Inspection and Teardown of Aged In-Service Bonded Repairs

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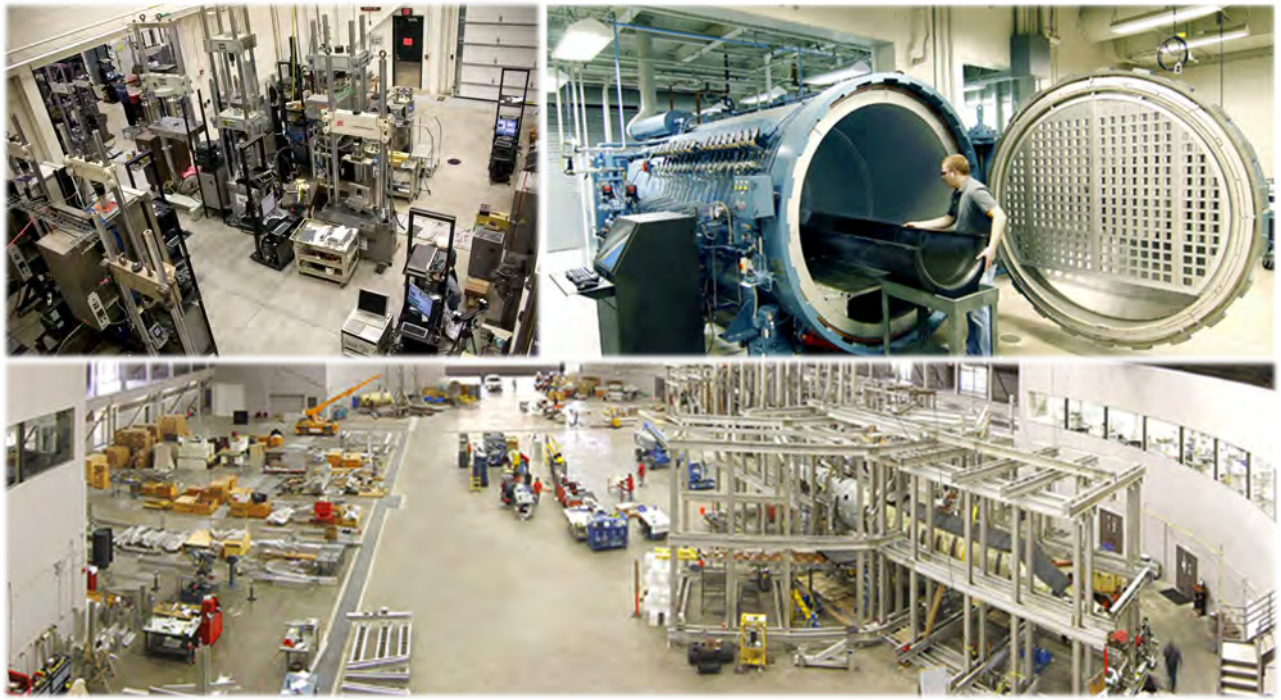


Program Overview

- The increased use of bonded applications in critical structures raises concerns related to process sensitivity of the bondline, as an improperly accomplished in-service repair could become a safety threat due to a weak bond being susceptible for further degradation in an unpredictable manner when subjected to operational environments and ground-air-ground (GAG) thermo-mechanical loads.
  - Therefore, 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 aging mechanism and any undetected material degradation.
  - Several decommissioned structural members, both metal and composites, with multiple repairs will be subjected to detailed inspections and cyclic loading in order to determine the remaining life of those repairs.
- The main goal of this research program is to evaluate bondline integrity and durability of in-service repairs on composite structures in commercial aircraft in order to provide guidance into 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)

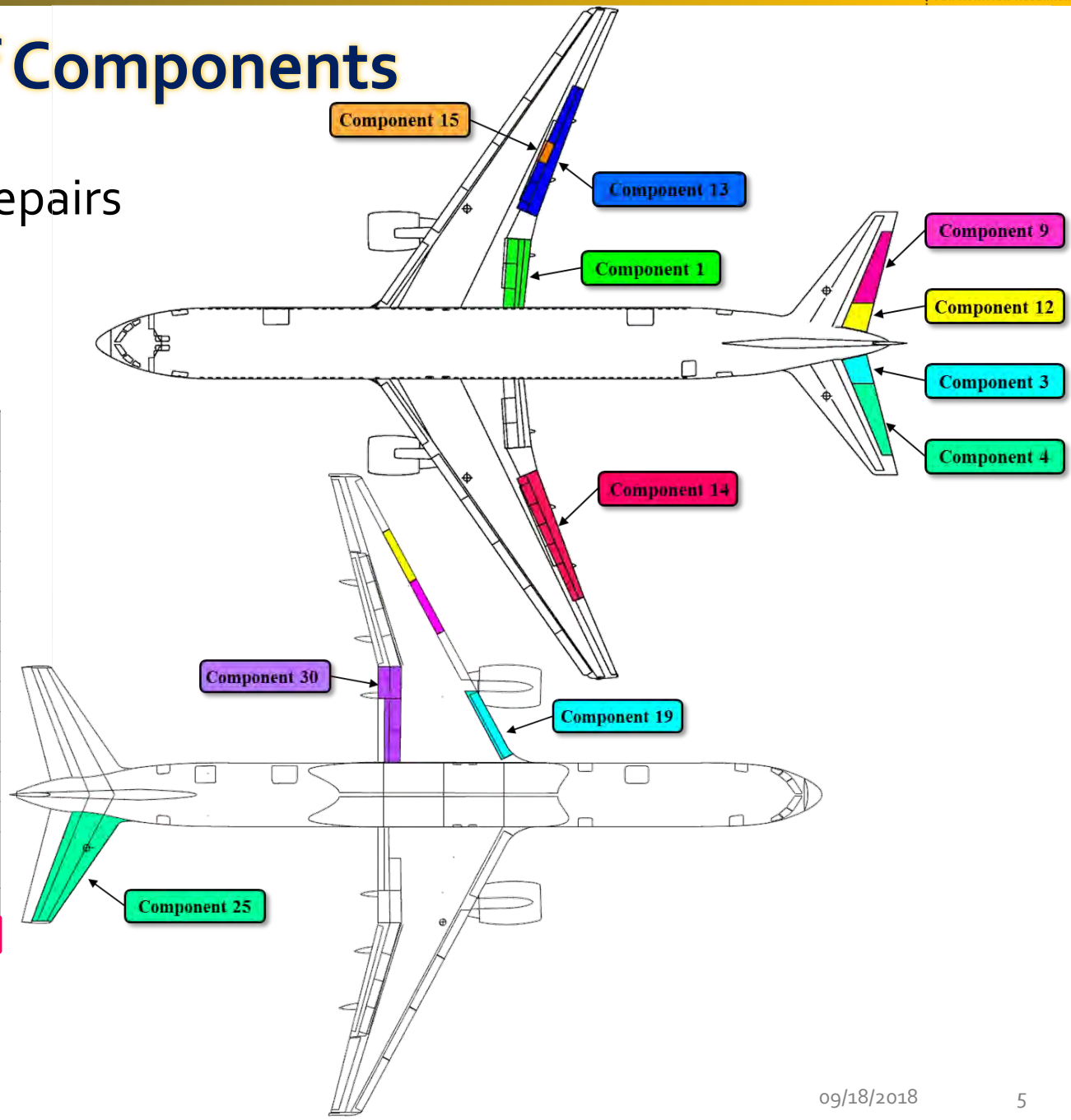
Technical Approach

- Phase 1: Acquisition of Aircraft Components with Documented Repairs
- Phase 2: Preliminary inspections at Sandia National Lab (SNL)
  - Upon completion of NDI, SNL will ship components to NIAR along with detailed NDI reports.
- Phase 3:
  - Teardown inspections
    - Assess the quality of the bonded repairs
  - Document findings related to repair integrity and viability on NDI methods
  - Detailed inspections, strain surveys, and material testing during cyclic testing of component/element testing are intended to provide insight into assessing current standard inspection methods to detect material degradation/wearout.
- Phase 4: Documentation of findings
  - Research team will engage in CACRC and CMH-17 activities related to guidance materials and training/qualification programs for composite maintenance technicians and certification approaches

Overview of Components

- Aircraft Components with Documented Repairs
  - Structural Repair Manuals (SRMs)
  - Engineering Repair Authorizations (ERAs)

Component Number	Repaired Component	Date of Repair	Stored Date	Flight Hours	Metallic Repairs	Composite Repairs
1	Flap, Right I/B	5/26/1995	10/1/2009	13448	7	-
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
7	Spoiler, NR 10	4/30/1995	10/1/2009	13324	TBD	TBD
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	2
15	Spoiler, NR 11	4/30/1995	10/1/2009	13324	TBD	TBD
19	Slat, NR 6	5/4/2011	5/1/2013	85359	TBD	TBD
25	Horizontal Stabilizer	1/16/2011	7/1/2012	75316	TBD	TBD
30	Flap, Right I/B	-	-	-	3	-
Total					19	45



SNL Shipment to NIAR

- Along with shipped components, SNL provided:
  - Identification code for each component and individual repairs
  - Size and location of each repair
  - Detailed NDI reports for each repair (visual, MAUS, IR Thermography)

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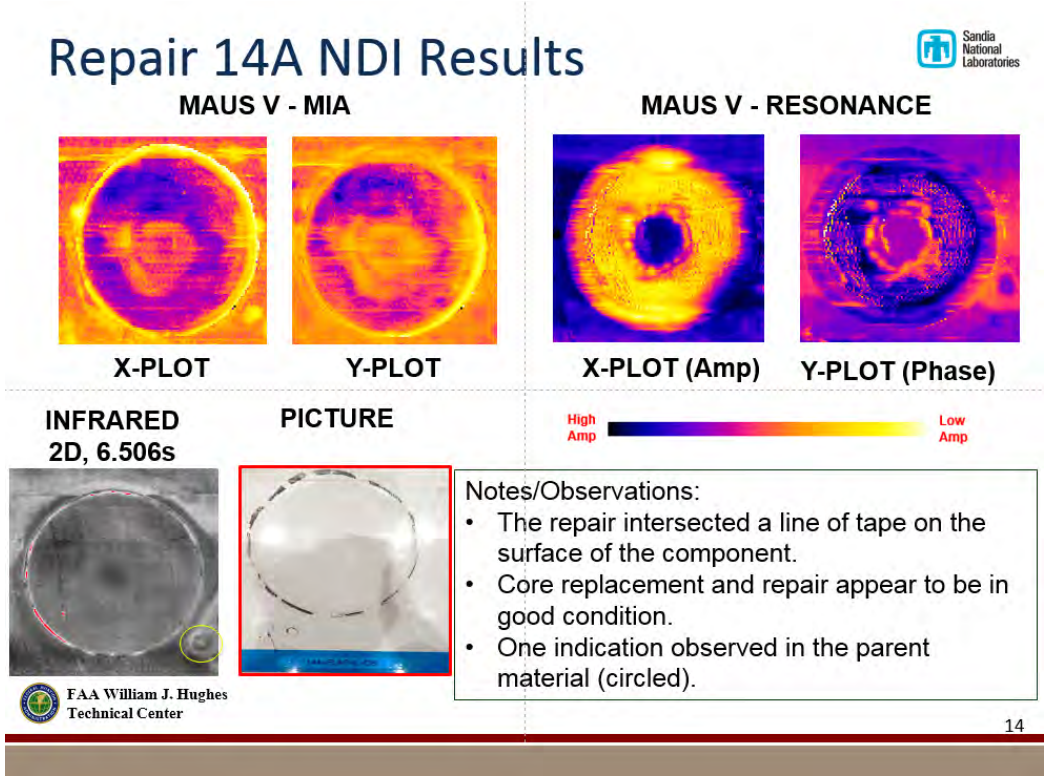

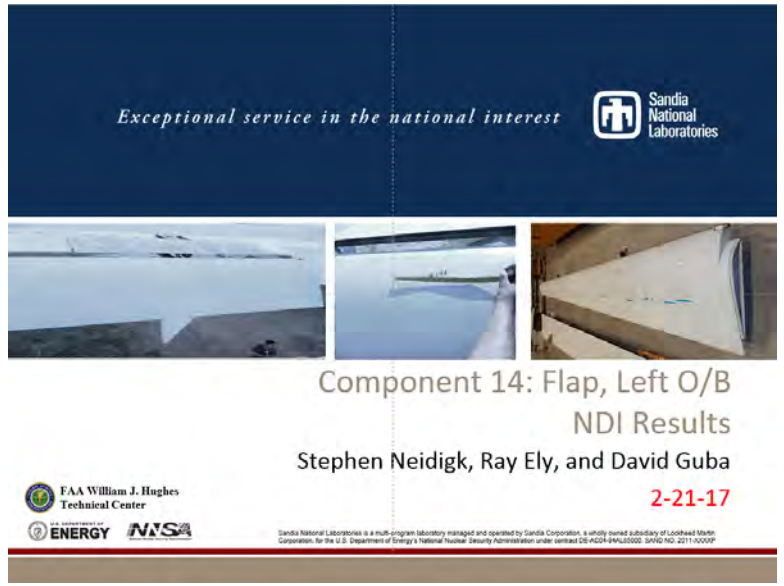

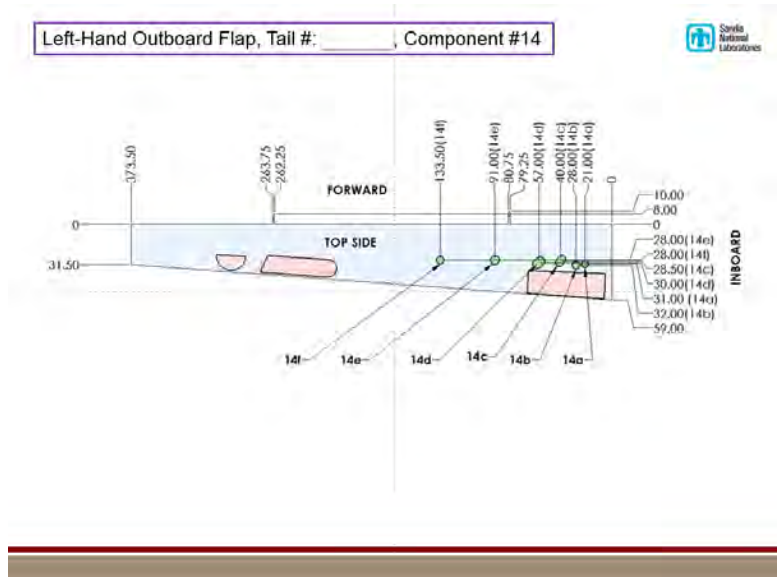

Inspection Methods

- Inspection Outline
  - Structural Level (SNL)
    - Visual
    - Mechanical Impedance Analysis
    - Resonance C-scan
    - Thermography
  - Structural Level (NIAR Receiving Inspection)
    - Visual
    - Mechanical Impedance Analysis
    - Resonance C-scan
    - Thermography
  - Panel Level (NIAR)
    - Through Transmission Ultrasonic (TTU)
  - Specimen/Element Level
    - Photomicrographs (cut repair)
    - Computed Tomography (CT) on select repairs

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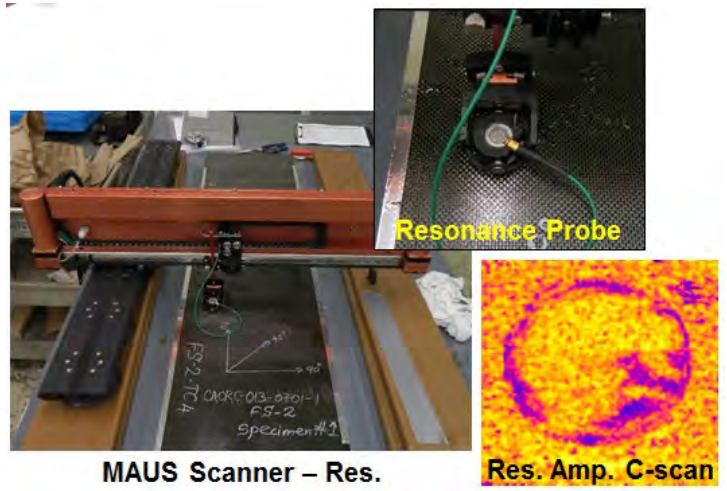
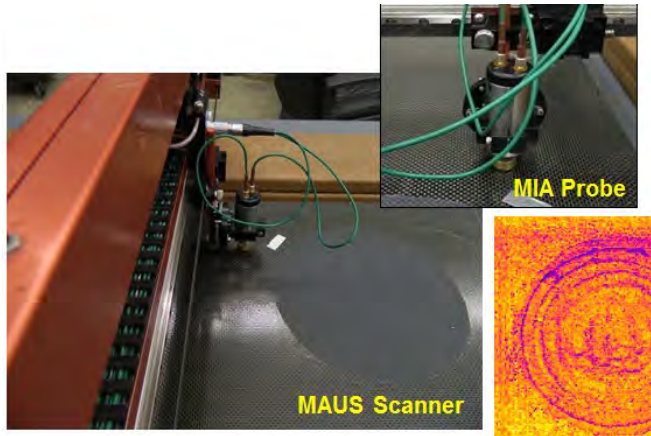
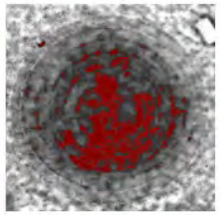
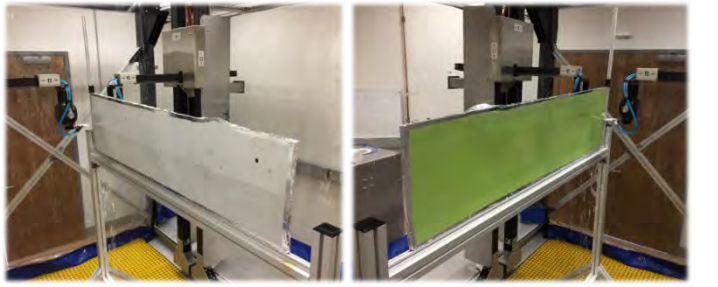
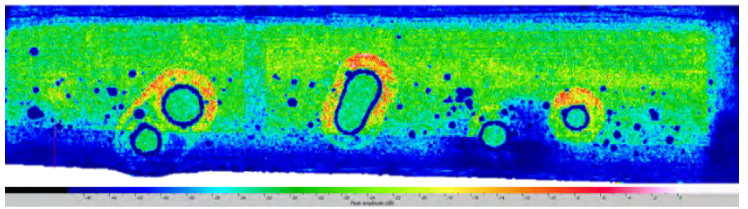




