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Inspection and Teardown of Aged In-Service Bonded Repairs

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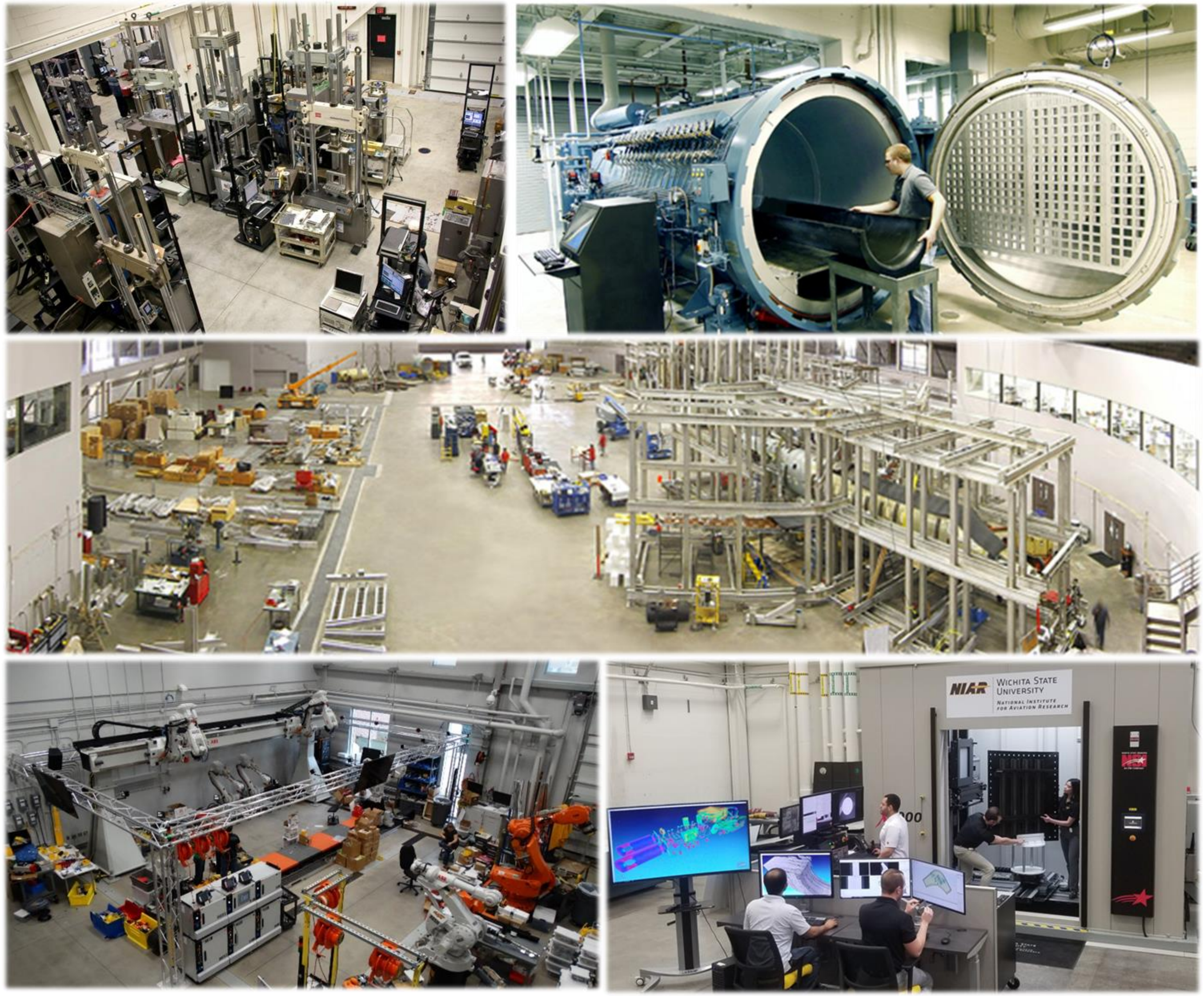
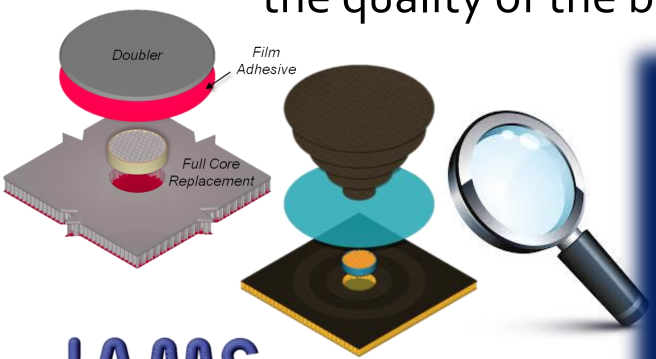


Background and Key Objectives

- The increased use of bonded applications in critical structures has raised concerns related to bondline integrity and durability.
  - Improperly accomplished in-service repairs could become a safety threat due to a weak bond being susceptible to further degradation in an unpredictable manners due to operational environments and ground-air-ground (GAG) thermo-mechanical loads.
  - Long-term durability under operational environments and GAG loading must be understood and the aging mechanism must be investigated to support maintenance practices and to establish criteria for structural retirement.
  - Detailed nondestructive inspections (NDI), teardown inspections, and laboratory testing of bonded repairs on aircraft components that have been retired from service provide vital information related to the quality of the bonded repairs, and any aging mechanism and any undetected material degradation.



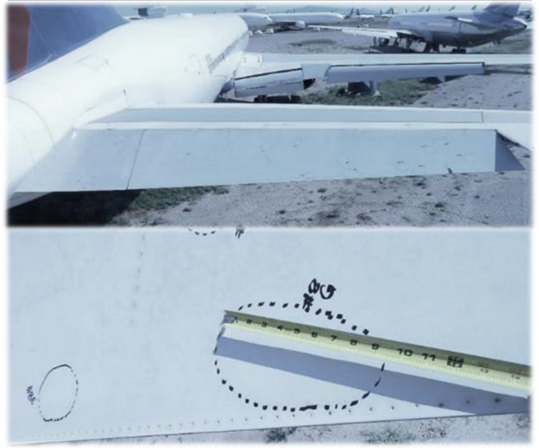
The primary goal of this research program is to evaluate repair bondline integrity and durability of in-service repairs on composite & metallic structures in commercial aircraft in order to provide guidance into:

- ***AC 65-33 (Development of Training/Qualification Programs for Composite Maintenance Technicians)***
- ***AC 43-214 (Repairs and Alterations to Composite and Bonded Aircraft Structure)***

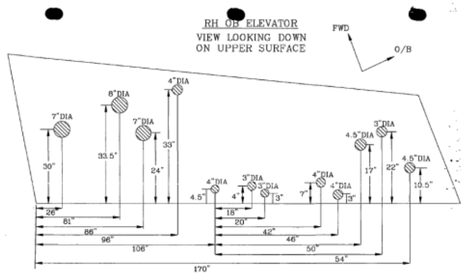
Roadmap of Technical Approach

Phase I: Component Acquisition

Service Difficulty Report (SDR) database to identify candidate A/C



Acquired SRMs, ERAs, & flight history

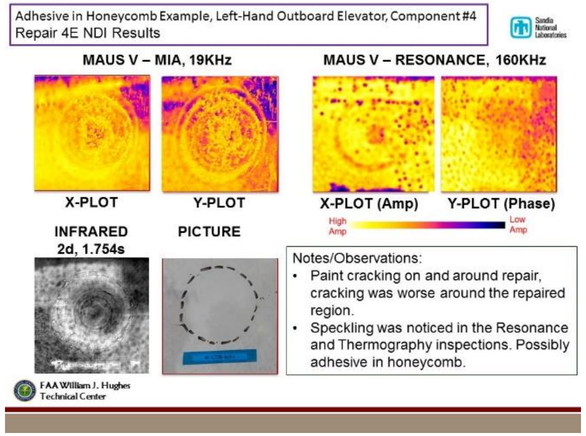


Phase II: SNL Inspections

Shipment to SNL & preliminary NDI

- Visual
- Resonance
- MIA
- Thermography

Detailed NDI Report


Adhesive in Honeycomb Example, Left-Hand Outboard Elevator, Component #4 Repair 4E NDI Results

MAUS V – MIA, 19KHz

X-PLOT
Y-PLOT

MAUS V – RESONANCE, 160KHz

X-PLOT (Amp)
Y-PLOT (Phase)
High Amp
Low Amp

INFRARED 2d, 1.754s

PICTURE

Notes/Observations:
- Paint cracking on and around repair, cracking was worse around the repaired region.
- Speckling was noticed in the Resonance and Thermography inspections. Possibly adhesive in honeycomb.

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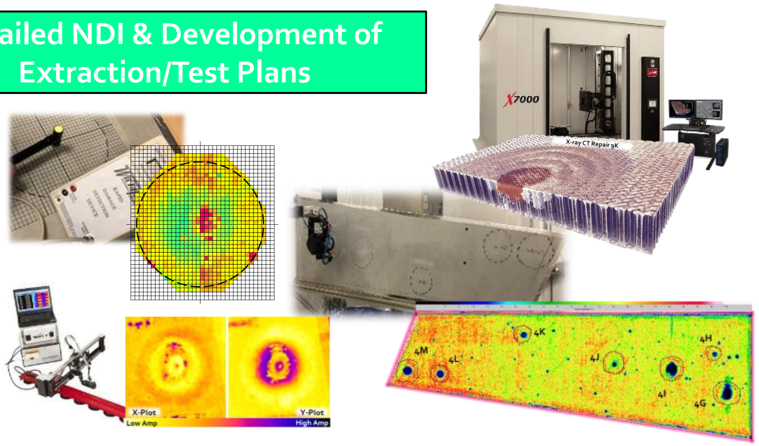
Phase III: Detailed Inspections & Teardown

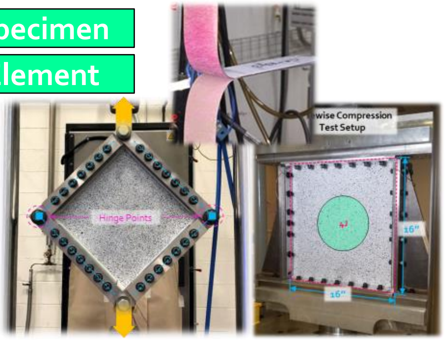
Detailed NDI & Development of Extraction/Test Plans

- Visual
- Tap Testing
- Resonance
- MIA
- Thermography
- TTU
- X-ray CT



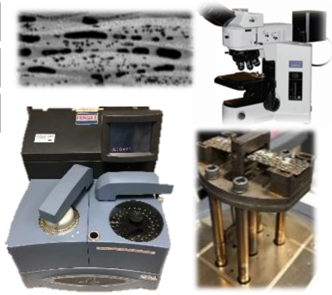
Mechanical Testing

- Specimen
- Element



Physical Testing

- Porosity
- Tg
- DOC



Phase IV: Documentation of Findings

Engage in CACRC and CMH-17 activities related to guidance materials and training/qualification programs for composite maintenance technicians and certification approaches

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Phase I: Acquisition of Components

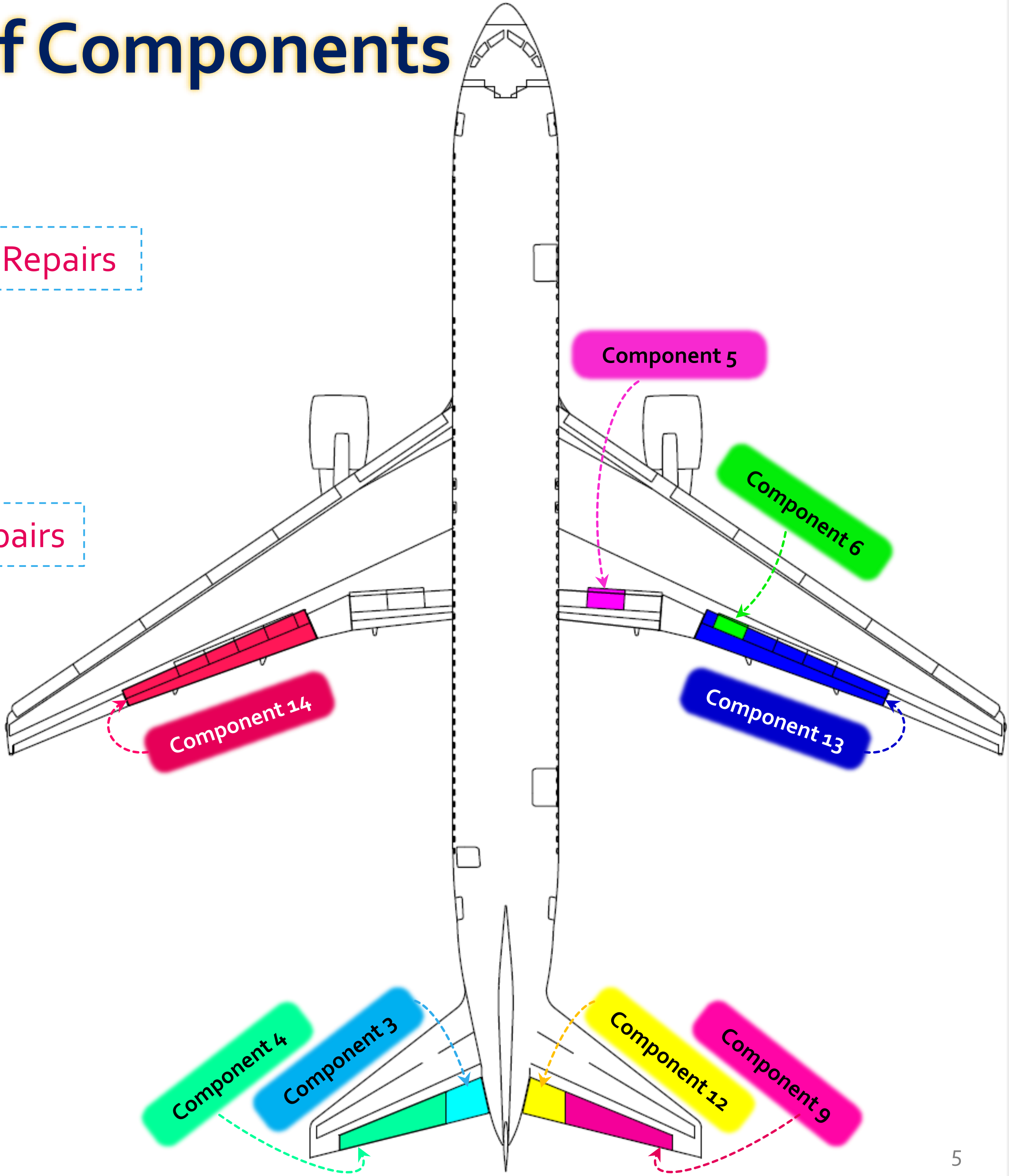
- Metallic Repair Inspection & Teardown (GFY17-GFY18)
  - **Component 13** (Right O/B Trailing Edge Flap) – 6 Repairs
  - **Component 14** (Left O/B Trailing Edge Flap) – 3 Repairs

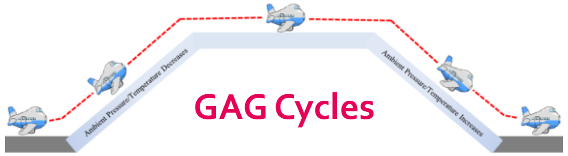
9 Metallic Repairs

- Non-Metallic Repair Inspection & Teardown (GFY18-GFY19)
  - **Component 3** (Left I/B Elevator) – 5 Repairs
  - **Component 4** (Left O/B Elevator) – 13 Repairs
  - **Component 5** (Spoiler NR 7) – 1 Repair
  - **Component 6** (Spoiler NR 9) – 1 Repair
  - **Component 9** (Right O/B Elevator) – 12 Repairs
  - **Component 12** (Right I/B Elevator) – 11 Repairs

43 Non-Metallic Repairs

Component Number	Repaired Component	Date of Repair	Stored Date	Flight Hours	Metallic Repairs	Composite Repairs
3	Elevator, Left I/B	4/30/1995	10/1/2009	13324	-	5
4	Elevator, Left O/B	4/30/1995	10/1/2009	13324	-	13
5	Spoiler, NR 7	4/30/1995	10/1/2009	13324	-	1
6	Spoiler, NR 9	4/30/1995	10/1/2009	13324	-	1
9	Elevator, Right O/B	4/30/1995	10/1/2009	13324	-	12
12	Elevator, Right I/B	4/30/1995	10/1/2009	13324	-	11
13	Flap, Right O/B	4/30/1995	10/1/2009	13324	3	-
14	Flap, Left O/B	4/30/1995	10/1/2009	13324	6	-
Total					**9**	**43**





