Bonded Repairs of Composite Panels Representative of Wing Structure

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Delft, The Netherlands 26-29 June 2023

Outline

- Background and Objectives
- Experimental Procedure
- Results
- Summary
- Future Work

Program Background

Cooperative Research and Development Agreement (CRDA)

October 2007 the FAA and Boeing entered into a CRDA to conduct research addressing safety and structural integrity of bonded repair technologies

COOPERATIVE RESEARCH AND DEVELOPMENT AGREEMENT

07-CRDA-0236

THE BOEING COMPANY

and

THE FEDERAL AVIATION ADMINISTRATION
WILLIAM J. HUGHES TECHNICAL CENTER

This Cooperative Research and Development Agreement (CRDA), dated OCT 3 0 2007 is entered into by and between The Boeing Company (BOEING), and the United States of America, as represented by the Federal Aviation Administration William J. Hughes Technical Center (FAA Technical Center), located at the Atlantic City International Airport, New Jersey.

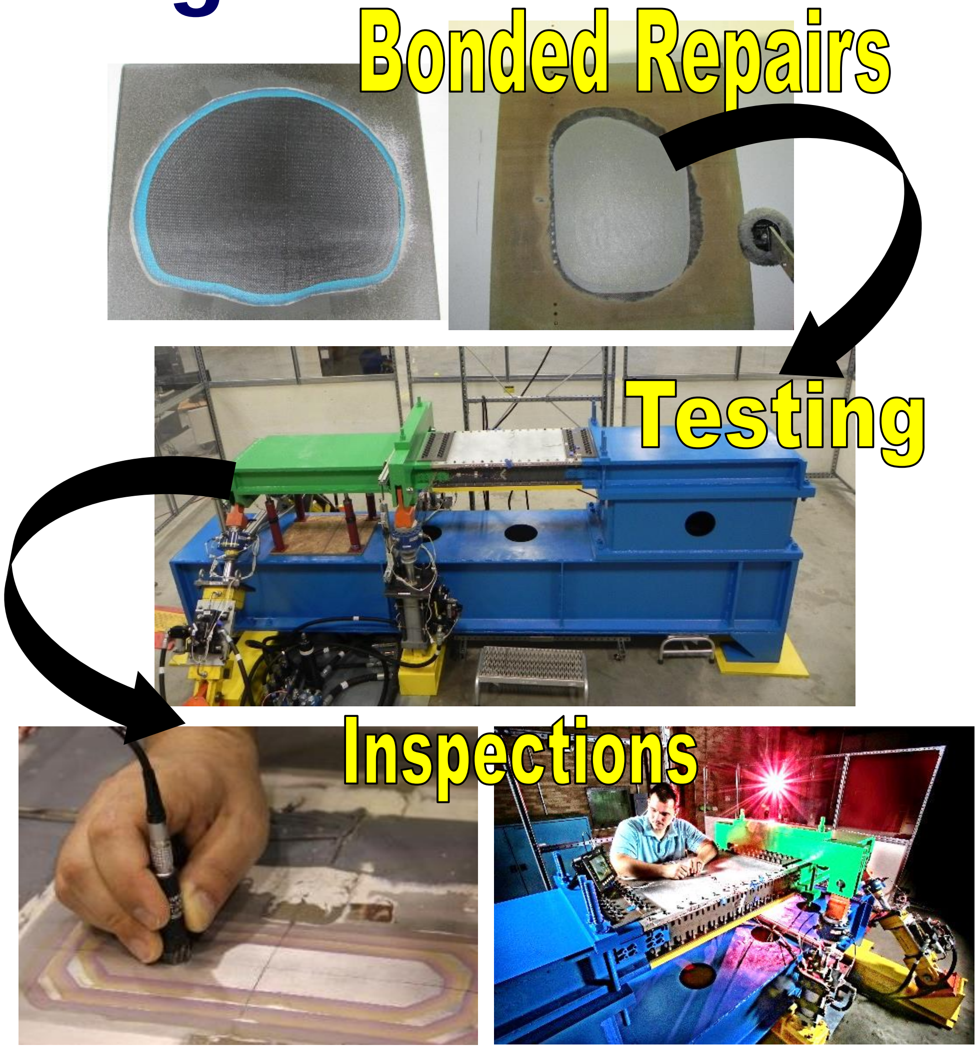
Bonded Repairs to Representative Composite Wing Panels

Objective:

- Study fatigue and residual strength performance of bonded repairs to representative composite wing panels

Output is Data:

- Assess damage tolerance capabilities and long-term airworthiness of bonded repairs
- Assess the ability of Structural Health Monitoring (SHM) and Non-Destructive Inspection (NDI) technologies to monitor repair integrity
- Verify and calibrate methods used to analyze and design bonded repairs



Team Members

- **FAA**
  - Reewanshu Chadha (Test Engineer)
  - Thuan Nguyen (Test Technician)
  - Burak Kumas
  - Ahmet Oztekin
  - Ed Weinstein
  - John Bakuckas

  Advisory panel and Sponsors:
  - Cindy Ashforth
  - Larry Ilcewicz
  - Walt Sippel

- **Drexel University**
  - Tim Labik (FAA-Drexel Fellow)
  - Jonathan Awerbuch (Professor)
  - Tein Min Tan (Professor)

- **Boeing**
  - Michael Fleming (Lead-BR&T)
  - John Lin (BR&T ATF Analysis)
  - Erick Espinar-Mick (BCA Structures)
  - Mohamed Azdamou (BR&T Structures)
  - Steve Wanthal (BR&T TF)
  - Michael Bailey (BR&T Structures)
  - Jon Marsh (BR&T Structures)
  - Lilly Owen (BR&T Structures)

  Advisory panel:
  - Pradeep Krishnaswamy (BCA TF)
  - Gary Oakes (BCA TF)
  - Larry Ridgeway (BCA ATF)
  - Steve Hinrichs (BCA Structures)
  - Patrick Enjuto (BCA TF)
  - Nihar Desai (BCA ATF)
  - John Spalding (BR&T ATF)

Project Phases

- Phase 1 – Design, fabricate and demonstrate full functionality of the panel test fixture, FY17-21
- Phase 2 – Baseline Testing: Conduct baseline testing and analysis to define appropriate experimental procedures and NDI methods, FY17-21
- Phase 3 – Bonded Repair Size Limits (BRSL): Develop data supporting BRSL assessment methods for solid laminates and composite honeycomb panels to support FAA guidance, FY18 – FY24
- Phase 4 – Assess emerging bonded repair technologies and inspection methods, FY22 – FY25
- Phase 5 – Large Configured Panel Testing: Develop and utilize Large Airframe Wing Structure (LAWS) fixture to expand studies in Phase 3 and 4, FY22 – 27:
  - Large damage – two bay
  - Impact damage
  - Repairs in proximity to other repairs
  - Effect of substructure

Bonded Repair Size Limits - Background

- Bonded Repairs, Advantages:
  - Desirable due to superior fit and finish
  - Aerodynamically and structurally efficient
  - Eliminates the region of high stress concentrations near the rivet holes
- Bonded Repairs, Challenges:
  - Repair processes are specialized and requires properly trained/qualified individuals
  - Lack of inspection methods to detect weak bonds that result in failure
- ***All critical structures must have a repair size limit no larger than a size that maintains limit load residual strength capability with the repair completely failed***

U.S. Department of Transportation
Federal Aviation Administration

Policy Statement

Subject: Bonded Repair Size Limits

Date: 11/24/14

Policy No: PS-AIR-100-14-130-001

Initiated By: AIR-100

A. Summary

This policy reviews the regulatory basis and establishes the guidance in setting size limits for bonded repair to critical composite (monolithic and sandwich structures) and metallic structure. Bonded repair of critical structure must first be constrained to the sizes allowed by substantiating

Phase 3 – Bonded Repair Size Limits

- Develop data supporting BRSL assessment methods for solid laminates and honeycomb panels to support FAA Guidance
- Validate BRSL analysis methods under development
- Characterize limit load residual strength for partial and fully failed scarf repair configurations

