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Perspectives on Nondestructive Evaluation of Bonded Joints

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Outline

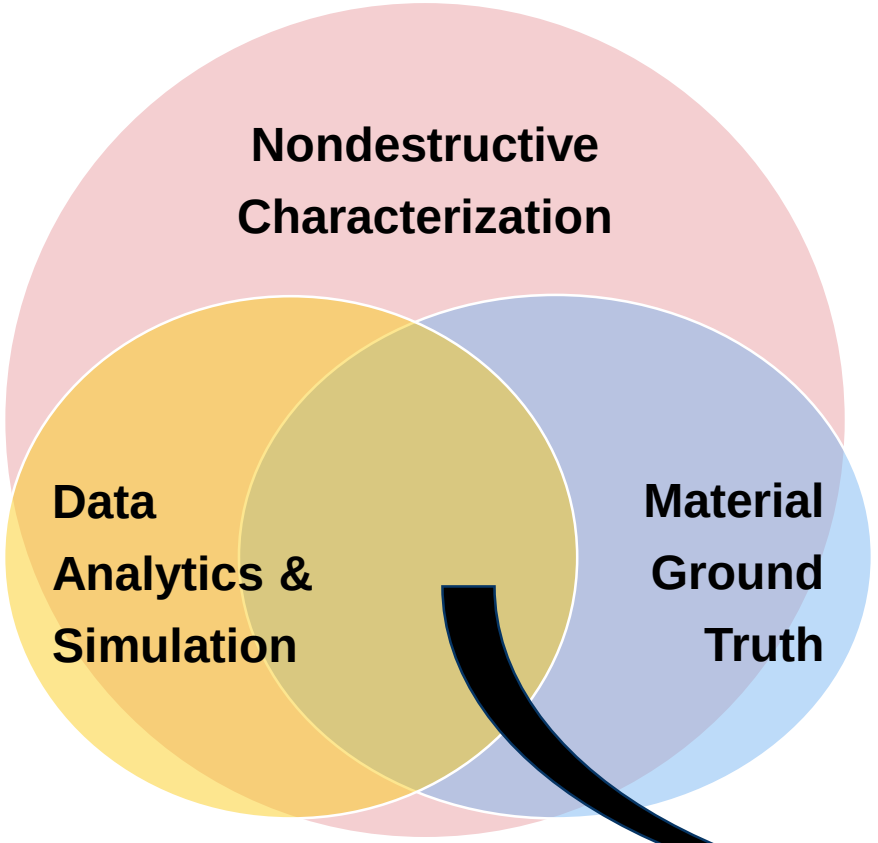
- Introduction to Nondestructive Evaluation (NDE) and Material State Awareness
- Desired Capabilities for Bond-line Inspection
- Current NDE Capabilities / Limitations
- Introduction to Laser Bond Inspection (LBI)
- Capabilities and Gaps
- Current Exploration
- Thoughts for the Future
- Discussion

Acknowledgments

- Air Force Research Laboratory Materials and Manufacturing Directorate
  - Manufacturing Technology Division
  - Structural Materials Division
  - System Support Division
- Air Force Life Cycle Management Center
- NAVAIR
- Boeing Research and Technology
- Northrup-Grumman
- Lockheed-Martin
- LSP Technologies
- TRI-Austin

Materials State Awareness

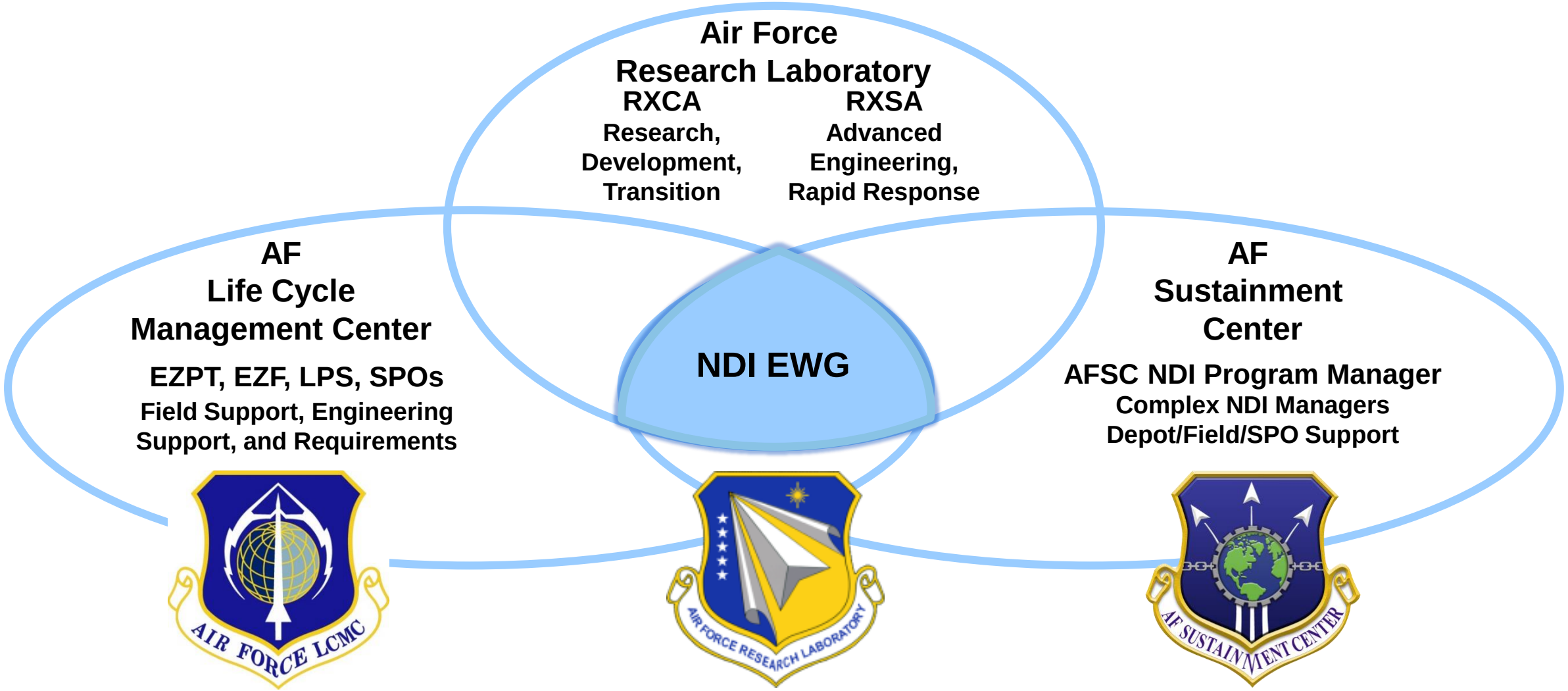
Reliable, Quantitative, Digitally-Enabled Materials & Damage Nondestructive Characterization; regardless of scale



