

Integrating Nondestructive Evaluation (NDE) into Modern Manufacturing

David Forsyth
SME Composites Forum
19 – 20 July 2022
Wichita, KS

What is TRI Austin?

- One of 8 companies owned by Texas Research International, Inc.
- About 40 engineers, scientists, technicians, and support staff.
- 40 years of contract research and development in materials and materials testing for government and commercial clients.

- I'm pleased to invite you to the Aerospace Composite Forum, produced by SME and NIAR and hosted by yours truly. The Forum will be July 18-20 at NIAR in Wichita KS. This is an invitation-only event **to talk about what's going on in aerospace composites and what the next decade looks like for the industry.**
- ...
- This will be two days of presentations on technical subjects such as **N**ondestructive evaluation (NDE), Next Generation Materials, Structural Design, Low-Cost Agile Manufacturing, Quality Assurance, Qualification and Certification, and Industry 4.0. In addition, there will be application-focused discussions on military aviation, commercial aviation, and Urban Air Mobility. The workshop will wrap up with a roundtable discussion, reviewing what was presented and reflecting on needs for future research.

How are we going to do this?

- Quick NDE refresher.
- NDE problems and possibilities.
- Digital transformation for NDE

- If you are building composite structures for aerospace, it's ultrasonics with full coverage.
 - Pulse echo
 - Through transmission
 - Air coupled
- Can be delivered many ways.
 - probe, array probe on robot in squirter or immersion
 - roller probe, dry “camera”, air coupled, laser...
- Thermography, shearography, tap test.

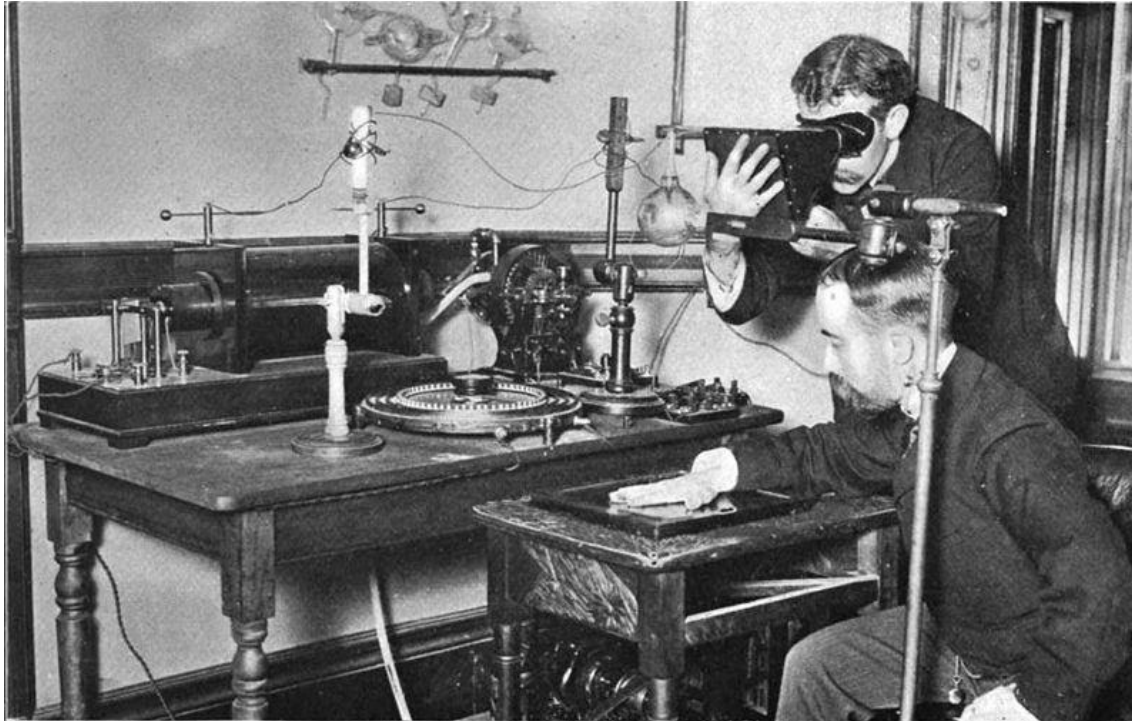
- Echoes! Reflections from changes
 - FOD, delam, disbond
 - Porosity
 - Bonds
 - Layers in composite
- Time of flight \sim thickness, density, modulus



How are we going to do this?

- Quick NDE refresher.
- NDE problems and possibilities.
- Digital transformation for NDE.



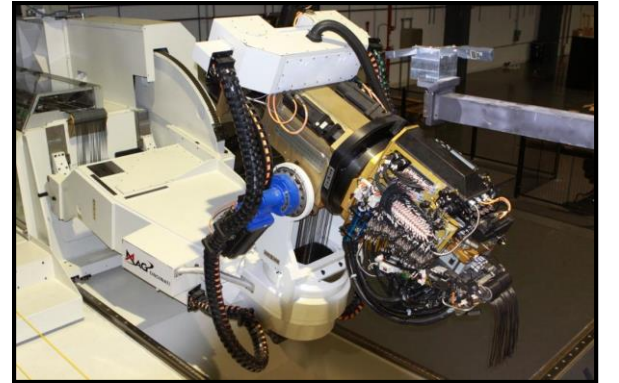



William J. Morton and Edwin W. Hammer (1896) The X-ray, or Photography of the Invisible and its value in Surgery, American Technical Book Co., New York, fig. 54

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Courtesy of HITCO
CARBON
COMPOSITES, INC

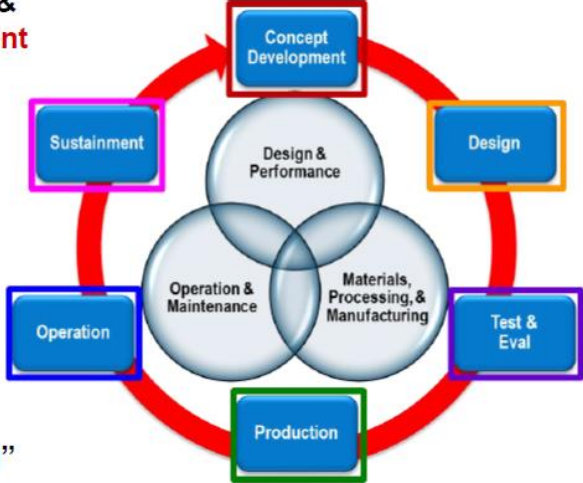




Digital Thread Vision: *Life Cycle Information Assurance*




- Develop preliminary models & req'ts in **Concept Development**
- Develop detailed “as designed” models & req'ts in **Design**
- Validate/calibrate in **Test & Evaluation**
- Update using “as built” data from **Production**
- Update using “as flown” data from **Operation**
- Update using “as maintained” data from **Sustainment**

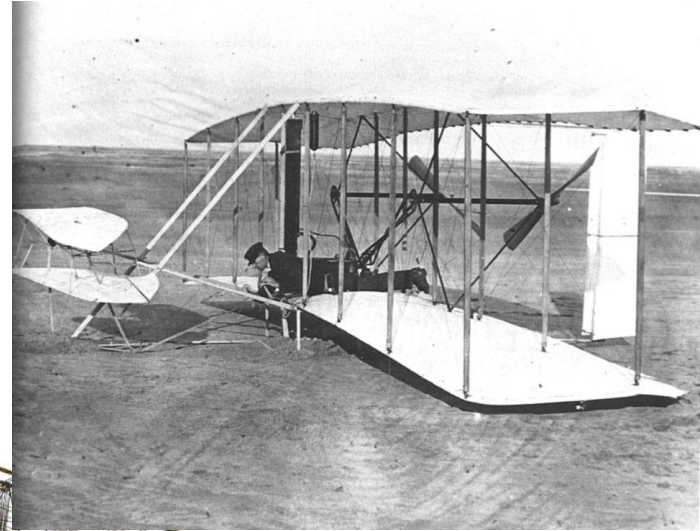
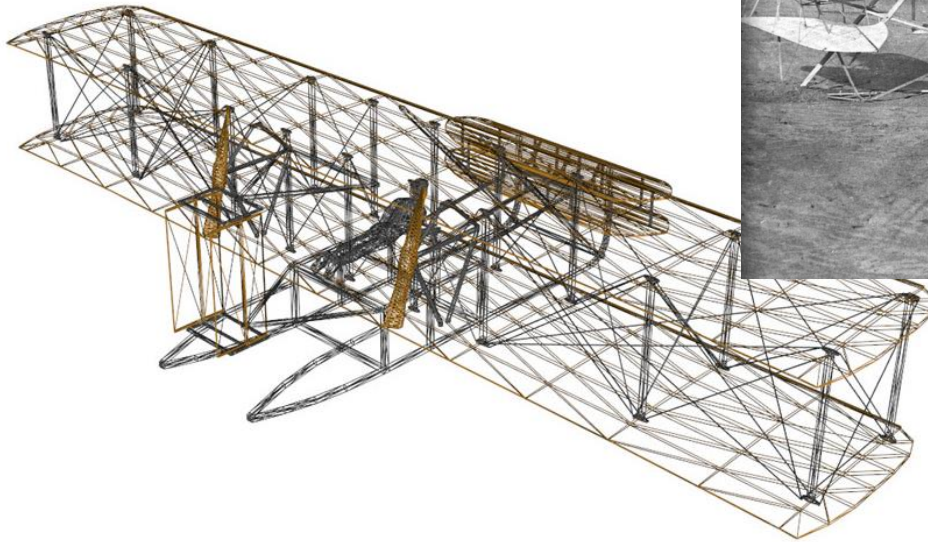


The **Digital Thread** is BIG DATA for Engineering

Distribution A. Public Release, distribution unlimited. 88ABW-2015-0845, 5 Mar 15.


