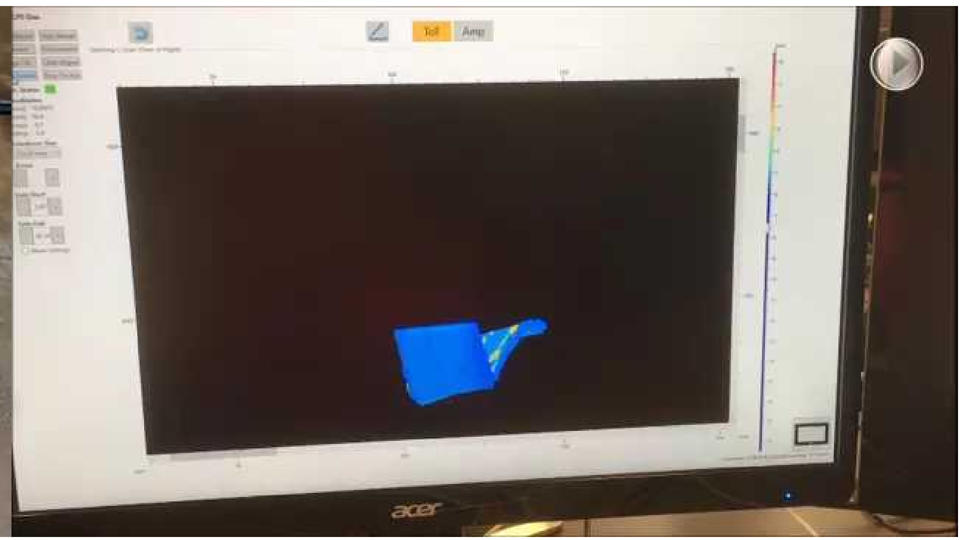
Wind Blade In-Service Inspection – Robot-Deployed NDI System



Robot Crawling on Vertical Surface

Raster Scan of Area to Produce C-Scan Inspection Image



Wind Blade Flaw Detection Needs – Role of Inspection in Production and Operation

- **Need for accurate NDI** becomes more important as the cost per blade, and lost revenue from downtime, grows
- **Many Inspection Challenges** - very thick and attentive spar cap structures, porous bond lines, varying core material & different manuf./in-service defects
- **NDI Practices Vary Widely** – differing levels of rigor & methods used
- **In-Service Inspection Needs** - damage from transportation, installation, stress, erosion, impact, lightning strike, and fluid ingress
- **In-Service Inspection Considerations** - NDI fidelity beyond what can be provided by visual methods is required; time, cost, & sensitivity needs (minimize production, maintenance and operation costs)
- **Sandia Labs NDI Evolution** – WBFDE quantitatively assessed performance of NDI to allow for optimum deployment of more sophisticated inspection methods; there are sensitive & rapid NDI options available
- Results can produce **improvements** in both **quality assurance measures during blade production** and **damage detection during operation** in the field - improve sensitivity, accuracy, repeatability & speed of inspection coverage
- Detection of fabrication defects helps enhance plant reliability while improved inspection of operating blades can result in efficient blade maintenance - **increase blade life; facilitate repairs before critical damage levels are reached and minimize turbine downtime**

Innovative, Efficient and Effective Methods to Address Wind Blade Production and In-Service Inspection Needs

Dennis Roach
Tom Rice
Ray Ely
Josh Paquette
Sandia National Laboratories

The need for viable, accurate nondestructive inspection (NDI) technology becomes more important as the cost per blade, and lost revenue from downtime, grows. NDI methods must not only be able to contend with the challenges associated with inspecting extremely thick composite laminates and subsurface bond lines but must also address new inspection requirements stemming from the growing understanding of blade structural aging phenomena. As the length of blades increase and more advanced materials are being used to manufacture blades, it has become increasingly important to detect fabrication defects during blade production - thus enhancing plant reliability - or the onset of damage during blade operation. The need for viable, accurate NDI technology becomes more important as the cost per blade, and lost revenue from downtime, grows. Thus, the need for in-service NDI of blades at wind farms is growing. Typical flaws encountered in wind blades include: disbonds, interply delaminations, dry or resin-starved regions, fiber misalignment, fluid ingress, porosity, voids, wrinkles, ply waviness, impact, erosion, lightning strike, snowflaking and installation damage. In addition, small defects can propagate to levels of concern during blade use while fatigue loading, impact, lightning strike and other in-service conditions can lead to new damage in the blades. Additional NDI fidelity beyond what can be provided by visual methods is required to identify and repair defects before they reach a critical size.