Model-enabled material representation

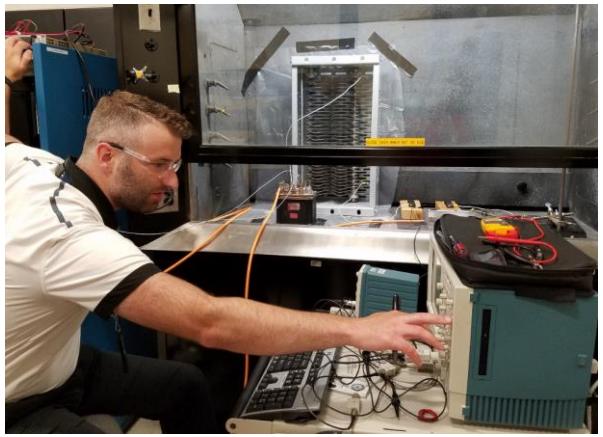
- **Damage, microstructure, properties**
- **Quantitative, statistical metrics**

NDE Executive Working Group



Material Assessment for Integrity Assurance

Desired Capability: NDE of Bonded Repairs



AFRL Testing

Representative Manufacturing

Representative Depot Maintenance

- Ensure bonded region has no unacceptable flaws
- Ensure bonded region has appropriate strength for application
- Research, manufacturing, and sustainment: differing requirements on accuracy / precision
- NDE capabilities must meet requirements of each location

NDE Sensing Physics

Electromagnetics

Includes Hz to 30+ PHz (x-ray)

- **Pros:**
  - **Hz – THz: very sensitive to surface features**
  - **PHz: can penetrate materials (e.g. x-ray)**
- **Cons:**
  - **Hz – THz: cannot penetrate conducting materials**
  - **PHz: safety considerations, not sensitive to low contrast features, e.g. cracks**
- **Uses:**
  - **Hz – THz: surface flaws, e.g. surface breaking cracks, local conductivity change**
  - **PHz: volumetric flaw, e.g. voids**

Mechanical Waves

Includes Hz to GHz (ultrasound)

- **Pros:**
  - **Penetrate into materials**
  - **Reflections from defects with impedance changes**
- **Cons:**
  - **Scattering and mode conversation can cause extraneous signals**
  - **Sensitivity and propagation distance as a function of frequency**
- **Uses:**
  - **Subsurface flaws, e.g. cracks and voids**

Thermal Diffusion

Requires thermal energy flow

- **Pros:**
  - **Visualize with IR imaging**
  - **Rapid for large areas**
- **Cons:**
  - **Less sensitivity than other methods**
  - **Resolution limited by lateral thermal diffusion**
- **Uses:**
  - **Polymer matrix composites to detect large flaws**

Advanced signal processing / analytics can be used for all methods

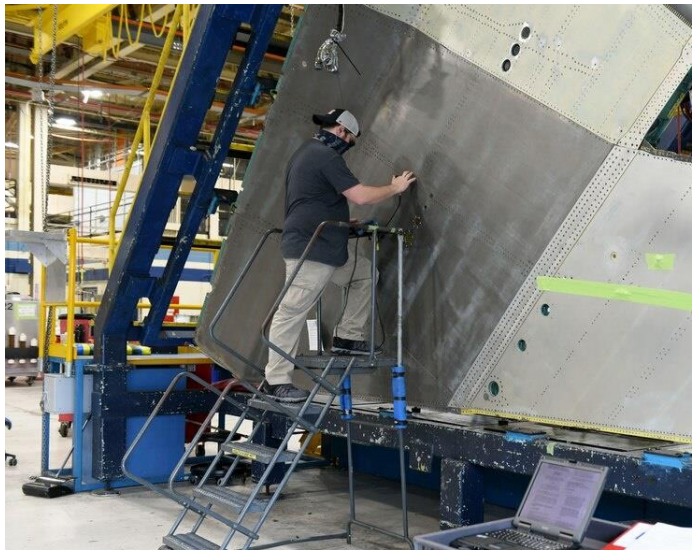
Capabilities and Limitations of NDE Methods