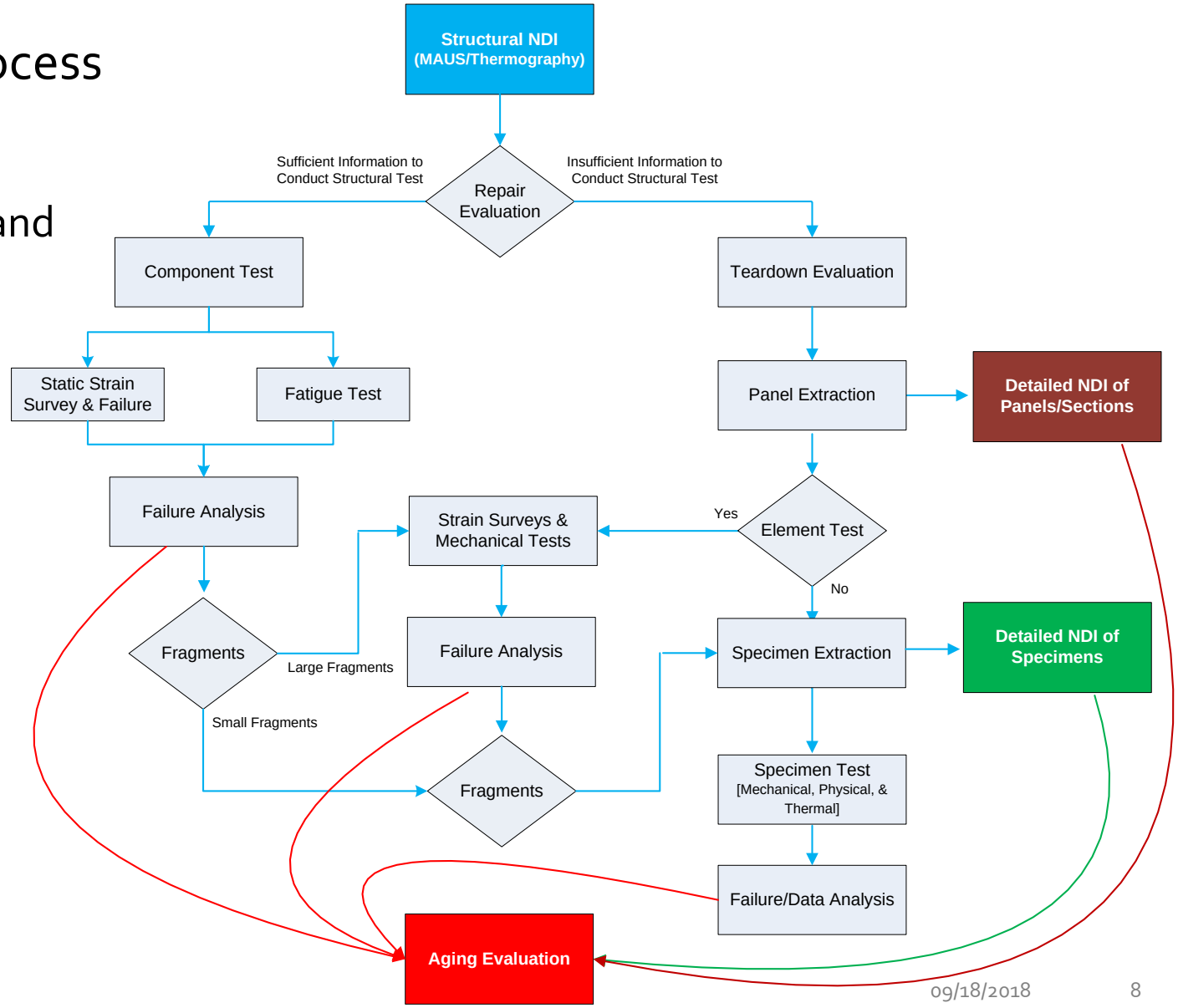






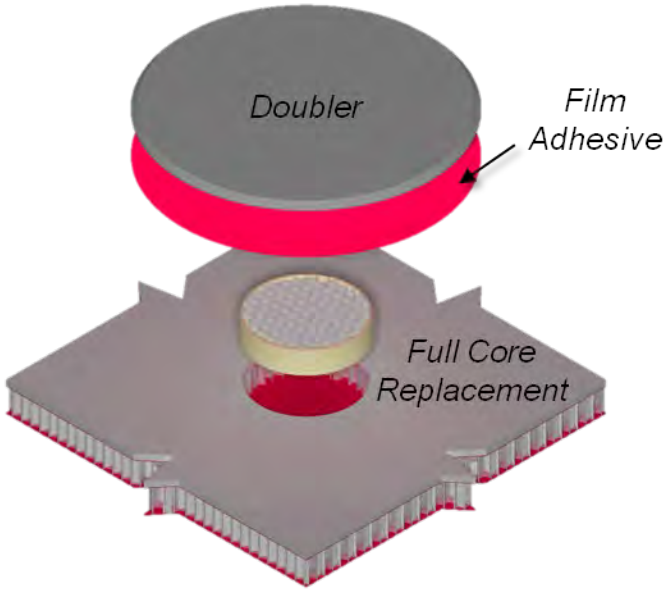
Teardown Procedure

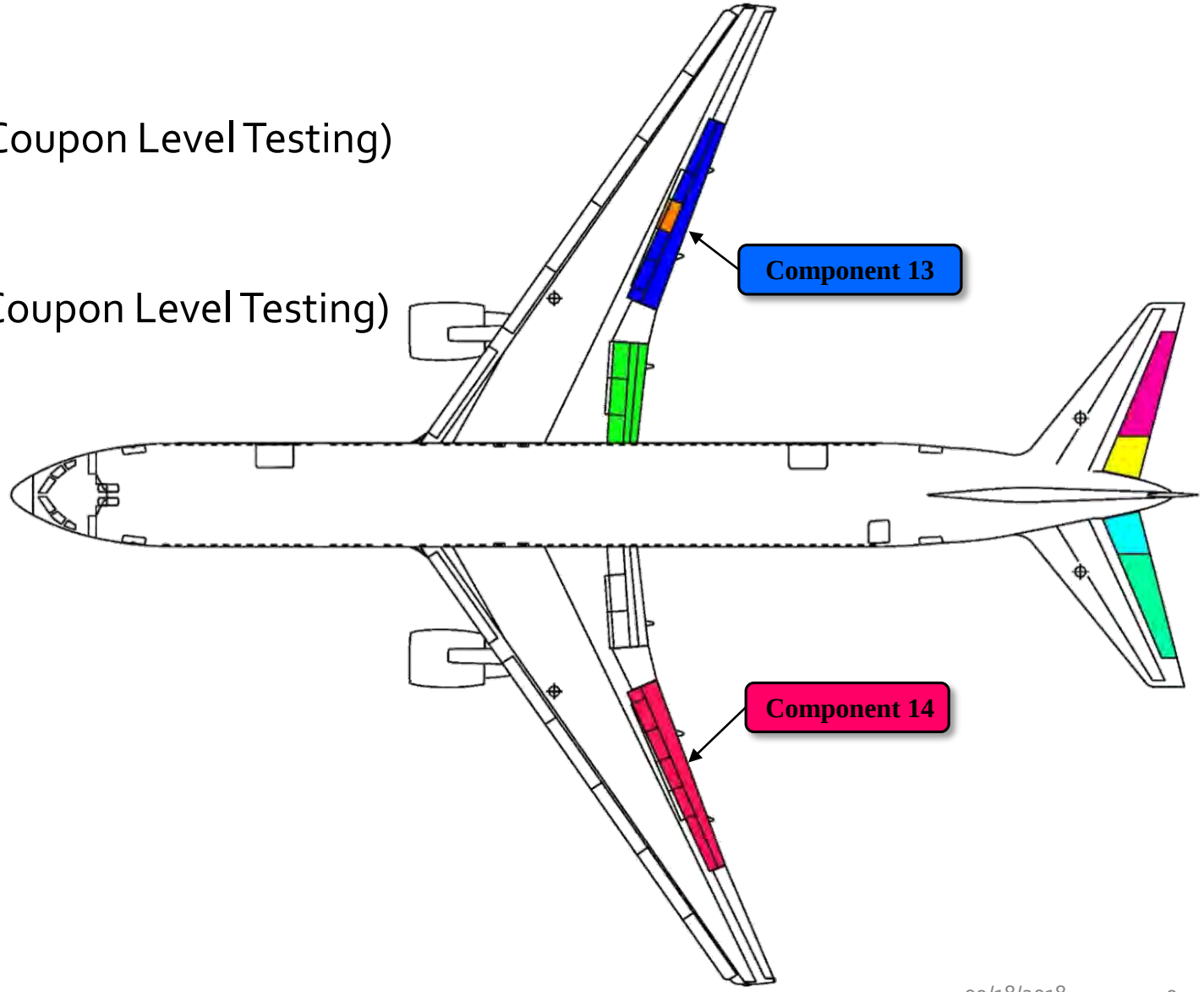
- Decision tree for selecting testing process
  - Level of documentation
  - Quantity of repairs with alike materials and geometry
  - Location of repair
  - Parent structure (underlying features)
  - Resources available to research team



Teardown of Metallic Bonded Repairs

- Component 14 Left O/B TE Flap
  - 6 Metallic Bonded Repairs (Specimen/Coupon Level Testing)
- Component 13: Right O/B TE Flap
  - 3 Metallic Bonded Repairs (Specimen/Coupon Level Testing)



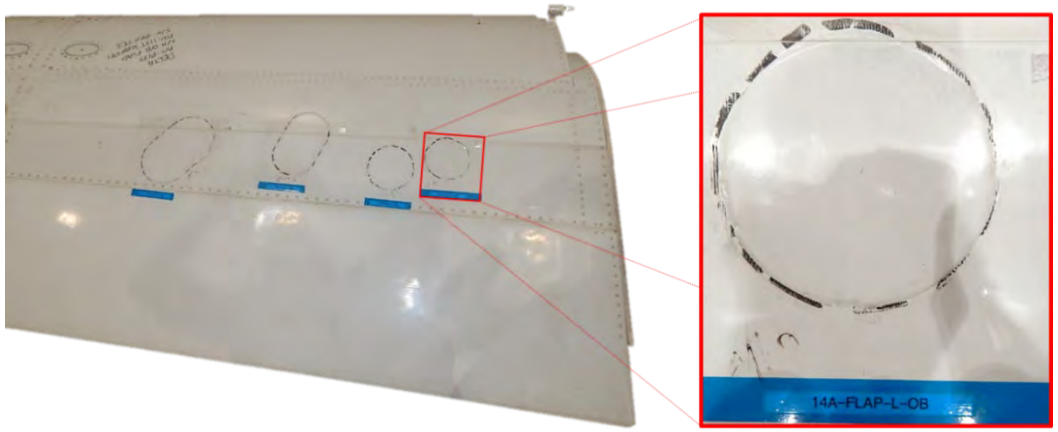


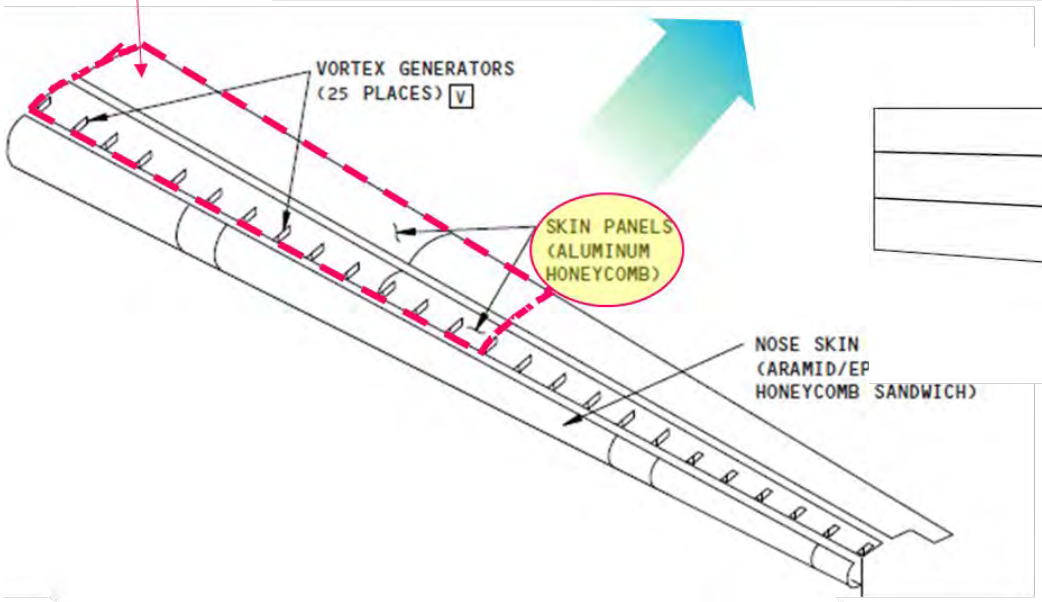
Component 14 – O/B Flap (LH)

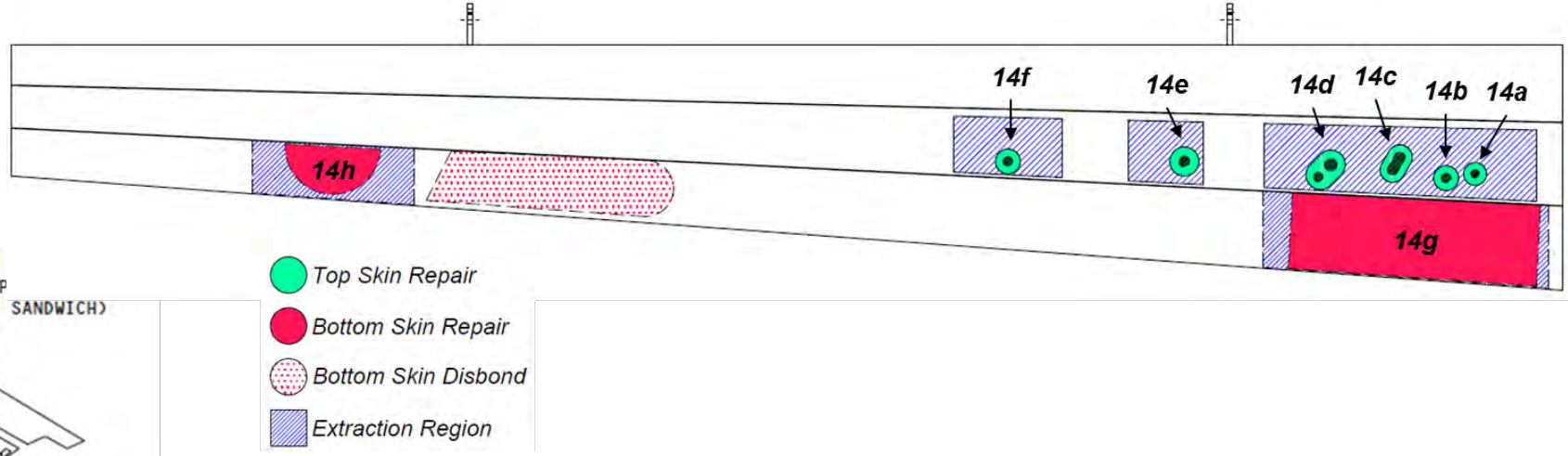
- Parent Material Identification from SRM