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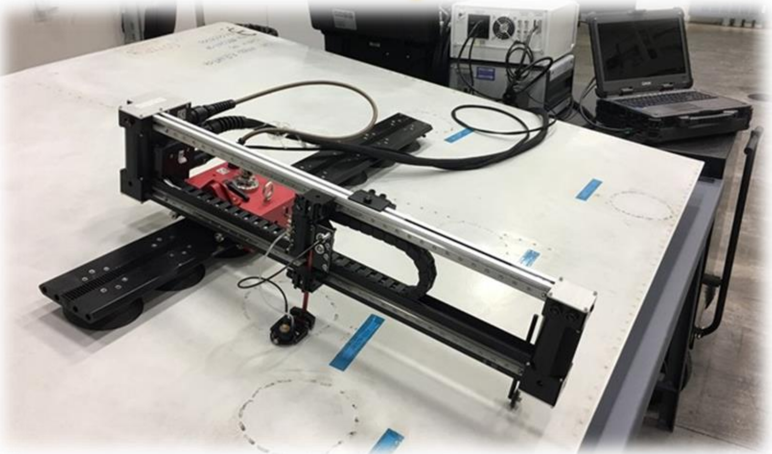
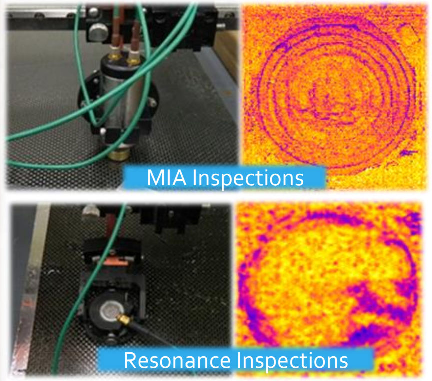
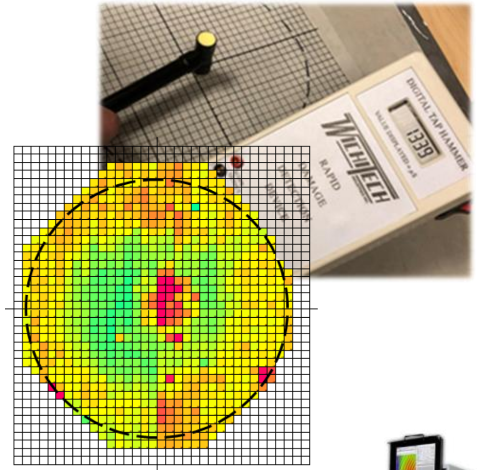
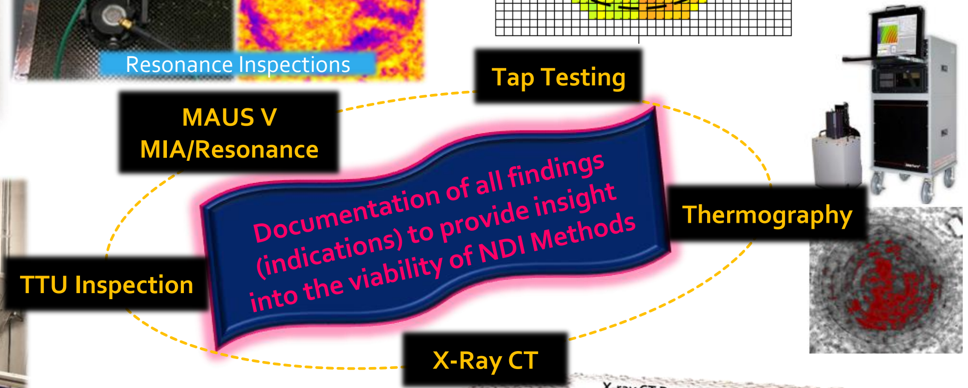
Outline of Inspection Methods

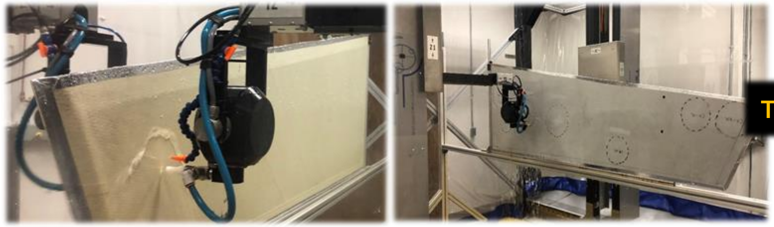
- **Phase II: SNL Inspections**
  - **Structural Level**
    - Visual
    - Mechanical Impedance Analysis
    - Resonance C-scan
    - Thermography
- **Phase III: NIAR Inspections**
  - **Structural Level (Receiving Inspection)**
    - Visual
    - Tap Testing
    - Mechanical Impedance Analysis
    - Resonance C-scan
    - Thermography
  - **Panel Level**
    - Through Transmission Ultrasonic (TTU)
  - **Specimen/Element Level**
    - Photomicrographs (cut repair)
    - Computed Tomography (CT) on select repairs

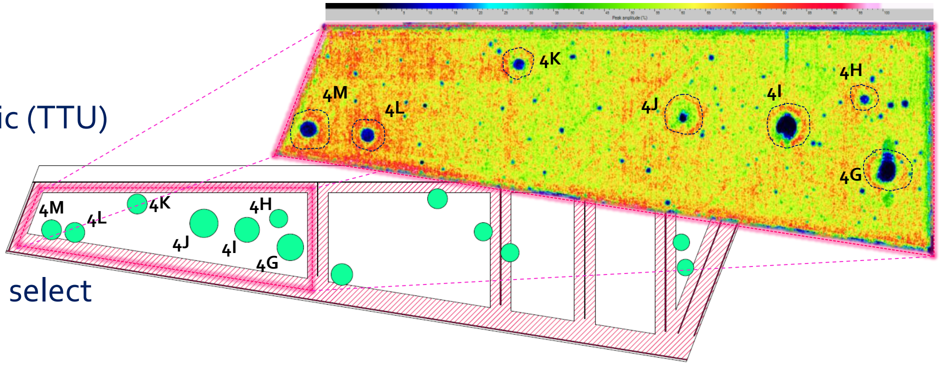


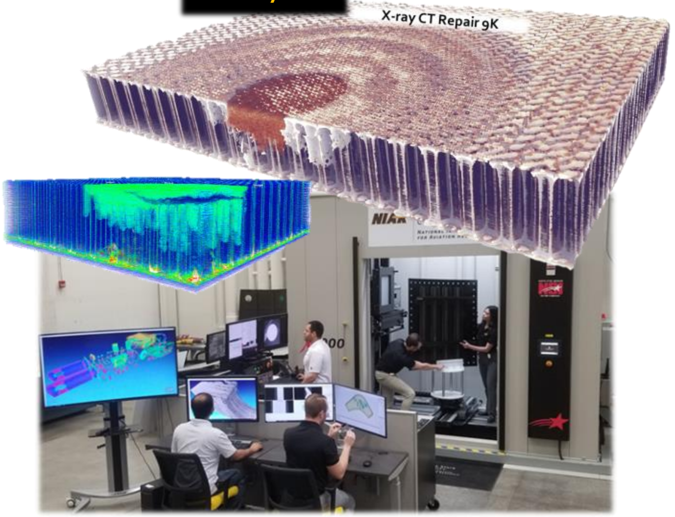






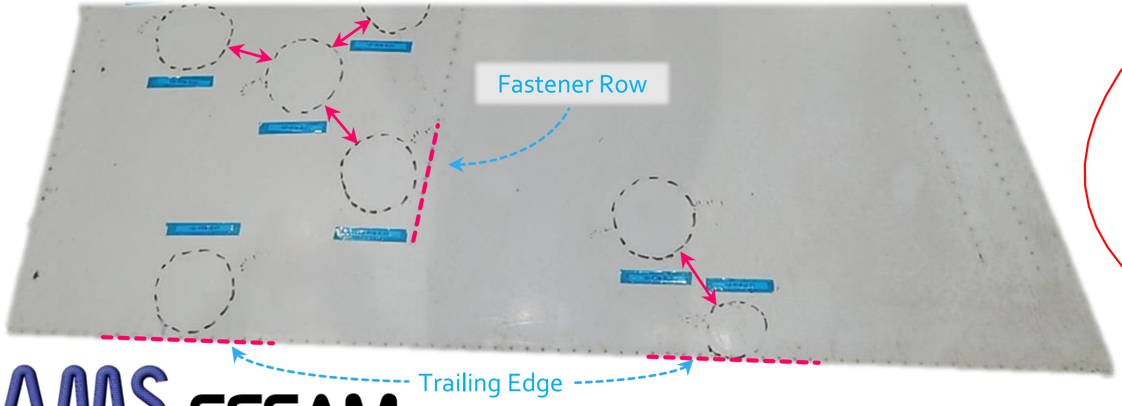


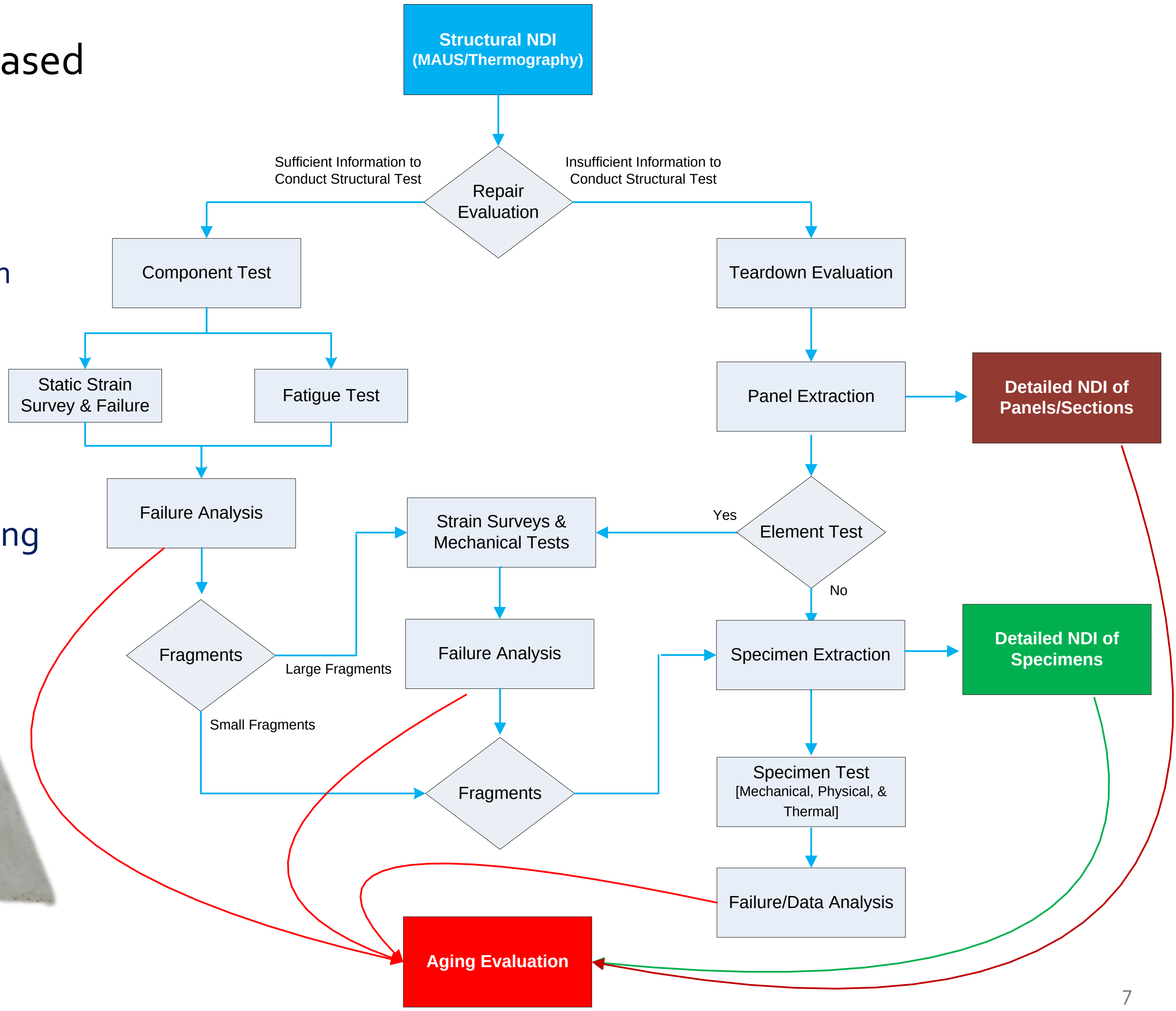




Phase III: Teardown Procedure Decision Tree

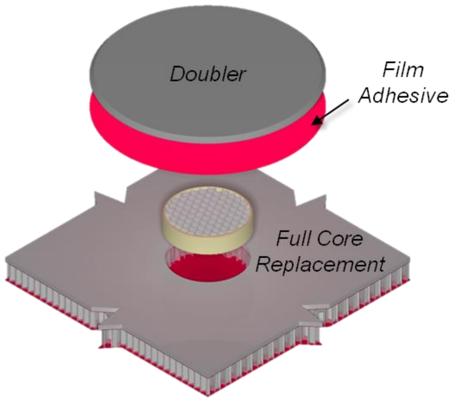
- Teardown procedure for each repair varied based on:
  - Level of documentation
    - Structural diagram of component (materials)
    - Stress levels and loading modes on repair region
    - Repair materials and process
  - Structural NDI findings
  - Quantity of repairs with alike materials and geometry
  - Location of repair on parent structure (underlying features)

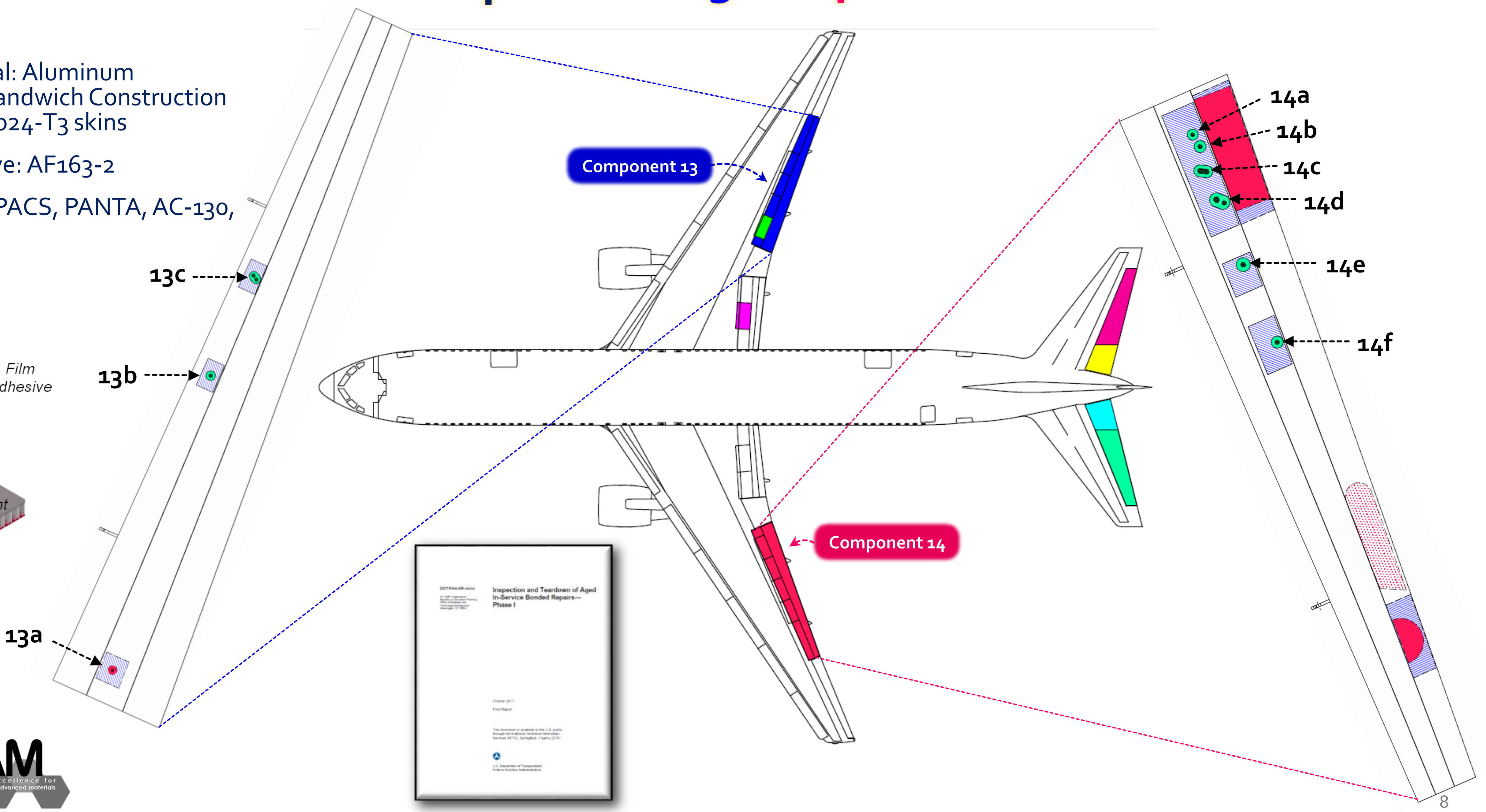




Teardown of Metallic Bonded Repairs (GFY17-GFY18)
Components 13 & 14

- **Right & Left Trailing Edge Flaps**
- **Repair Materials:**
  - Parent Material: Aluminum Honeycomb Sandwich Construction w/ 7075-T6 / 2024-T3 skins
  - Repair Adhesive: AF163-2
  - Surface Prep: PACS, PANTA, AC-130, or HF