Capabilities

- Detects volumetric flaws: e.g. voids, delaminations
- Detects 2D flaws: e.g. cracks
- Detects material changes: e.g. cure state, microstructure
- Quantifies some material properties: e.g. elastic moduli, electromagnetic properties

Limitations

- Cannot directly measure strength



Addressing Limitation

Hypothesis

- Use NDE-based capabilities to perform localized proof-test

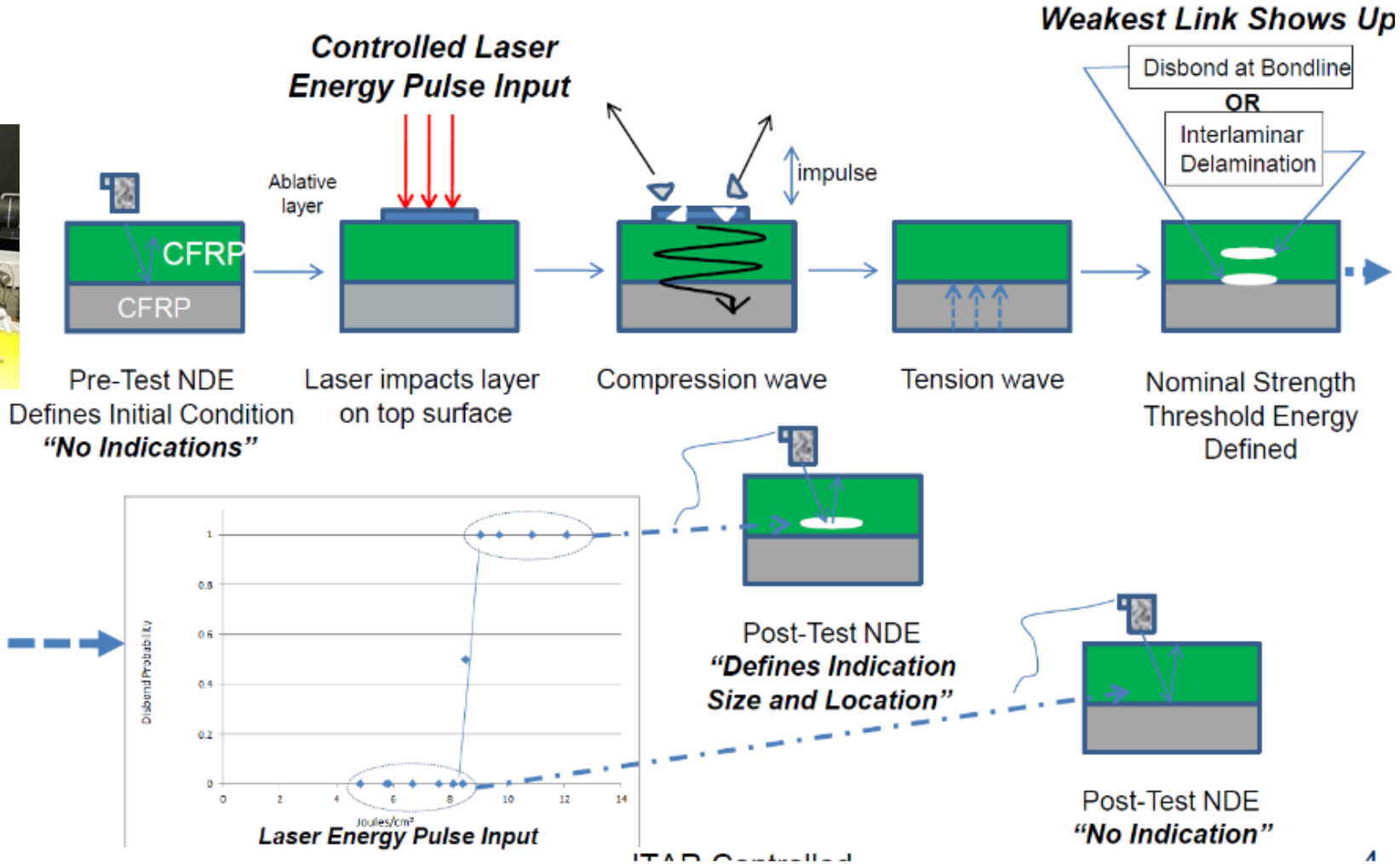
Approach

- Insert sufficiently large elastic tensile wave to test bond strength
- Laser pulse to achieve desired tensile wave
- NDE methods to detect delaminations if weak bond

Pay-off

- Localized method to ensure bond strength

How Laser Bond Inspection (LBI) Works



LBI Validation Programs

Phase I

- Verify composite bond strength measurement
- Establish TRL5/MRL5 and identify required maturation to validate technology