4

- We have digital plans...



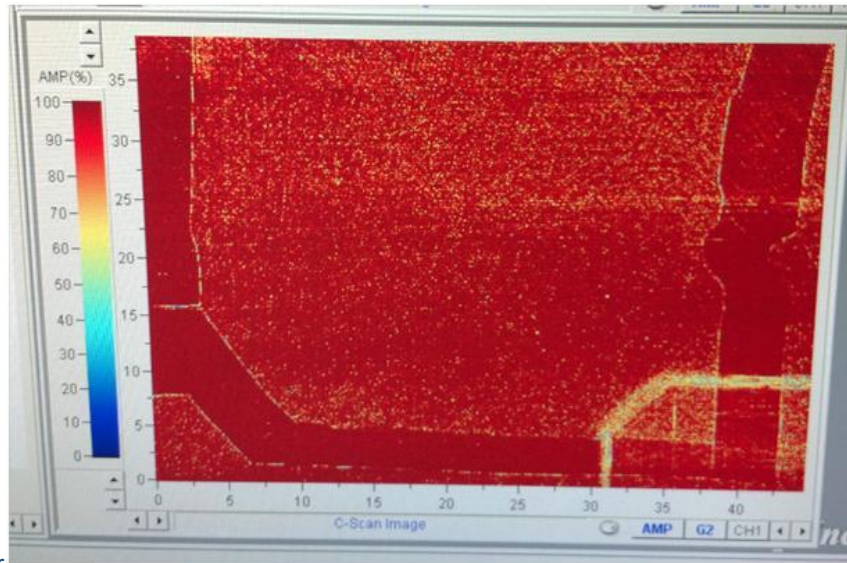
- We have machines that can build from digital plans...



- We have inspection systems that provide digital data...



- Digital thread right up to the point where we get digital NDT data like this...



Digital Thread stops at the Level III

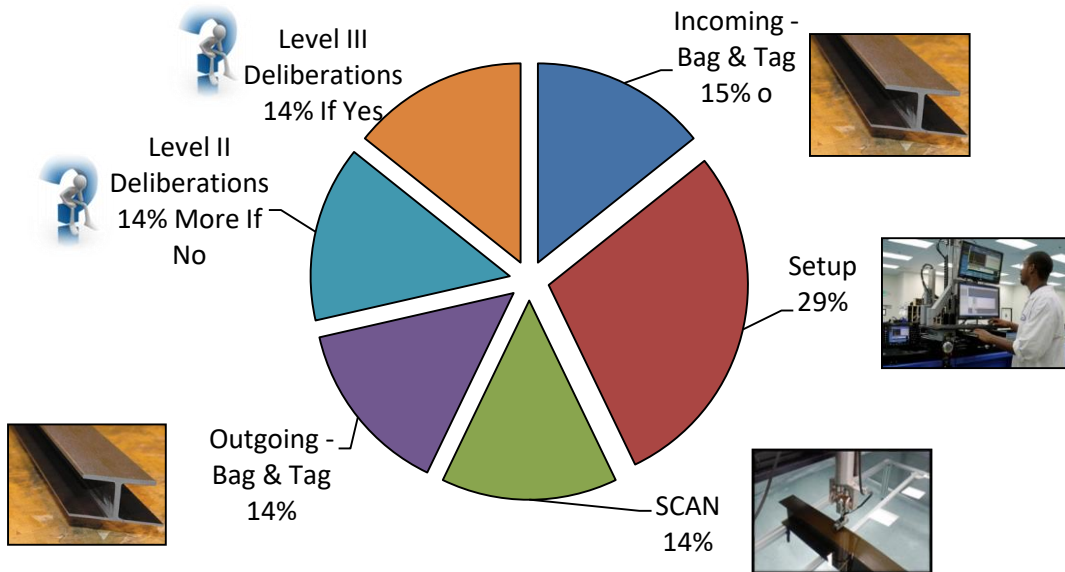


➤ 210 minutes

✓ if Level II deliberations identify that a Beam meets part qualification criteria.

➤ 240 minutes if Level II deliberations identify that a Beam does not meet part qualification criteria.

✓ This additional to validate deliberations basically scraps the part or puts it on hold..



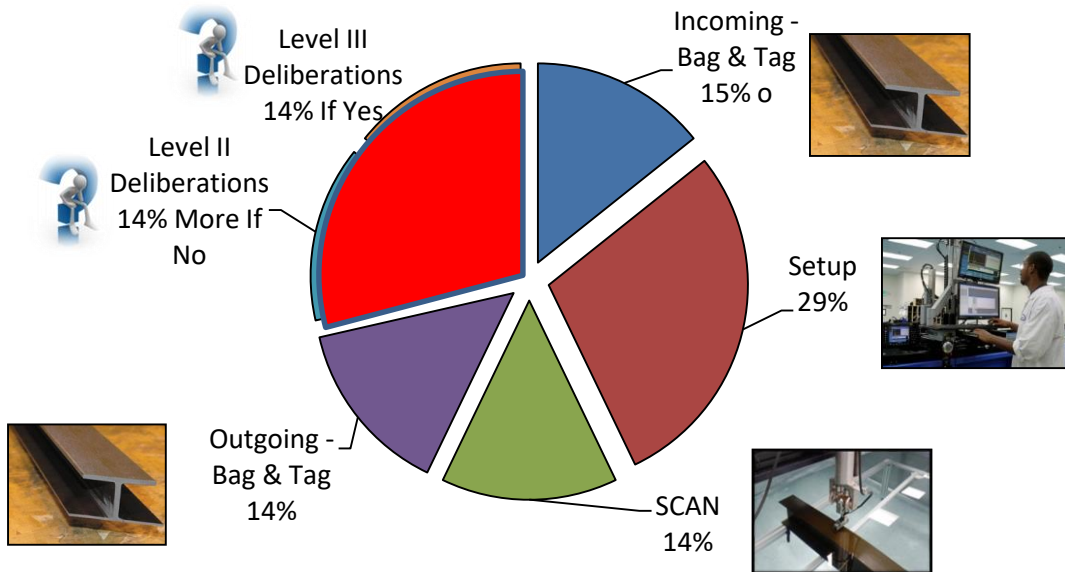
Courtesy of HITCO
**CARBON COMPOSITES,
INC**

➤ 210 minutes

✓ if Level II deliberations identify that a Beam meets part qualification criteria.

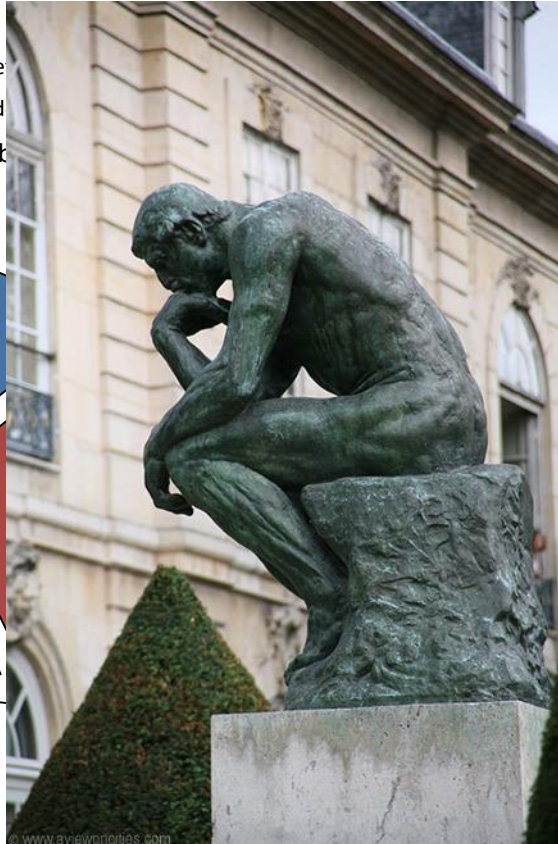
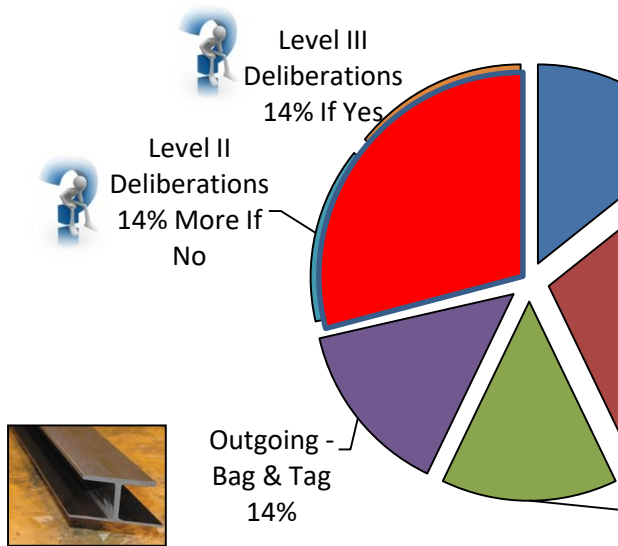
➤ 240 minutes if Level II deliberations identify that a Beam does not meet part qualification criteria.

✓ This additional to validate deliberations basically scraps the part or puts it on hold..