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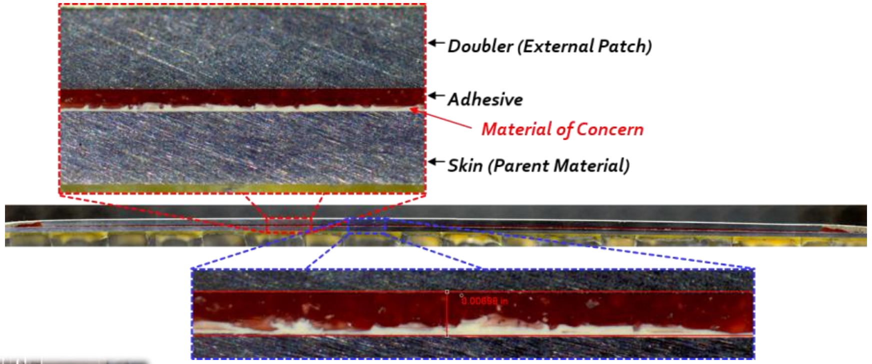
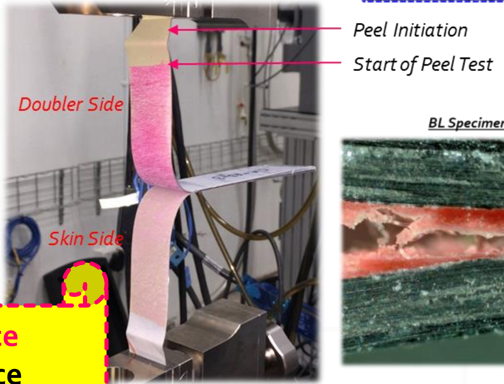
Inspection and Teardown of Aged In-Service Bonded Repairs—Phase I
October 2017
Final Report

Metallic Repair Summary – C13 & C14

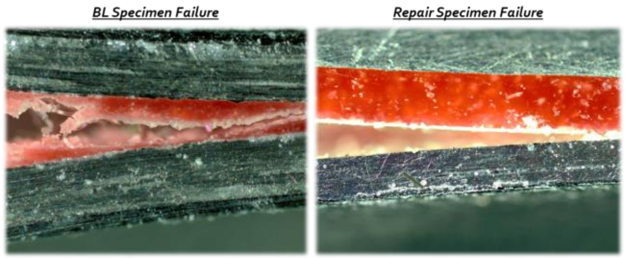
- **Lab prepared coupons used as "baseline" & compared to repair test results**
- **Component 14**
  - Interfacial anomaly between the film adhesive and parent structure when an external patch was bonded over metallic honeycomb core repairs (<u>witnessed on all 6 bonded repairs</u>)
  - Mechanical Testing: Post mechanical test failure analysis showed fracture across interfacial anomaly in all specimens
    - Repair Peel Strength: **≈64% of BL panels**
    - Lap Shear Strength: **≈50% of BL panels** (BL panel strength controlled by adherend failure)
  - Thermal analysis
    - T_g of the repair material to be within 11% of the BL panels in all moisture configurations
    - Average repair adhesive DOC **≈100%**
- **Component 13**
  - Interfacial anomaly found in <u>2 out of 3 repairs</u>
    - T_g higher for repair with no interfacial anomaly
  - Thermal analysis
    - T_g of the repair material to be within 8% of the BL panels in as extracted moisture configuration
    - Average repair adhesive DOC **≈97%**

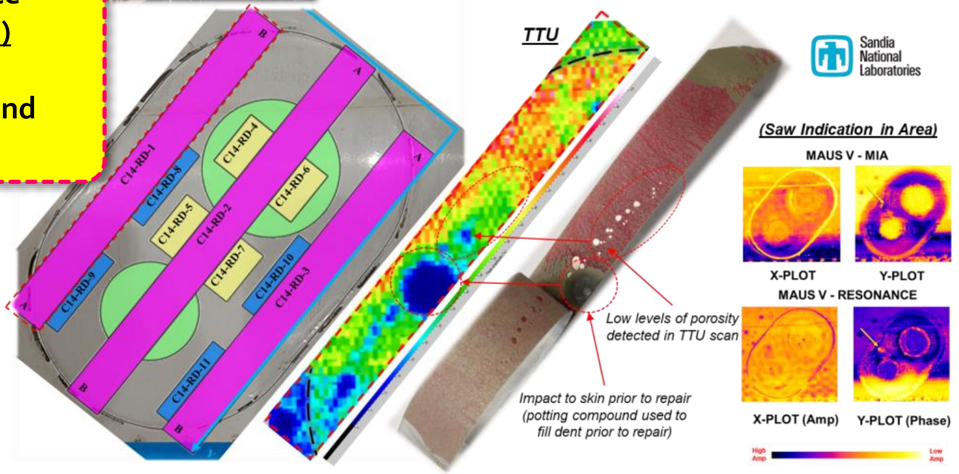
- **Poor bond performance related to repair surface preparation <u>(not aging)</u>**
- **NDI methods cannot guarantee absolute bond integrity**





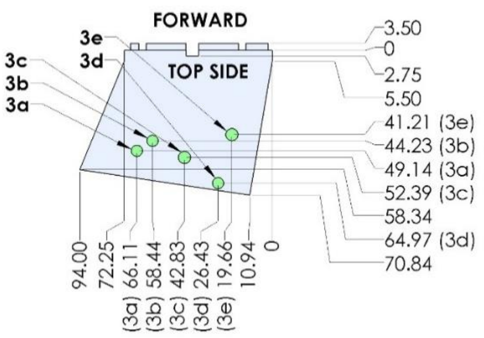
Failure Analysis

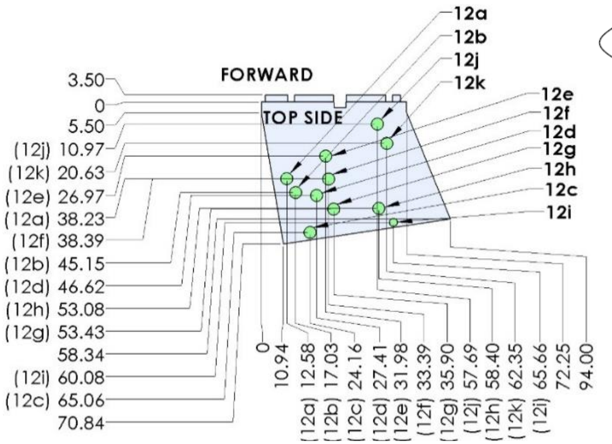


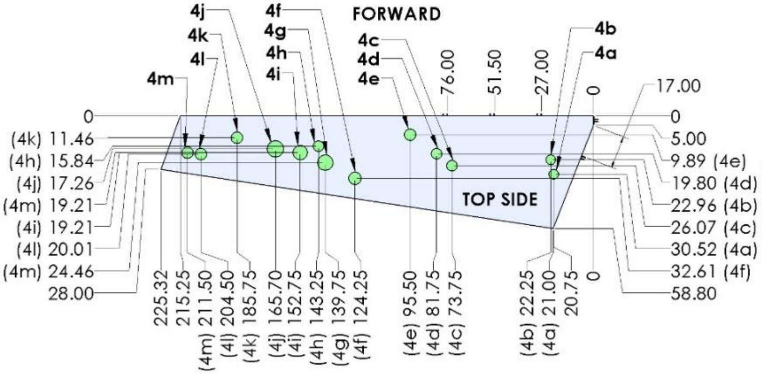


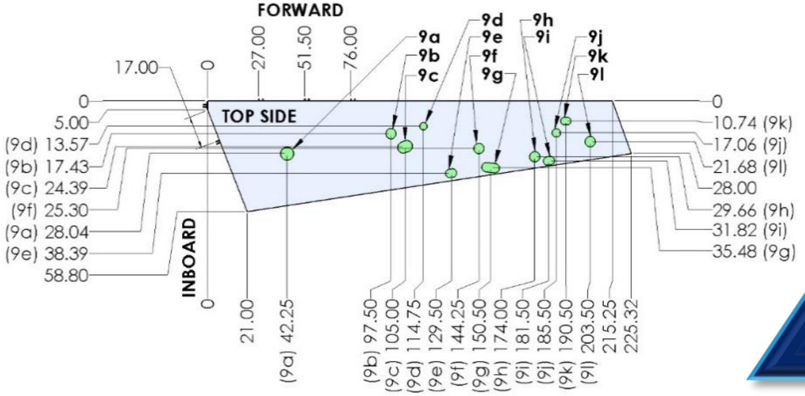
Teardown of Non-Metallic Bonded Repairs (GFY18-GFY19)
Components 3, 4, 9 & 12

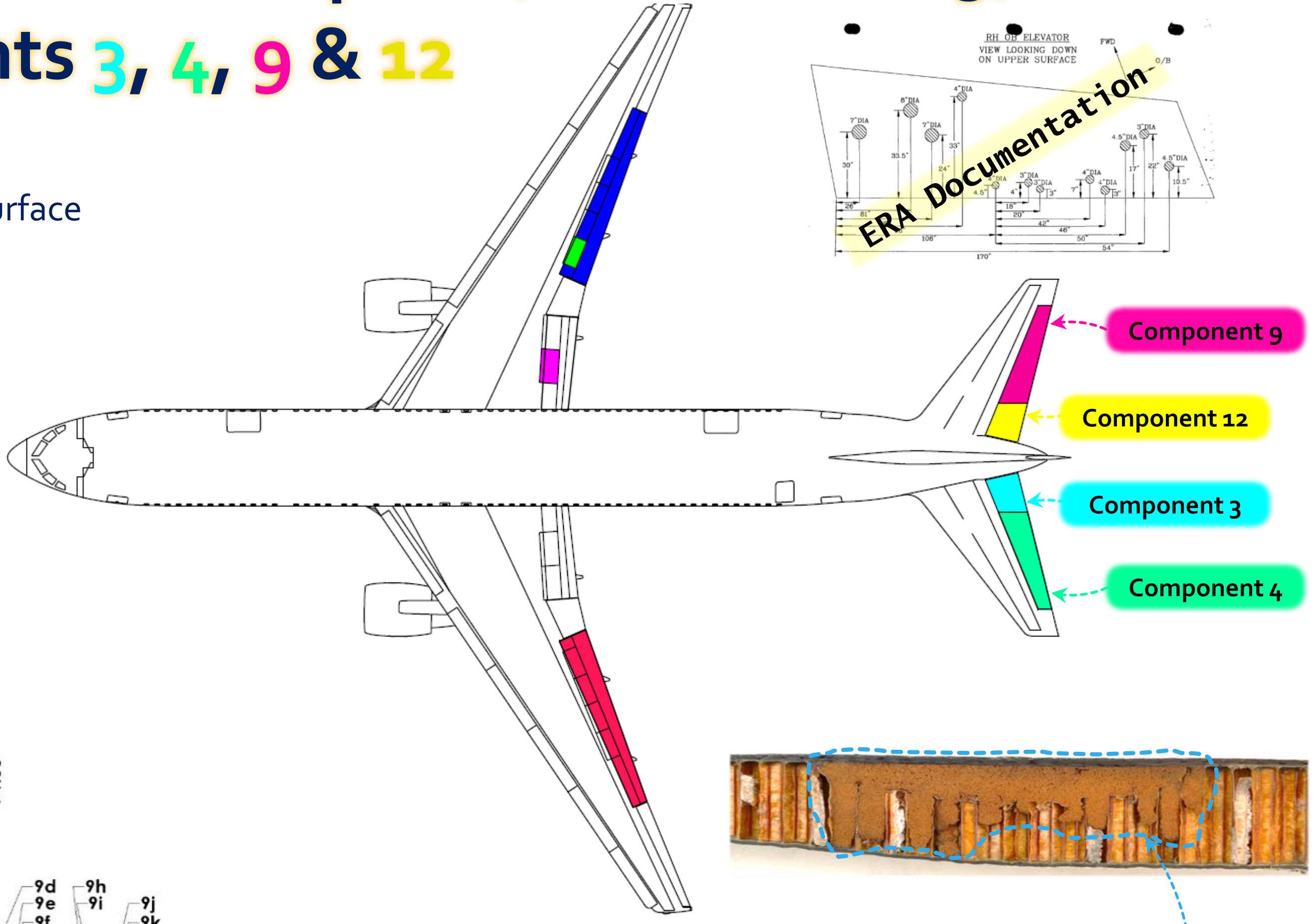
- Right & Left I/B & O/B Elevators
  - **41 Composite Repairs** (Similar Constructions / Repairs) to Upper Surface
- Honeycomb Sandwich Construction
  - 350°F cured CFRP Facesheets (2-4 plies in thickness)
  - Nomex Honeycomb Core









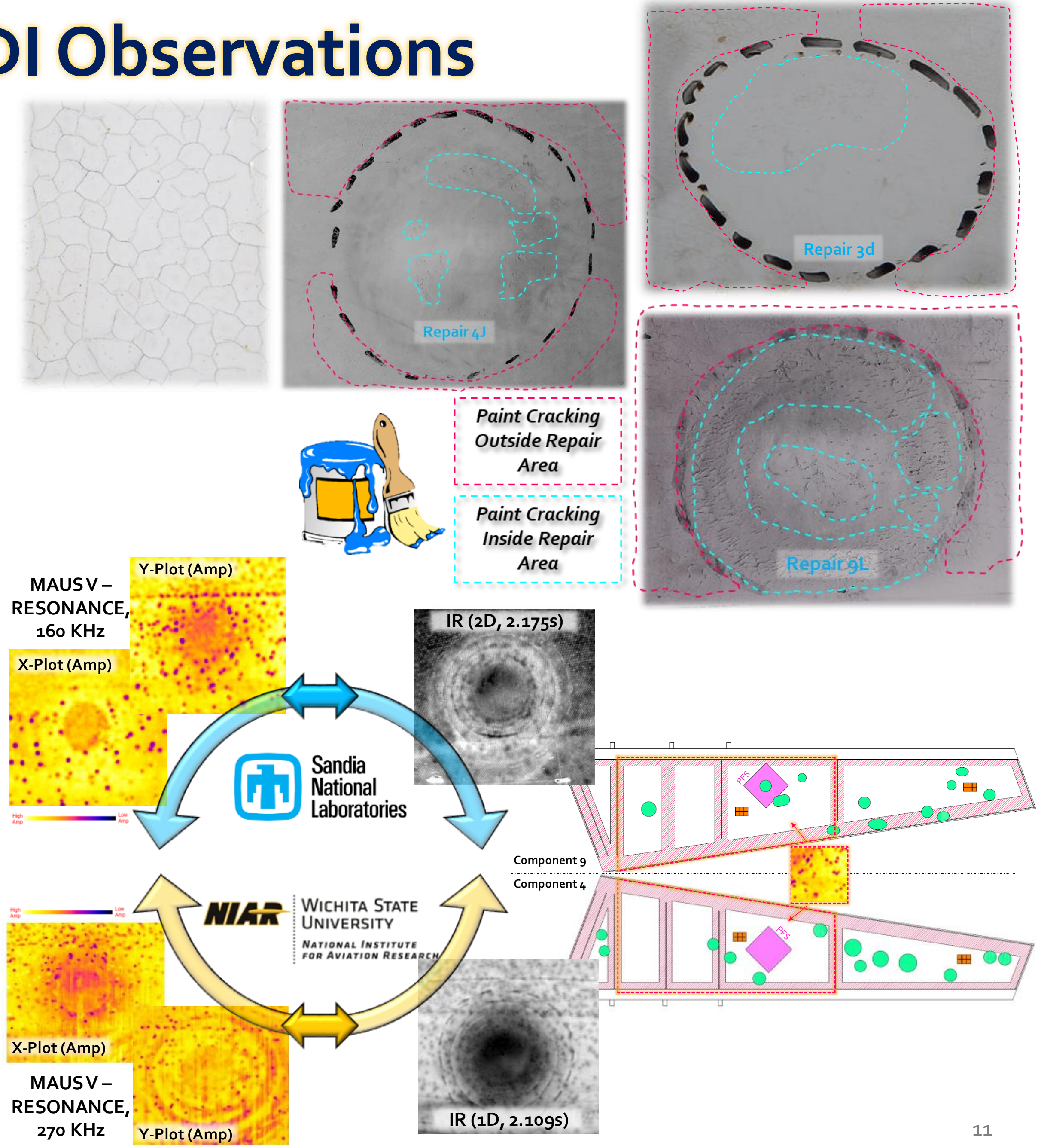


Repair Materials & Process

- 200-230°F Cure Wet Layup (Permanent Repair)
  - Laminating Resin – EA9390
  - Potting Resin – EA9390 w/ Cab-O-Sil
- No Core Replacement (Potted)
- External Fiberglass Cover Ply Added

Structural Level NDI Observations

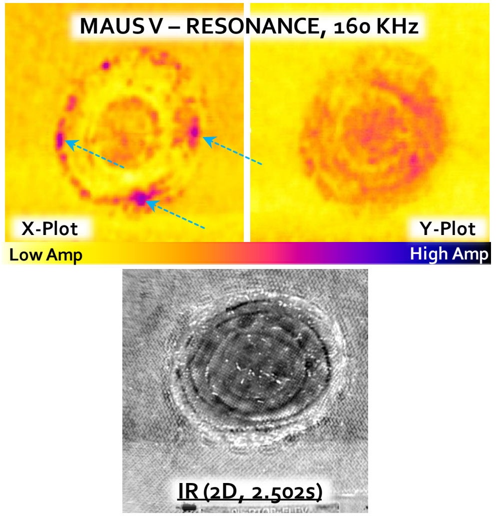
- Inspection Findings
  - Repair extended away from surface (not fully flush)
  - Paint Cracking (**32 of 41 repairs**)
    - Once cracking occurs, paint can no longer perform as an environmental barrier and can provide paths for moisture ingression to the structure
      - Concern for sandwich constructions with thin facesheets
  - Speckling Pattern (**9 of 41 repairs**)
    - Only witnessed in particular regions of O/B Components (4 & 9) – <u>finding not related to repairs</u>
    - Found in Resonance & Thermography (not witnessed with MIA)
    - Consistent amplitude change and pattern indicates build-up of material in individual honeycomb cells