Phase II

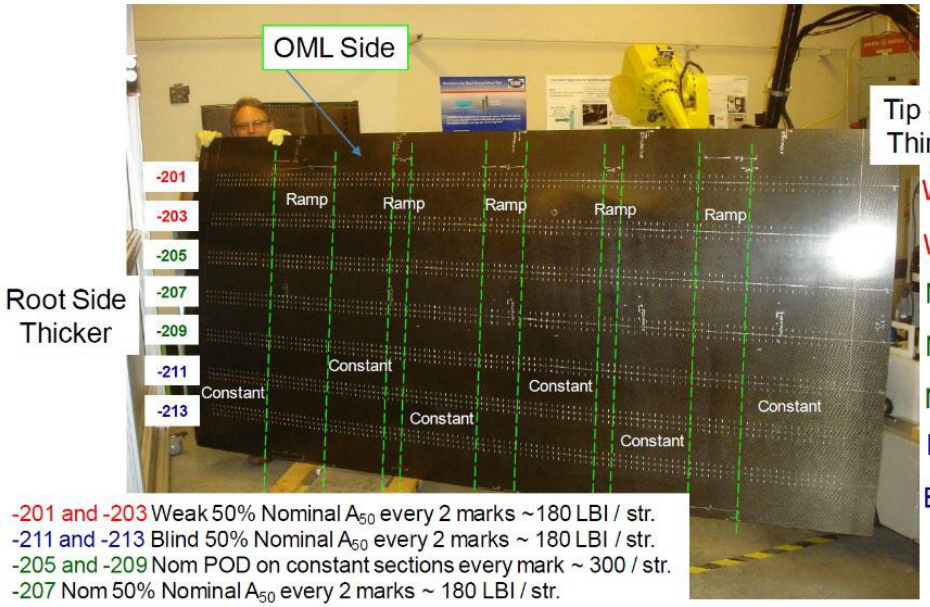
- Develop LBI methodology / protocols for inspection of composite material systems
- Validate methodology on two material systems / part-specific features
- Demonstrate full-scale configured component LBI testing with varying bond quality

Add Work

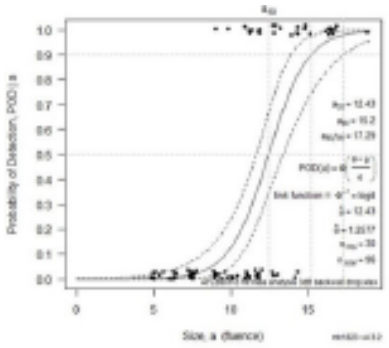
- Complete fatigue studies
- Demonstrate LBI on scarf or repair geometries, including investigating levels of porosity
- Transition methodology and calibration approach to industry

Summary of Testing to Date

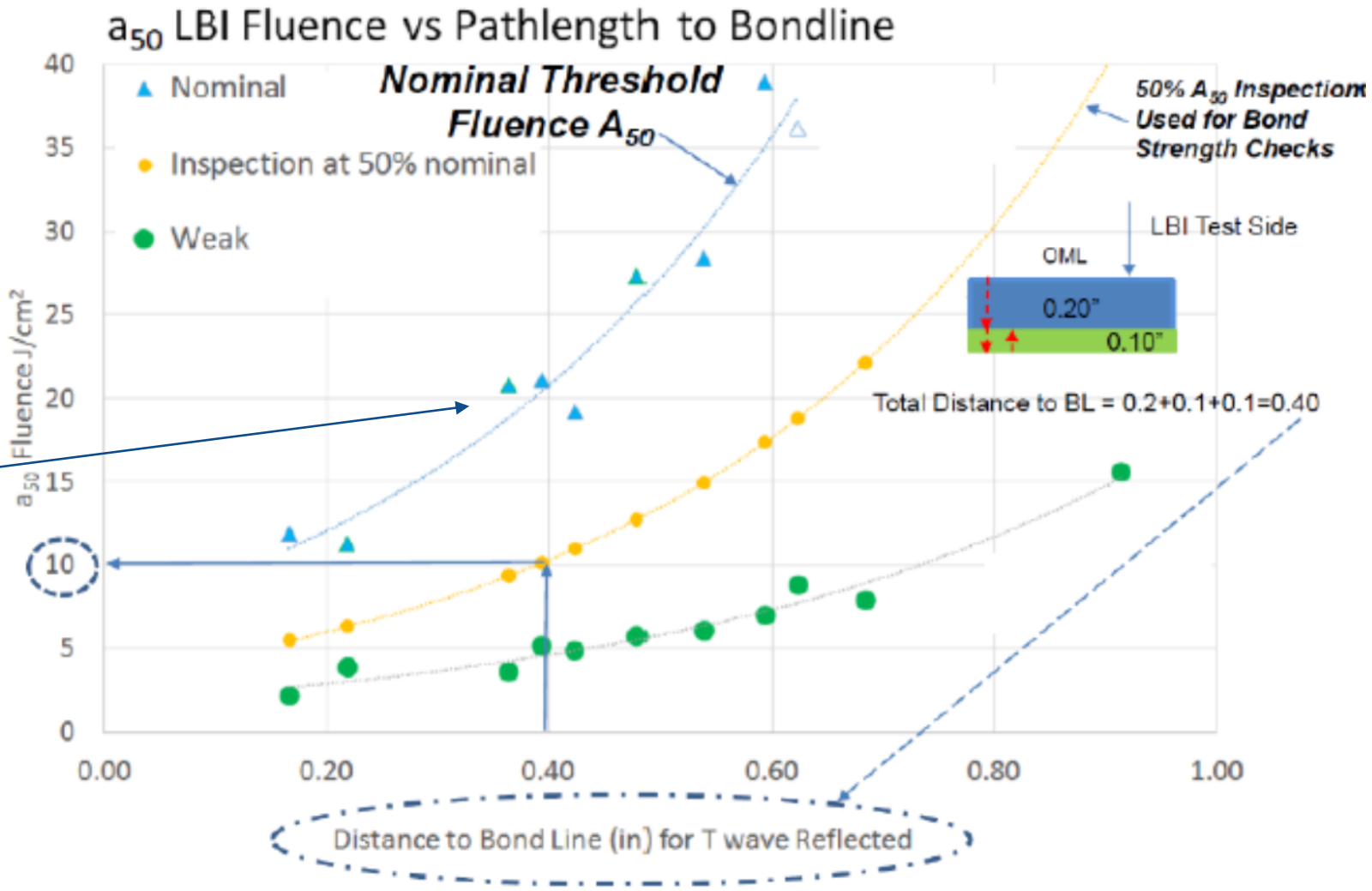
Description Panel / Test / Inspection	IM7+AS4 / 977-3 FM300-2M	IM7+T650 / 5320-1 FM309-1	Total
Two Independent LBI Systems	2	2	2
Laminate Panels	19	6	25
Bond Assemblies	50	14	64
- Oven Cured	12	0	12
- Autoclave Cured	38	14	52
Mechanical Testing			
Flatwise Tension	144	36	180
Single Lap Shear	144	36	180
Double Cantilevered Beam (DCB)	55	10	65
Post LBI (DCBs)	45	-	45
DCB Fatigue (single/multi shot)	5	-	5
Mech. Coupon Failure Analysis	393	82	475
High Resolution Failure Analysis	4	-	-
Photo-microscopy	30	-	30
Total LBI Testing			**11556**
- Boeing	6073	3528	9601
- LSPT	1815	140	1955