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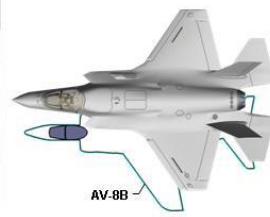

- 210 minutes
 - ✓ if Level II deliberations identify that a Beam mee
- 240 minutes if Level II deliberations identify that a Beam d
 - ✓ This additional to validate deliberations k



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 INC**



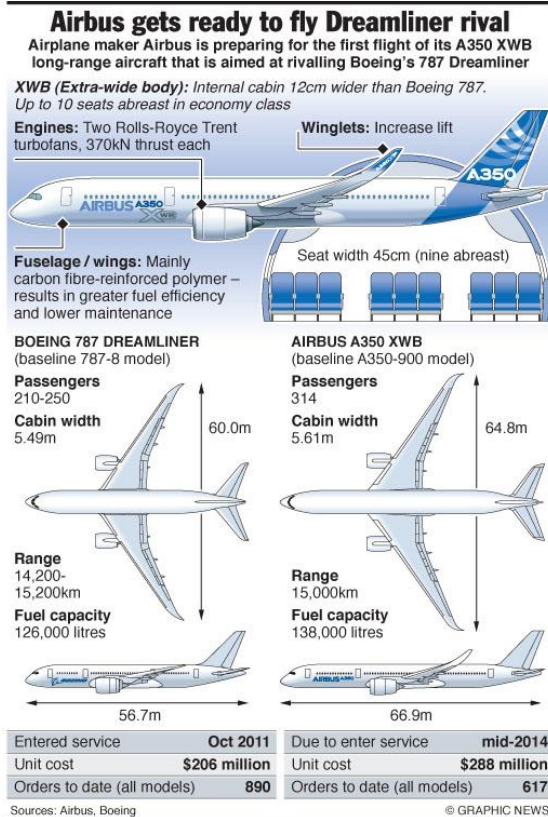
Configuration 240-4

CTOL	STOVL	CV
		
Span (ft) 35 Length (ft) 51.4 Wing Area (ft ²) 460	Span (ft) 35 Length (ft) 51.1 Wing Area (ft ²) 460	Span (ft) 43 Length (ft) 51.4 Wing Area (ft ²) 668
		
Weight Empty (lb) 29,036* Internal Fuel (lb) 18,480	Weight Empty (lb) 32,161* Internal Fuel (lb) 14,003	Weight Empty (lb) 32,072* Internal Fuel (lb) 20,085
All Mission Fuel Internal -- Very large Fuel Fraction Support Extended Range Requirements In VLO		

DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

F-35 public information:

- 2mm scan spacing = 25 scan points per cm²
- 668 ft² = 620,000 cm²
- For each of upper and lower wing, evaluate 15 million A scans
- Add in some covers and empennage and etc.
- **Maybe 40 million ultrasonic signals**



- 2mm inspection spacing = 25 per cm²
- Wing area approximately 5.4 x 10⁶ cm²
- For each of upper and lower wing, evaluate 135 million ultrasonic A scans
- Add in some covers and empennage and etc.
- **Maybe 300 million ultrasonic signals per aircraft**

- Inspectors only review a fraction, selected C scans out of the data set.
- Most of the data is good.
 - Large, monocoque structures are easy!
- So what does science tell us about this type of inspection situation?

U.S.

Head of T.S.A. Out After Tests Reveal Flaws

By JADA F. SMITH JUNE 2, 2015

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WASHINGTON — The [Department of Homeland Security](#) on Monday reassigned the acting director of the [Transportation Security Administration](#) and ordered the agency to revise its security procedures after screeners at airport checkpoints failed to detect weapons and other prohibited items 95 percent of the time in a covert test.

Jeh Johnson, the secretary of Homeland Security, which oversees the T.S.A., said that he took the findings of the investigation by the department's inspector general "very seriously." He called on the T.S.A. to retrain [airport security](#) officers, retest screening equipment and increase its use of covert testing in airports.

In the investigation, undercover agents were able to get prohibited items through security checkpoints in 67 of 70 instances, according to ABC News, [which first reported the findings](#).

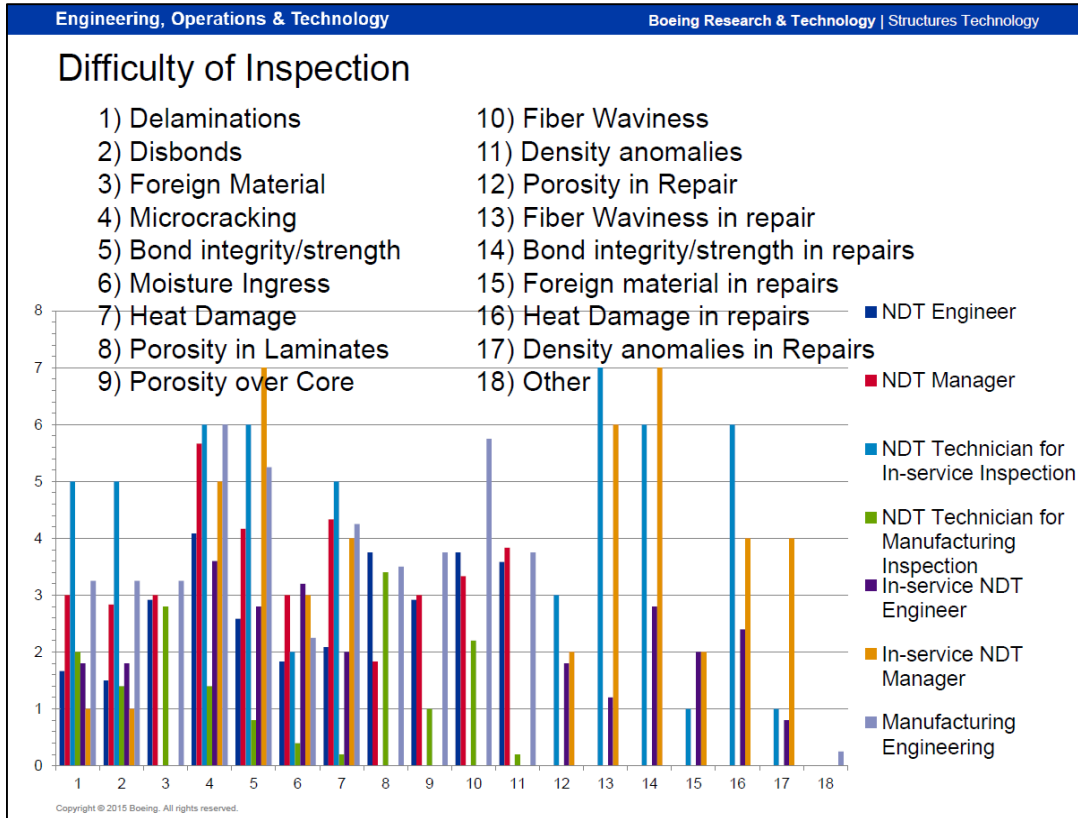


Engineering, Operations & Technology
Boeing Research & Technology

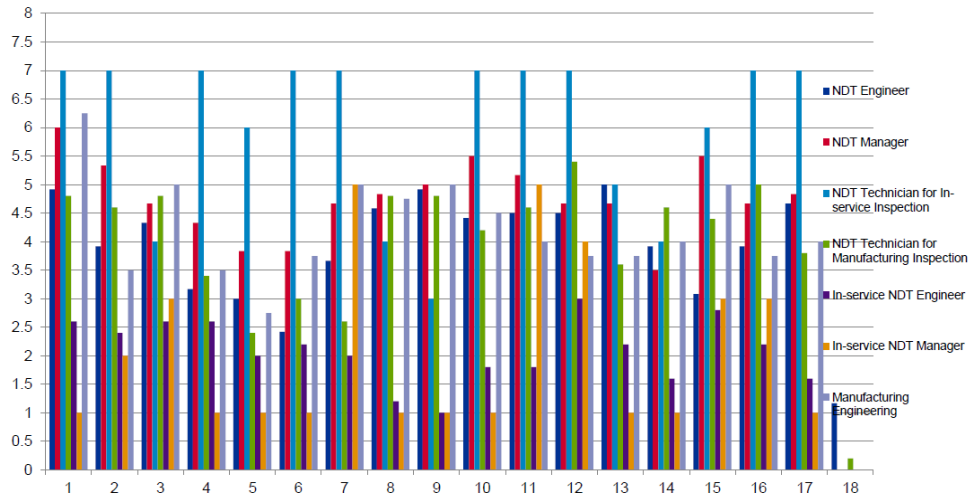
NASA Composites NDE State of Practice Survey

Gary Georgeson
Morteza Safai
Boeing Research & Technology
Gary.e.georgeson@boeing.com

April 10-14, 2016
ASNT Spring Research Symposium
New Orleans, LA



Where is further development needed, according to those working fabrication issues?



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Some Insights/Recommendations

- **Composite manufacturing methods could benefit significantly from post-fabrication and in-process automated NDT processes**

What does inspector deal with?

- Robotics, sensors, signal path, data acquisition, inspection techniques, standardization, CAD, M&P, probability of detection, defect characterization.

What are minimum education requirements for an ASNT Level 3?



- Minimum education is zero.
 - On the job training plus pass the exams.
- Inspectors rely on the vendors for equipment expertise.
- Inspectors rely on the M&P people for relevant M&P information and defect criteria.
- Do you have engineering support? Does your engineer have background in NDE?



Definition of new NDE roles

			
<p>System developer</p>	<p>Caretaker</p>	<p>Decision maker</p>	<p>User experience (UX) designer</p>
<p>Dictates strategy Develops the system and integrates it with other systems Defines performance metrics Responsible for reliability</p>	<p>Oversees the functioning of the system Notices failures Undertakes measures to repair or adapt the system Responsible for the day-to-day deployment and operation of the system</p>	<p>Strategic decision maker and flexible problem solver Know-how to diagnose more substantial problems in the systems use or to offer further explanation of the results and their meaning High flexibility and adaptability to continuously changing conditions.</p>	<p>Creates the user interface and dictates user experience Carried out by a multidisciplinary team (engineer, IT expert, designer, UX expert)</p>

*Berovic, M., & Vrkkunen, I. (2021). In review). NDE 4.0: New paradigm for the NDT Inspection Personnel. Handbook of NDE 4.0. Springer.