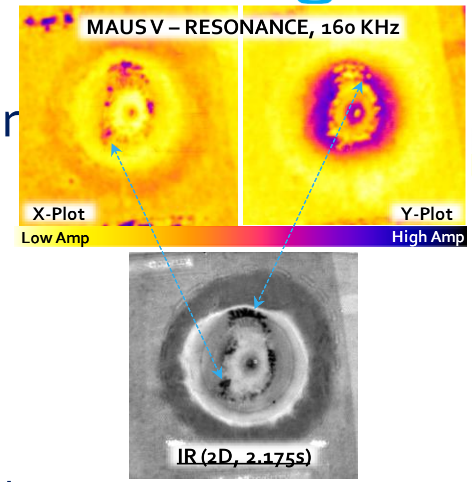
Structural Level NDI Observations

- Structural Level Inspection Findings
  - **4 of41** repairs contained indications isolated within the repair region (Repairs **4I, 4G, 9J, & 9L** – **highest interest**)
    - Indications isolated within the repair region were most pronounced in resonance and thermography inspections (not witnessed with MIA)
    - Indications could be due to porosity or small damages near repaired damage that fell within allowable damage criteria (not repaired)
    - Digital tap hammer inspections showed similar features

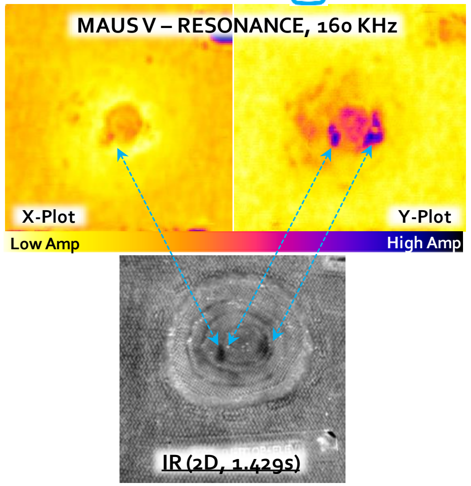
Repair 9L



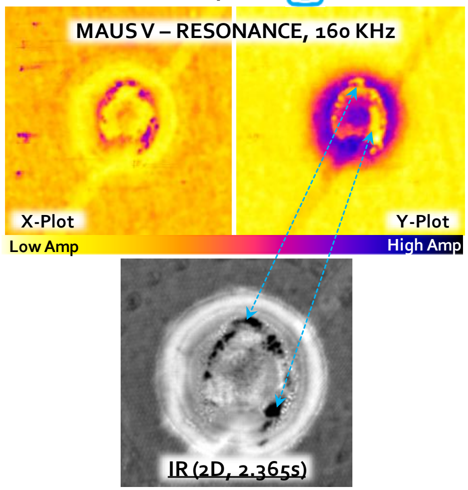
Repair 4G

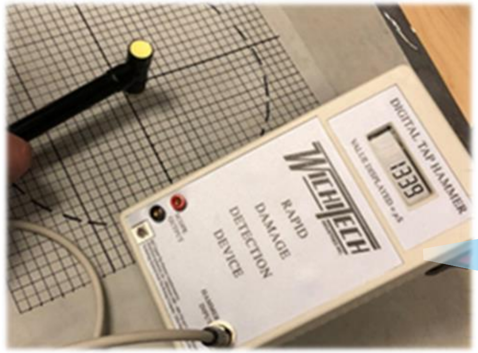


Repair 9J

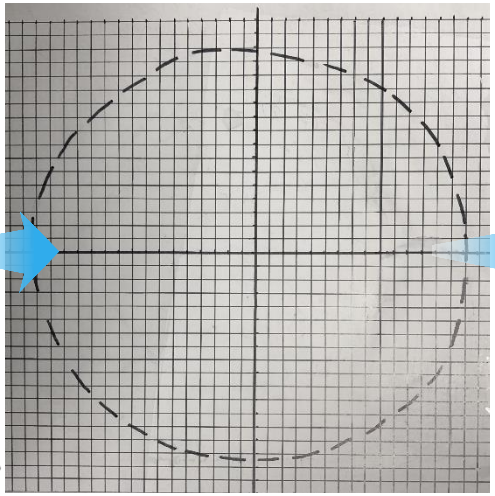


Repair 4I

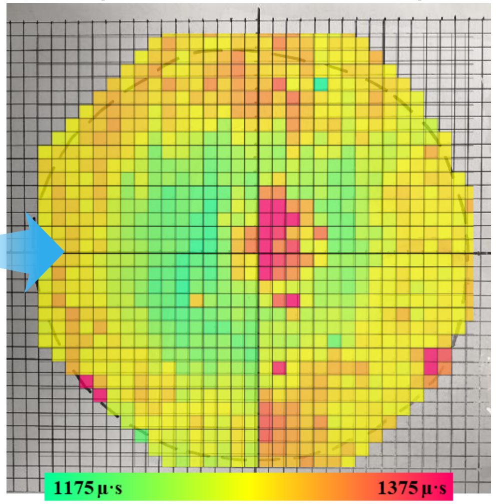




Repair 4I



Repair 4I DTH Results Overlay



Repair 4I

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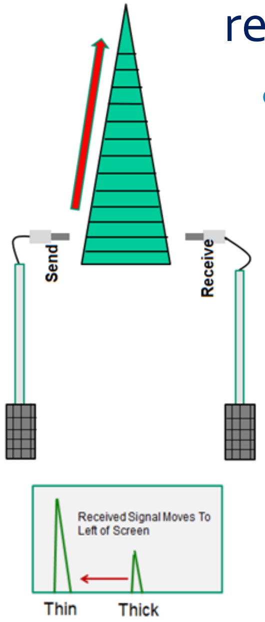
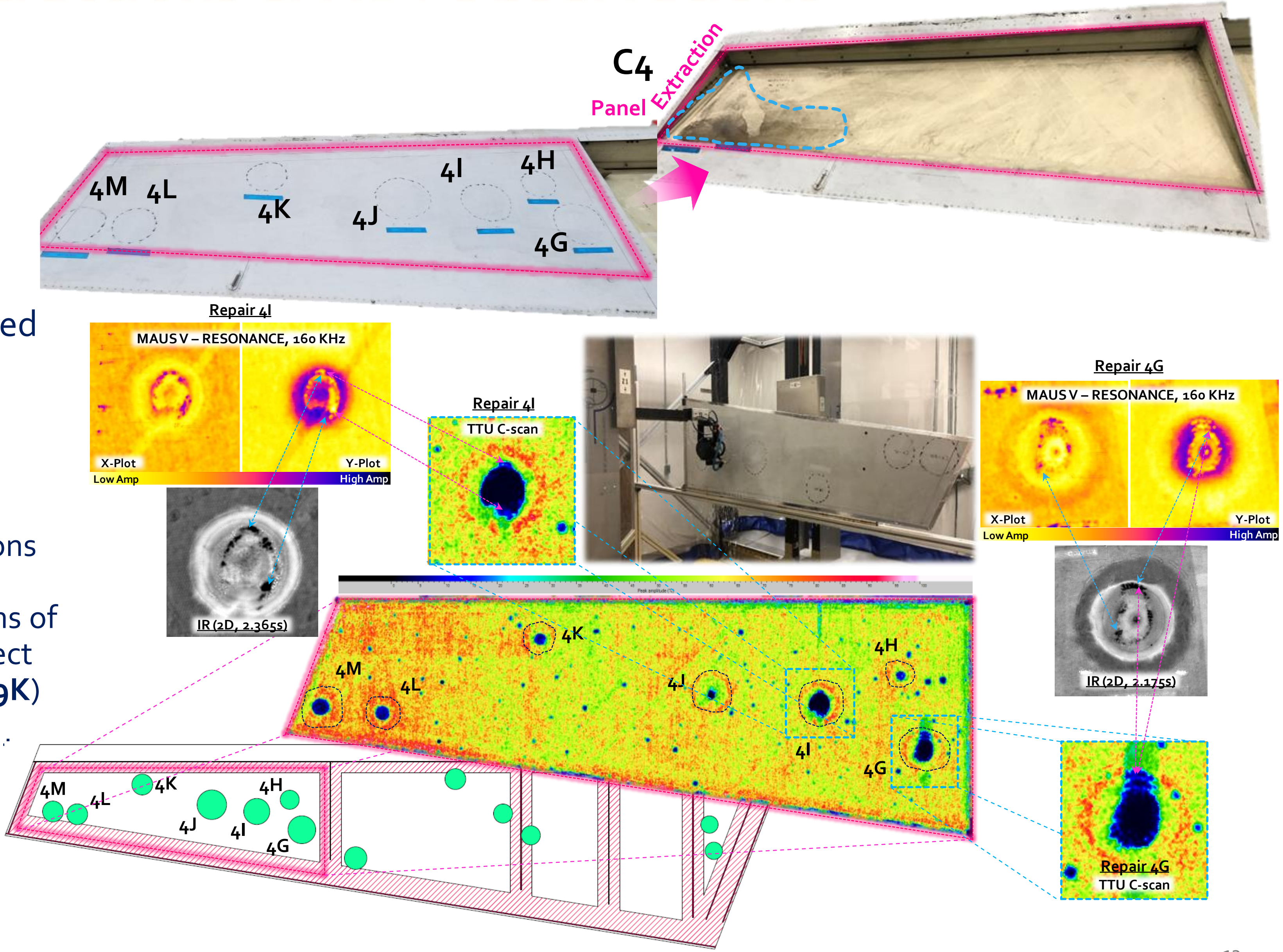
Panel Extractions & NDI Observations

- Panel Level TTU C-scan Inspection Findings
  - 6 of 41 repairs contained indications isolated within the repair region
    - 4 of these 6 repairs were noted within structural level inspections for containing indications within the bond region
      - 2 repairs contained indications missed at structural level inspections due to limitations of the methods applied to detect sub-surface features (**9B & 9K**)
    - Panel inspections compared to structural level findings





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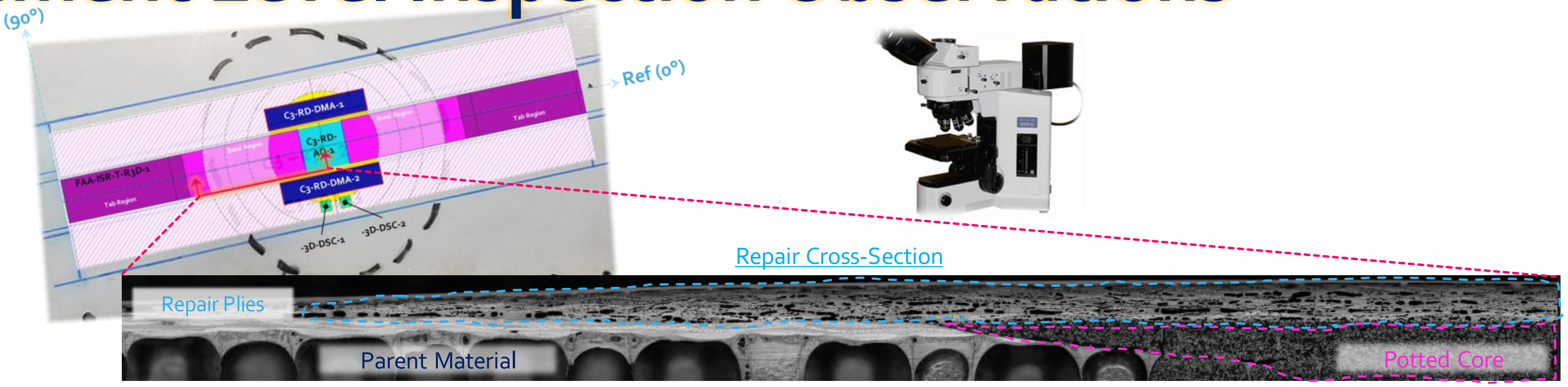
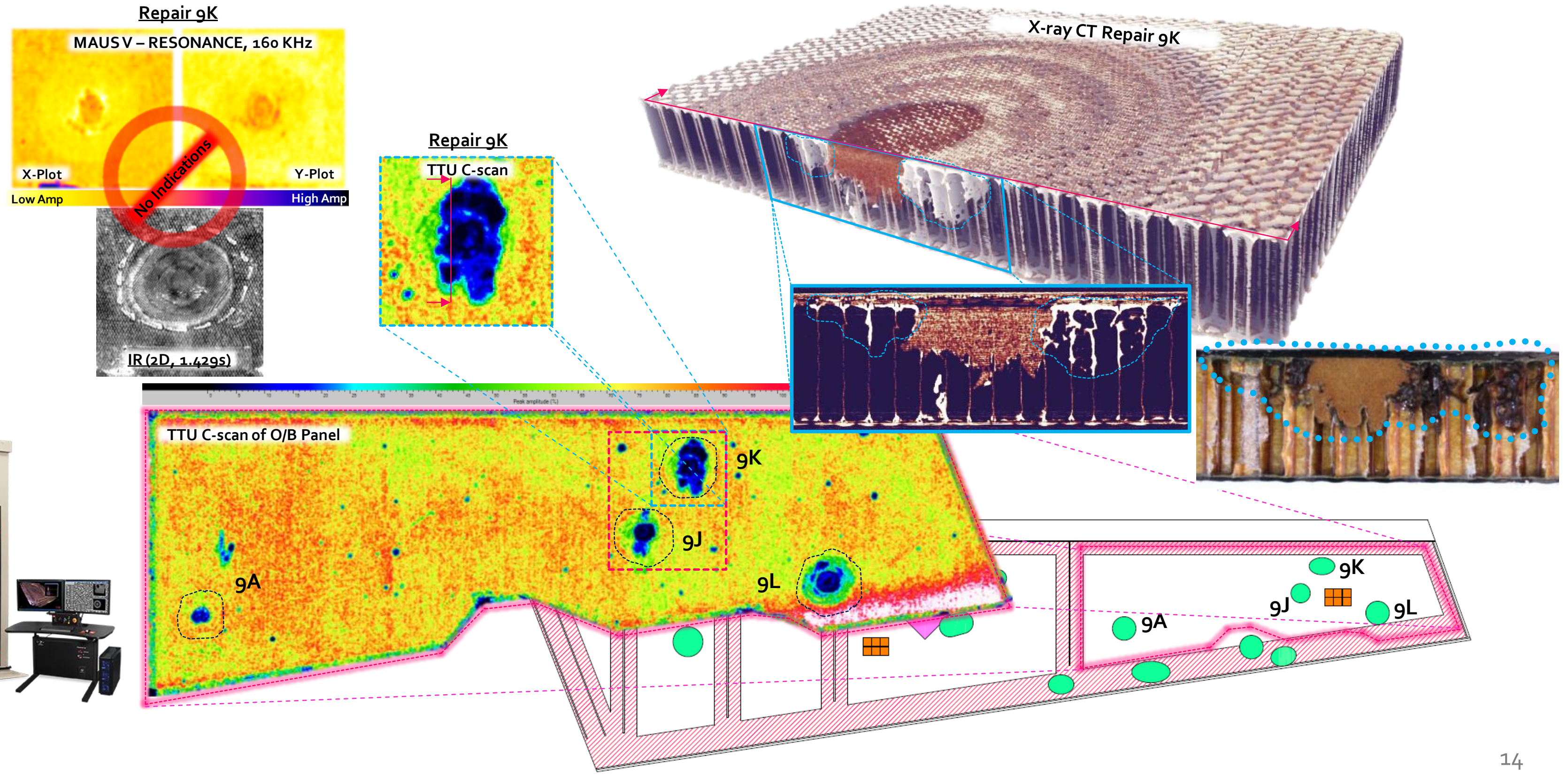
Specimen/Element Level Inspection Observations

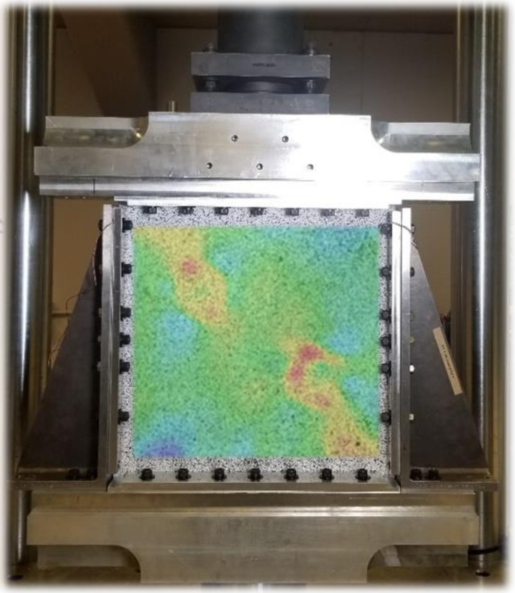
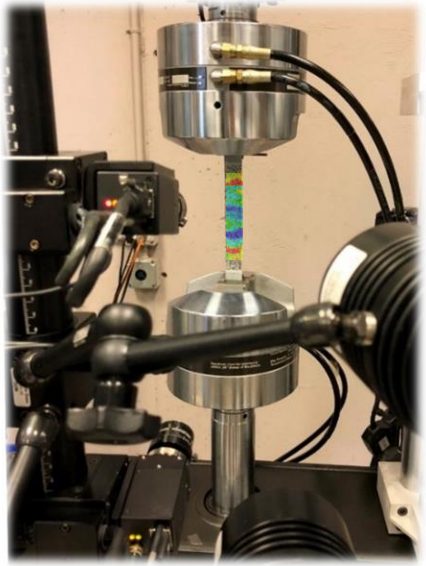
- Microscopic Inspection
  - High levels of porosity noted
  - Cross-sections evaluated to determine root-cause of indications
- X-ray CT
  - Select repairs evaluated prior to element level testing
    - Focused on repairs with indications within repair region at panel level and not structural level inspections