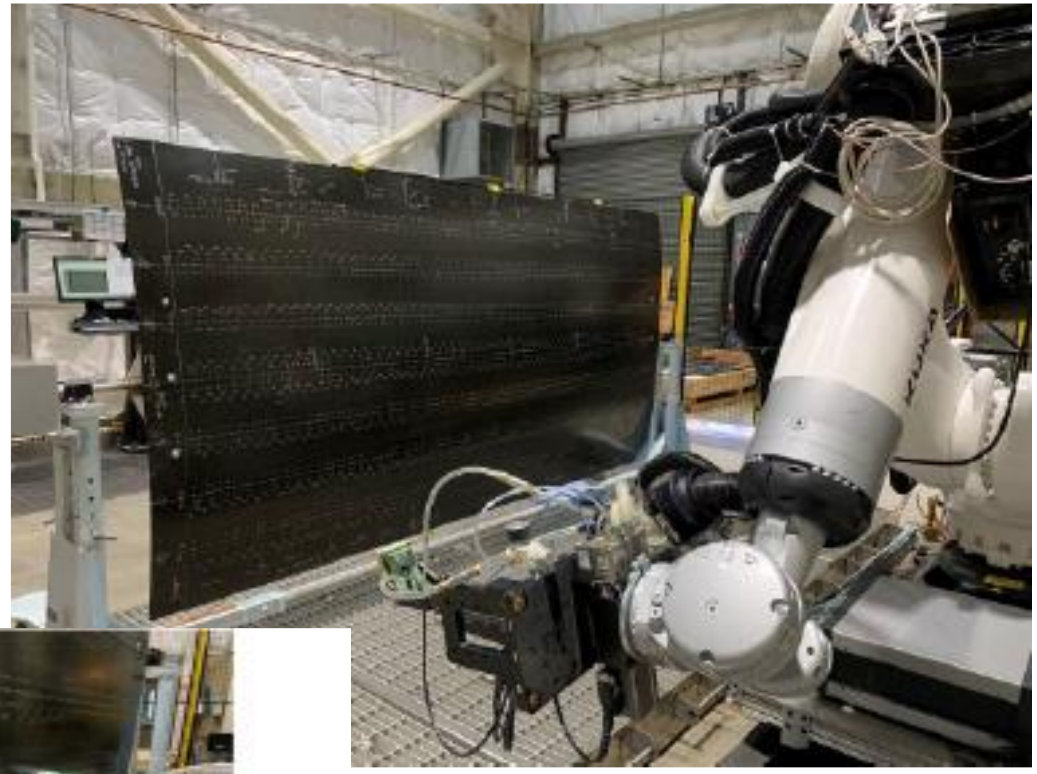
LBI POD for Design Considerations



Each Data Point is A50 (comprised of ~60+ LBI tests)