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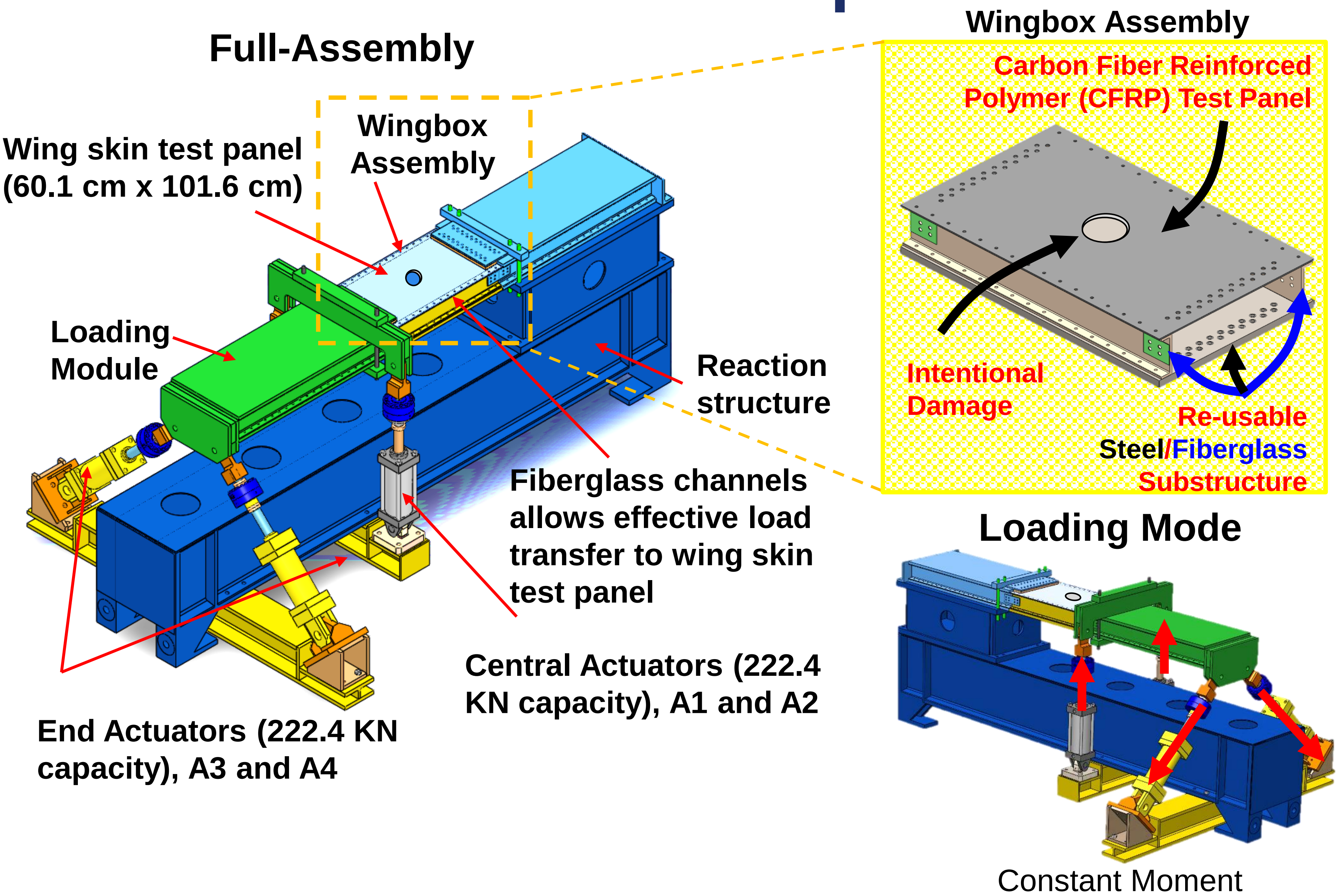