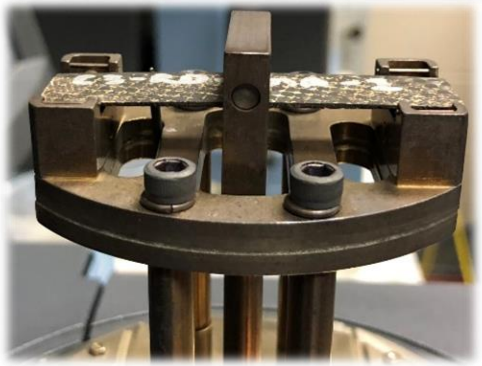




Evaluation of Non-Metallic Bonded Repairs

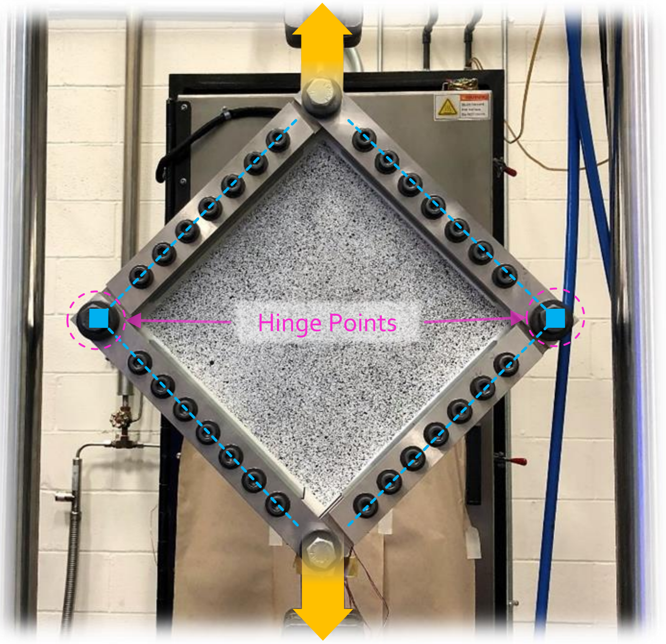
- **Mechanical Testing**
  - **Element**
    - Picture Frame Shear (PFS) Testing
    - Edgewise Compression Testing
  - **Specimen**
    - Tension Testing (Shear Strength Evaluation)
    - Flatwise Tensile Testing (parent material)
- **Physical Testing**
  - Void Content
    - Acid Digestion – ASTM D792-13/D3171-15/D2374-16
    - Image Analysis
- **Thermal Analysis**
  - Dynamic Mechanical Analysis (DMA) ASTM-D7028
  - Differential Scanning Calorimetry (DSC) ASTM-D3418

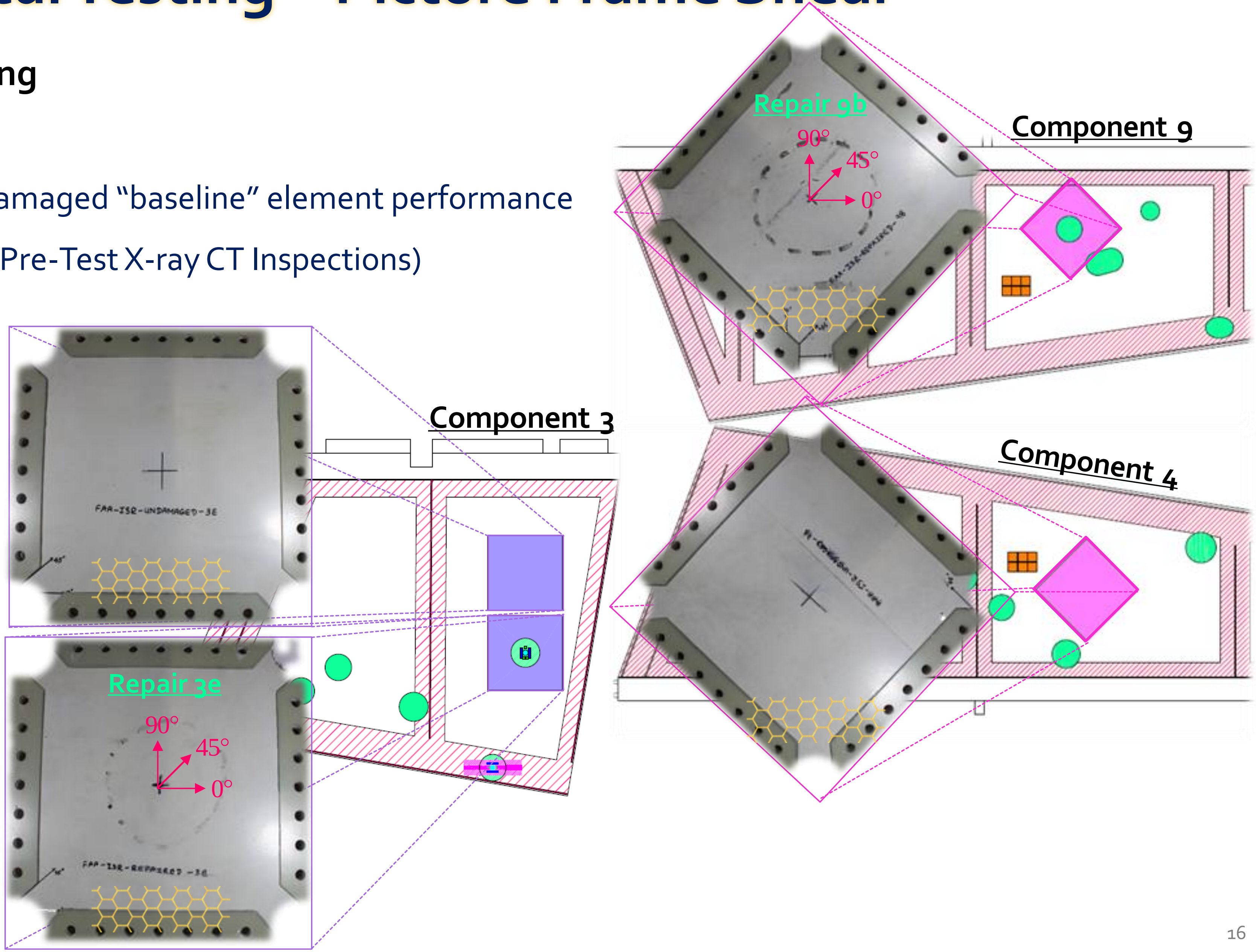







Mechanical Testing – Picture Frame Shear

- **Picture Frame Shear (PFS) Testing**
- 15.375" x 15.375" element
- Repaired element compared to un-damaged "baseline" element performance
  - Performed on repair 3e and 9b (Pre-Test X-ray CT Inspections)
  - Full-field strain (ARAMIS)





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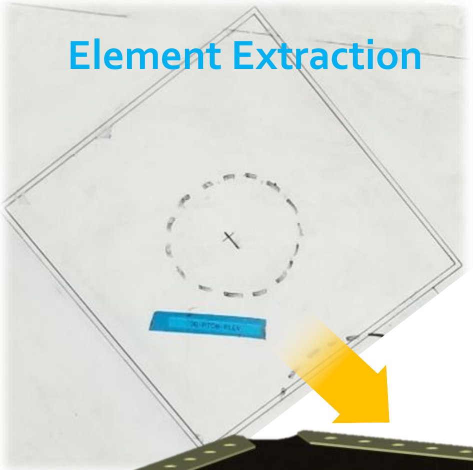
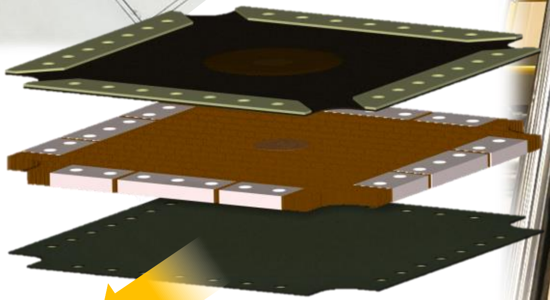
Mechanical Testing – Picture Frame Shear

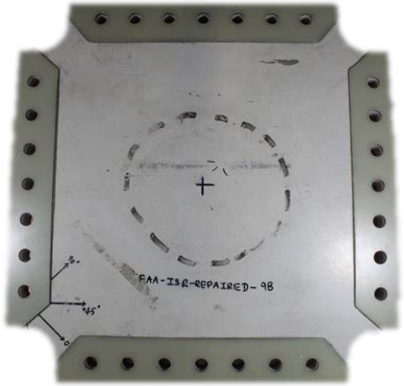
- **Picture Frame Shear (PFS) Test Approach**
  - Potting and tabs used to reduce stress concentrations at holes
  - Following testing, a failure analysis was performed and testing was completed on fragments of repair material

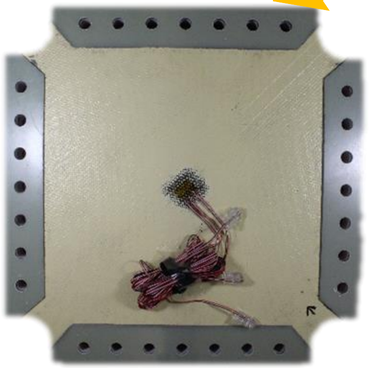
Element Extraction



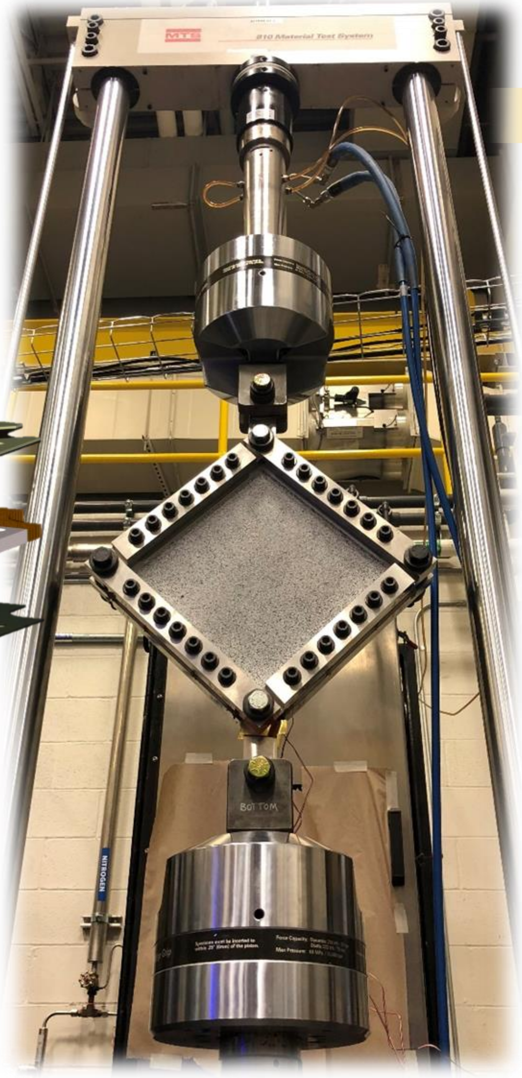
Potting/Tabbing/ Machining





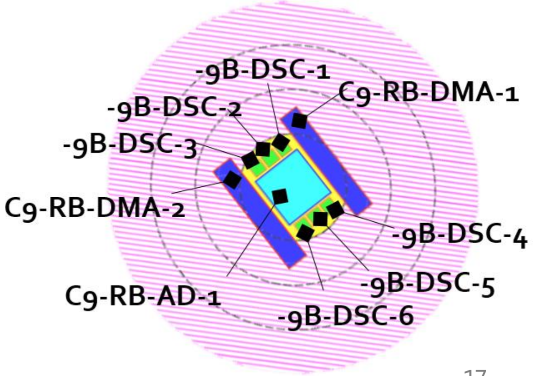


Mechanical Testing



Failure Analysis

Fragment Physical/Thermal Testing



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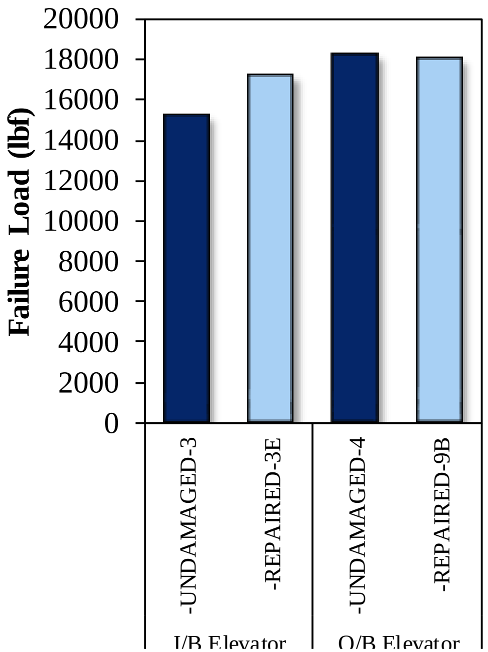
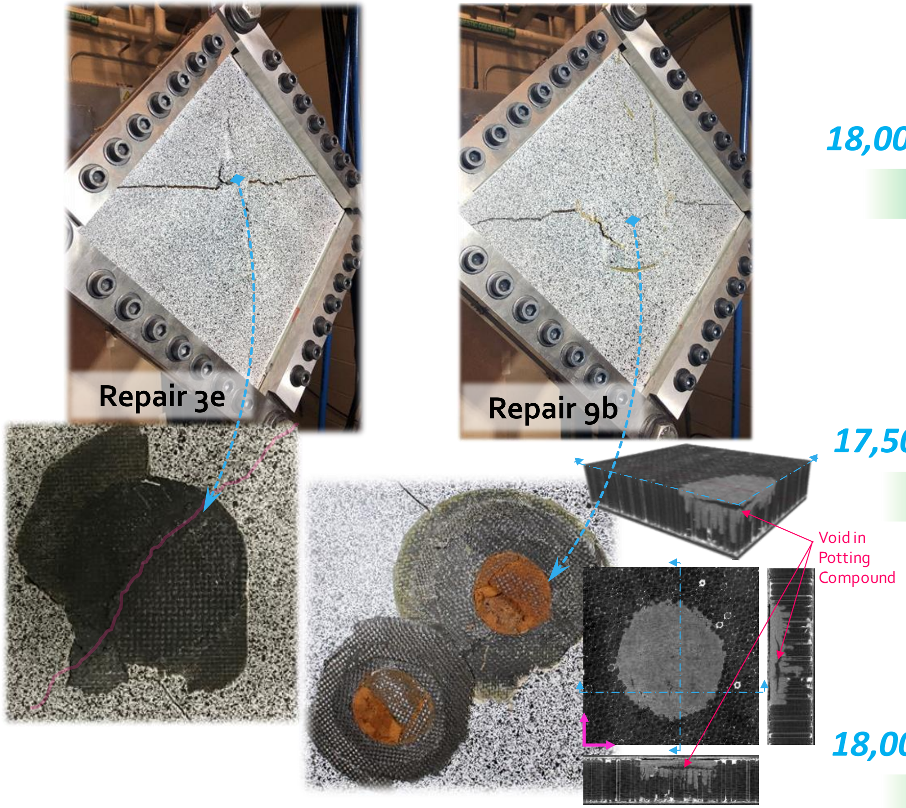
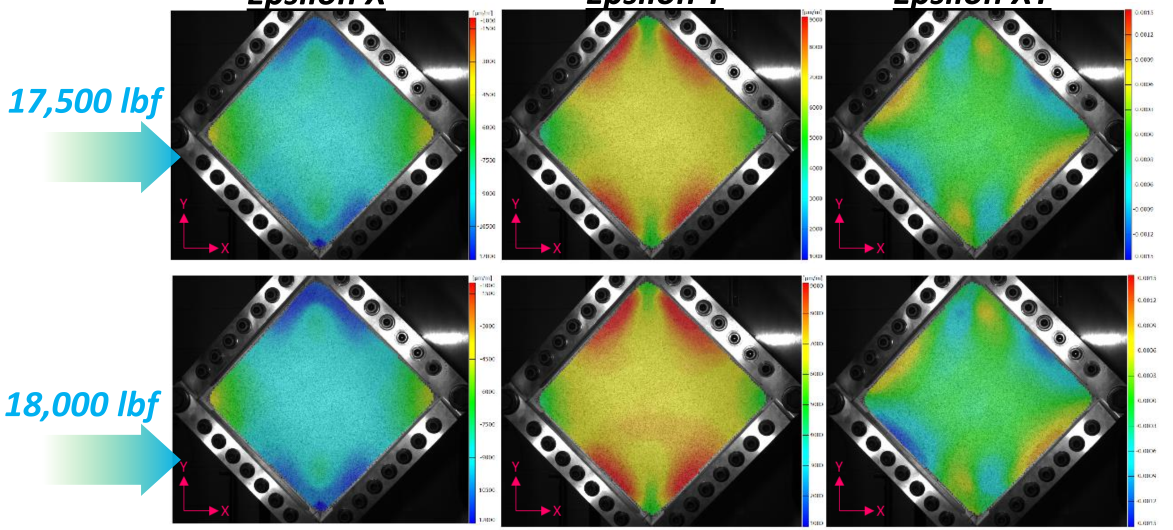
Picture Frame Shear Test Results