Post LBI Ultrasonic NDE



3.5 MHz, 3.5" array while scanning

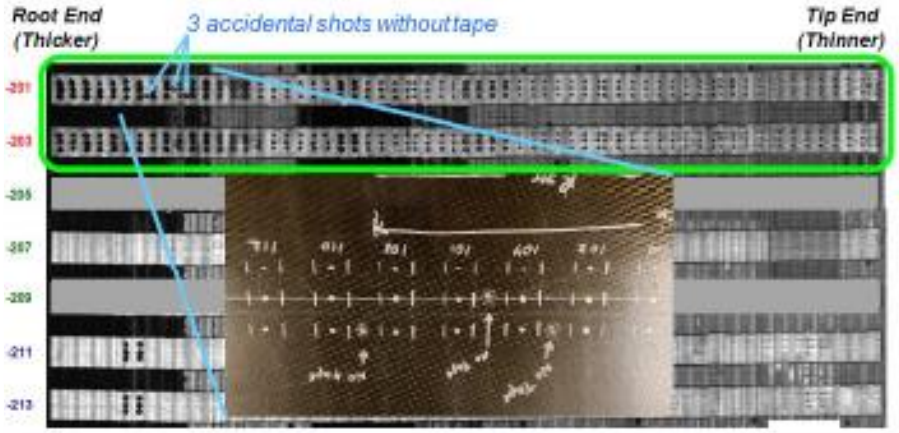
Production Scanner

- Scan entire panel with one scan
- High quality data / high positional accuracy
- No loss of coupling
- 0.5 day: set up, 3 minute: scan, no time: stitch images

Portable Scanner

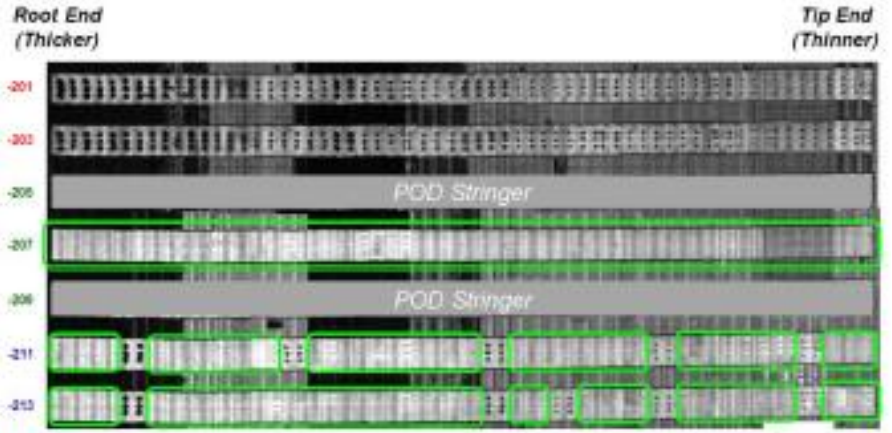
- Limited area of scan
- Positional hysteresis
- Coupling losses
- Slower scan speeds
- 0.5 day: set up, 0.5 day: scan, 1 day: stitch images

Representative LBI Test Results



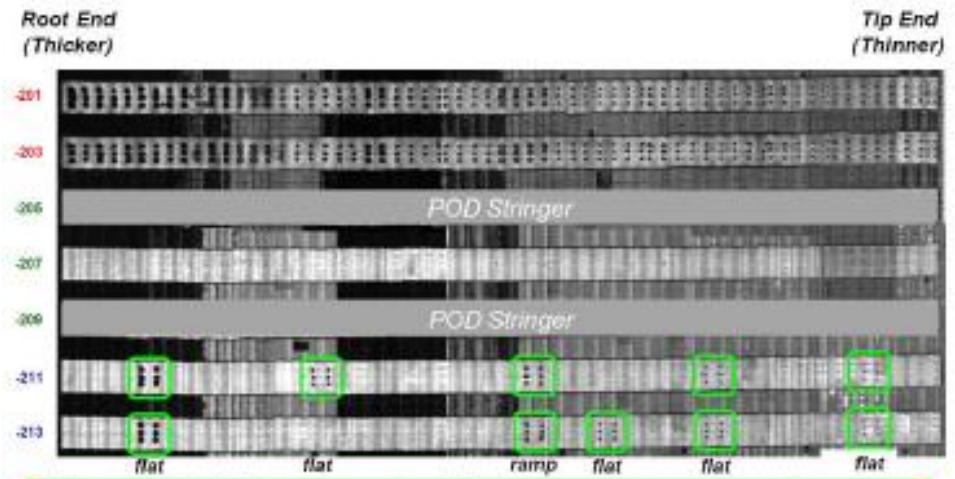
Stringers -201 and -203 are intentional weak bonds. Every location shot at 50% a_{50}. Every shot, ramp or flat, appears clearly.

Intentionally Weak Stringers



Stringer -207 and most of stringers -211 and -213 are nominal strength. Every location shot at 50% a_{50}. No NDI indications.

Nominal Strength Stringers



Stringers -211 and -213 contain 10 blind, weak areas. Every location shot at 50% a_{50}. All 10 weak areas clearly detected.