Repair	Location	Size [in.]	Host Skin Material	Host Core Material	Skin to Core Adhesive
14a	Top Skin	≈ ⌀5.50	7075-T6 Aluminum	Aluminum Honeycomb	-
14b	Top Skin	≈ ⌀6.00	7075-T6 Aluminum	Aluminum Honeycomb	-
14c	Top Skin	≈ 9.50 x 6.00	7075-T6 Aluminum	Aluminum Honeycomb	-
14d	Top Skin	≈ 10.50 x 7.00	7075-T6 Aluminum	Aluminum Honeycomb	-
14e	Top Skin	≈ ⌀7.00	7075-T6 Aluminum	Aluminum Honeycomb	-
14f	Top Skin	≈ ⌀6.00	7075-T6 Aluminum	Aluminum Honeycomb	-

Repair Host Material Region

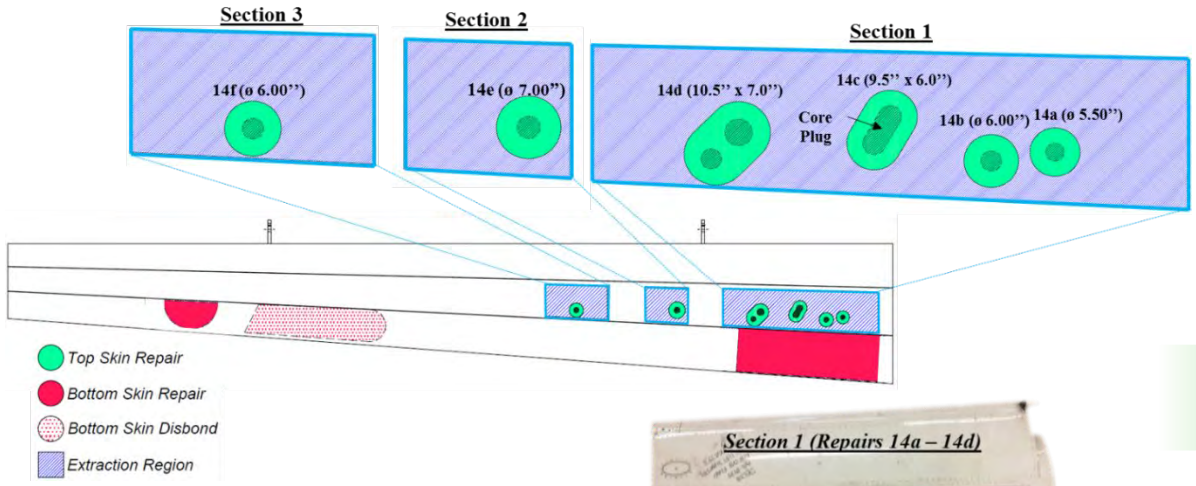


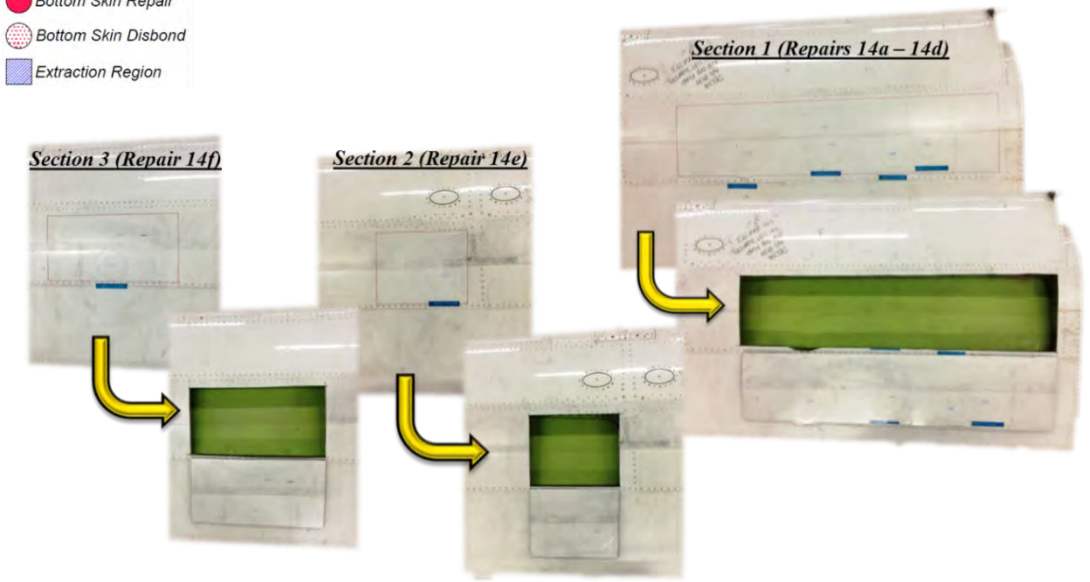




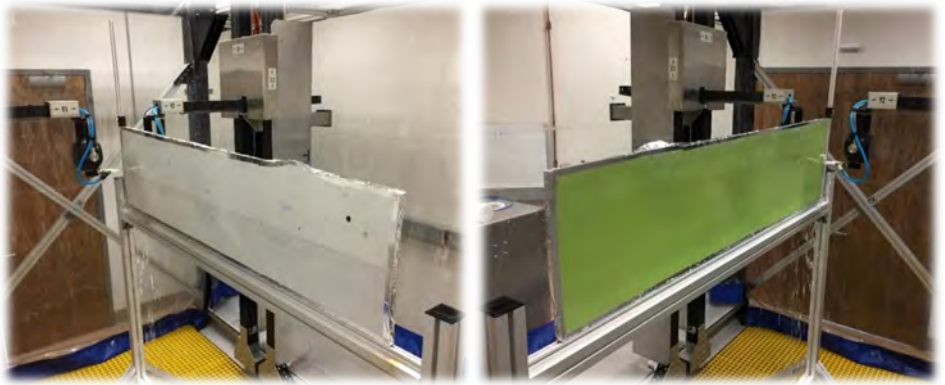
Panel Extractions & Inspections

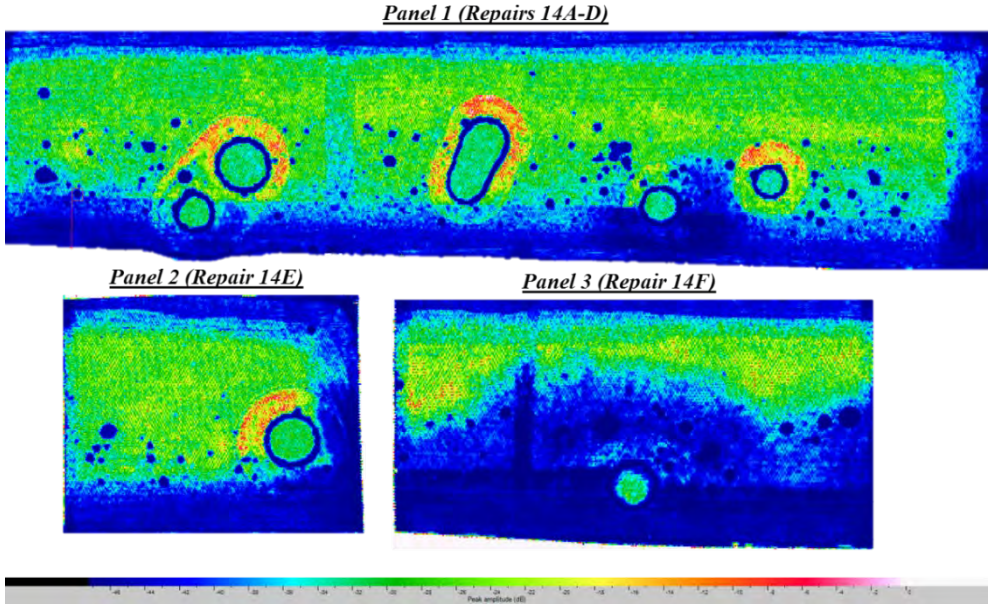
Panel Extractions





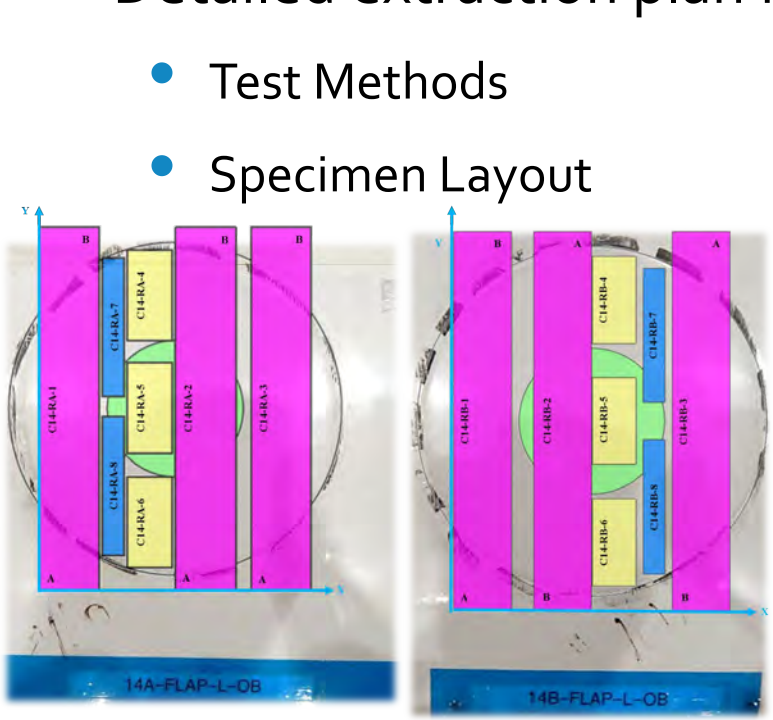
Panel Level TTU C-scans

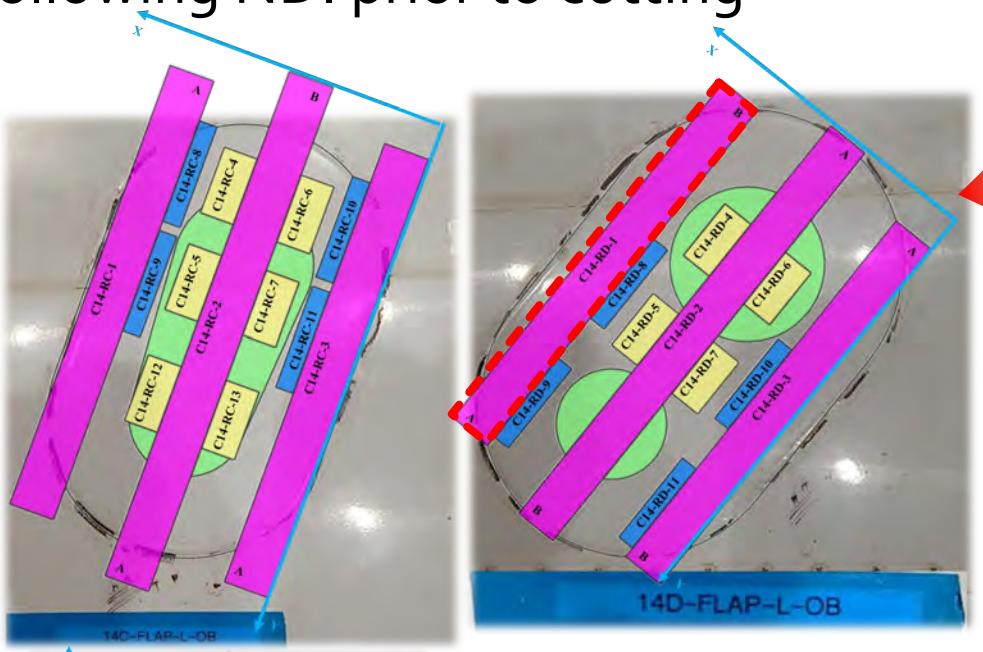


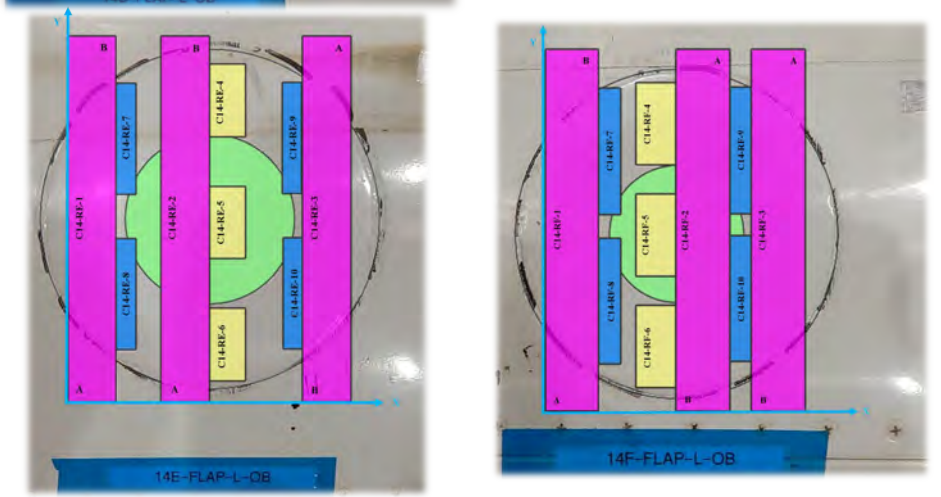


Repair Specimen Layout

- Detailed extraction plan following NDI prior to cutting
  - Test Methods
  - Specimen Layout







- ASTM D1876/D3165
- ASTM D5229/D3418
- ASTM E1640
- Core Plug

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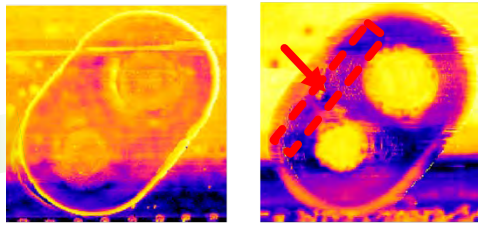
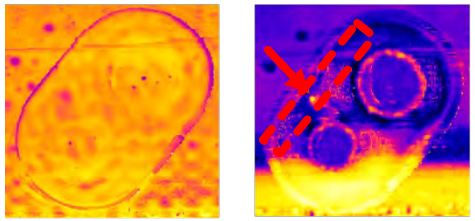
MAUS V - MIA



X-PLOT Y-PLOT

MAUS V - RESONANCE

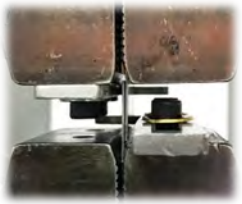


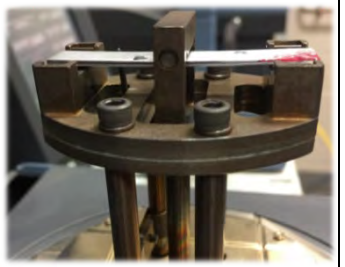
X-PLOT (Amp) Y-PLOT (Phase)

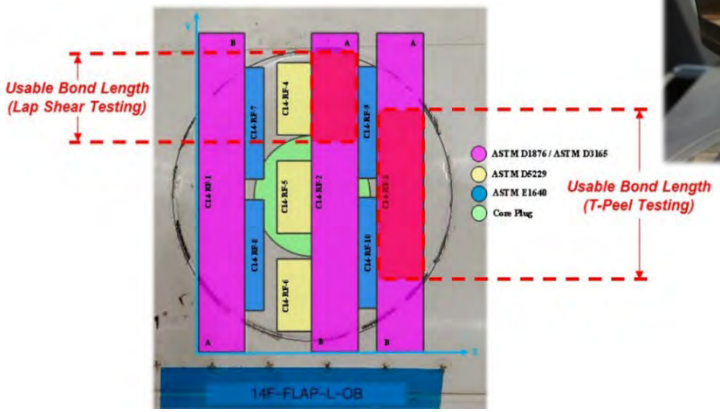
Strategic placement of specimens considering all NDI data

Combined Evaluation Matrix

- Test Methods
  - Mechanical Testing
    - T-Peel Testing (ASTM D1876)
    - Lap-Shear Testing (ASTM D3165)
    - Flatwise Tensile Strength (ASTM C297)
    - Climbing Drum Peel (ASTM D1781)
  - Thermal Testing
    - Dynamic Mechanical Analysis (ASTM E1640)
    - Differential Scanning Calorimetry (ASTM D3418)
  - Chemical Testing
    - FTIR-ATR (ASTM E1252)
    - Energy Dispersive X-ray Spectroscopy (EDS)