- **PFS Test Results**
  - No significant loss in strength witnessed
  - Repair 9b popped away from parent material with no failure through patch material
  - Repair 3e failed through repair patch material

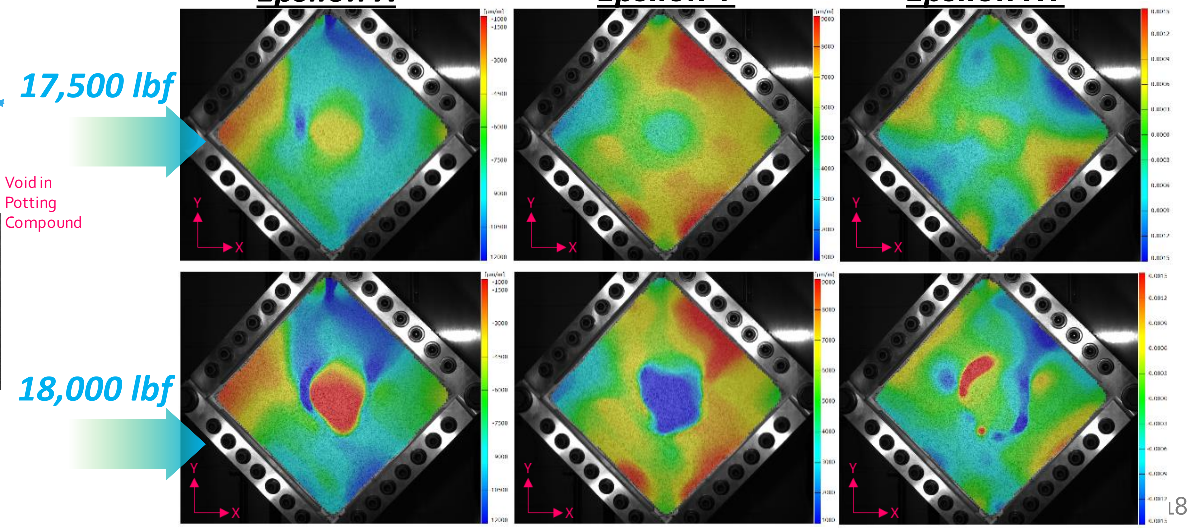




Baseline (Undamaged – Component 4) – ARAMIS



Repaired (Repair 9B) – ARAMIS



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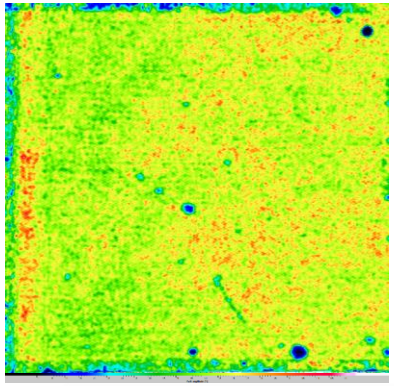
Mechanical Testing – Edgewise Compression

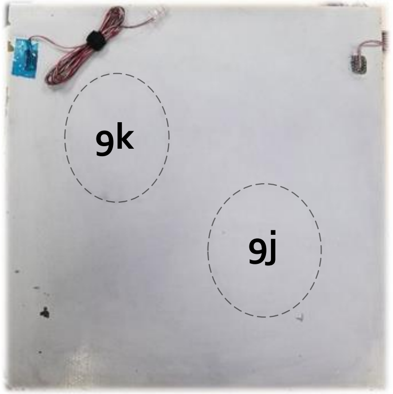
- **Edgewise Compression Configurations (16-inches x 16-inches)**
  - Pristine “Baseline” – Extracted from component 9 adjacent to repairs 9j/9k
  - Multiple Repairs (Close Proximity w/ Indications from NDI) – Component 9 repairs 9j & 9K
  - Single Repair (no indications) – Component 4 repair 4j

Pristine “Baseline” (No Repair)

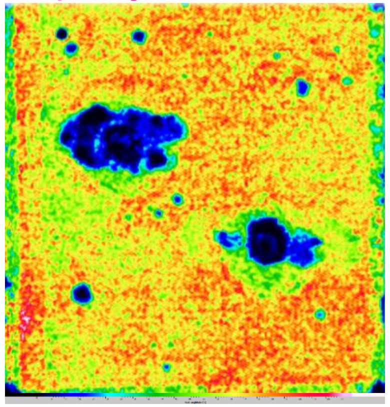
Pristine TTU C-scan



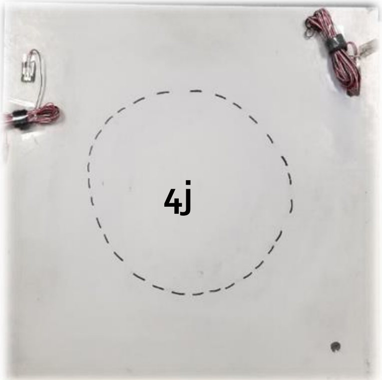
Repair 9j/9k (Multiple Repairs)



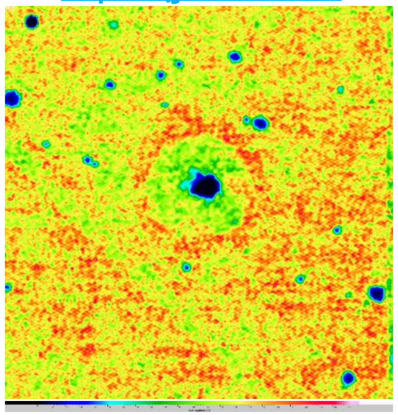
Repair 9j & 9k TTU C-scan

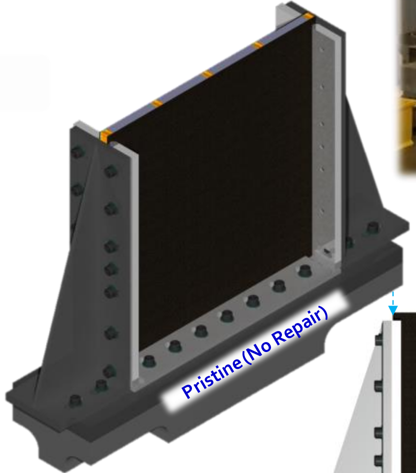


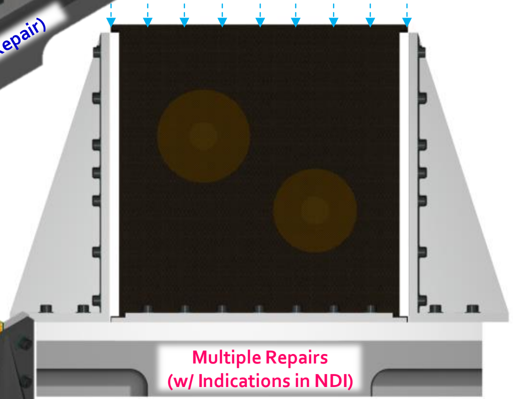
Repair 4j (Single Repair)

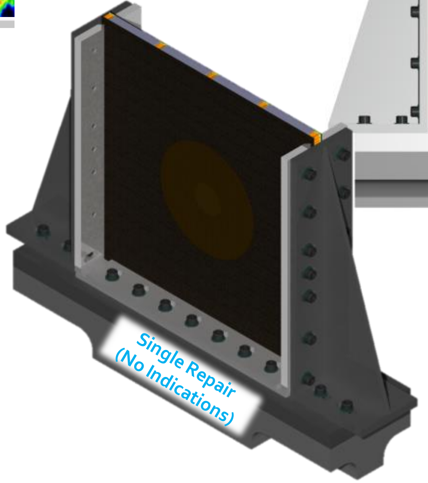


Repair 4j TTU C-scan



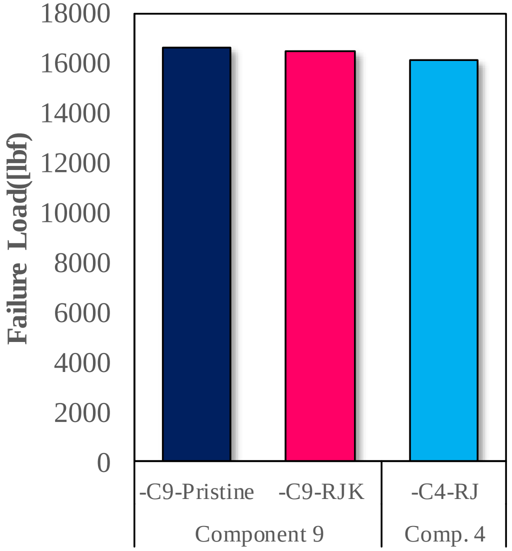


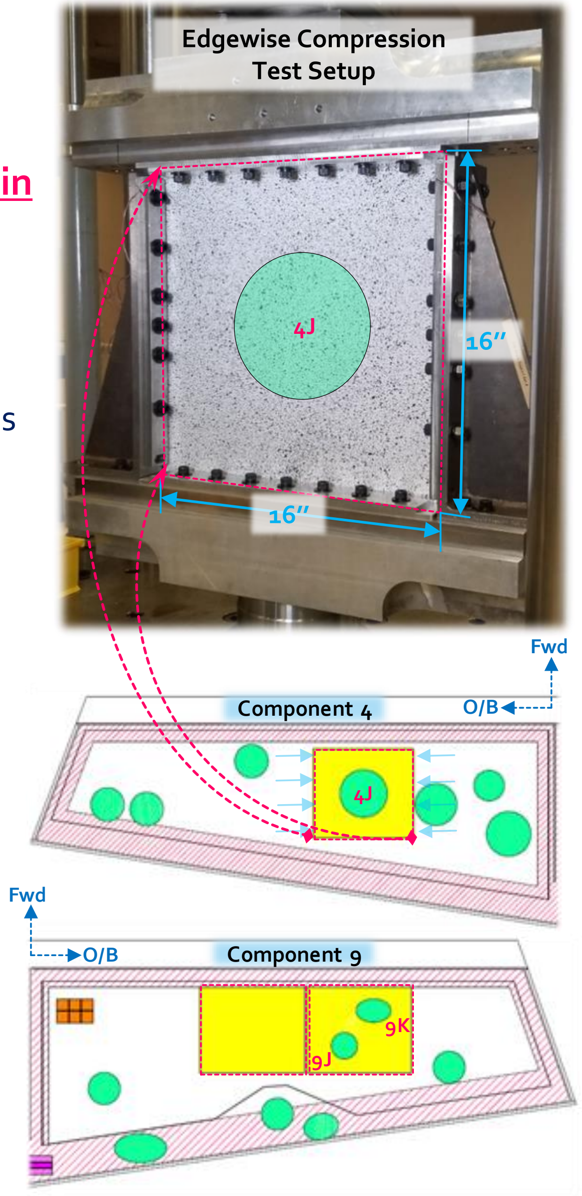


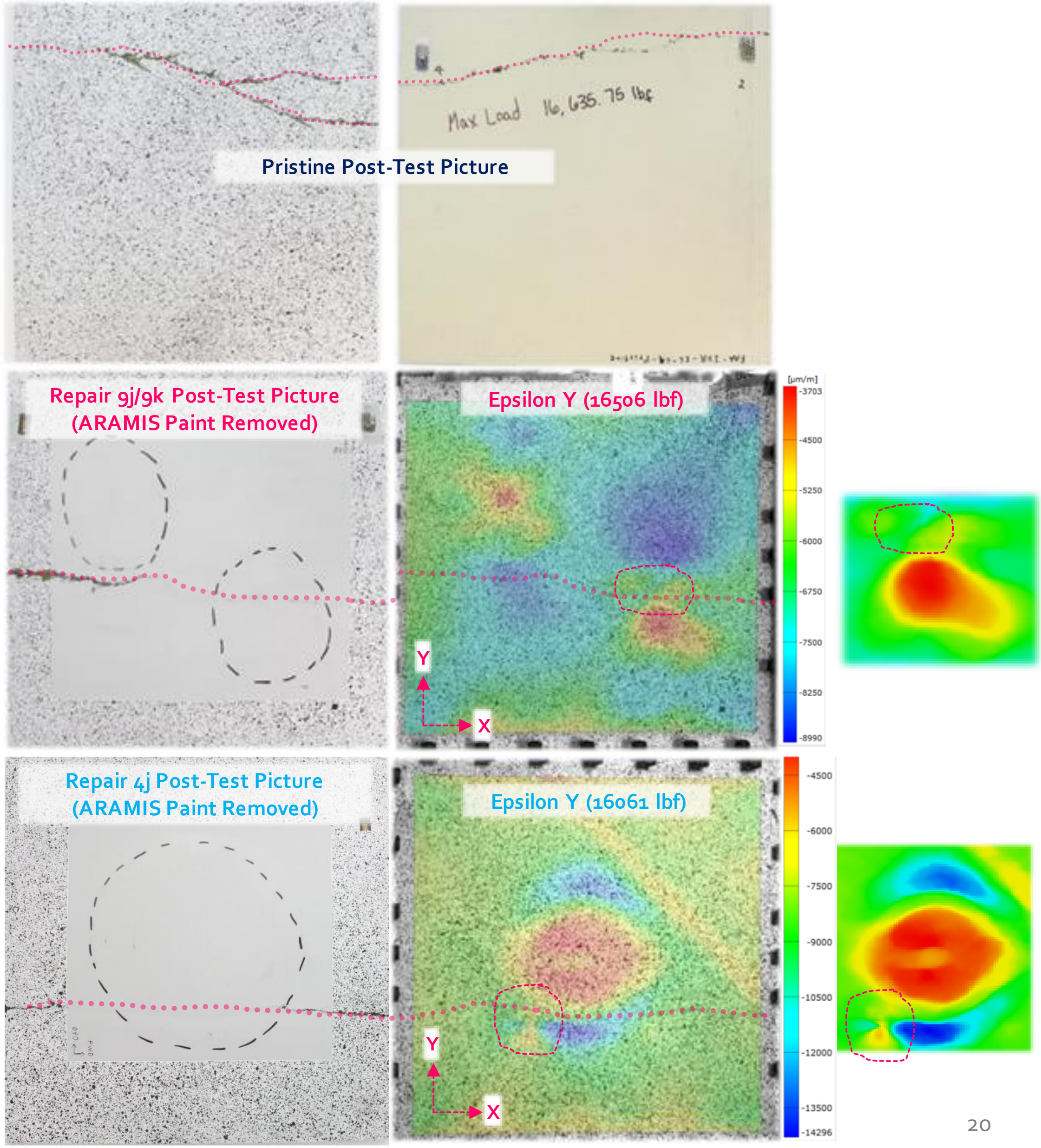


Edgewise Compression Test Results

- **Edgewise Compression Test Results**
  - No significant loss in strength witnessed (repair failure loads **within 3.2%** of pristine failure load)
  - Failure witnessed through repairs
    - Failure was not witnessed through any of the indications noted in the pre-test inspections for repair 9k

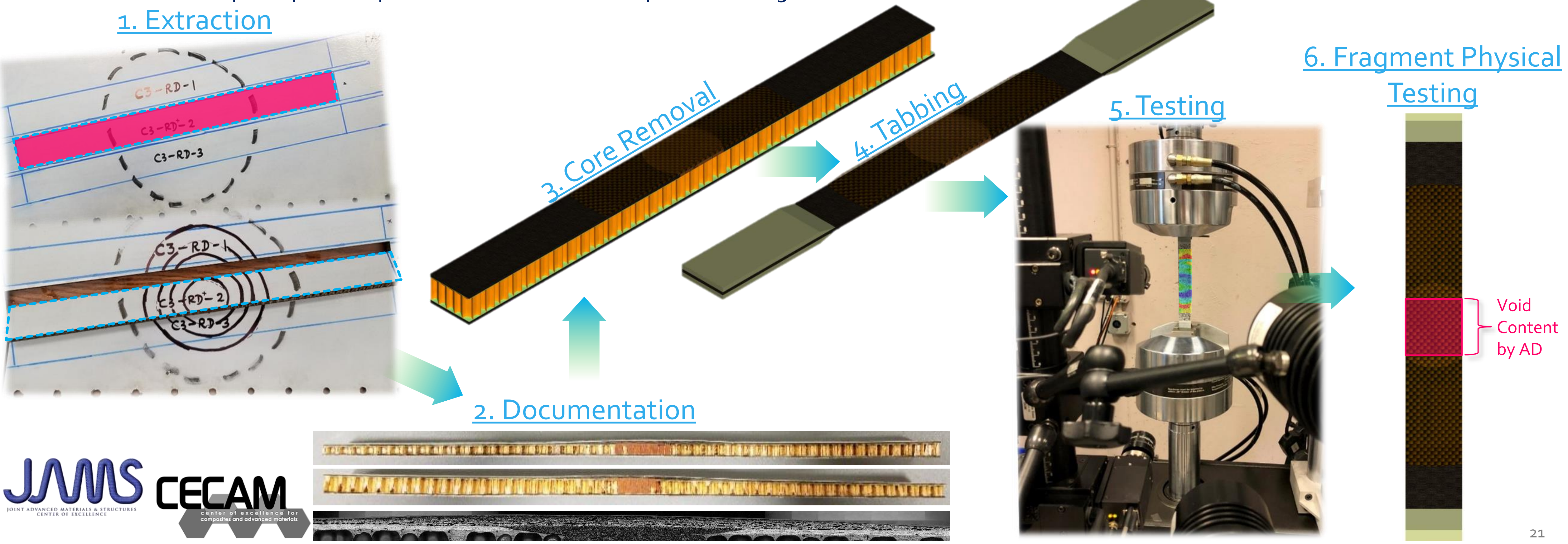






Mechanical Testing – Tension

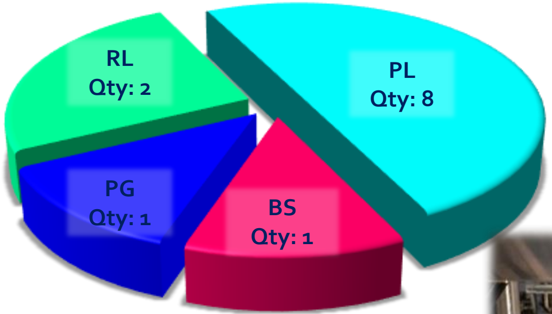
- **Evaluation of tensile strength of repair joint (Mod. ASTM D8131-17)**
  - Failure mode indicative of “weak link” (parent laminate, repair laminate, joint shear strength..etc)
  - Performed on repairs above core that varies in thickness
    - Near trailing edge of components
  - Microscopic inspections performed on cross-section prior to testing