The goals of the Sandia Labs wind blade reliability program are to assess the performance of NDI as applied to blades during and after the manufacturing process, determine the level of inspection requirements and standardization within the industry, develop new and customized NDI methods to meet the inspection needs of the industry and work with blade inspectors to test and apply state of the art inspection techniques in manufacturing environments. This includes the possible introduction of automated inspections, a comprehensive assessment of various conventional and advanced NDI techniques in manufacturing environments, close interface with blade original equipment manufacturers (OEMs) to determine inspection requirements, and the completion of NDI technology transfer activities with the wind turbine blade industry. The benefit will be optimum deployment of automated or semi-automated NDI to detect undesirable flaws in blades before the blades enter service while minimizing the time and cost required to complete the inspections. Another objective of this program is to determine what NDI technologies are most promising for wind turbine blade inspections, assess and evolve those technologies, and transfer these new technologies to industry through inspection procedure development and inspector training. Sandia studies have revealed that enhanced NDI training, focused on the specific challenges of blade inspections can yield significant improvements in damage detection. Furthermore, Sandia has initiated programs to integrate drone and robot-deployed NDI in order to make full, through-thickness in-service blade inspections feasible, rapid and inexpensive.

The Wind Blade Flaw Detection Experiment (WBFDE) was conducted to study the capabilities and limitations of applicable NDI methods in identifying the different flaw types in wind blade construction. The general goal was to determine which NDI method(s) have high sensitivity, accuracy and reliability in order to facilitate improvements in both quality assurance measures during blade production and critical damage detection during operation in the field. This effort also identified the factors influencing composite wind blade inspections so that improved methods and procedures can be developed. These tests provided the Probability of Detection information needed to generate industry-wide performance curves that quantify:1) how well current inspection techniques are able to reliably find flaws/damage in wind structures, and 2) the degree of improvements possible through the integration of more advanced NDI techniques and procedures.

Under its Blade Reliability Collaborative program, Sandia Labs has developed and adapted customized pulse-echo ultrasonic inspection (UT) methods to optimize sensitivity and depth of signal penetration in large wind turbine blades. Specific hardware, system deployment and data analyses approaches were conceived to overcome the unique challenges associated with blade inspections. Some of the key items include optimized inspection frequency, use of focused transducers and focusing apparatus, use of compatible pulser excitations, use of data filters, transducer housing to improve signal coupling, and multiple gate settings to uncouple and identify signals of interest. These innovations optimize signal strength and clarity while allowing the user to focus on key signatures within the blade. This allows for interrogation of both the composite laminate structures and the bond lines below the spar cap and at the trailing edge. Automated and encoded phased array UT inspections were integrated to enable the production of two-dimensional, color coded C-scan images of wide area inspections. This feature improves probability of damage detection, minimizes false calls and improves overall health assessment efforts. Inspection procedures, necessary for the comprehensive and repeatable deployment of the UT technique, were also produced.

This paper will present the results to date from the Sandia Labs wind blade inspection program and describe how blade manufacturers and wind farm operators can optimally utilize NDI to enhance blade reliability. The detection of fabrication defects helps enhance plant reliability and increase blade life while improved inspection of operating blades can result in efficient blade maintenance, facilitate repairs before critical damage levels are reached and minimize turbine downtime. The optimum deployment of automated or semi-automated NDI to detect undesirable damage in blades will help the blades reach their design lifetime or beyond.

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