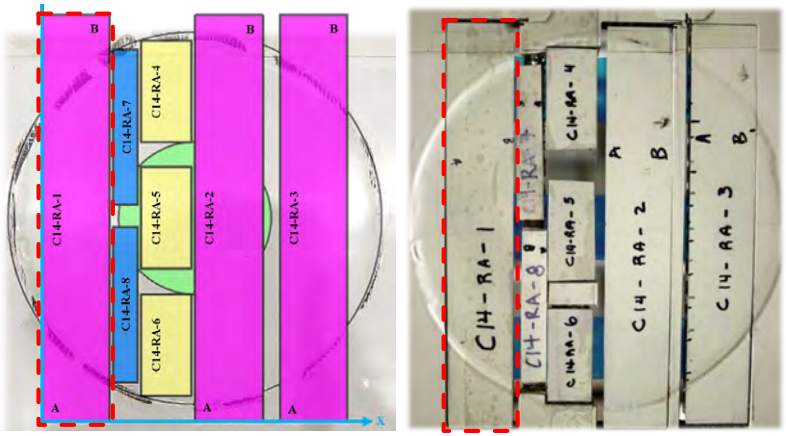


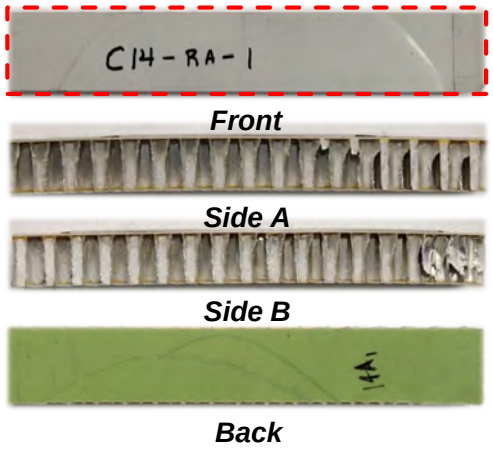


Material Definition	Specimen Configuration	Target Result to Achieve	Moisture Configuration	Test Method	Quantity
Extracted Repair Material	-	Peel Strength of Repair Adhesive	As Extracted	ASTM D1876	12
		Apparent Shear Strength of Repair Adhesive		ASTM D3165	10
		Moisture Content of Repair Adhesive		ASTM D5229	6
		T_g of Repair Adhesive	Wet	ASTM E1640	6
			As Extracted		20
			Dry		6
		Repair Adhesive Composition	As Extracted	EDS	6
				ASTM E1252	6
		Repair Adhesive Degree of Cure	As Extracted	ASTM D3418	6
Parent Material	-	Climbing Drum Peel Strength of Exterior Side Top Skin	As Extracted	ASTM D1781	9
		Climbing Drum Peel Strength of Interior Side Top Skin			9
		Climbing Drum Peel Strength of Exterior Side Lower Skin			9
		Climbing Drum Peel Strength of Interior Side Lower Skin			9
		Flatwise Tensile Strength Top Skin		ASTM C297	6
		Flatwise Tensile Strength Lower Skin			6
Baseline Material (Lab Prepared per SRM)	Configuration 1 (AF163-2OST Adhesive)	Peel Strength of Repair Adhesive	As Extracted	ASTM D1876	4
		Apparent Shear Strength of Repair Adhesive	As Extracted	ASTM D3165	3
		T_g of Repair Adhesive	Wet	ASTM E1640	3
			As Extracted		6
			Dry		3
		Repair Adhesive Composition	As Extracted	ASTM E1252	1
		Repair Adhesive Degree of Cure	As Extracted	ASTM D3418	1
	Configuration 2 (AF163-2OST Adhesive with PF on Tacky Side)	Peel Strength of Repair Adhesive	As Extracted	ASTM D1876	4
		Apparent Shear Strength of Repair Adhesive	As Extracted	ASTM D3165	3
		T_g of Repair Adhesive	Wet	ASTM E1640	3
			As Extracted		6
			Dry		3
		Repair Adhesive Composition	As Extracted	ASTM E1252	1
		Repair Adhesive Degree of Cure	As Extracted	ASTM D3418	1
	Configuration 3 (AF163-2OST Adhesive with PF on Mat Surface (Incorrect))	Peel Strength of Repair Adhesive	As Extracted	ASTM D1876	4
		Apparent Shear Strength of Repair Adhesive	As Extracted	ASTM D3165	3
		T_g of Repair Adhesive	Wet	ASTM E1640	3
			As Extracted		6
			Dry		3
		Repair Adhesive Composition	As Extracted	ASTM E1252	1
		Repair Adhesive Degree of Cure	As Extracted	ASTM D3418	1

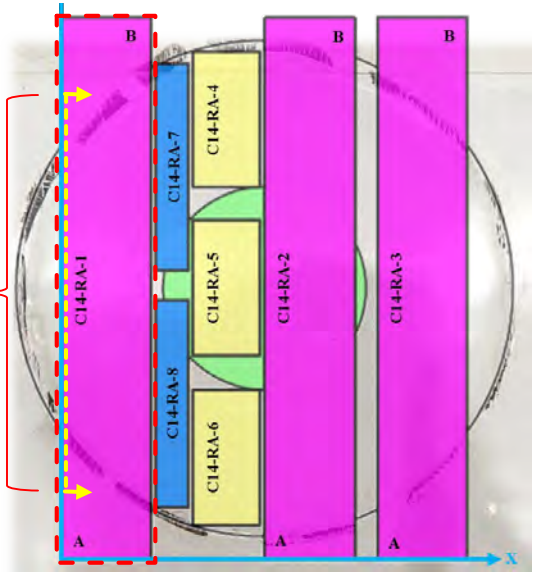
Repair Specimen Extractions

- Specimen Extraction Documentation
  - Each extraction was documented with pictures prior to photomicrographs

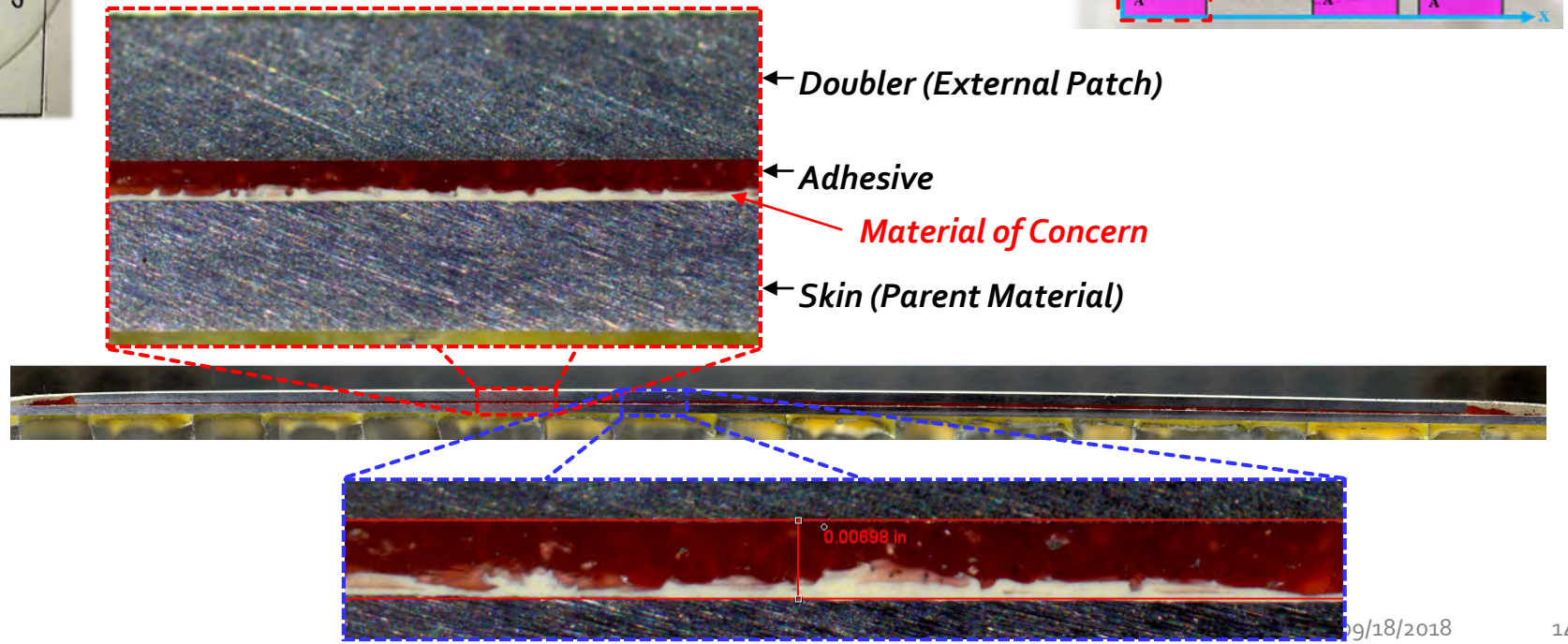




Specimen: C14-RA-1 (Side A)



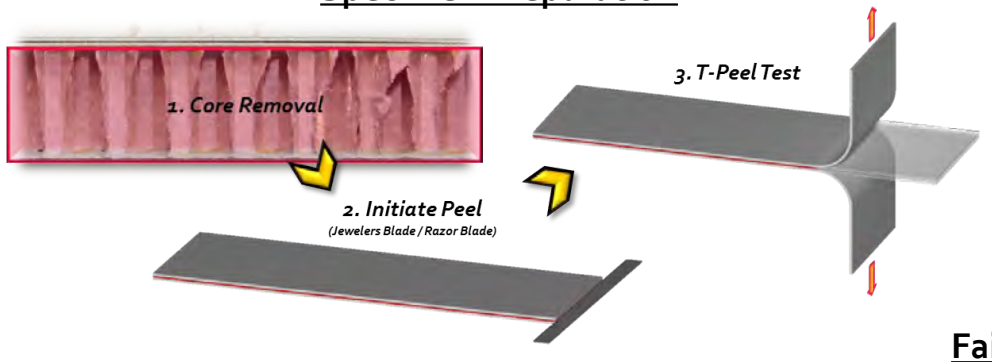
C14-RA-1 Cross-Section



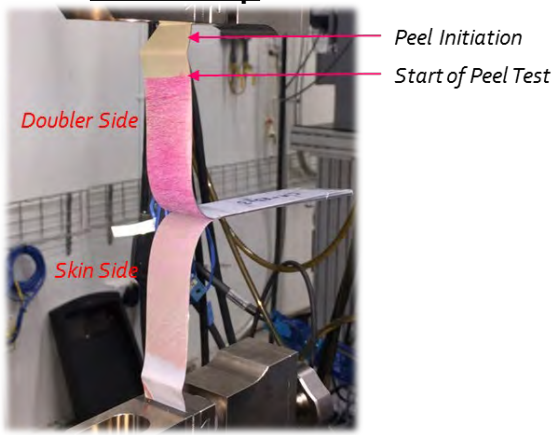
Repair Mechanical Testing – T-Peel

- T-Peel (ASTM D1876)
  - Repair Peel Strength: ≈64% of BL panels
  - Repair failure along interfacial anomaly
  - BL specimens: Cohesive failures

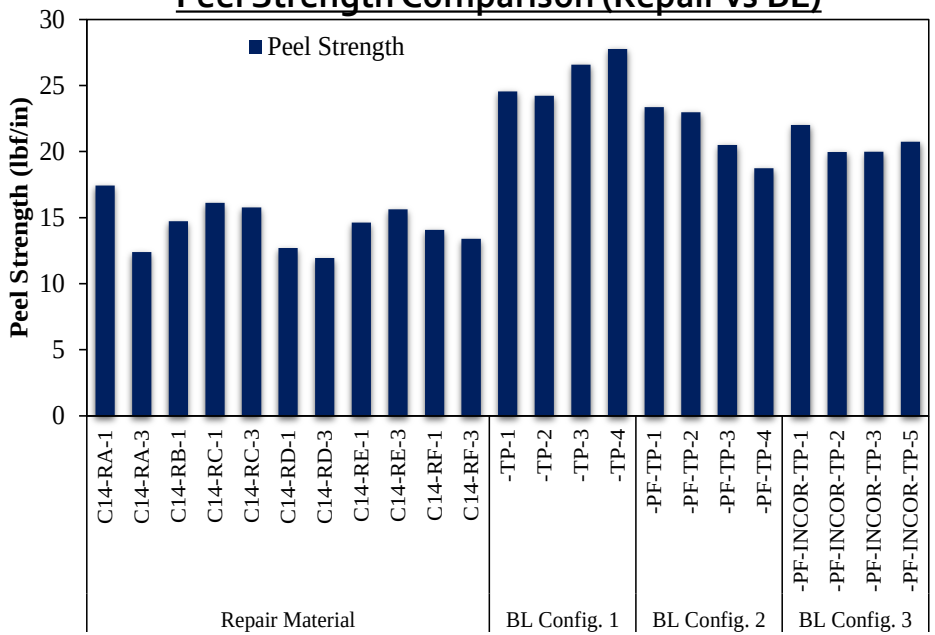
Specimen Preparation



Test Setup

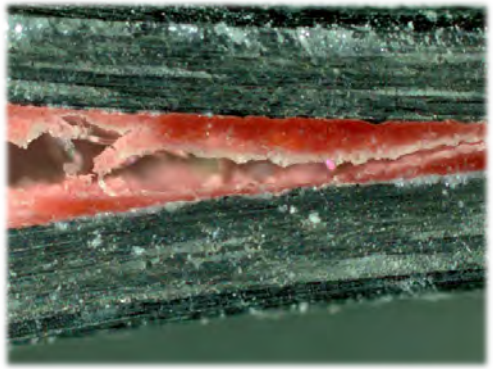


Peel Strength Comparison (Repair vs BL)

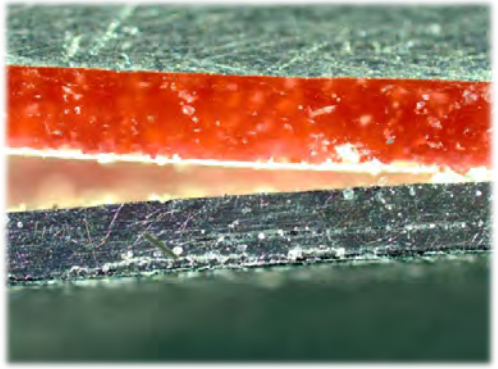


Failure Analysis

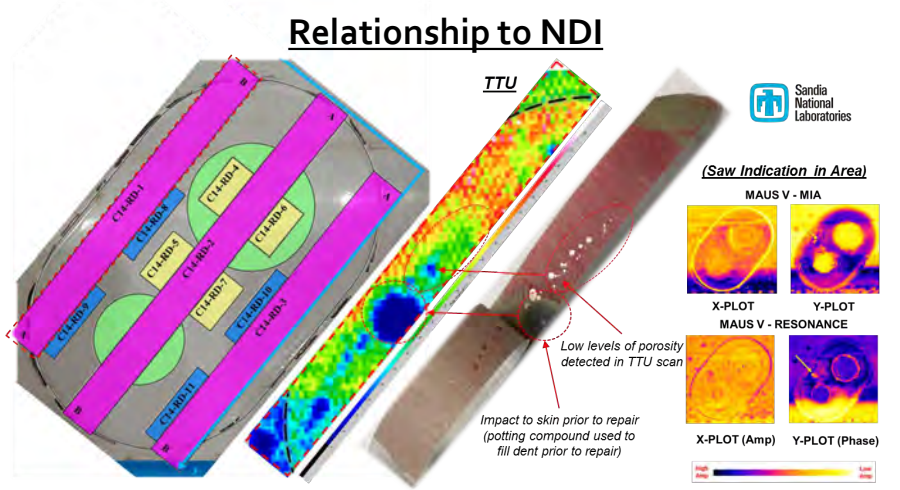
BL Specimen Failure



Repair Specimen Failure



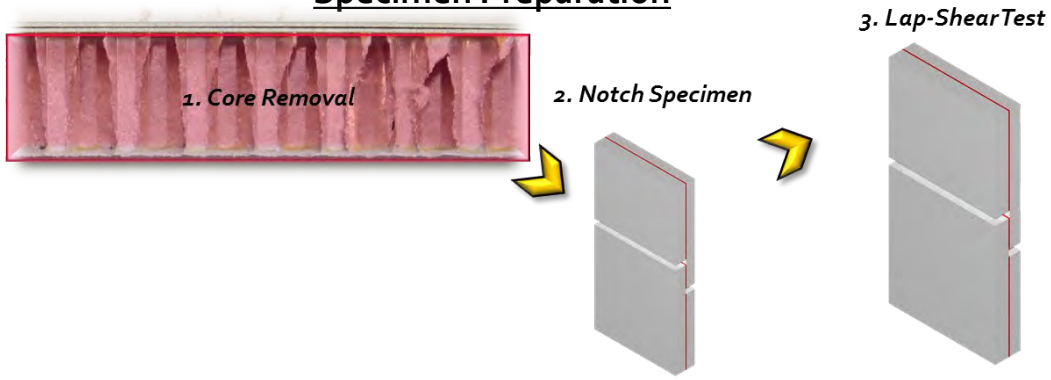
Relationship to NDI



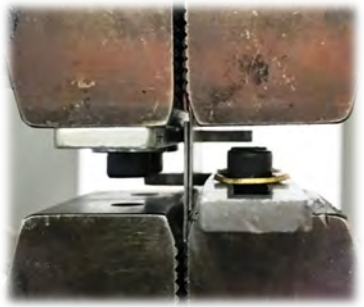
Repair Mechanical Testing – Lap-Shear

- Lap-Shear Testing (ASTM D3165)
  - Repair Shear Strength at failure: ≈50% of BL panels
  - BL specimen failure controlled by adherened tensile strength
  - Repair specimens: Adhesive failure (primer)