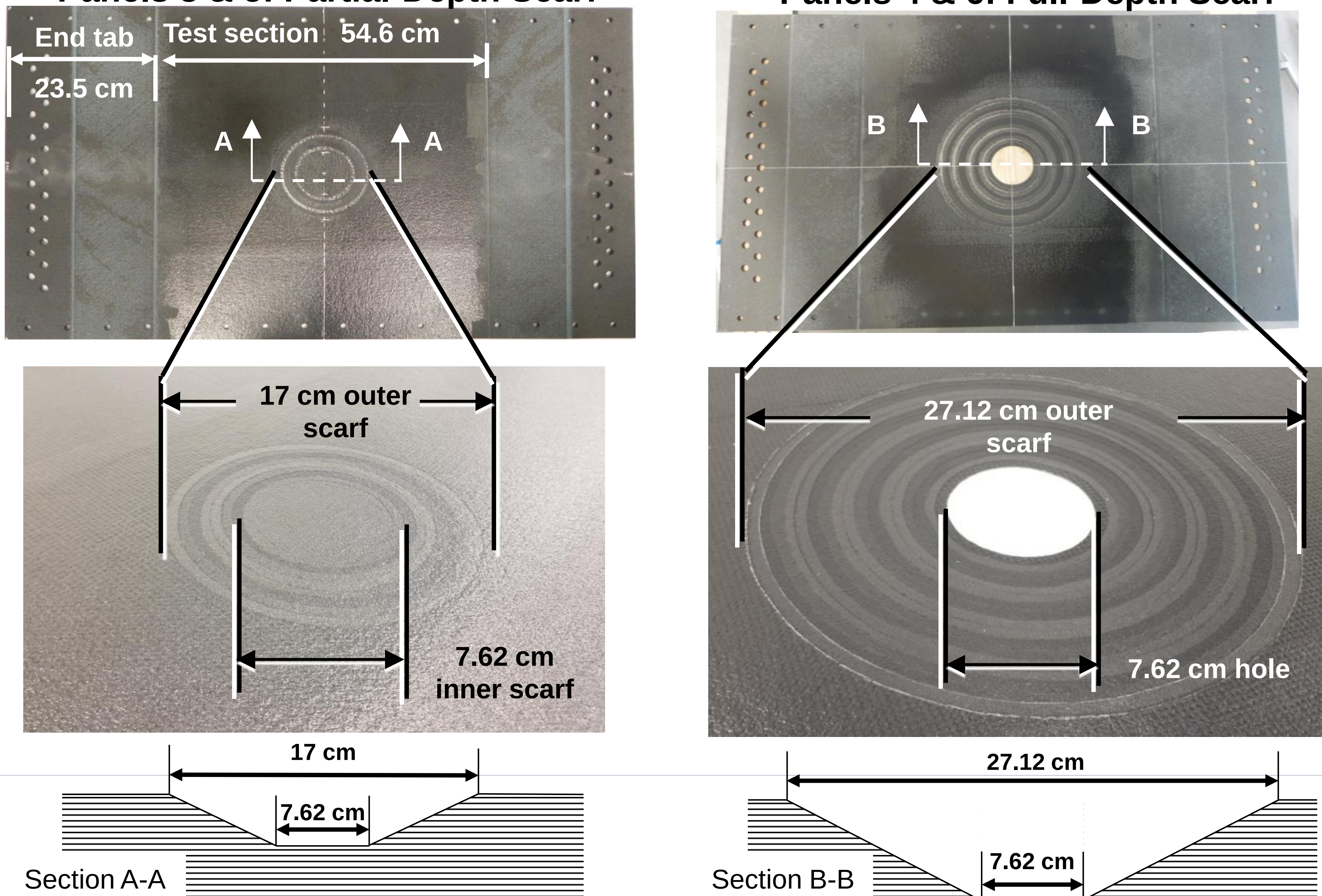
Airframe Beam Structural Test (ABST) Fixture Description