- NDE data proprietary.
 - Vendors want all your business.
 - Pick best?
 - Supplier audits?
 - Data analytics?
- With ISU CNDE we have written a specification and provided code to support an open NDE data file format.

- Composites manufacturing evolving.
 - OOA material systems have more porosity.
 - Built up structures: too expensive to scrap.
 - Need better NDE information to do better repair
 - Built up structures, curvatures, joints are harder to inspect.

How are we going to do this?

- Quick NDE refresher.
- NDE problems and possibilities.
- **Digital transformation for NDE.**

- Initial development and validation via simulation
- Rapid prototyping
- UT full matrix capture and post processing
- Intelligence Augmentation during inspection
- Assisted Defect Analysis post inspection
- Digital handoff to engineering

- Commercial software tools can be used to predict coverage for UT, RT, ET.
 - Am I getting sound everywhere, and I am getting sound BACK from defects?
 - High fidelity modeling of arbitrary defects in 3D in PMC's is not mature.



Model Driven Development and Validation of Nondestructive Inspection

David Forsyth, John Aldrin, Mark Warchol, Lyudmilla Warchol, Jennifer Flores-Lamb, Ajay Shah,
John Nagel, Sarah Williams, Kaleb Liburd

2021 Aircraft Structural Integrity Program (ASIP) Conference,
November 21 – December 2, 2021
Austin, TX

Distribution A Approved for public release; distribution unlimited.
Case Number: AFRL-2021-3979.

Nondestructive Evaluation | Advanced Sensing | Materials Characterization | AI / ML

Probe: 5MHz, Incident Angle in H2O 45°

Observations: No defect

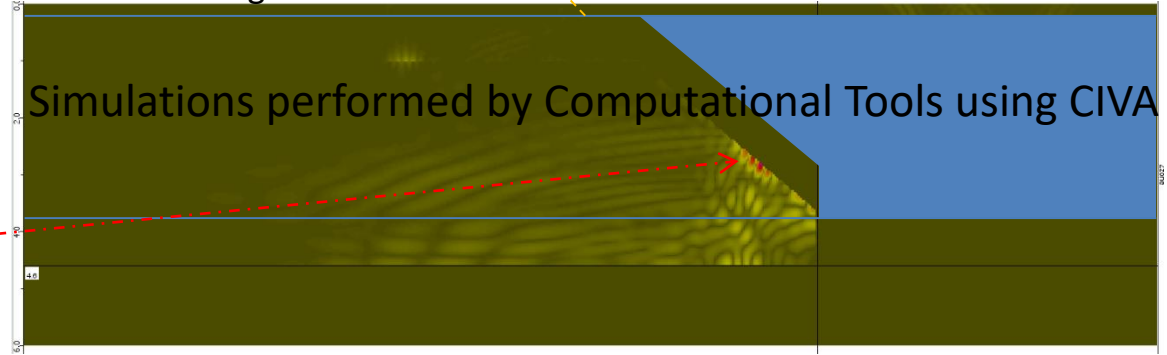
- qS mode wavespeed close to water (~1800 m/s compared to 1483 m/s)
- qS wave deflection not perpendicular to propagation path (anisotropy)
- Surface wave generated and scatters from countersink corner with hole
- Far corner reflection observed following countersink corner signal

Observations: Hidden delamination

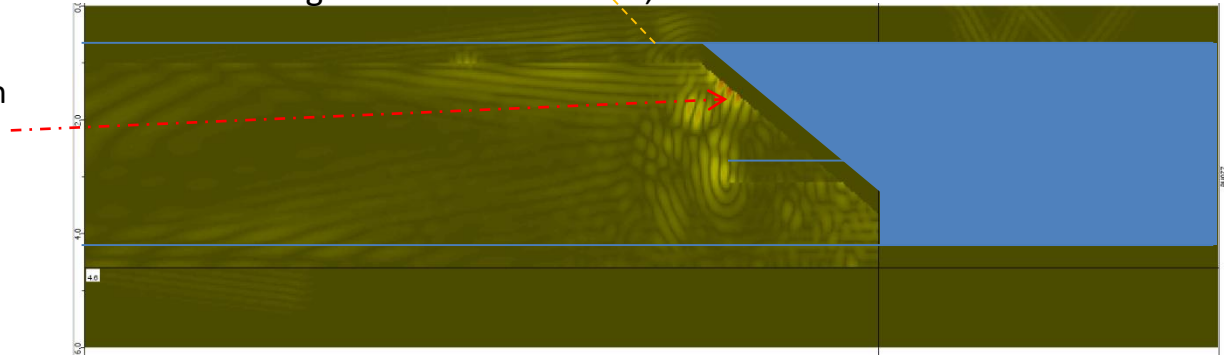
- Delam. produces early reflection (both specular and corner diffraction) before countersink corner(s)
- Delam. also blocks later hole corner reflection signals

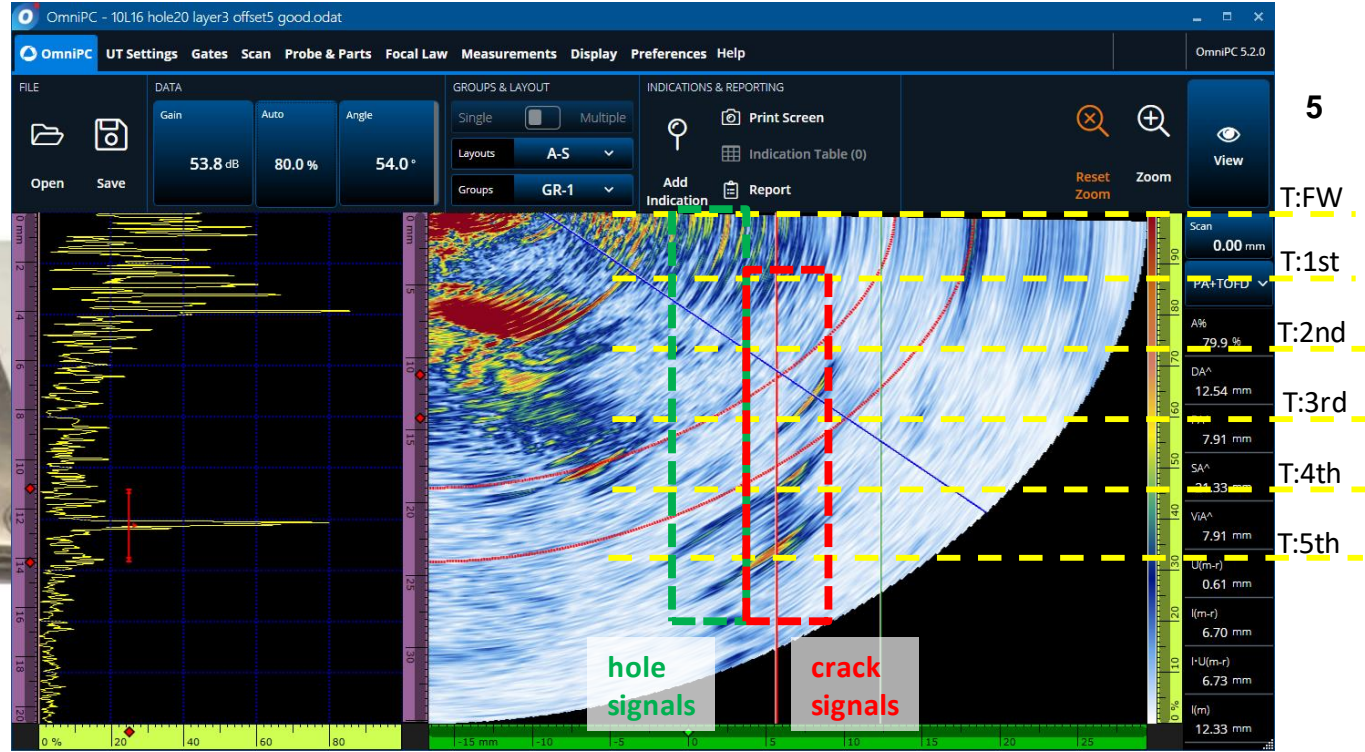
Time: 16.88 μs

Wavefield image - no hidden defect



Wavefield image - with 2 mm delam., 2.1 mm from surface

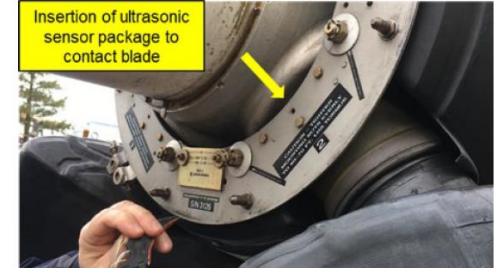






On-Wing Inspection Development

- ISO level inspection needed to detect cracks on-wing
- Limited access (spinner removal only), and blade rotation (≤ 100 degrees)
- Developed multi-element ultrasonic transducer
- Standalone self contained kit employs field available ultrasonic instrument
- Requires blade cleaning
 - 2 stage cleaning kit developed
- System features:
 - 6 elements, captured water column w/ flex. membrane
 - Novel reflector design monitors coupling
 - Couplant supplied through custom pressurized system
 - Sequencer allows for use on single channel instrument