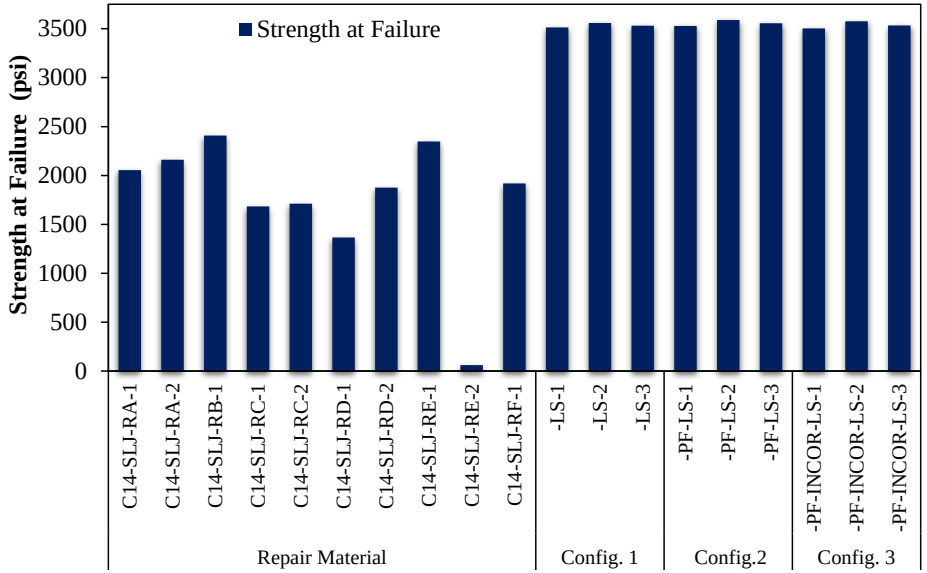
Specimen Preparation



Test Setup

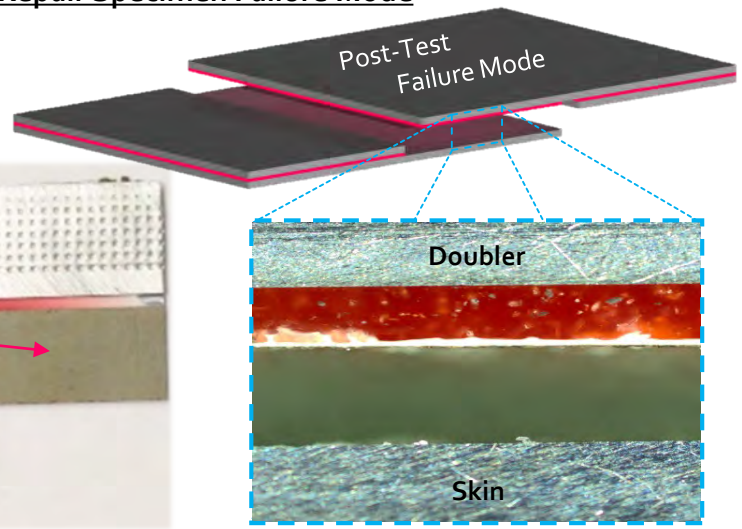


Shear Strength Comparison (Repair vs. BL)

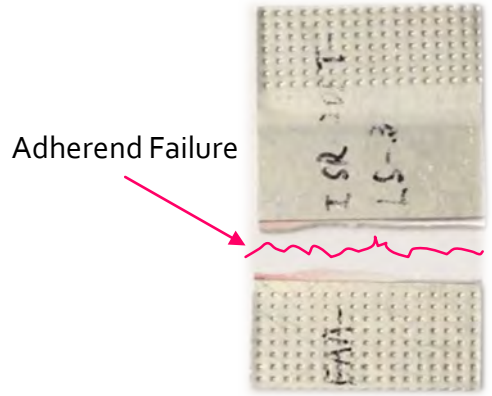


Failure Analysis

Repair Specimen Failure Mode



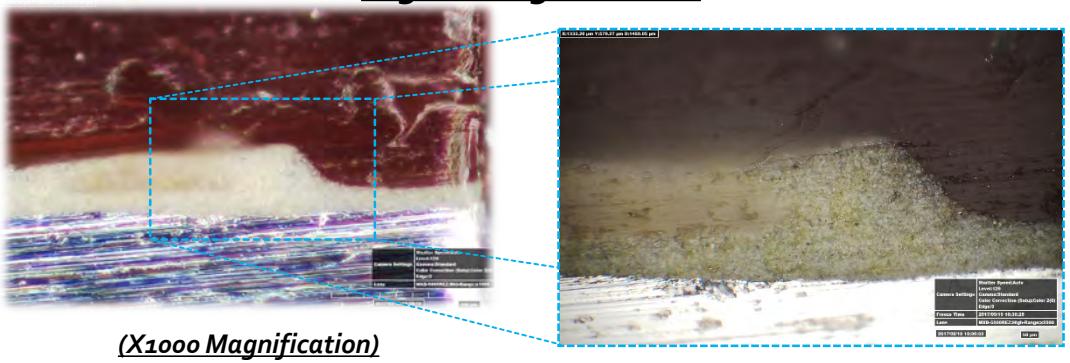
BL Specimen Failure Mode



Interfacial Anomaly

- Component 13/14
  - Noticed in 8 out of 9 repairs
    - Repair on lower surface of C13 (likely different damage event – repaired separately)
  - Controlled performance of bond
  - EDS on surface of failed T-peel specimen
    - Chrome present
  - Layer terminates outside of repair region (≈0.5-inches outside repair doubler)
    - Induced from surface preparation for repair

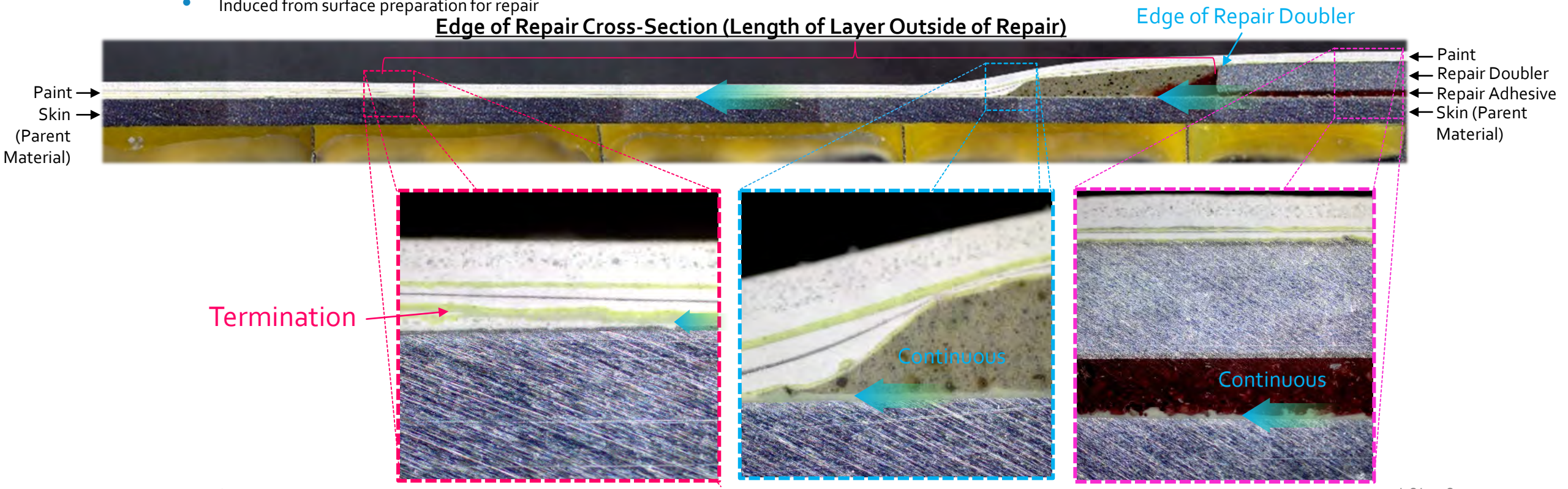
Higher Magnification



(X1000 Magnification)

(X2000 Magnification)

Edge of Repair Cross-Section (Length of Layer Outside of Repair)

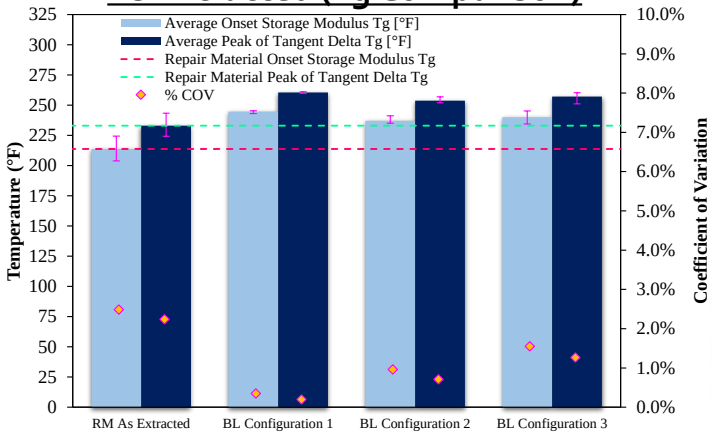


Thermal Analysis

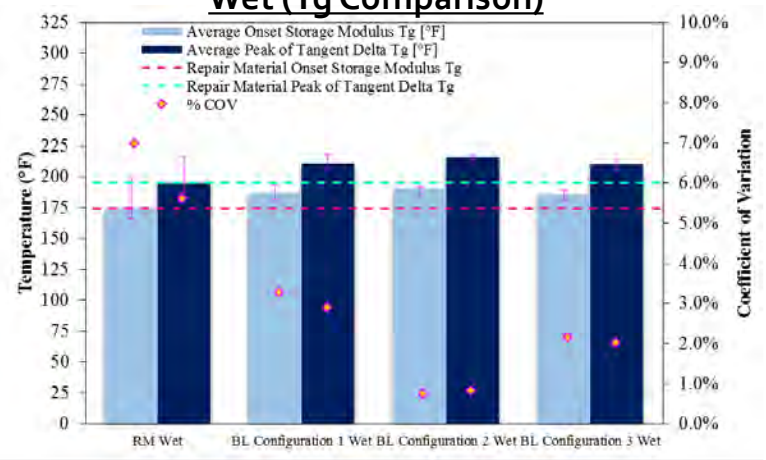
- Dynamic Mechanical Analysis
  - As extracted
  - Conditioned: Dry
  - Conditioned: Wet
- Differential Scanning Calorimetry
  - Degree of Cure (%DOC)

Configuration	Specimen	Exotherm Onset [°C]	Exotherm Peak [°C]	Heat of Reaction of Exotherm [J/g]	Degree of Cure [%]
Uncured	AF 163-2OST	125.850	152.20	175.5	-
BL Material 1	-2OST-DSC	198.370	228.29	9.536	94.57
BL Material 2	-2OST-PF-DSC	184.960	226.130	14.3	91.85
BL Material 3	-2OST-PF-INCOR-DSC	191.220	219.260	7.17	95.91
Repair A	C14-RA-5	-	-	-	≈100
Repair B	C14-RB-5	-	-	-	≈100
Repair C	C14-RC-6	-	-	-	≈100
Repair D	C14-RD-4	-	-	-	≈100
Repair E	C14-RE-5	-	-	-	≈100
Repair F	C14-RF-5	-	-	-	≈100

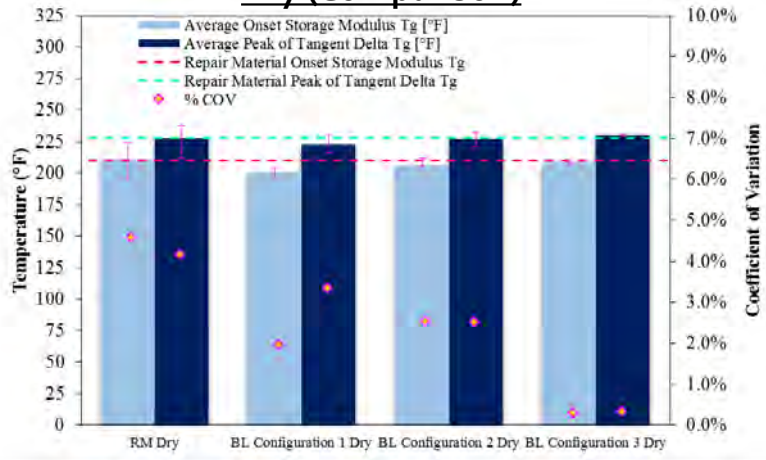
As Extracted (Tg Comparison)



Wet (Tg Comparison)



Dry (Comparison)

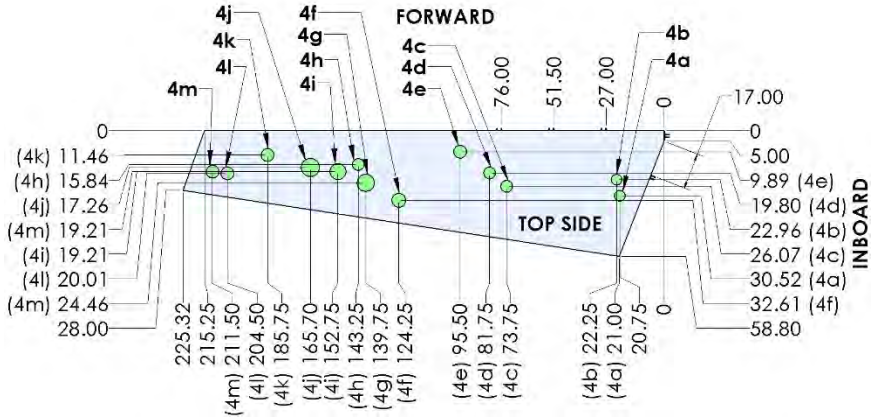


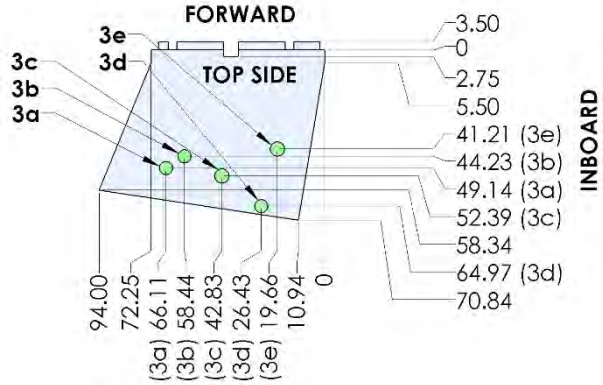
Metallic Repair Summary

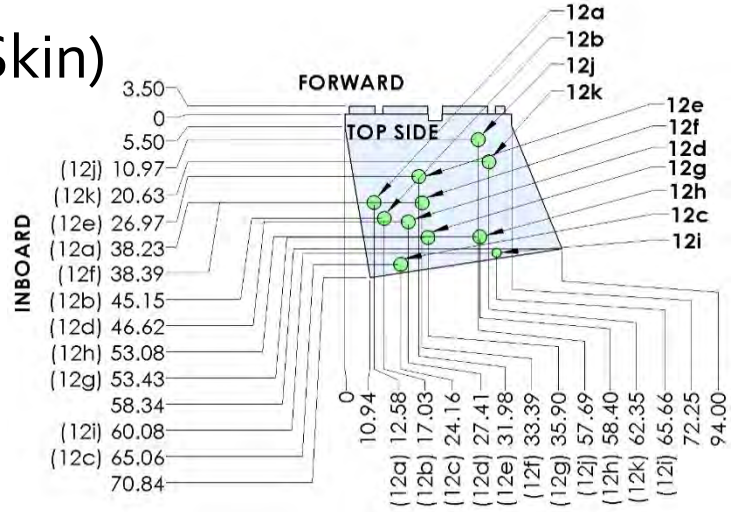
- **Component 14**
  - Interfacial anomaly between the film adhesive and parent structure when an external patch was bonded over metallic honeycomb core repairs
    - Continuous across all 6 bonded repairs
  - Mechanical Testing: Post mechanical test failure analysis showed fracture across interfacial 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 2 out of 3 repairs
    - 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%