Phase 3 –Panel Configurations

Solid Laminate: 18-ply quasi-isotropic $[\pm 45_{fabric}/-45°/90°/45°/0°/-45°/90°/45°/0°]_s$

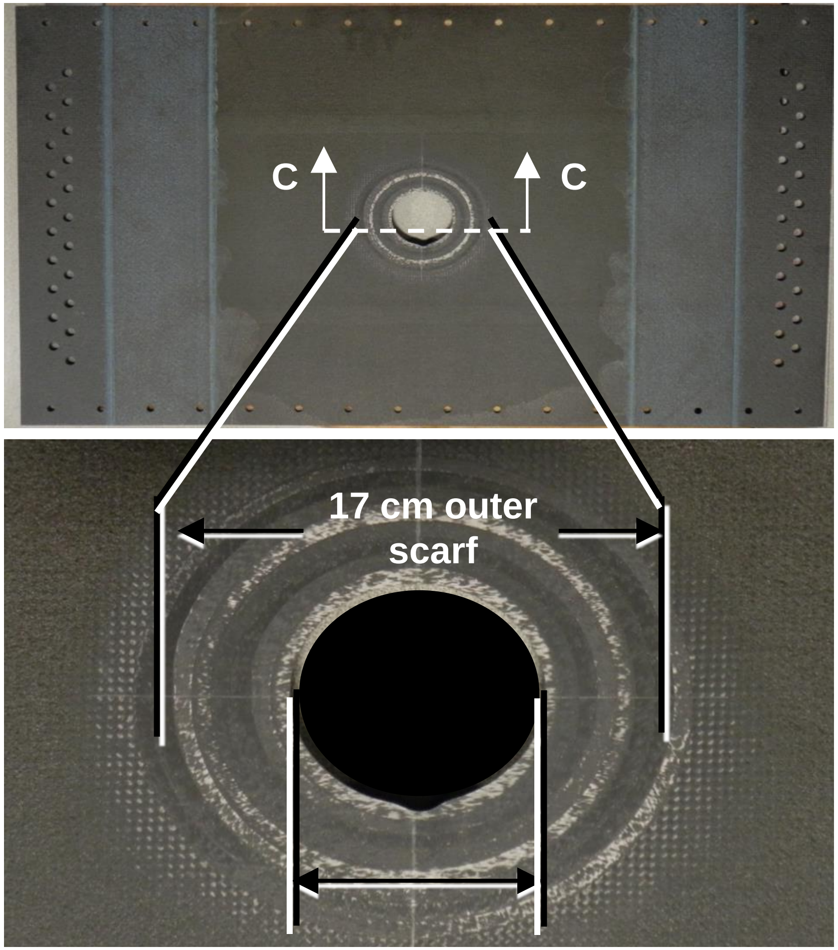
Panels 3 & 5: Partial-Depth Scarf | **Panels 4 & 6: Full-Depth Scarf**