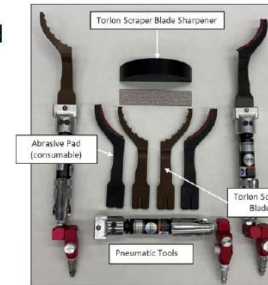
Delivering Comprehensive Inspection Solutions for the C-130 Propeller

ASIP Conference 2021

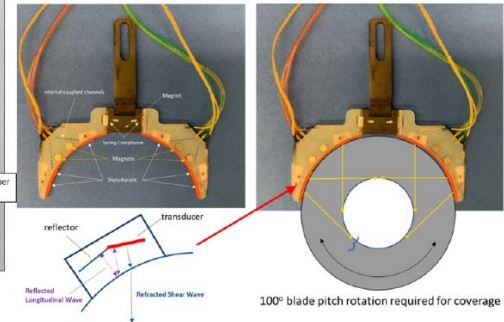
Ryan Mooers¹, John Brausch¹, Ken LaCivita¹,
Nicholas Bunnell², Mike Fisher³

¹Materials Integrity Branch, System Support Division
Materials and Manufacturing Directorate
²NDI Program Office, Warner Robins Air Logistics Complex
³C-130 Engineering, Warner Robins Air Logistics Complex

Distribution Statement A: Approved for Public Release. Unlimited Distribution. Case Number: AFRL-2021-4096



Cleaning Tools



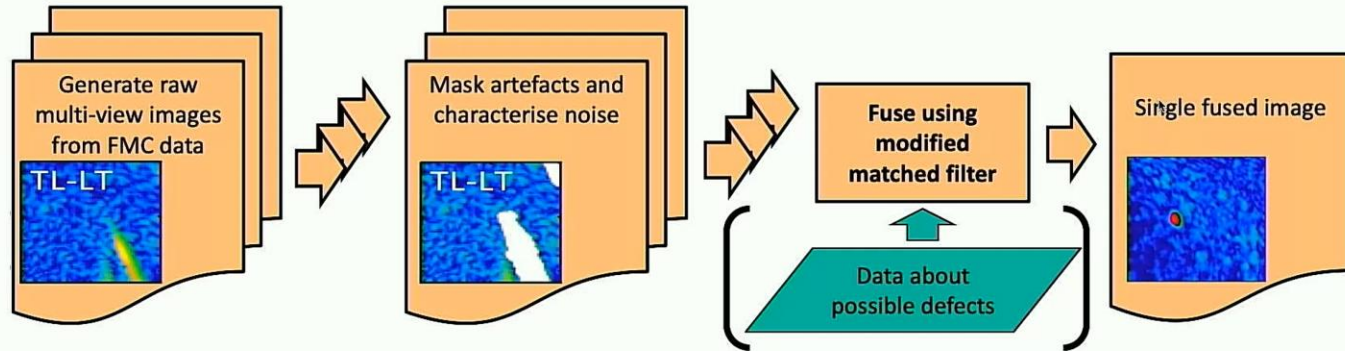
THE AIR FORCE RESEARCH LABORATORY

Distribution Statement A: Approved for Public Release. Unlimited Distribution. Case Number: AFRL-2021-4096

19

Multi-view imaging

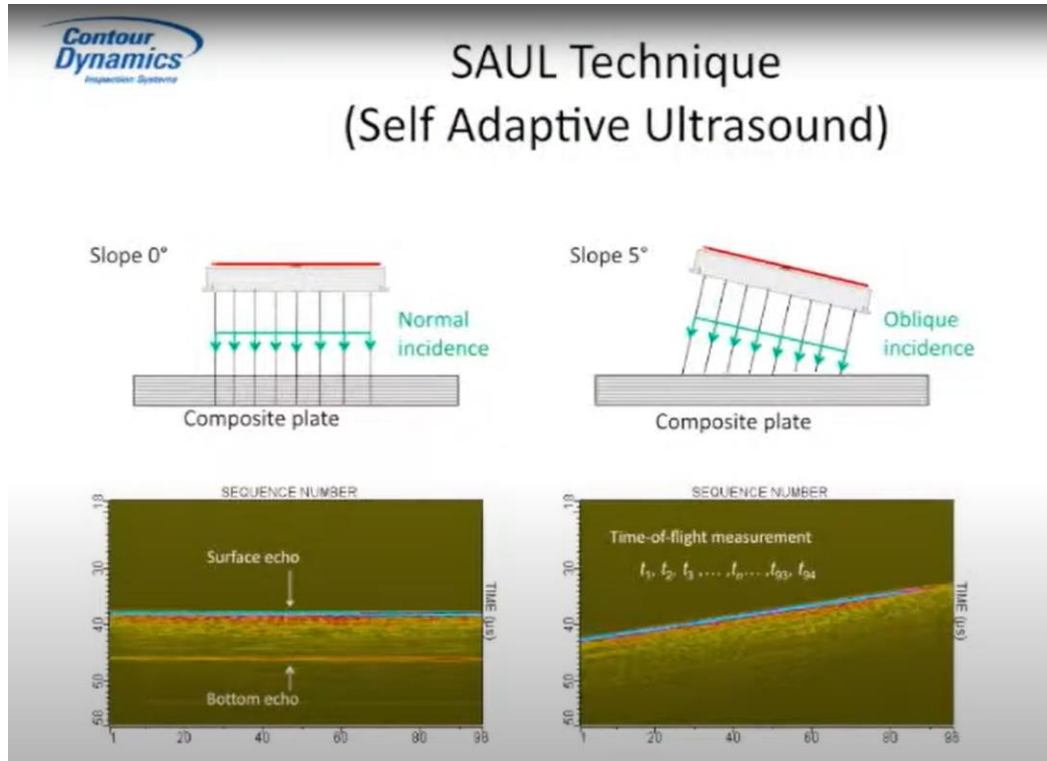
- Workflow – fuse images using statistical method to maximise sensitivity



bristol.ac.uk

ndtatbristol.com

Paul D. Wilcox, "Computational ultrasound: how arrays and data are reshaping ultrasonic NDE," Proc. SPIE PC12047, Nondestructive Characterization and Monitoring of Advanced Materials, Aerospace, Civil Infrastructure, and Transportation XVI, (18 April 2022); <https://doi.org/10.1117/12.2622246>



<https://www.tdnde.com/about-us/>

- “Intelligence Augmentation” is the term for a variety of possible technologies that can be used to help the inspector.
 - Correct instrument settings.
 - Correct calibration.
 - Go to the right location.
 - Data was collected and is good.



Integrating NDI into the ASIP

David Forsyth¹, Satish Rajaram¹, John Aldrin², Doyle Motes¹, John Nagel¹
1. TRI Austin, 2. Computational Tools

2021 Aircraft Structural Integrity Program (ASIP) Conference,
November 21 – December 2, 2021
Austin, TX

DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited. Case Number: AFRL-2021-3980

Nondestructive Evaluation | Advanced Sensing | Materials Characterization | AI / ML

Inspection Assist Tools

- **Input Data Structure(s):**
 - Inspection Panel View
- **GUI Interface:**
 - Interactive CAD View
 - Linked photos of inspection sites
 - **Presentation of Workflow**
 - **Inspection Steps**
 - **Support Documentation**
 - NDI Results - View
- **Output Data Structures:**
(Inspection Results / Reporting)

The screenshot displays the NDI Assistant software interface. On the left, a vertical navigation pane includes 'Pick a File', 'Calibration', 'Inspection', 'Inspection Capture', and 'Inspection Model'. The main area is divided into several sections:

- Inspection:** Shows a grid of points with a yellow dot indicating the current location. Bolt Selected: 1-79.
- Supporting Images:** A large image showing a close-up of a bolted joint with annotations. Text overlays include 'Partially Covered by Panel', 'Fasteners: 1-79; 22, 23, 24, 29 & 30 Blocked by Wire Bundle', and a distance measurement of '≈ XF 104.00'. A scale bar at the bottom right indicates '1:33.1 (1:25.3 - 34. & 62)'. Navigation arrows are visible on the left and right sides.
- Bolt Information:**

Coordinates: (-104.2, 58.6)
 Hole Diameter: 0.625
 Layer Thickness: 1.4200000000000000
 Layer Seq: T1/T1/T1/T1
 Available Pics: 5
- Inspection Step: 3:**

Locate Fastener Site and Verify Dimensions
 If Different ... Retest Standard with Matching Case - Verify Hole Signal(s)
 If Different ... Retest Standard with Matching Case - Setup for Notch Signals
 Fastener Site - Acquire Hole Signals and Calc. Gain Correction
 Fastener Site Inspection - Guide User on Distance
 Complete Report Documentation for Fastener Inspection
- Evaluate Hole Signal Reference Response:**