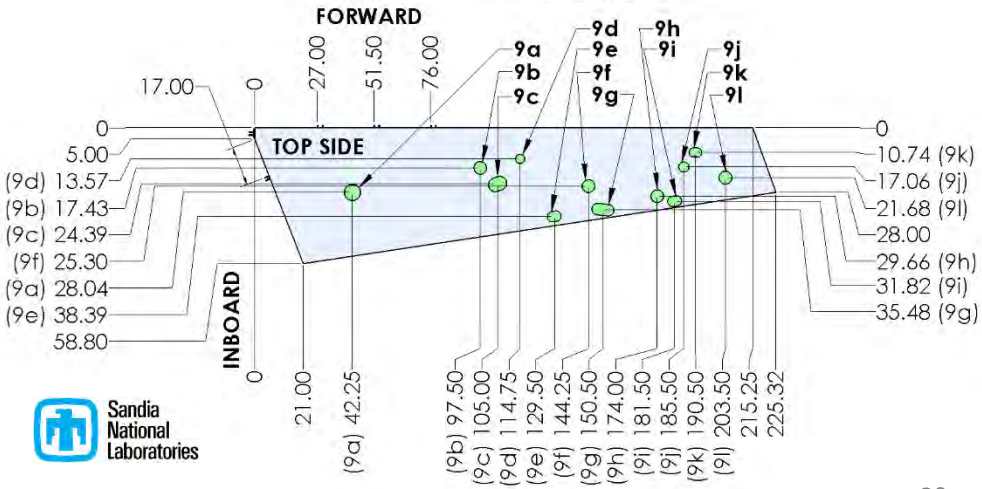
Teardown of Non-Metallic Bonded Repairs

- Component 3, 4, 9, 12 are similar in construction
  - Composite Sandwich construction with thin facesheets
    - Inboard Elevators (3,12):
      - Exterior: 3 Plies (Varies) (PW)
      - Interior: 2 plies (Varies) (PW)
    - Outboard Elevators (4,9):
      - Exterior: 4 Plies (Varies) (PW & UNI)
      - Interior: 4 plies (Varies) (PW & UNI)
- Wet Layup Repairs (Top Skin)
  - 41 repairs total
  - EA9390 Laminating Resin







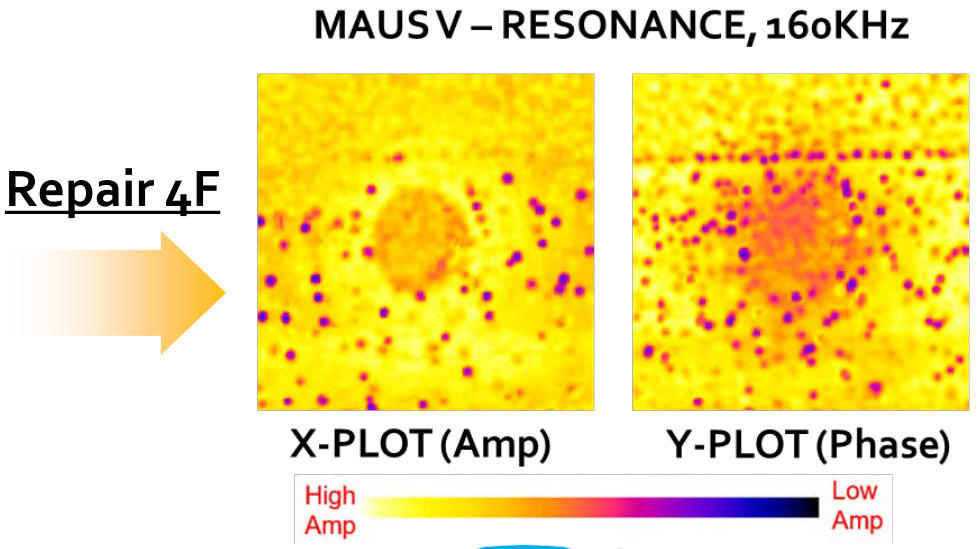


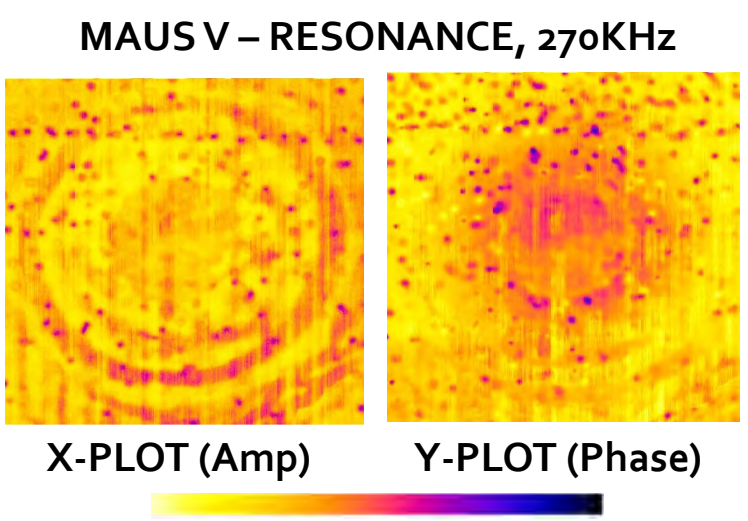
Sandia National Laboratories

Structural Level NDI Observations

- Structural Level Inspection Findings
  - Visual
    - Repair extended away from surface (not fully flush)
    - Paint Cracking
  - Speckling pattern noticed in many repairs and surrounding structure (Component 4 &9)
    - Known that honeycomb structure can exhibit long-term degradation due to thermodynamic effects of trapped moisture in the honeycomb cells
      - Note that this can be evaluated away from the repair as it is seen in parent structure

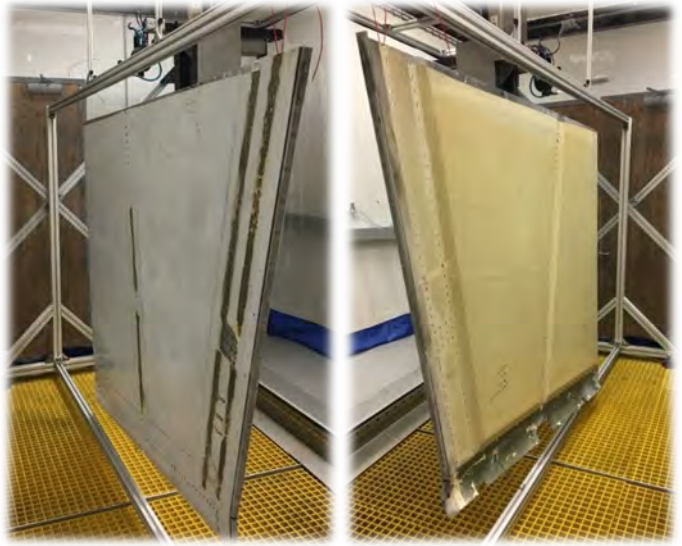
Repair 4F



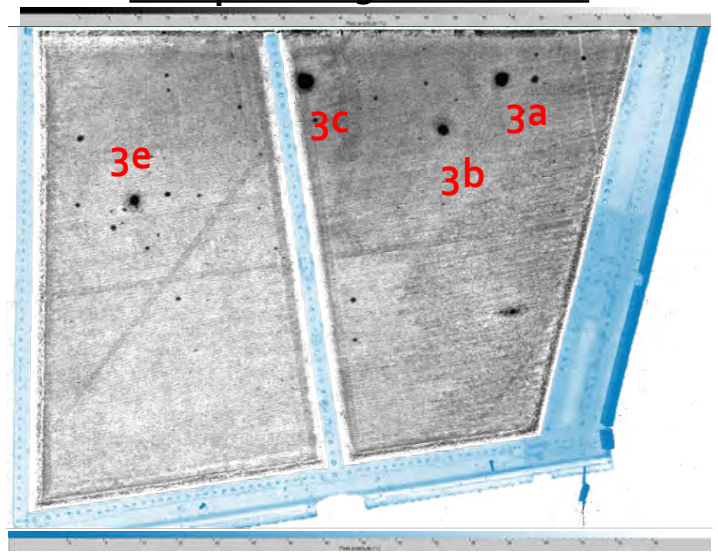


Panel Level NDI Observations

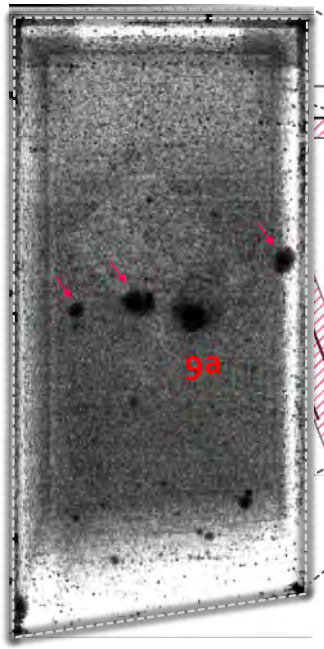
- Inspection Findings
  - Large amount of indications outside of repair regions
  - High levels of attenuation in center of repairs
    - Not representative of a core plug (potting compound used)



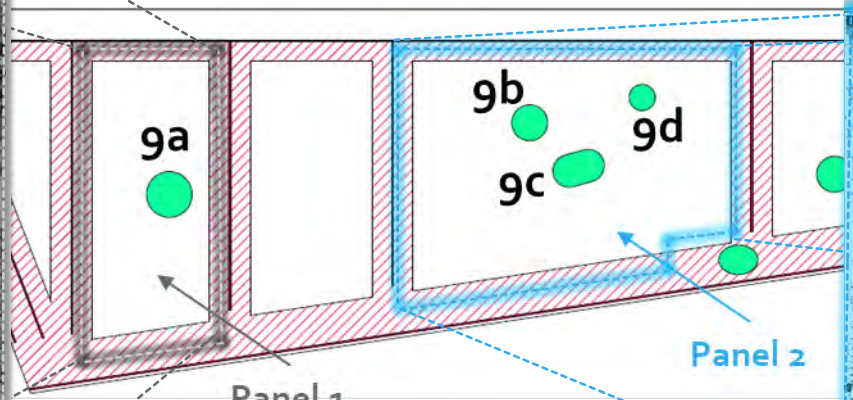
Component 3 TTU C-scan



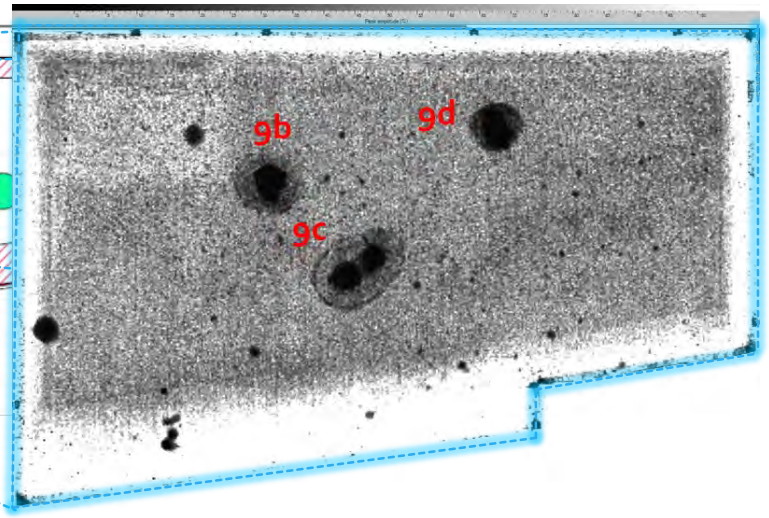
Panel 1



Component 9 TTU C-scans



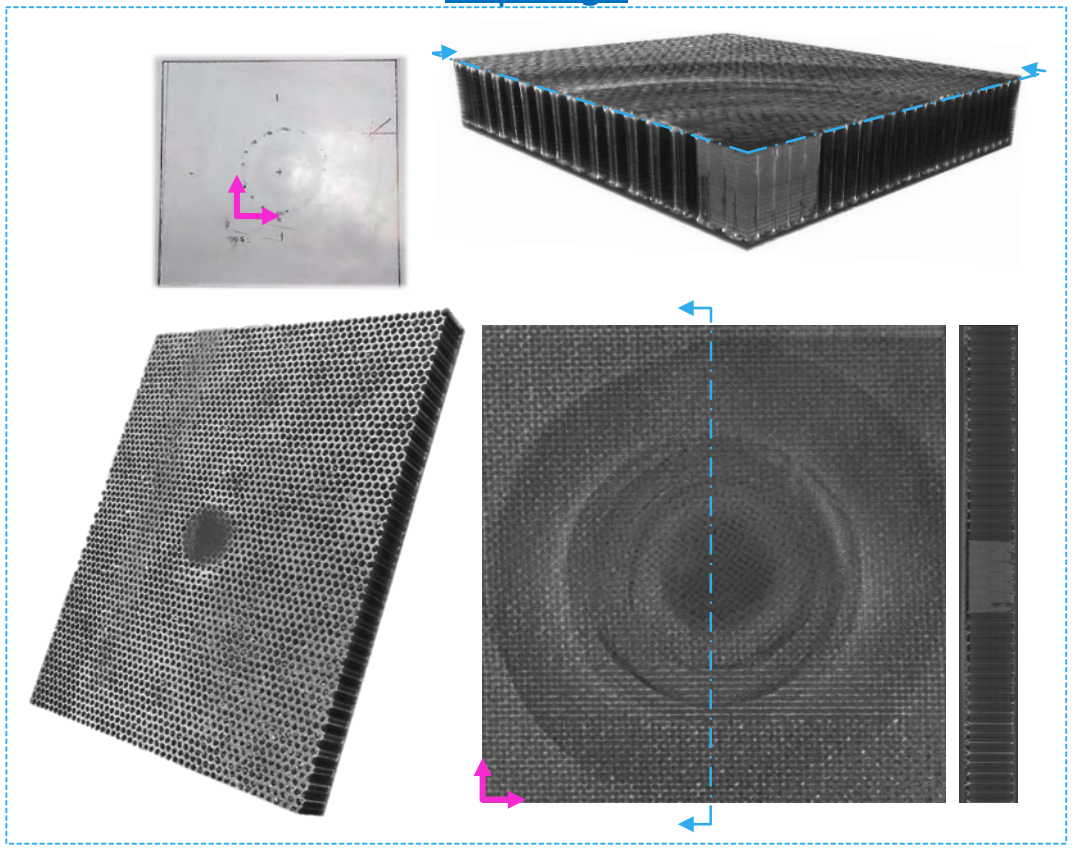
Panel 2



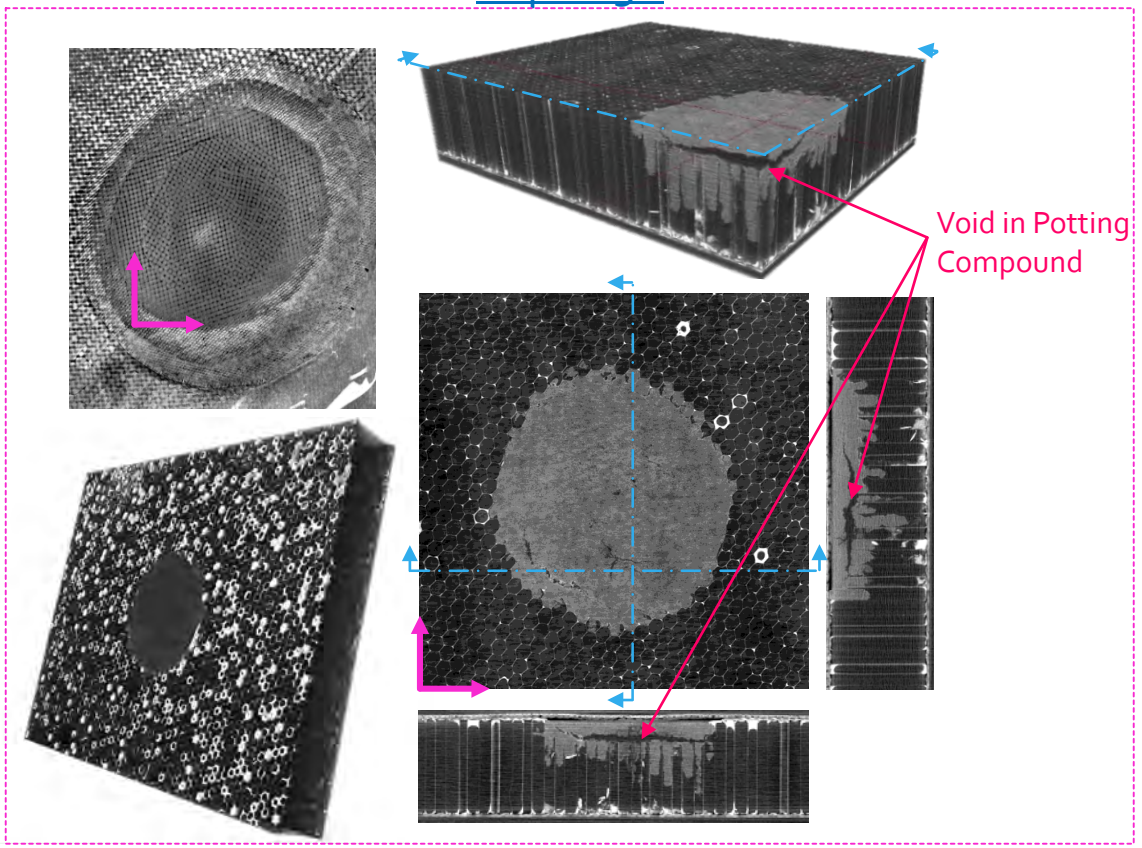
Detailed Level NDI Observations

- X-ray CT Inspections
  - A clean repair and a repair with multiple indications was inspected
    - Repair 3e – No Speckling Pattern in Resonance C-Scans
    - Repair 9b – Speckling Pattern in Resonance C-Scans