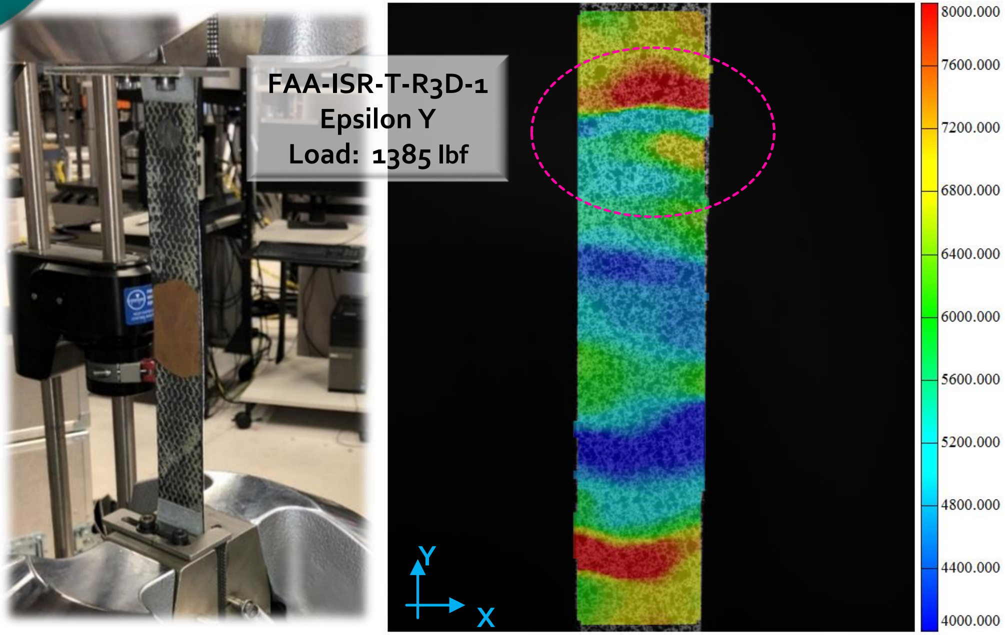


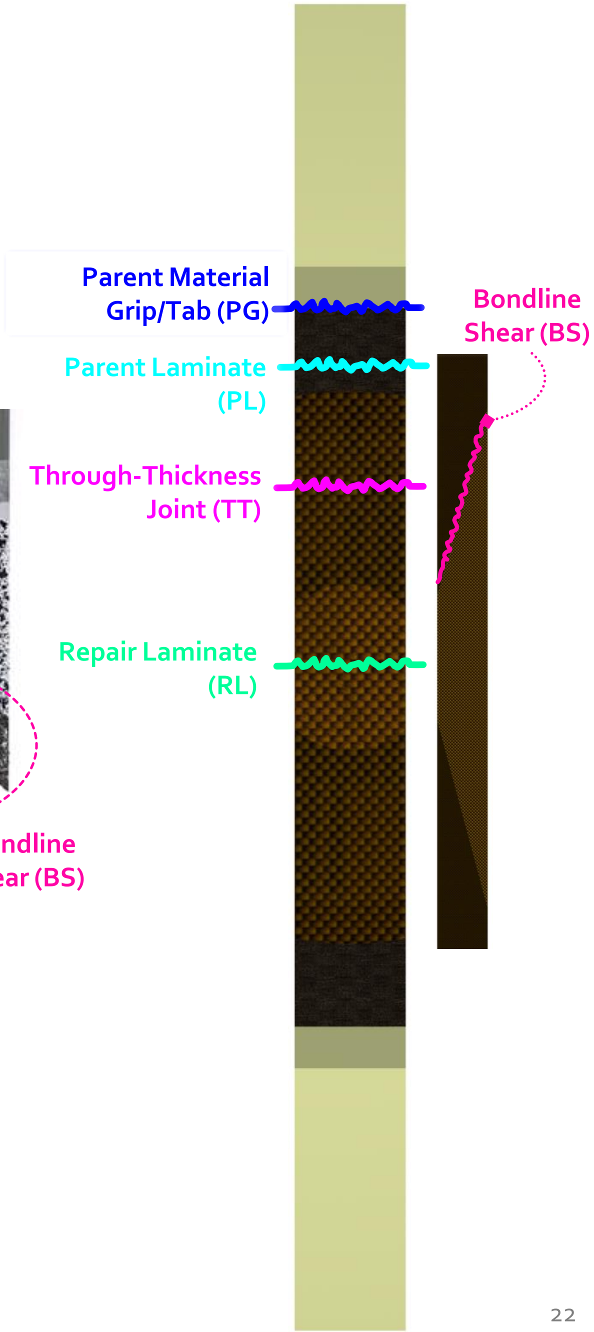
Tension Test Results

- Evaluation of tensile strength of repair joint (Mod. ASTM D8131-17)
  - High variation in results
  - Only 1 bondline shear failure

Specimen Name	Failure Load [lbf]	PL Failure Stress [ksi]	RL Failure Stress [ksi]	Failure Mode
C3-RC-2	1010.601	23.216	20.458	RL
C3-RD-2	1394.197	43.031	26.287	BS
C4-RC-2	1293.195	34.513	25.947	RL
C4-RG-2	736.913	43.708	36.427	PL
C4-RI-2	1041.473	40.057	33.063	PL
C9-RD-2	332.520	32.066	11.791	PL
C9-RE-2	1084.178	30.116	27.448	PG
C12-RC-2	1594.913	35.978	25.249	PL
Failure Stress [ksi]		**37.067**	**26.602**	
Standard Deviation		6.944	7.500	
% Coefficient of Variation		18.733	28.194	

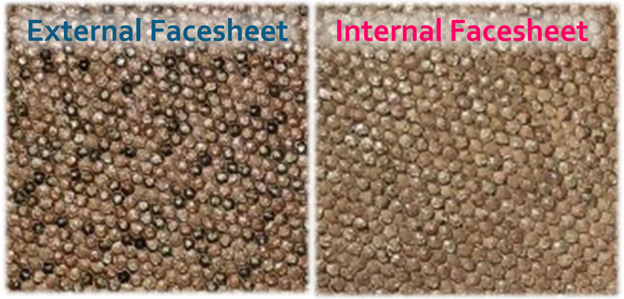


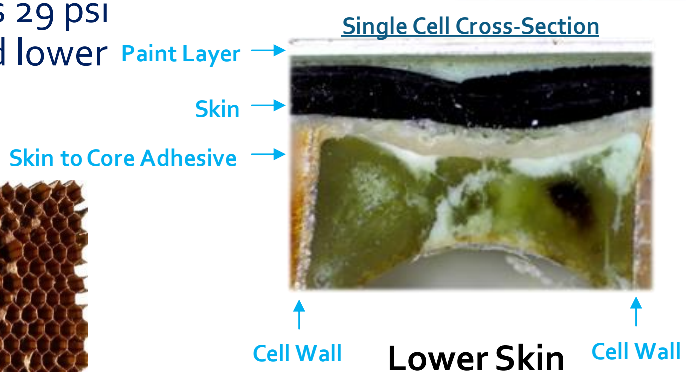




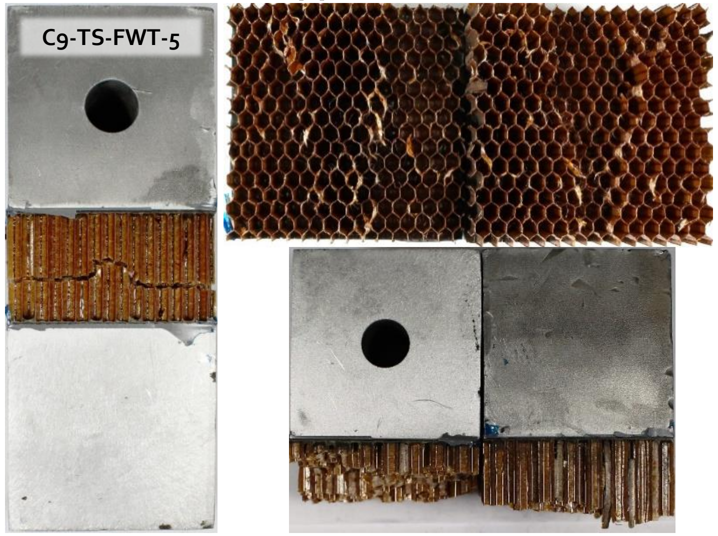
Mechanical Testing – Flatwise Tensile Strength (Parent Mat.)

- **FWT Test Results**
  - Average FWT Strength: 306.882 psi
    - Core Failure
    - On average, the inboard upper skin FWT strength was 29 psi lower than the inboard lower skin FWT strength