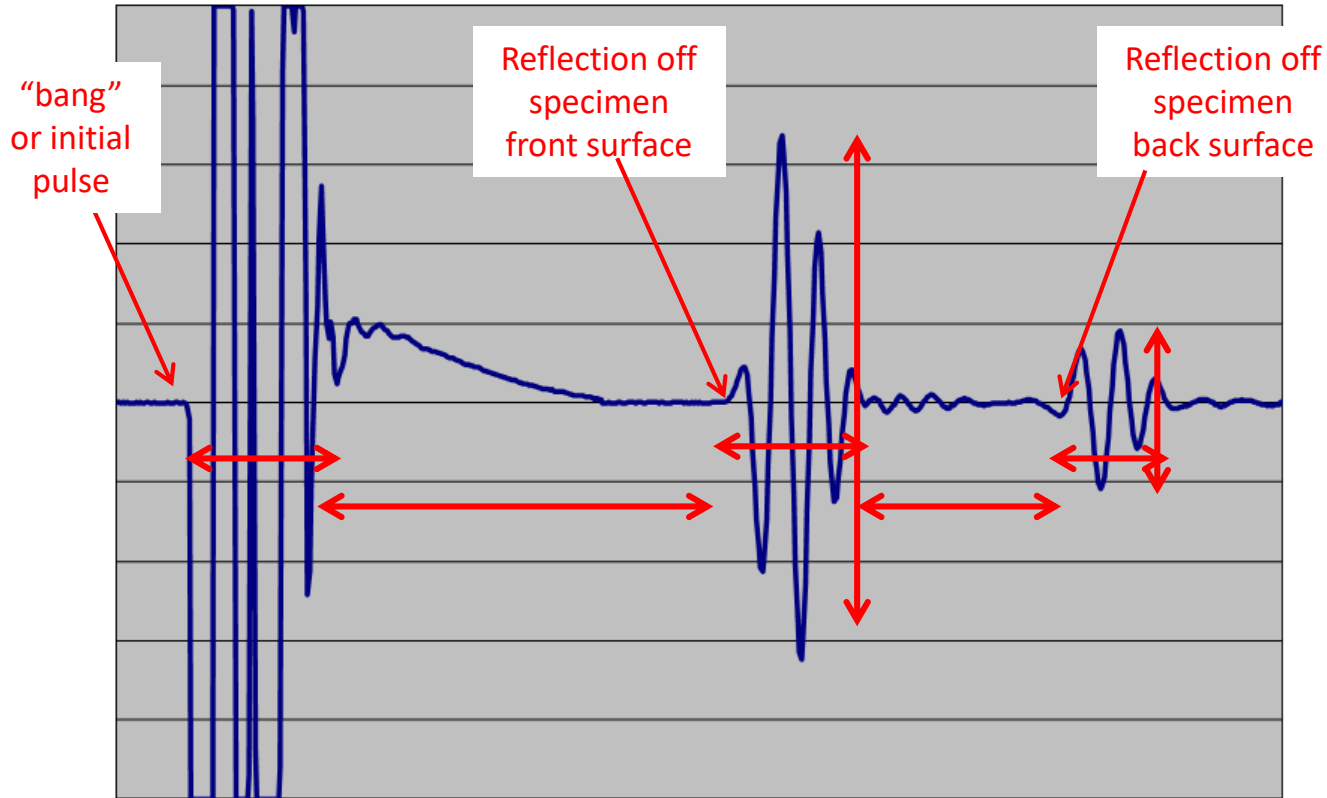
From TO-338-1-1

Place the transducer back on the reference standard to obtain the signal from the saw cut. Increase the gain until the signal is at some convenient level, for example, 80-percent of saturation. At this gain 20-percent of full scale would be the rejection level, since any signal exceeding 25-percent of the saw cut signal is cause for rejection

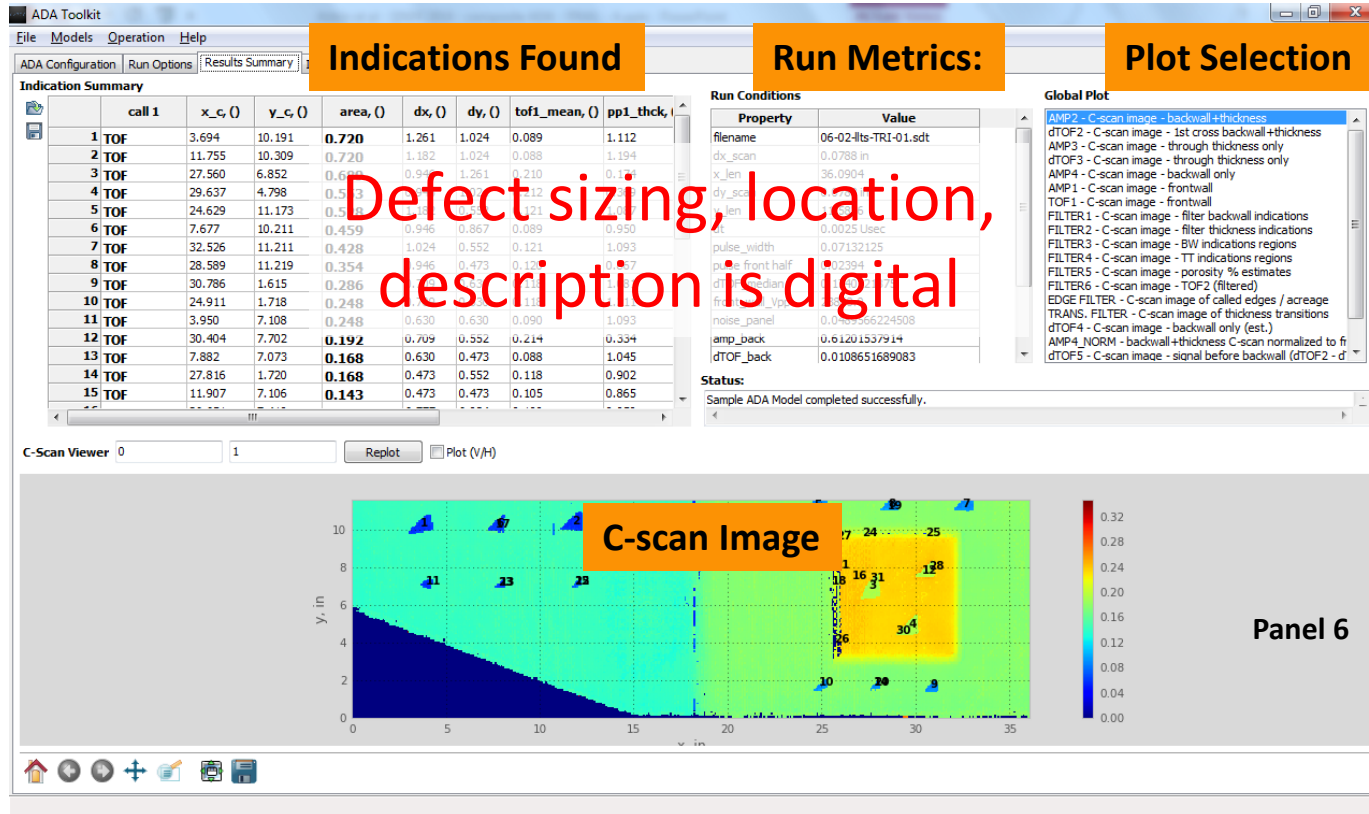
E. Gain Settings for Threshold Call			
Cal. setting for peak (full skip) hole signal	50.0	%FSH	(FSH = Full Screen Height)
Measured %FSH skin (full skip) hole signal		%FSH	
Hole signal correction factor			
Cal. setting for peak (full skip) flaw signal	80.0	%FSH	
Threshold for flaw detection call	20.0	%FSH	
Corrected threshold for flaw call			
- Report User Interface:**
 - To Inspect
 - No Indication
 - Indication Found
 - Uninspectable Site

A yellow box in the center of the interface contains the text: "Inspection Steps with Support Images / Videos".

- ADA, ADR, ...
- TRI Austin and Computational Tools philosophy is to use ADA to find indications
 - Pixels that violate criteria
- Then inspector dispositions indications.
 - Relevant
 - Non relevant



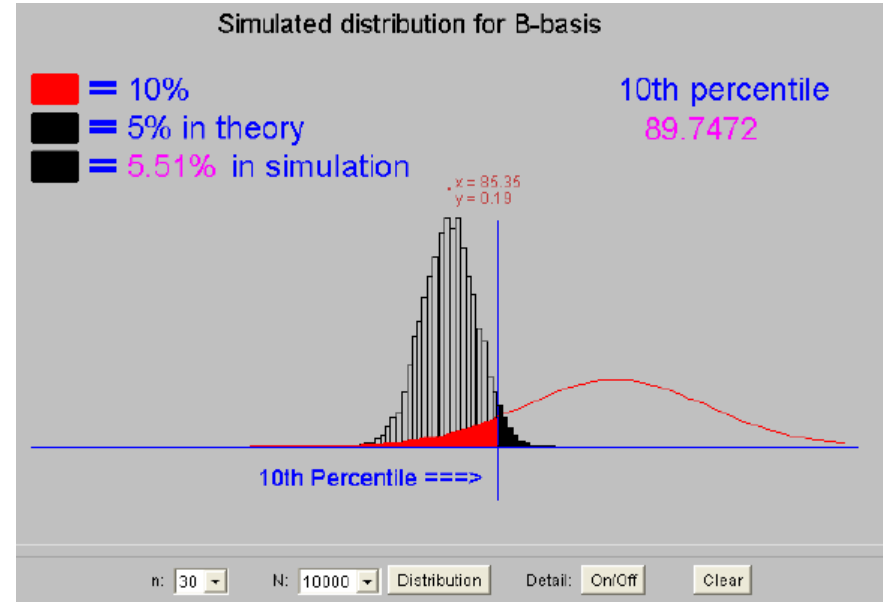
- Criteria of signal amplitude and signal time of flight.
- Criteria of area.
- Criteria of nearest neighbors.
- NO DEFECT TYPING.



- Two options:
 1. Part is good, process continues.
 2. Part is bad. Go to Manufacturing Review Board (MRB).

Option 1. Passed. Is that all you want to know?

- Part has passed NDE.
- What do you know about the part?
- Tracking quality metrics from NDE?