Repair 3e

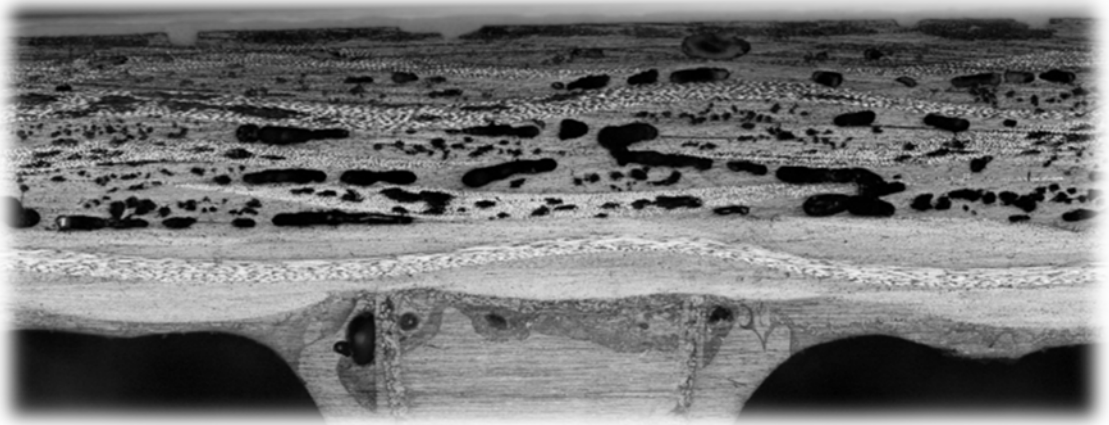


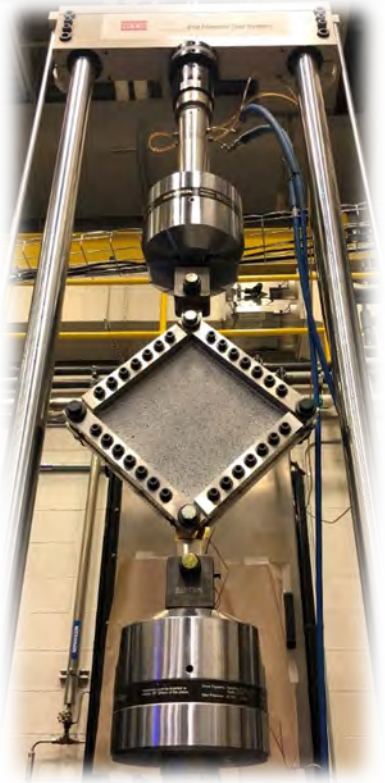
Repair 9b

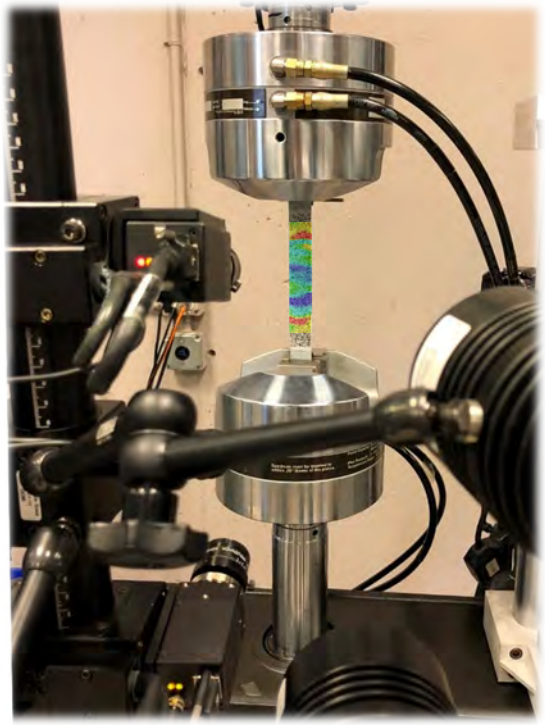


Evaluation of Non-Metallic Bonded Repairs

- **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 (PFS) Testing
  - Tension Testing (Shear Strength of Bonded Repair)
  - Flat-wise Tensile Testing





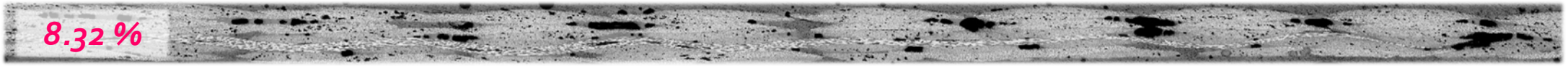


Physical Testing – Void Content

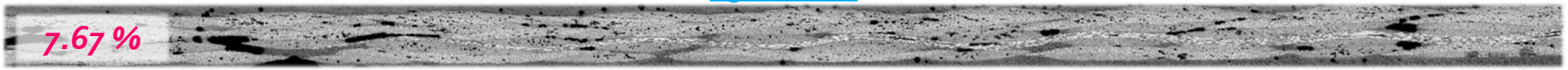
- **Acid Digestion (AD)**
  - Requires 1" x 1" extraction and known fiber/resin densities
    - **ASTM D792-13** – *Standard Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement*
    - **ASTM D3171-15** – *Standard Test Methods for Constituent Content of Composite 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

Repair	Specimen	Void Content [%]
9b	C9-RB-AD-1	6.04
	C9-RB-IA-1	8.32
	C9-RB-IA-2	7.67
9d	C9-RD-AD-1	10.04
9e	C9-RE-AD-1	3.74
3d	C3-RD-IA-1	14.65
Average **Void Content (%)**		**8.41**

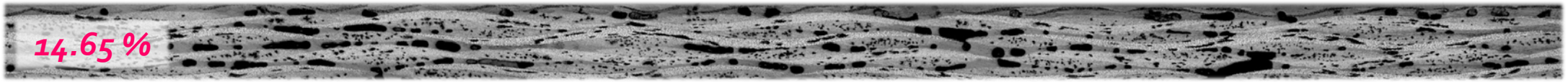
C9-RB-IA-1



C9-RB-IA-2



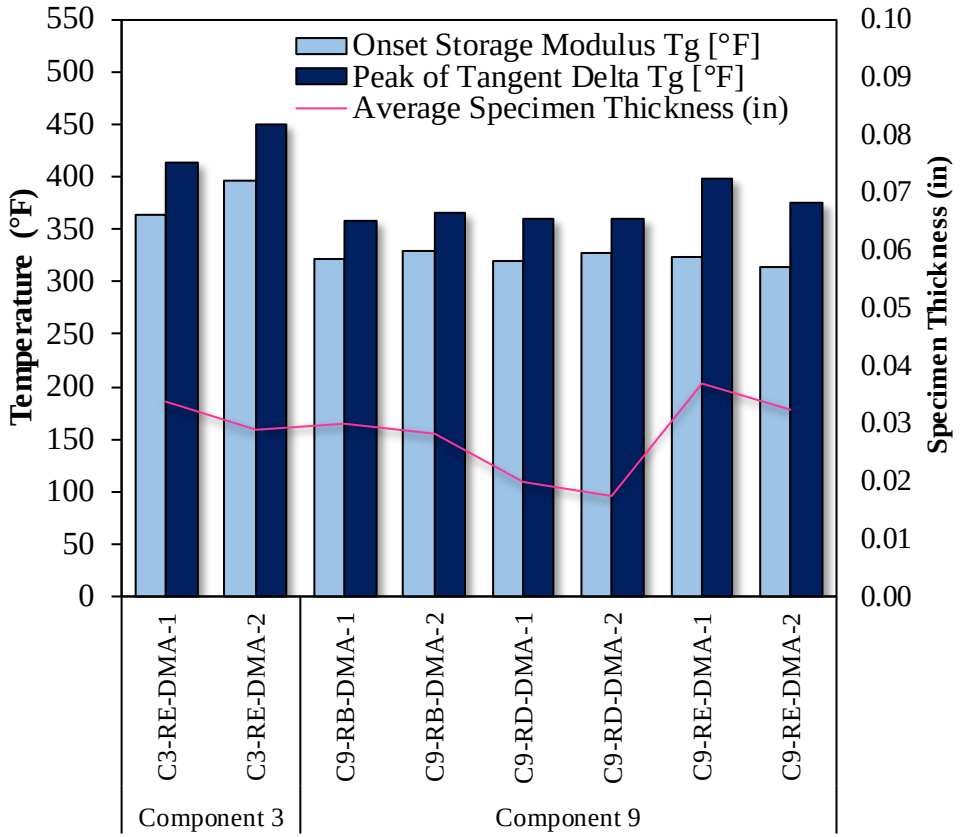
C9-RB-IA-2



Thermal Analysis – DMA

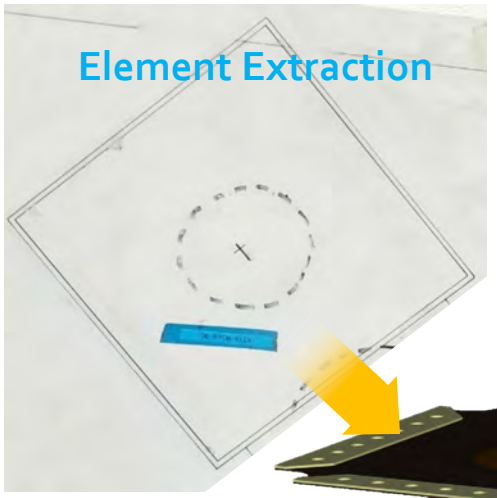
- **Dynamic Mechanical Analysis (DMA)**
  - 2.3" x 0.5" specimen used for 50 mm 3-point bend (repair patch material separated from parent material)
    - **ASTM D7028-07** – *Standard Test Method for Glass Transition Temperature (DMA Tg) of Polymer Matrix Composites by Dynamic Mechanical Analysis (DMA)*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

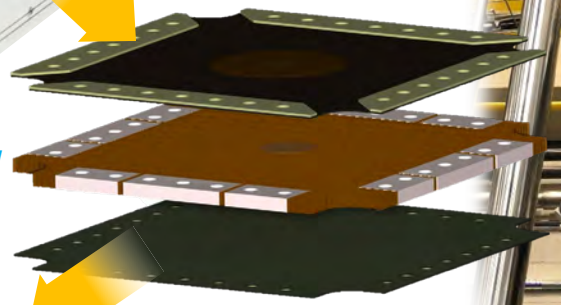
Component	Component	Specimen	Onset Storage Modulus Tg [°F]	Peak of Tangent Delta Tg [°F]
3	Component 3	C3-RE-DMA-1	362.89	412.84
		C3-RE-DMA-2	397.02	450.52
9	Component 9	C9-RB-DMA-1	321.51	357.85
		C9-RB-DMA-2	329.29	364.82
		C9-RD-DMA-1	318.99	359.15
		C9-RD-DMA-2	326.84	359.17
		C9-RE-DMA-1	323.13	397.08
		C9-RE-DMA-2	313.77	375.89
		Average **Tg [°F]**	**339.95**	**384.67**
		Standard Deviation	28.61	33.33
		%COV	8.42	8.66

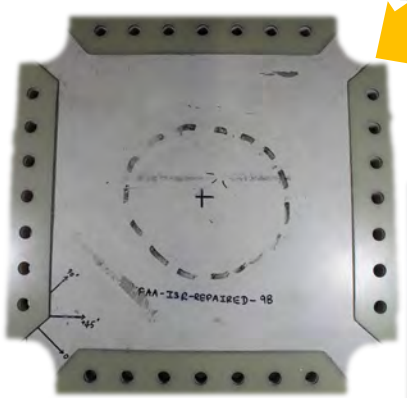


Mechanical Testing – Picture Frame Shear

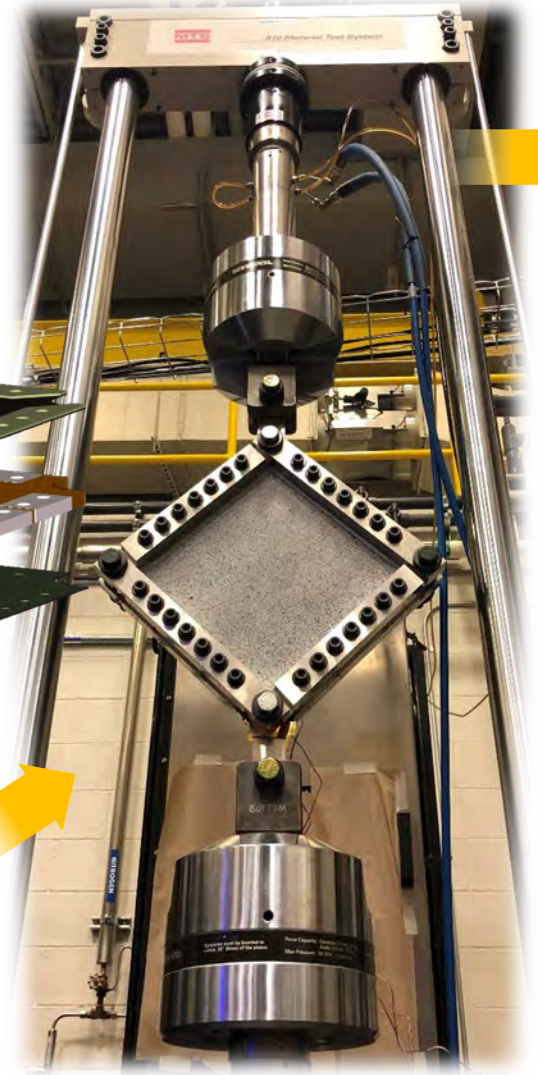
- **Picture Frame Shear (PFS) Test Approach**
  - Repaired element compared to Un-damaged
  - Performed on repair 3e and 9b (X-ray CT Inspections)
  - Following testing, a failure analysis was performed and physical testing was completed on fragments of repair material
  - Full-field strain (ARAMIS)