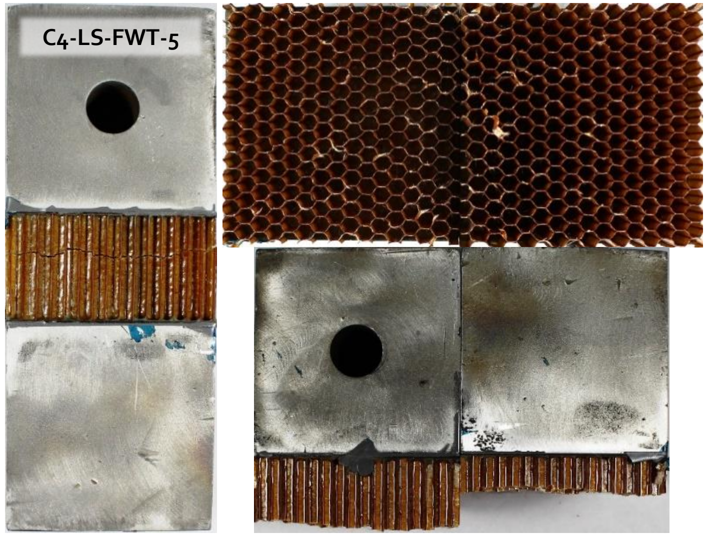


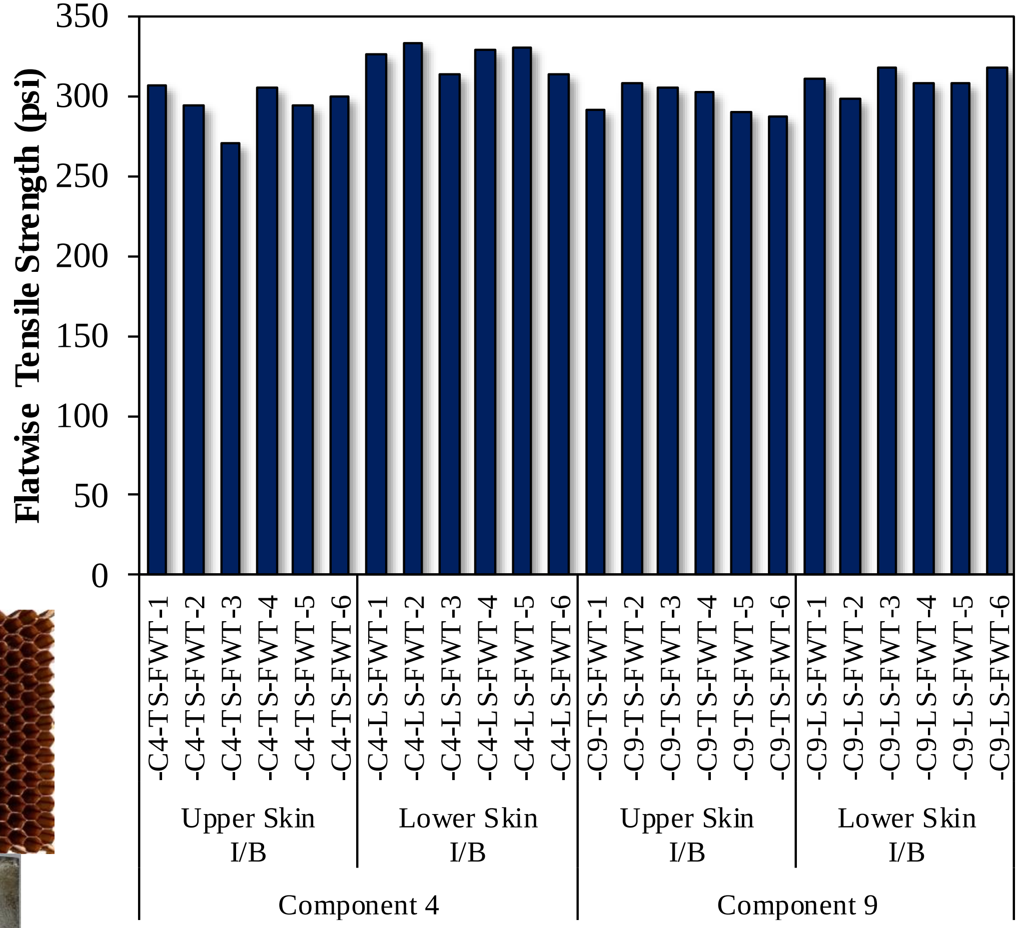


Upper Skin



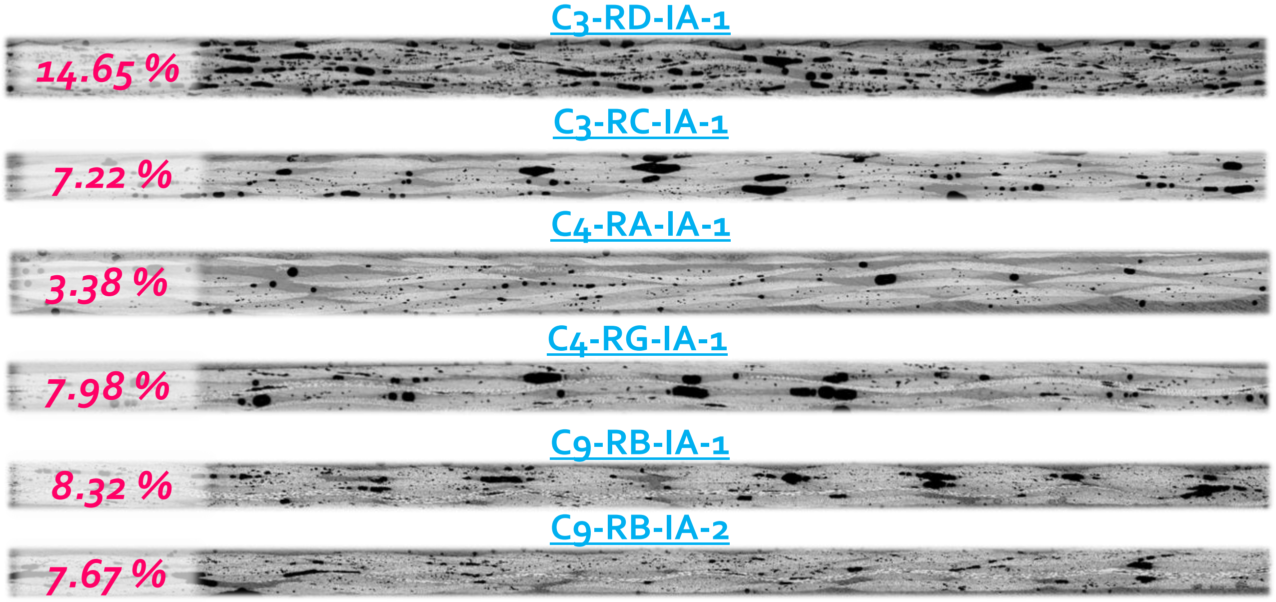
Lower Skin

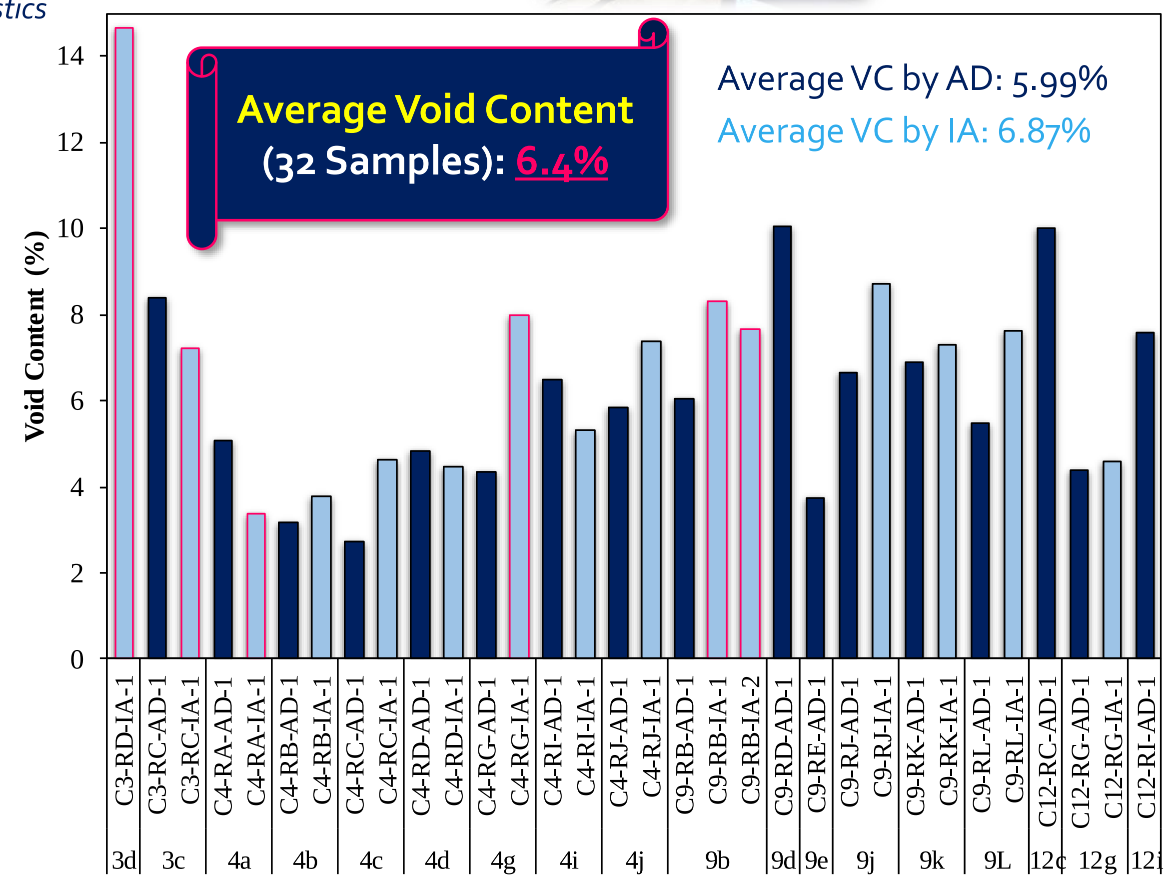




Physical Testing – Void Content

- Acid Digestion (AD)
  - Requires 1" x 1" extraction and known fiber/resin densities
    - **ASTM D792-13** – *Standard Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement*
    - **ASTM D3171-15** – *Standard Test Methods for Constituent Content of Composite Materials*
    - **ASTM D2734-16** – *Standard Test Methods for Void Content of Reinforced Plastics*
- Image Analysis (IA)
  - Performed when a 1" x 1" extraction was not feasible
    - Compared to AD results on select repairs





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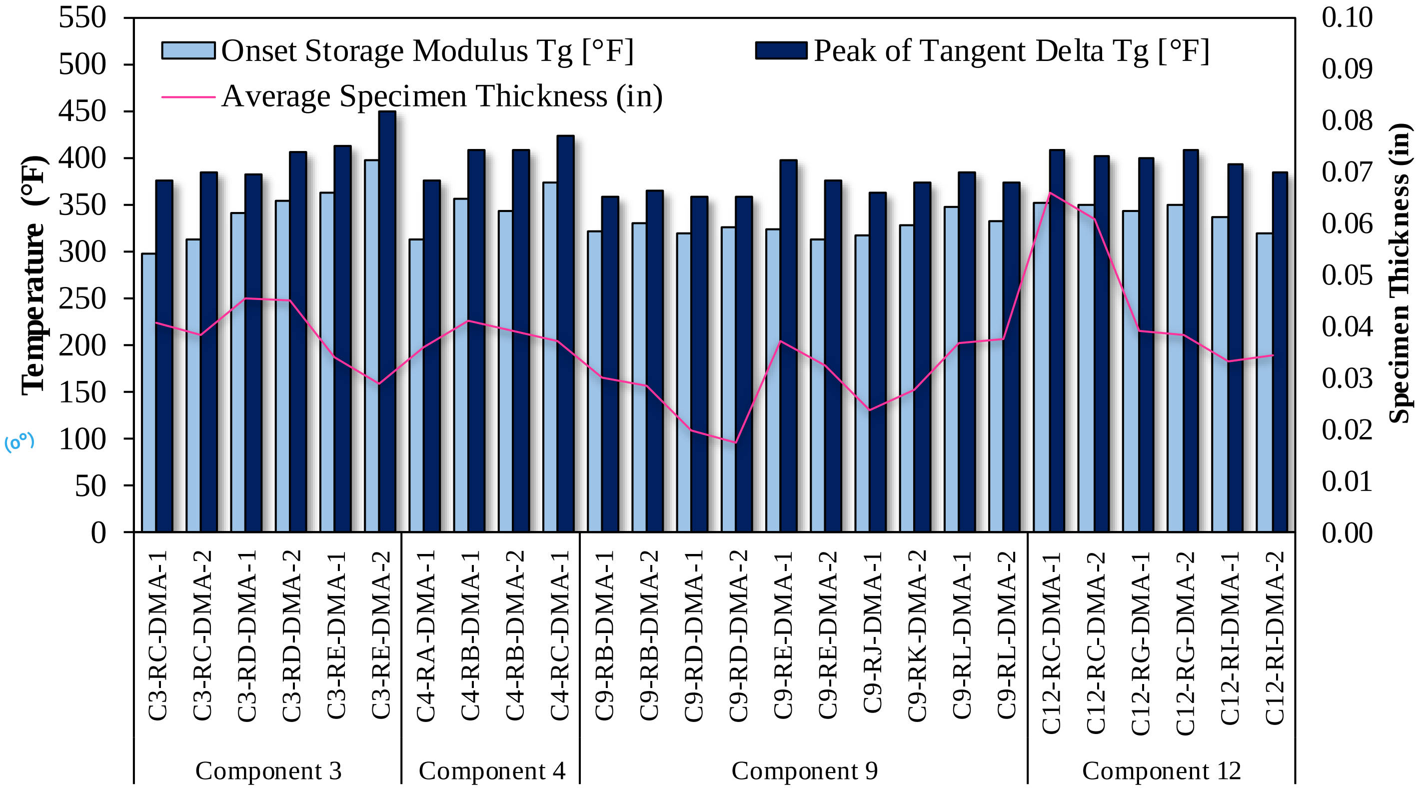
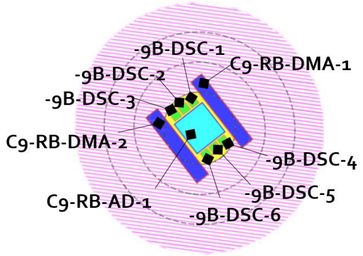
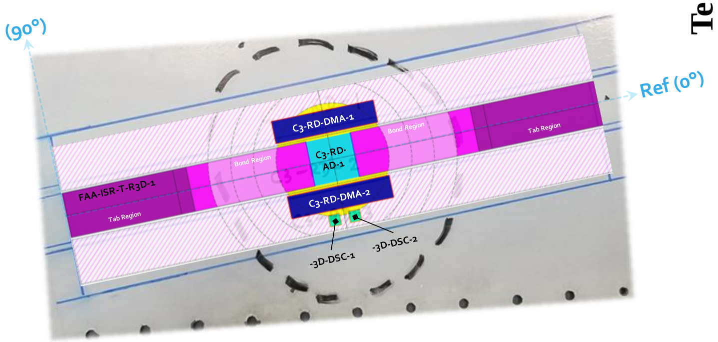
Thermal Analysis – DMA

- **Dynamic Mechanical Analysis (DMA)**
  - Evaluation of glass transition temperature (T_g)
  - 2.3" x 0.5" specimen used for 50 mm 3-point bend (repair patch material separated from parent material)
    - **ASTM D7028-07** – *Standard Test Method for Glass Transition Temperature (DMA Tg) of Polymer Matrix Composites by Dynamic Mechanical Analysis (DMA)*
  - Tested in as-extracted moisture configuration

Average Onset Storage Modulus Tg: **338.16°F** (6.48% COV)
Average Peak of Tangent Delta Tg: **389.70°F** (5.80% COV)
EA9390 TDS:
- **Dry Tg: 345°F**
- **Wet Tg: 302°F**

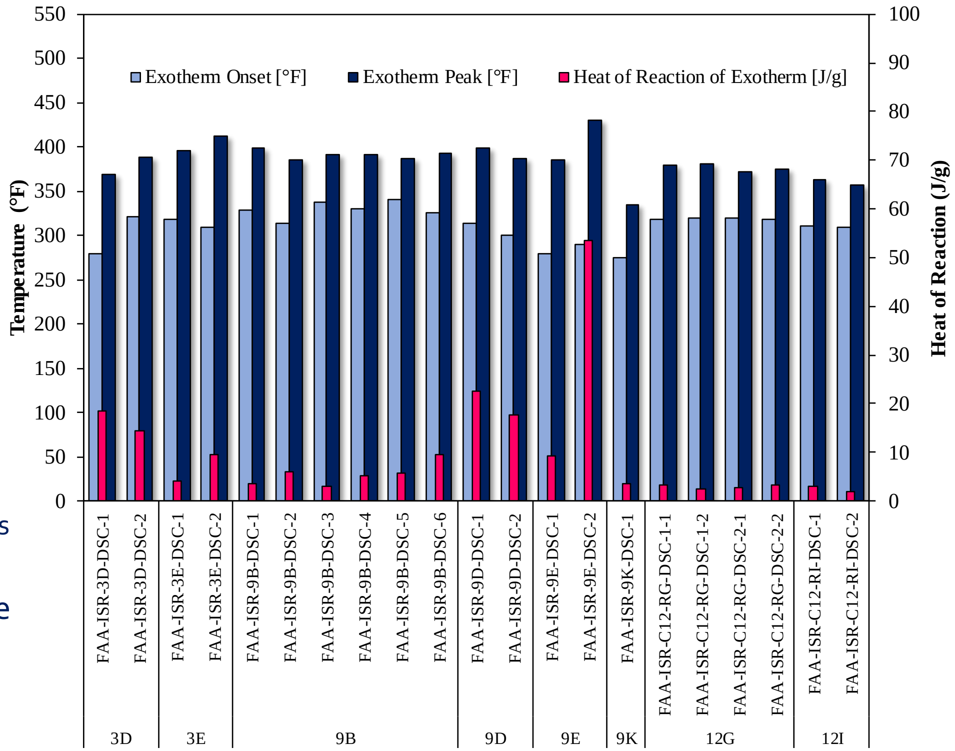


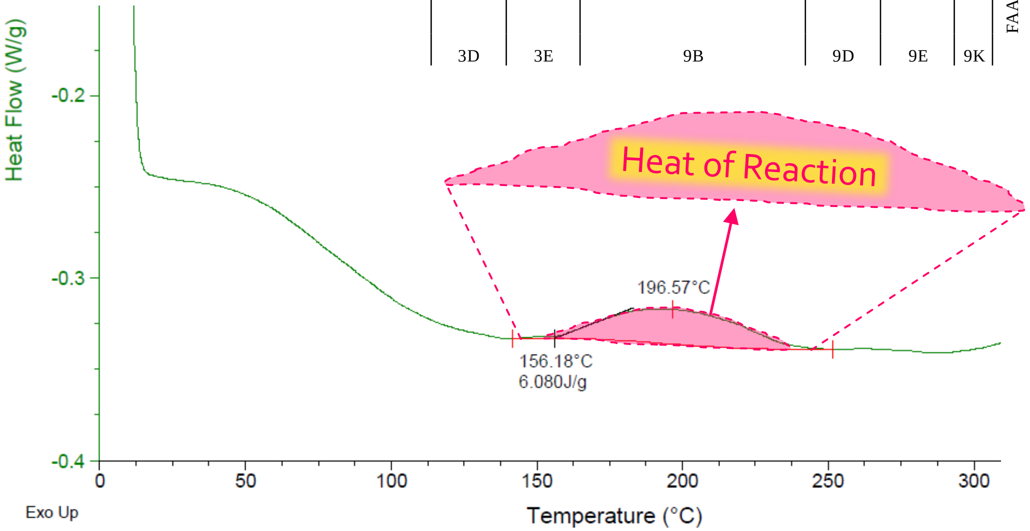




Thermal Analysis – DSC

- **Differential Scanning Calorimetry (DSC)**
  - Evaluation of degree of cure
  - 5-10 mg samples
    - **ASTM D3418-15** – *Standard Test Method for Transition Temperatures and Enthalpies of Fusion and Crystallization of Polymers by Differential Scanning Calorimetry*
  - Extracted repair material was used as an indicator for the degree of cure
    - Average heat of reaction of **9.66 J/g**
    - High amounts of variation can be attributed to low sample weight (thin repairs) and high levels of porosity
  - Tg increases linearly with respect to the degree of cure





Repair	Specimen	Exotherm Onset [°F]	Exotherm Peak [°F]	Heat of Reaction of Exotherm [J/g]
3C	FAA-ISR-C3-RC-1	-	-	-
	FAA-ISR-C3-RC-2	-	-	-
	FAA-ISR-C3-RC-3	-	-	-
3D	FAA-ISR-3D-DSC-1	278.58	369.14	18.60
	FAA-ISR-3D-DSC-2	321.17	389.05	14.32
3E	FAA-ISR-3E-DSC-1	318.76	395.67	4.11
	FAA-ISR-3E-DSC-2	309.61	411.78	9.42
4A	FAA-ISR-4A-DSC-1	-	-	-
	FAA-ISR-4A-DSC-2	-	-	-
4B	FAA-ISR-4B-DSC-1	-	-	-
	FAA-ISR-4B-DSC-2	-	-	-
4C	FAA-ISR-4C-DSC-1	-	-	-
	FAA-ISR-4C-DSC-2	-	-	-
4D	FAA-ISR-4D-DSC-1	-	-	-
	FAA-ISR-4D-DSC-2	-	-	-
4I	FAA-ISR-4I-DSC-1	-	-	-
	FAA-ISR-4I-DSC-2	-	-	-
4J	FAA-ISR-4J-DSC-1	-	-	-
	FAA-ISR-4J-DSC-2	-	-	-
9B	FAA-ISR-9B-DSC-1	329.00	398.80	3.67
	FAA-ISR-9B-DSC-2	313.12	385.83	6.08
	FAA-ISR-9B-DSC-3	338.04	391.64	3.08
	FAA-ISR-9B-DSC-4	330.75	391.64	5.06
	FAA-ISR-9B-DSC-5	340.18	386.08	5.70
	FAA-ISR-9B-DSC-6	325.58	392.38	9.39
9D	FAA-ISR-9D-DSC-1	313.54	398.75	22.67
	FAA-ISR-9D-DSC-2	300.24	386.47	17.71
9E	FAA-ISR-9E-DSC-1	279.28	384.76	9.19
	FAA-ISR-9E-DSC-2	289.69	430.50	53.63
9J	FAA-ISR-9J-DSC-1	-	-	-
	FAA-ISR-9J-DSC-2	-	-	-
9K	FAA-ISR-9K-DSC-1	274.24	333.84	3.61
	FAA-ISR-9K-DSC-2	-	-	-
12C	FAA-ISR-C12-RC-DSC-1	-	-	-
	FAA-ISR-C12-RC-DSC-2	-	-	-
12G	FAA-ISR-C12-RG-DSC-1-1	318.60	378.82	3.22
	FAA-ISR-C12-RG-DSC-1-2	319.60	380.23	2.52
	FAA-ISR-C12-RG-DSC-2-1	319.77	372.45	2.70
	FAA-ISR-C12-RG-DSC-2-2	318.04	374.86	3.35
12I	FAA-ISR-C12-RI-DSC-1	311.29	362.62	2.98
	FAA-ISR-C12-RI-DSC-2	308.88	356.56	1.90

Program Status & Summary

- **Metallic Repairs – Components 13 & 14**
  - JAMS/AMTAS – April 2018 presented on metallic bonded repair work
  - **Report** – Inspection and Teardown of Aged In-Service Bonded Repairs – Vol. I
- **Non-Metallic Repairs**
  - **Components 3, 4, 9,12**
    - Inspection & Teardown of repairs on components 3, 4, & 9 complete (comp. 12 repairs near completion)
      - DTH showed similar indications as resonance/thermography
      - MIA did not show indications seen in resonance/thermography
    - Repair element tests showed no significant reduction in strength when compared to baseline tests performed outside repair region
    - High average porosity content witnessed (6.4%)
    - Reporting in-progress
  - **Components 5 & 6**
    - Inspections in-progress (E.C.D August 2019)
  - **Report** – Inspection and Teardown of Aged In-Service Bonded Repairs – Vol. II (In-progress)

Looking Forward

- **Benefit to Aviation**
  - Evaluation of bondline integrity and durability of in-service repairs on metallic/composite structures in commercial aircraft
  - Guidance materials for AC 65-33 (Development of Training/Qualification Programs for Composite Maintenance Technicians) and AC 43-214 (Repairs and Alterations to Composite and Bonded Aircraft Structure)
- **Future needs**
  - Current research performed on single A/C with components having consistent service history
    - Need to consider variable A/C with variable materials and repair procedures
  - Information on stress levels and loading modes on repair regions necessary for durability testing
- **Contact:**

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