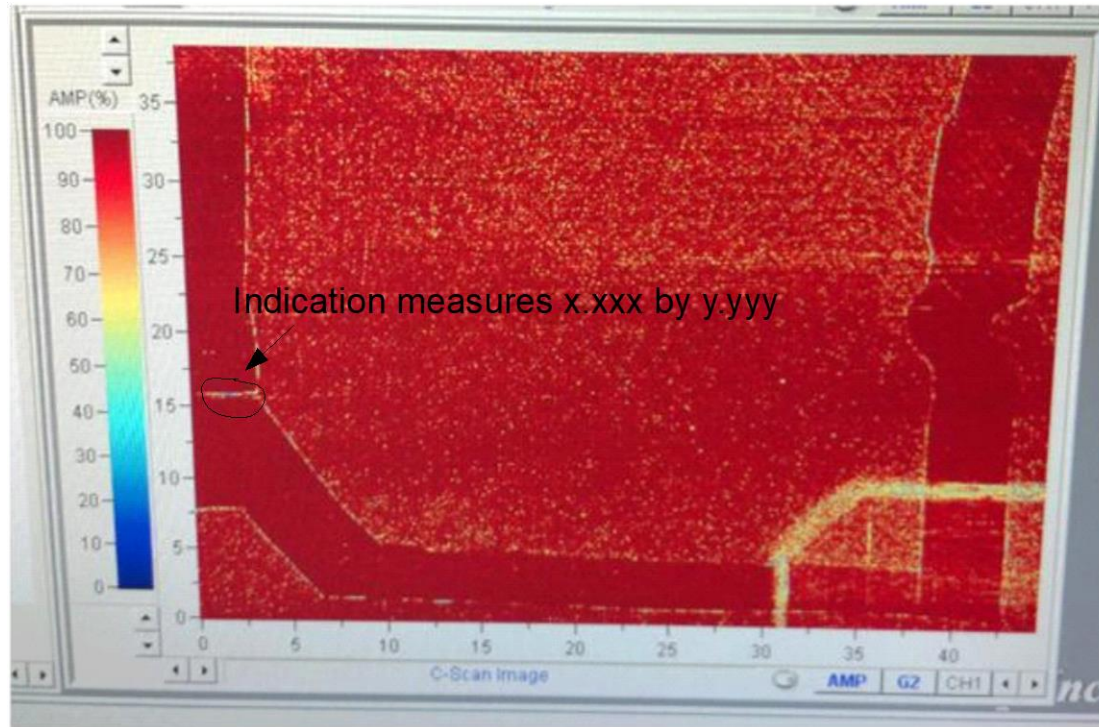


The internet browser-based simulation program is available at NCAMP website
http://www.niar.wichita.edu/coe/ncamp_media.asp

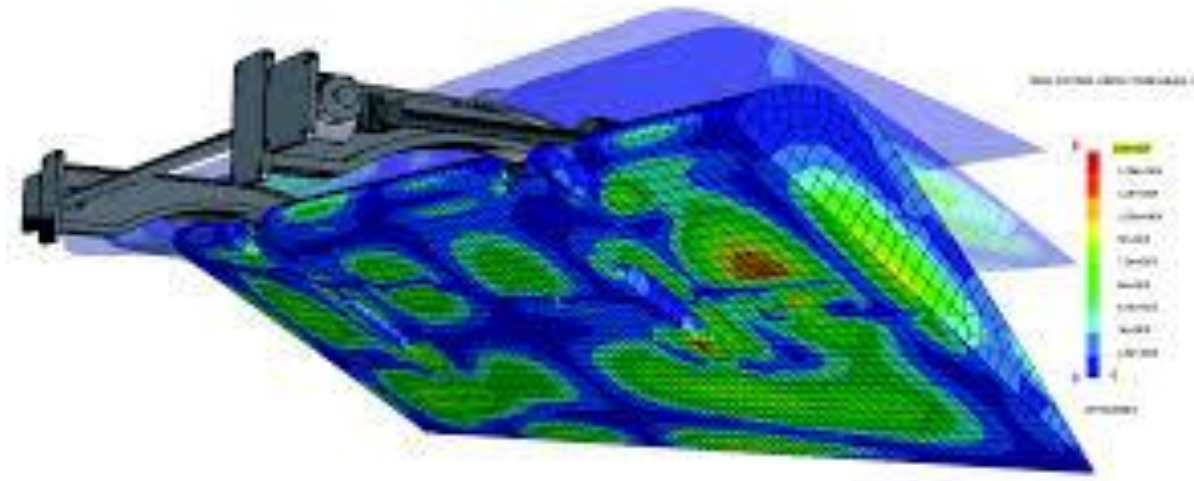
- There is an indication in the NDE data that violates your defect criteria.
 - If the part is low cost, discard.
 - If the part is high cost, go to Manufacturing Review Board.
-
- How does NDE support the MRB?

- Results of NDE are translated by hand into finite element model.
 - Reliable? Reproducible?
- Unknown properties of defect.
 - “Open hole” criteria used in design.
- “Effects of defects” models require detailed definition of defect.

Digital thread broken?

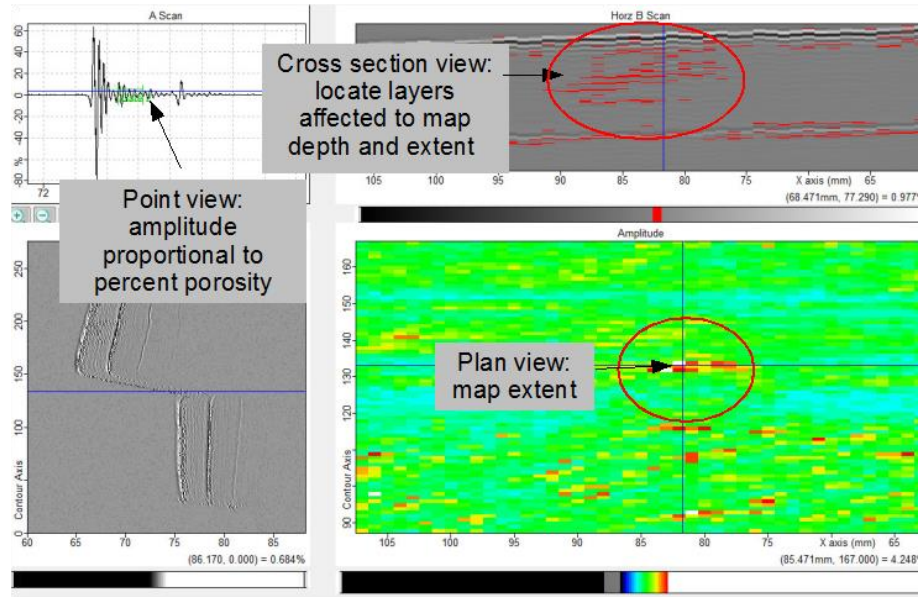


Where, how to modify model?



- Detection, typing, and spatial registration of discontinuities in 3D.
 - FOD/delam/disbond, porosity
 - Wrinkles
 - Matrix rich
- Bulk materials properties.
- Ply count and fiber direction through the thickness.
- Weak bond detection.

- Ultrasonic inspection data can be used to describe defect type and dimensions.

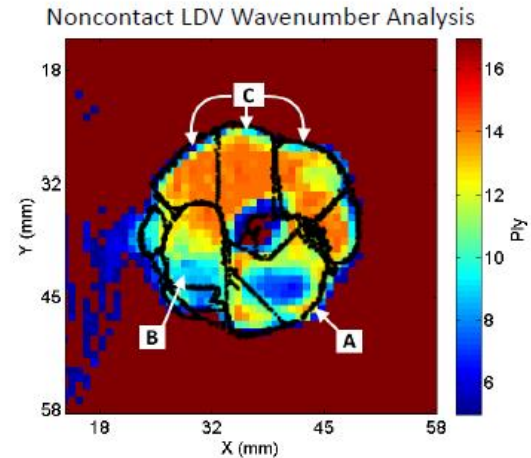
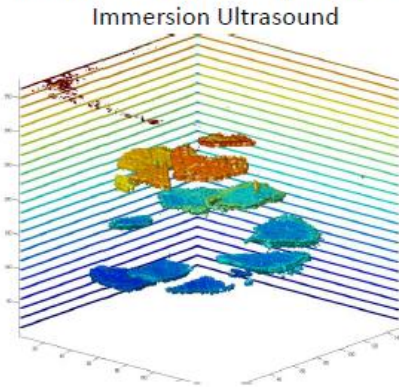