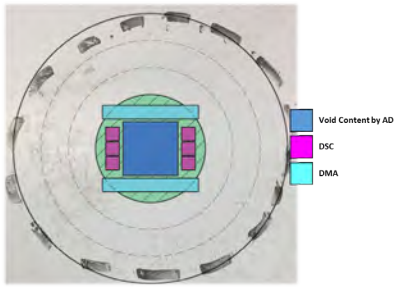


Mechanical Testing



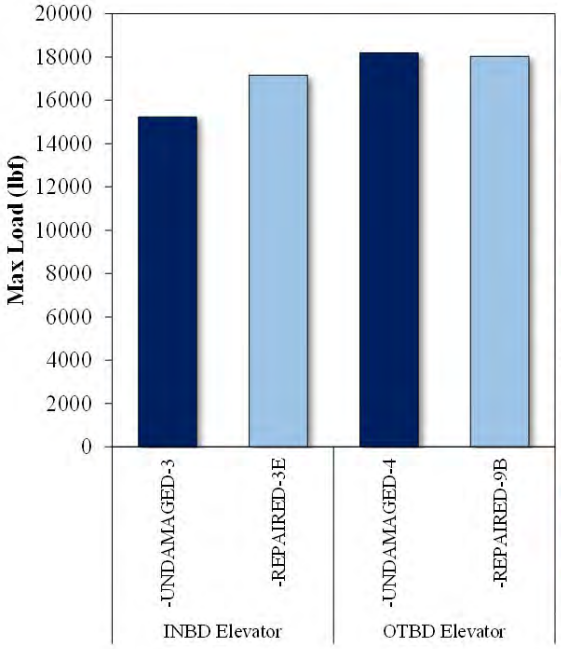
Failure Analysis

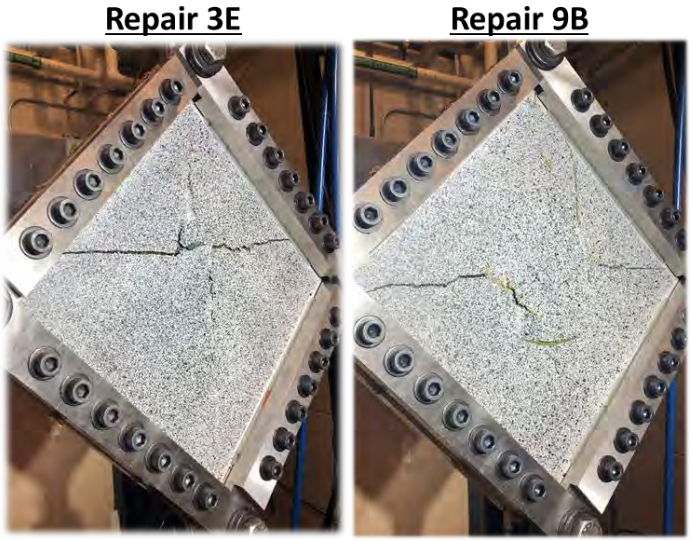
Fragment Physical Testing



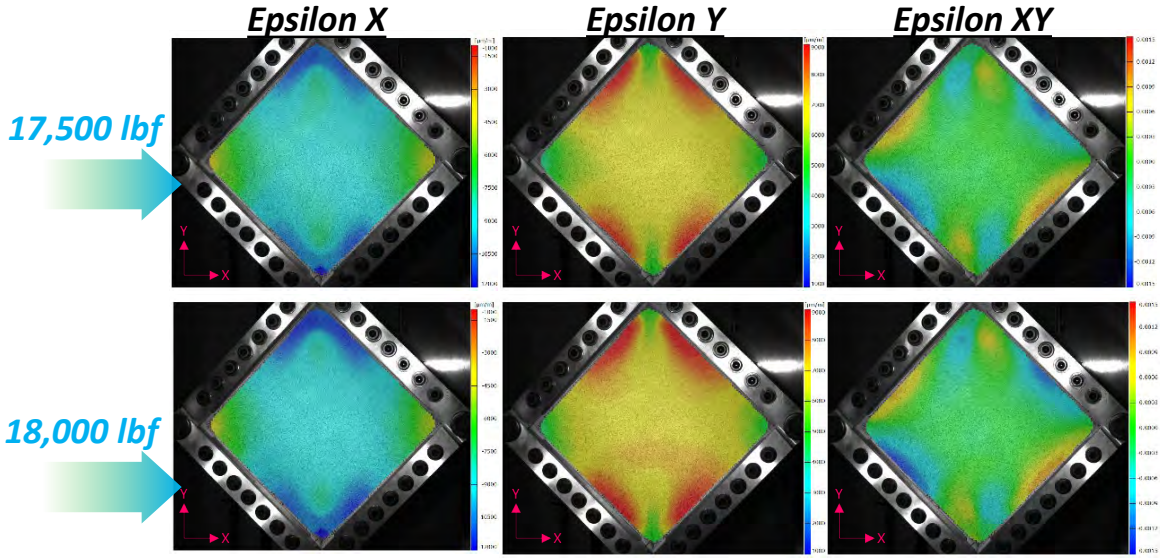
Picture Frame Shear Testing

- **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

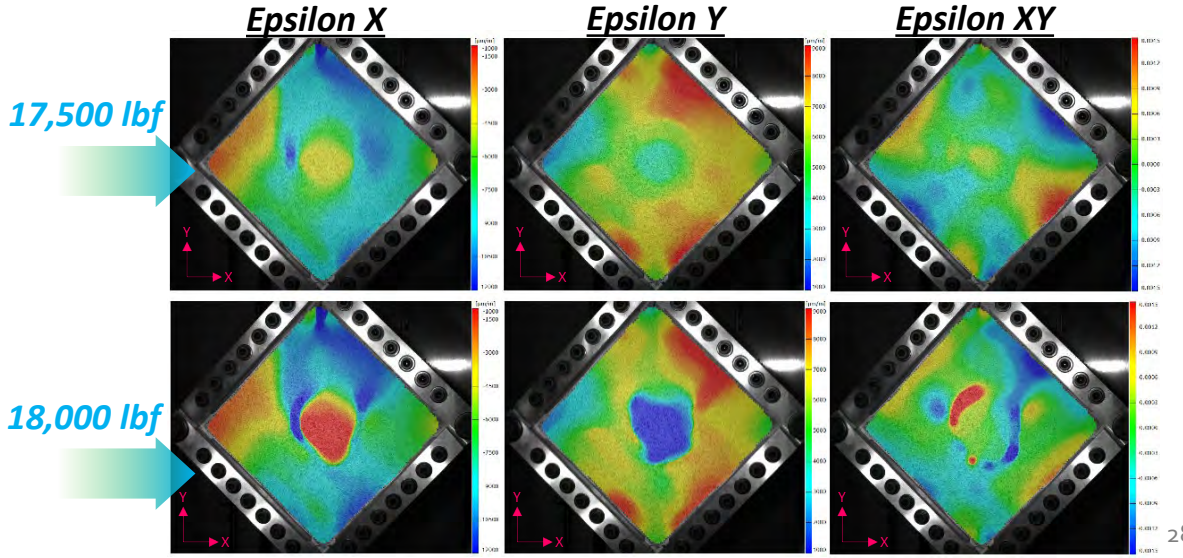




Baseline (Undamaged – Component 4) – ARAMIS

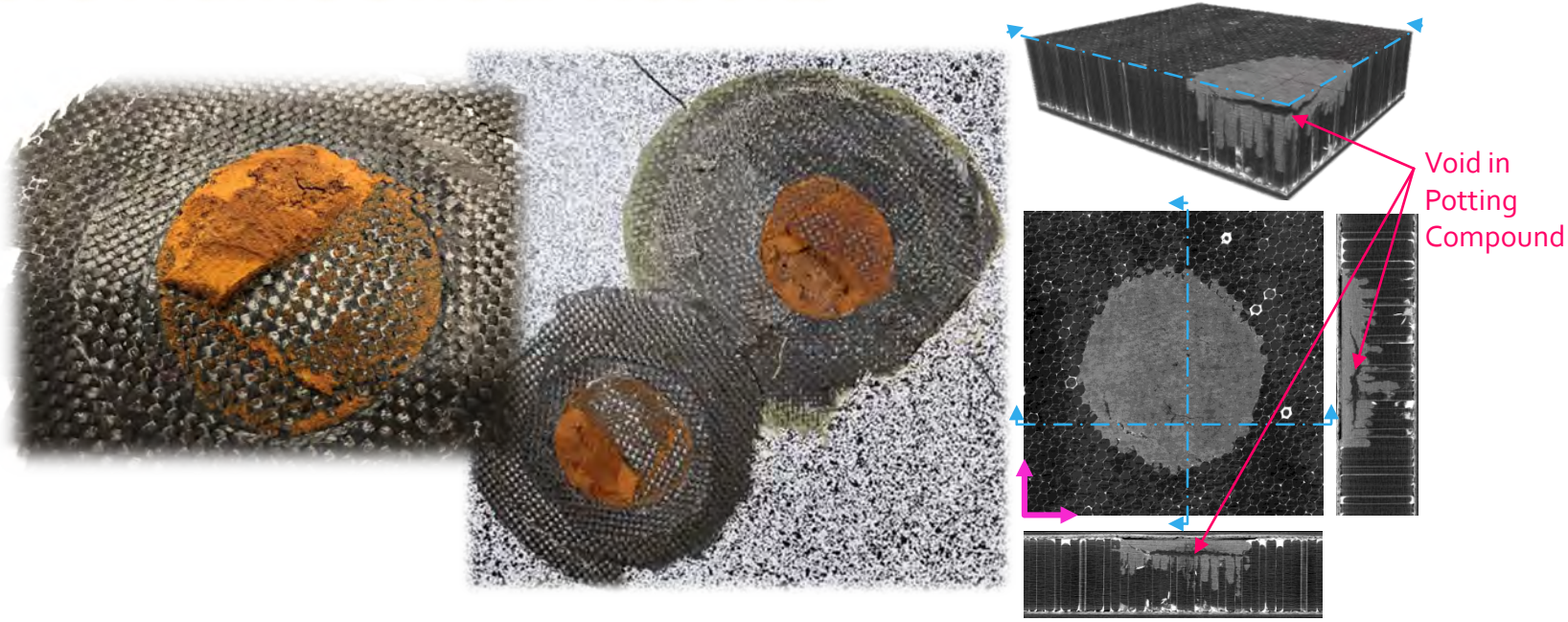


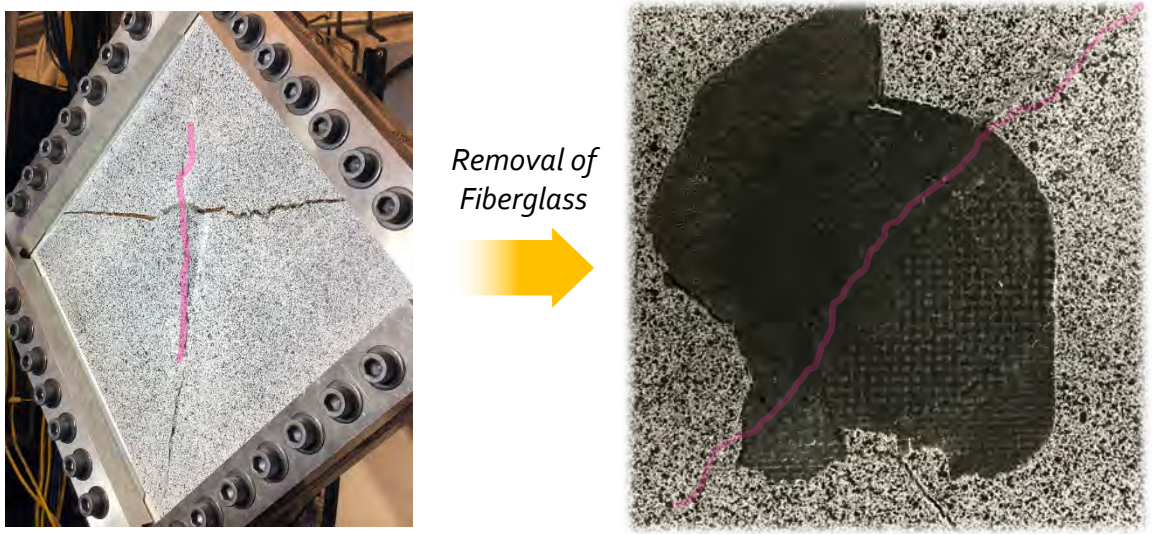
Repaired (Repair 9B) – ARAMIS



Picture Frame Shear Results

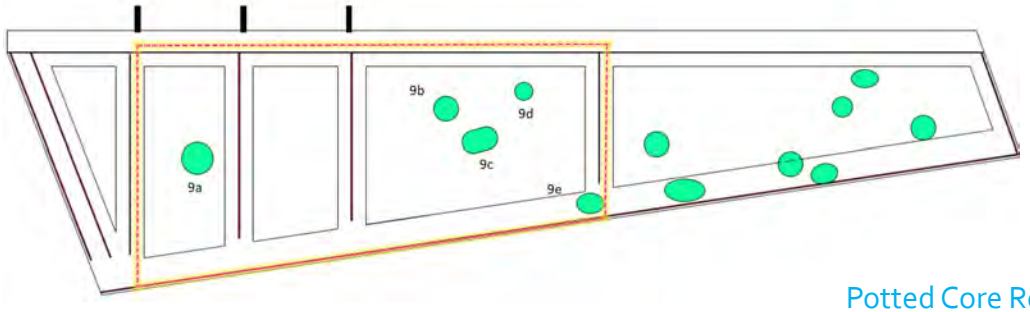
- **Failure related to NDI**
  - Repair 9b
    - Failure through void in potting compound allowing patch separation from core
    - Speckling further investigated following completion of testing and removal of repair patch
  - Repair 3e
    - Failure through repair material





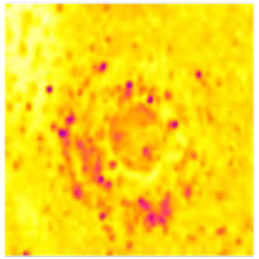
Picture Frame Shear Element Teardown

- **Post-test teardown of PFS Elements**
  - Evaluation of speckling pattern noted in NDI results on Component 4 and 9
    - Build-up of material in honeycomb cells stemming from external facesheet (top and bottom skins)
      - Green in color and small levels witnessed on internal facesheets
      - Less defined on lower skin
    - Random distribution
    - Located in specific regions on the components

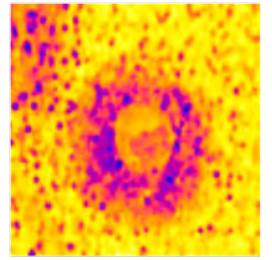


X-ray CT

MAUS V – Resonance, 160 KHz



X-PLOT (Amp)



Y-PLOT (Phase)

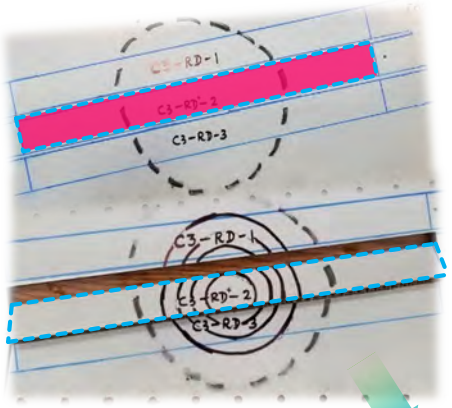
Repair 9b Core Sectioned
Top Skin

Potted Core Region of Repair

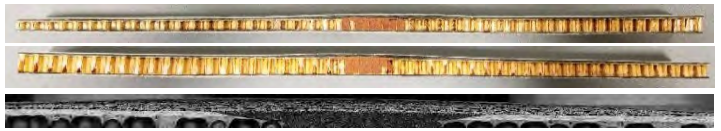
Mechanical Testing – Tension

- **Evaluation of bond strength between repair and parent material**
  - Performed on repairs above core that varies in thickness
    - Near trailing edge of components
  - Microscopic inspections performed on cross-section prior to testing
    - Overlap length (bonded region) evaluated from microscopic inspection and verified in post-test measurements

1. Extraction

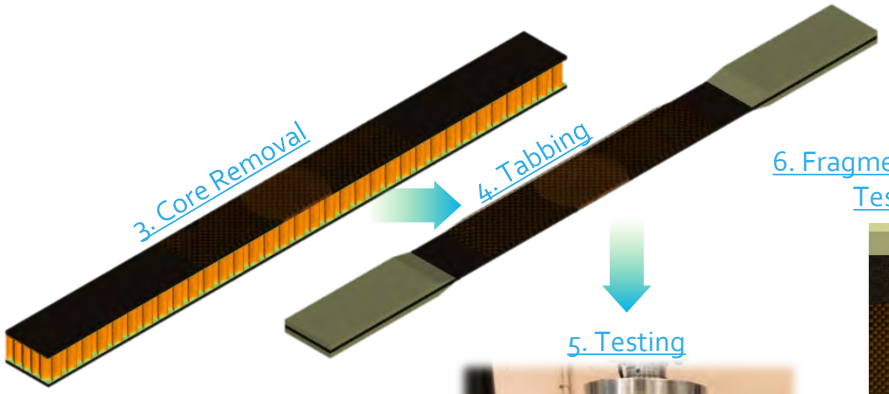


2. Documentation

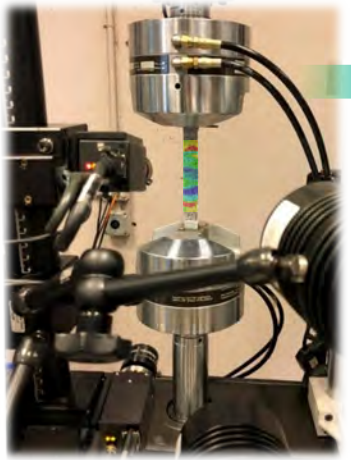


3. Core Removal

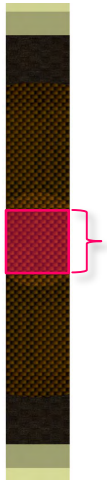
4. Tabbing

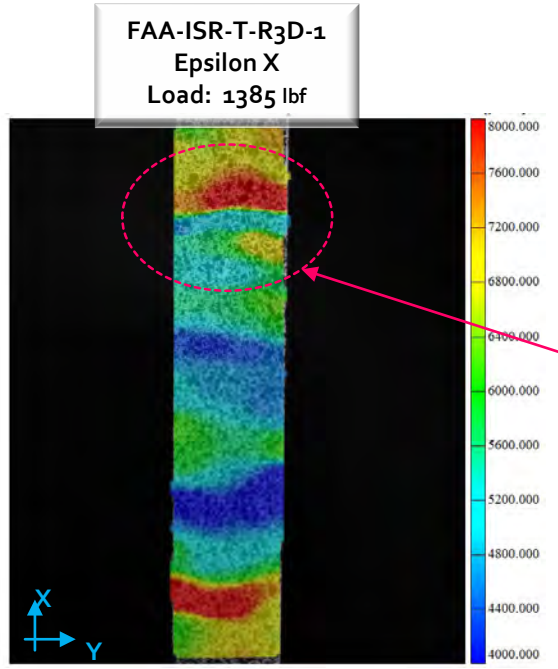


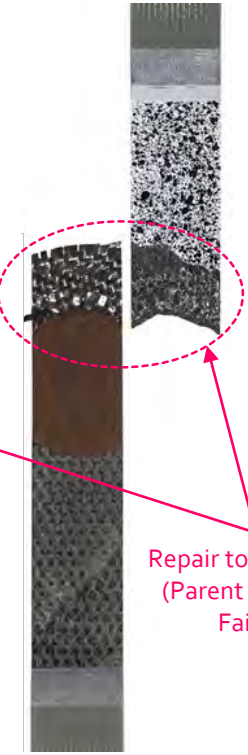
5. Testing



6. Fragment Physical Testing







Summary

- **Program Status**
  - Metallic bonded repair teardown and testing completed and documented in FAA Technical Report (Inspection and Teardown of Aged In-Service Bonded Repairs Vol. I)
  - Non-metallic repair teardown and testing in progress
- **Benefit to Aviation**
  - Evaluation of bondline integrity and durability of in-service repairs on 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)

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