Blind Weak Stringers

Capabilities and Challenges

Validated Capabilities

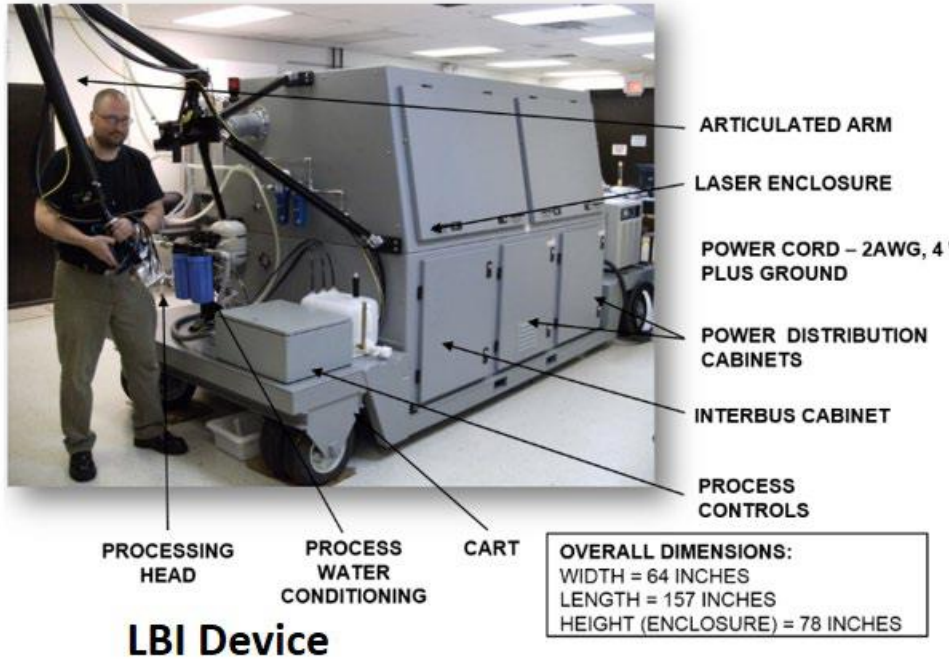
- Bond strength determination
  - This is **HUGE!**

Challenges

- Non-planar geometry
- Post LBI NDE assessment
  - Ultrasonic signal interpretation
- System physical dimensions
  - Constraint for outside of manufacturing
- System durability and capability verification
  - Down-time concerns and sensitivity calibration

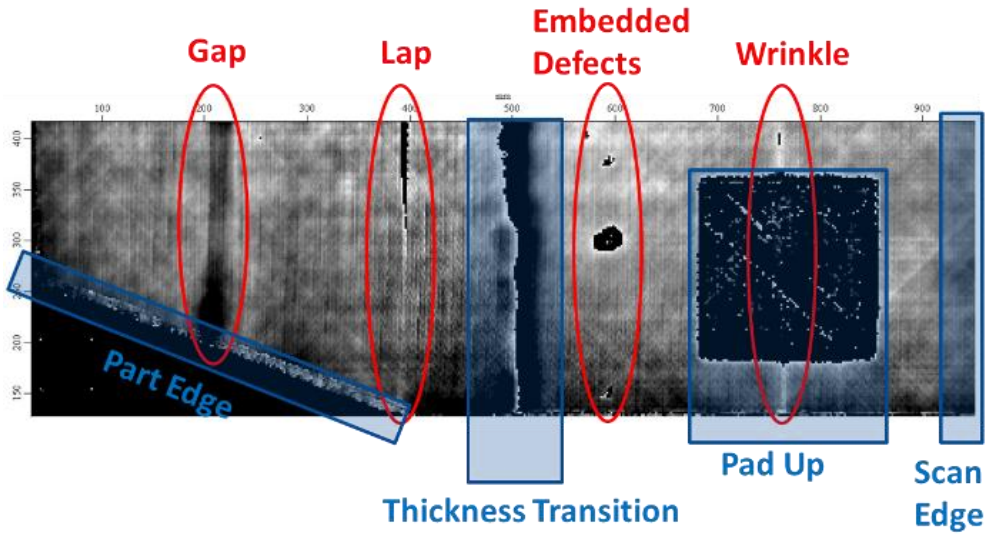
Challenges being addressed in ongoing programs

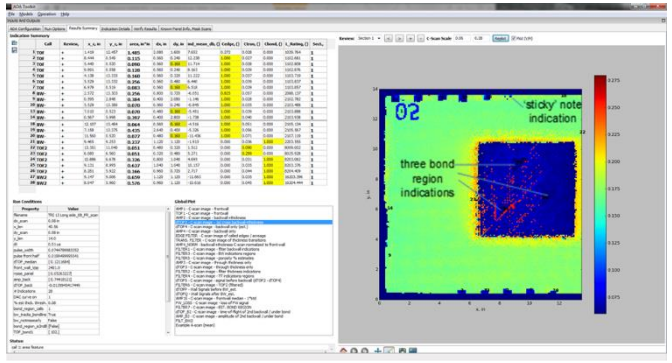
- Successful completion simplifies implementation



LBI Device

Post LBI Assessment





- Implement Human Data Review Procedures in Algorithms
- Assisted Data Analysis (ADA) for UT of Composite Panels
  - 100% Ultrasonic inspection for manufacturing QA
  - Adapt to LBI accept / reject criteria
  - In-progress SBIR with TRI-Austin