Experimental Results



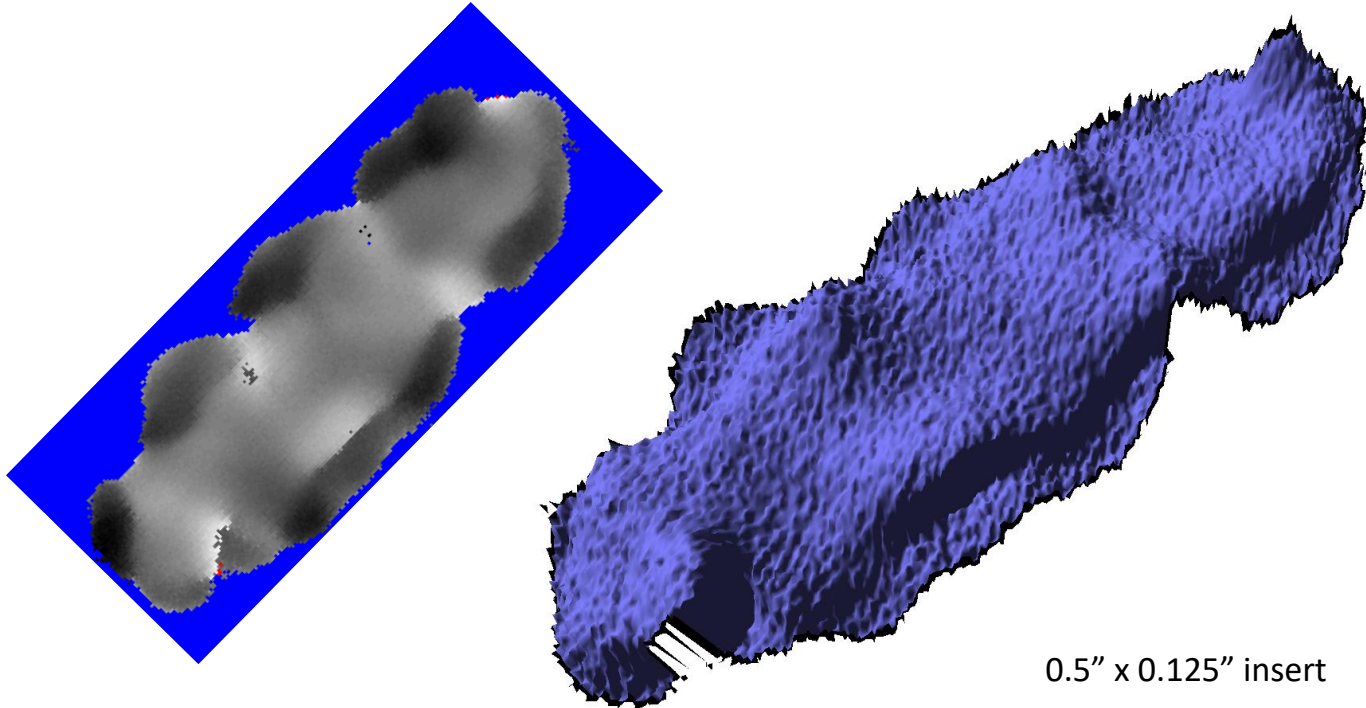
Nondestructive Evaluation Sciences Branch

- Multi-frequency wavenumber analysis



¹ Juarez, P. and Leckey, C. "Multi-frequency Local Wavenumber Analysis and Ply Correlation of Delamination Damage". *Submitted to Ultrasonics*

Defects can be mapped in 3 dimensions.



Determining fiber direction

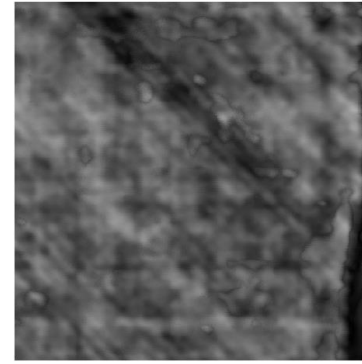
45°



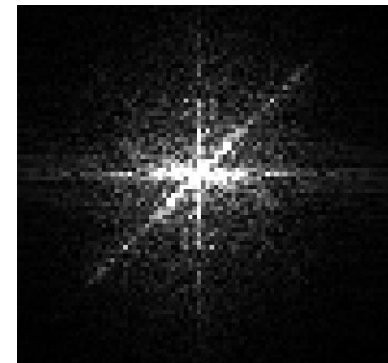
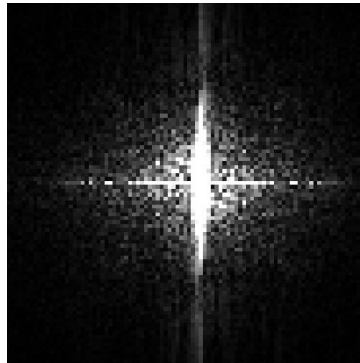
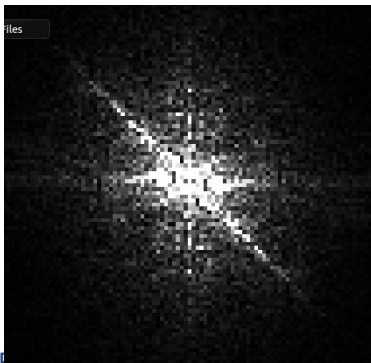
Max signal per ply.
0°

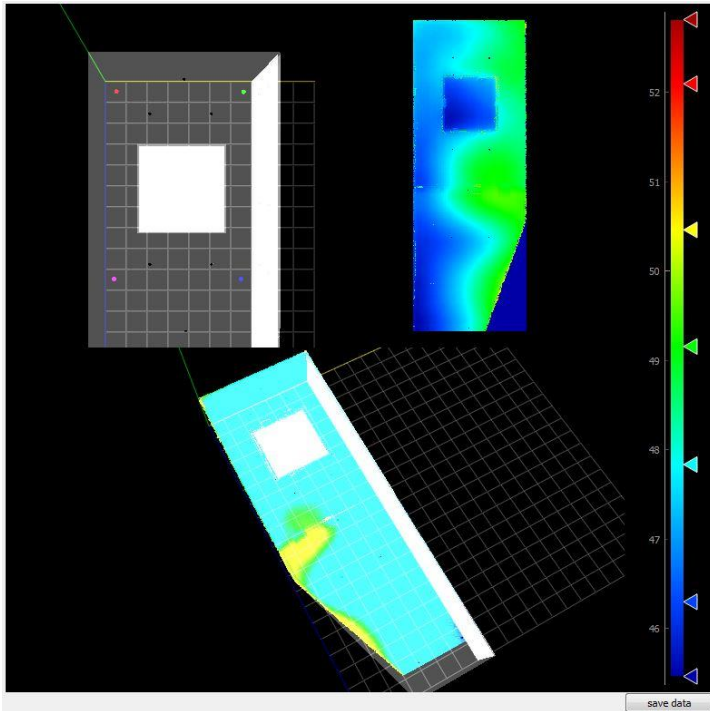


-45°



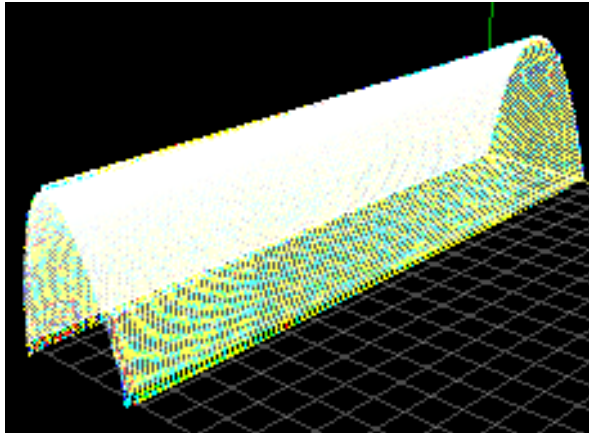
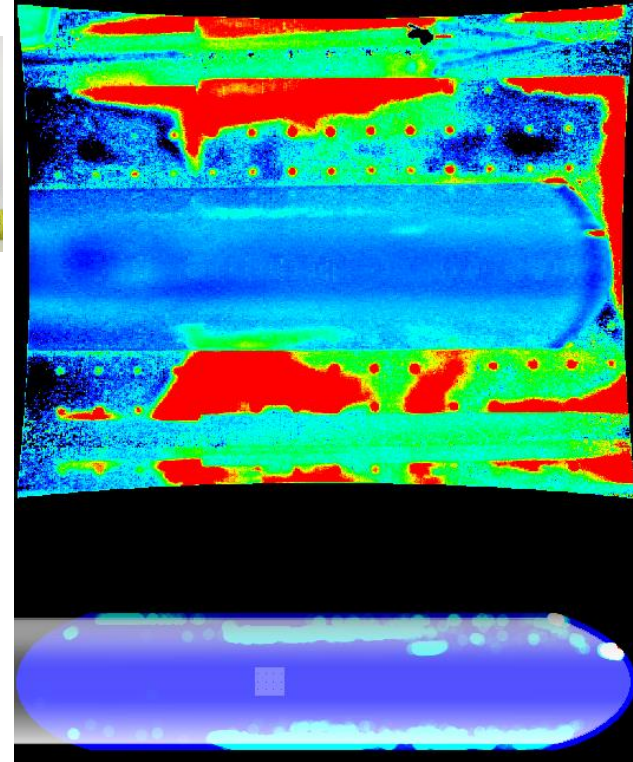
2D FFT





- NDE data is mapped to CAD coordinates
- Ensures full inspection coverage
- Highlight difference between as-designed and as-built
- Ties data to digital thread

Combine data in CAD space



NDI Shop

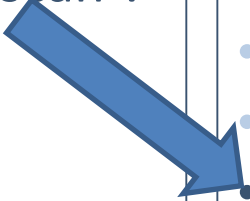
- Find it on “C scan”.
- Go handscrub it.
- [all mgmt shows up and argues about what it really is]
- Back to computer, use software to draw around it and make dimensions. Export to image file.
- Email to engineering.
- On to next part.

Engineering

- Locate on part.
- Check allowables.
- Check knockdowns.
- Run local model.
 - where is it in plane?
 - where is it in thickness?
 - what mechanical properties?
- Release, repair, scrap.

NDI Shop

- Algorithm finds it on “C scan”.
- Level III review.
- Go handscrub it.
- Back to computer, use software to draw around it and make dimensions. Export to image file.
- Email to engineering.
- On to next part.



Engineering

- Locate on part.
- Check allowables.
- Check knockdowns.
- Run SI model.
 - ✓ where is it in plane
 - ✓ where is it in thickness
 - ✓ what mechanical properties
- Release, repair, scrap.



- Initial development and validation via simulation
- Rapid prototyping
- UT full matrix capture and post processing
- Intelligence Augmentation during inspection
- Assisted Defect Analysis post inspection
- Digital handoff to engineering

- SME organizers.
- TRI Austin.
- Multiple Air Force and NASA sponsored programs have supported this technology.
 - No project data used in this presentation without prior clearance as noted on the charts.
- I appreciate your time and feedback.

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