System Dimensions / Durability / Calibration

Dimensions

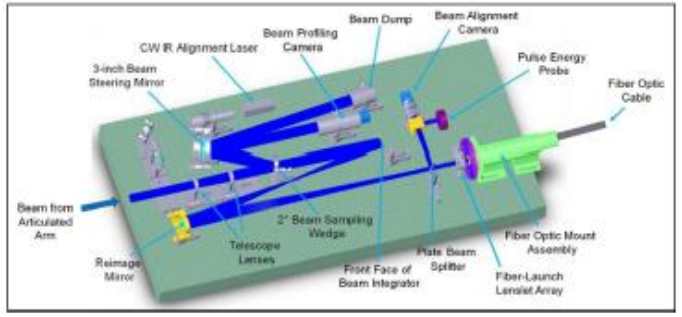
- Fiber-optic delivery system
  - In development at LSP Technologies
- Improved delivery system
  - In development at LSP Technologies

Durability

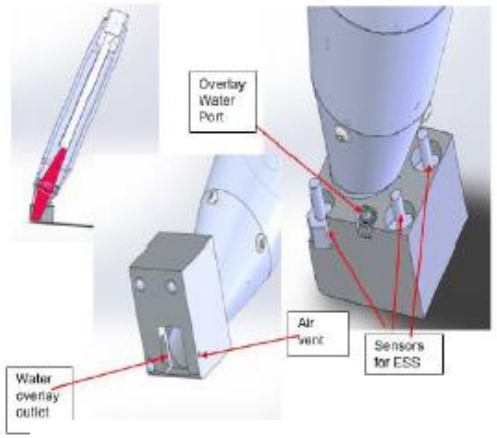
- Engineering solutions / work-arounds
  - LSP Technologies / Boeing / Northrup-Grumman
  - Cooperative lessons learned!

Calibration

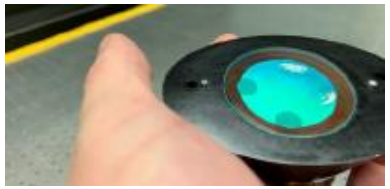
- Multiple solutions in work
  - Boeing / LSP Technologies



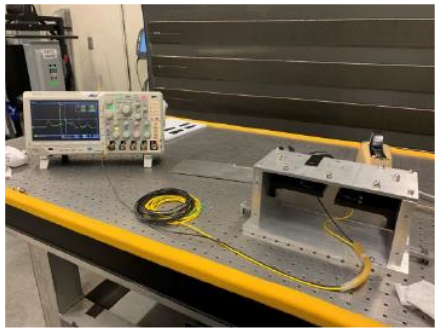
Proposed Fiber-optic Launch System



Proposed Fiber-optic Launch Box

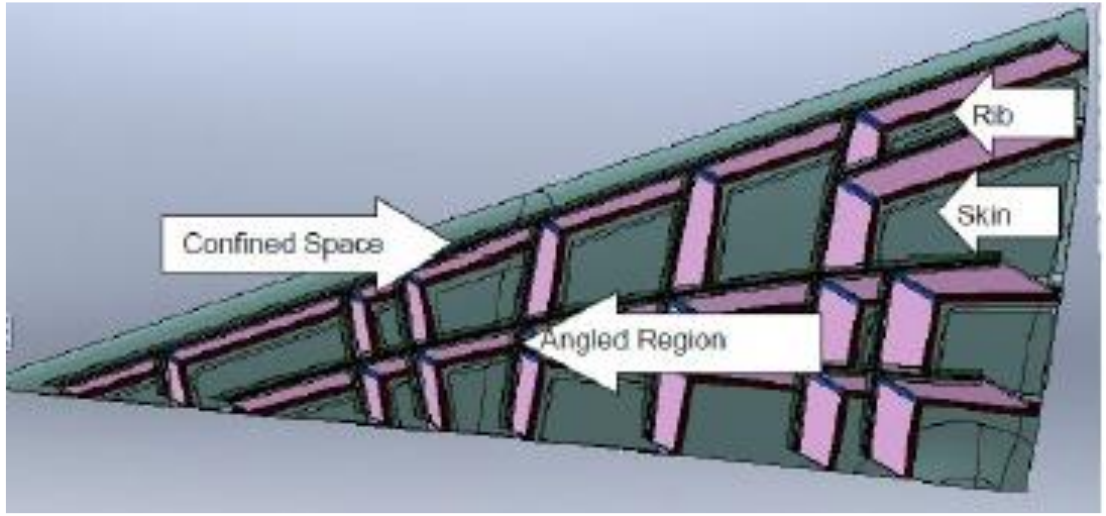


Mirror Failure



Proposed calibration fixture

Non-planar Geometry



- Most testing to date on bonded flat panels
- Curve samples in work
- Scarf joints in work
- Geometry verified by case-by-case testing
  - Simulation capability would be beneficial

Way Forward to Realize LBI Capability

Validated capability, more engineering required

Address identified challenges:

- Geometry
  - Additional testing in progress
- Post test NDE
  - Development program underway
- Durability
  - Additional robustness being integrated into new designs
- Dimensions
  - Multiple contracts to address size and weight
- Sensitivity Calibration
  - Several options being pursued

Summary

- Enduring challenge for NDE: measure bond strength
- LBI holds promise to address need
  - Strength measurement by a local proof test
  - Capability validated
- Additional challenges remain
  - Test article geometry
  - Test system dimensions / durability
  - Post-test NDE efficiency
  - Sensitivity calibration
- Programs addressing challenges
- Integrated team pursuing success
  - DOD R&D, Large and small businesses
- Potential to address bonded repair strength verification

Discussion

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