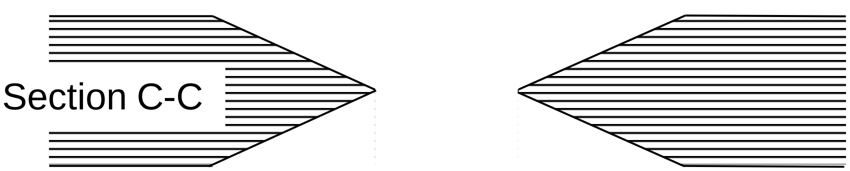
Phase 3 – Panel Configurations

Solid Laminate: 18-ply quasi-isotropic $[\pm 45_{fabric}/-45°/90°/45°/0°/-45°/90°/45°/0°]_s$

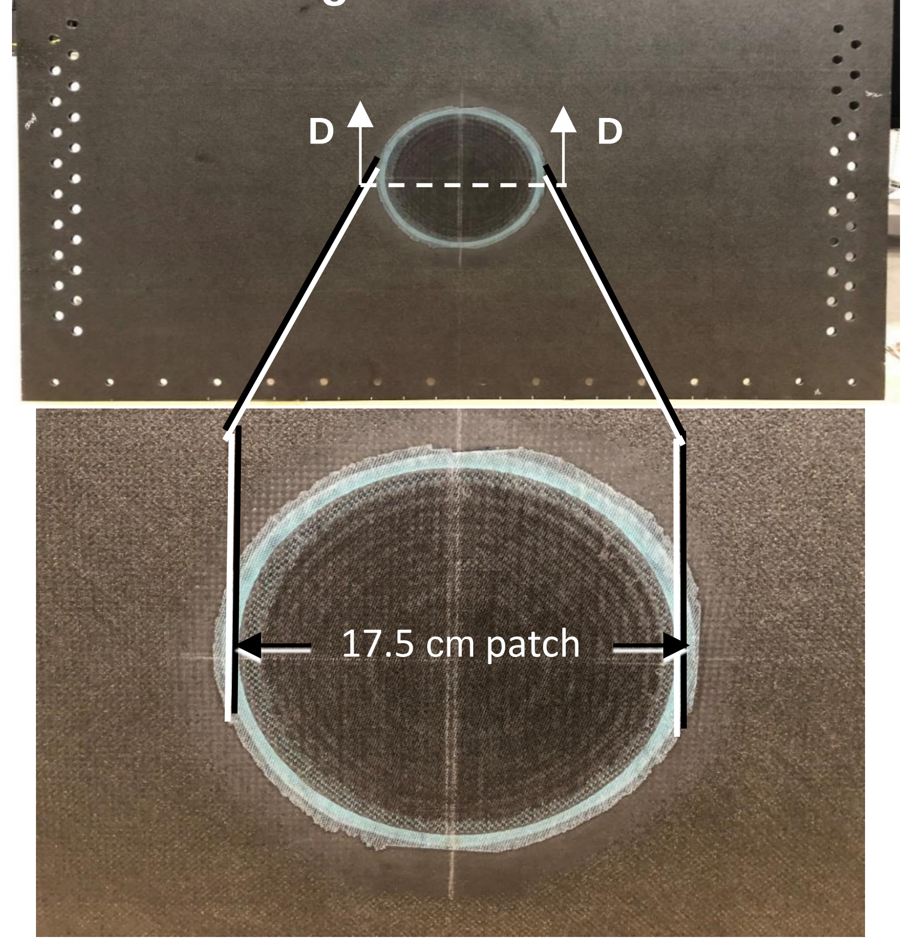
Panels 7 & 8: Double-Sided Scarf

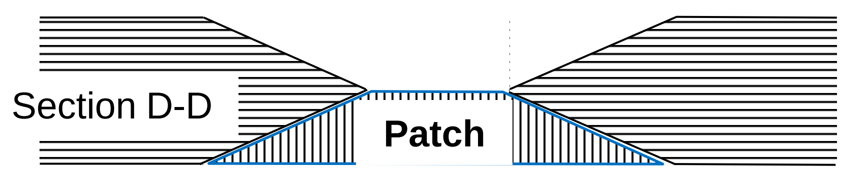


7.62 cm hole



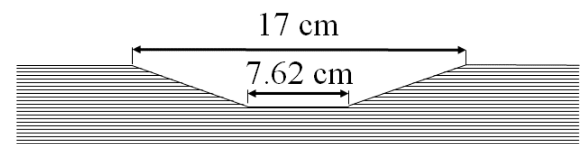
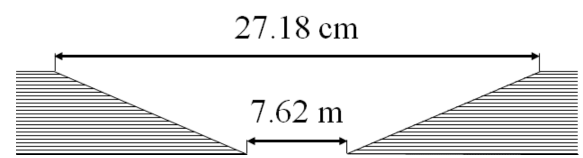
Panels 9, 10 & 11: Double-Sided Scarf w/ Single-Sided Patch





Phase 3 – Test Matrix

- **Solid Laminate: 18-ply quasi-isotropic**
  $[\pm 45_{fabric}/-45°/90°/45°/0°/-45°/90°/45°/0°]_s$
- **Scarf Configurations: Partial, Full and Double**
- **Loading Mode: Constant Moment – Tension**

Panel No.	Scarf Configuration	Test Description	
3	Partial-Depth Scarf (PDS)	Baseline Residual Strength	
5	Partial-Depth Scarf (PDS)	Fatigue to 6 DSO (330,000 cycles) under 2200$\mu\varepsilon$ (service load conditions)	
		Post Fatigue Residual Strength	
4	Full-Depth Scarf (FDS)	Baseline Residual Strength	
6	Full-Depth Scarf (FDS)	Fatigue to 3 DSO (165,000 cycles) under 2200$\mu\varepsilon$ (service load conditions)	
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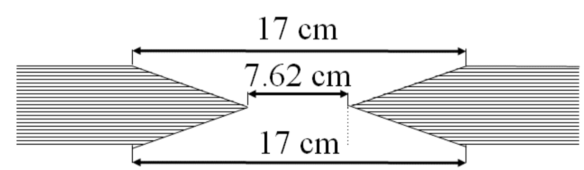
7	Double-Sided Scarf (DDS)	Baseline Residual Strength	
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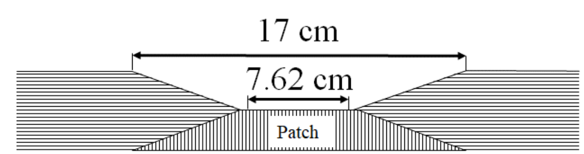
9,10 and 11	Double-Sided Scarf with Single-Sided patch	Baseline Residual Strength: Compare with Partial Depth Scarf	

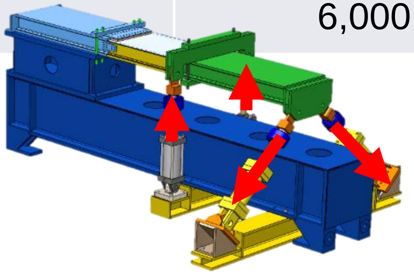
Applied Test Loads

Fatigue loading conditions simulated operational strain levels experienced by typical transport category composite wing panels

- Estimated to be 36% of the ultimate strain based on notched coupon allowables

Test Description	Load Type	Target Strains
		Tension (µStrain)
Fatigue – Normal operational conditions (36% of Ultimate Strains)	Cyclic (R = 0.1)	2,200
Fatigue - Elevated Loads to induce damage growth (40-60% of Ultimate Strains)	Cyclic (R = 0.1)	2,400 – 3,600
Residual Strength	Static	6,000

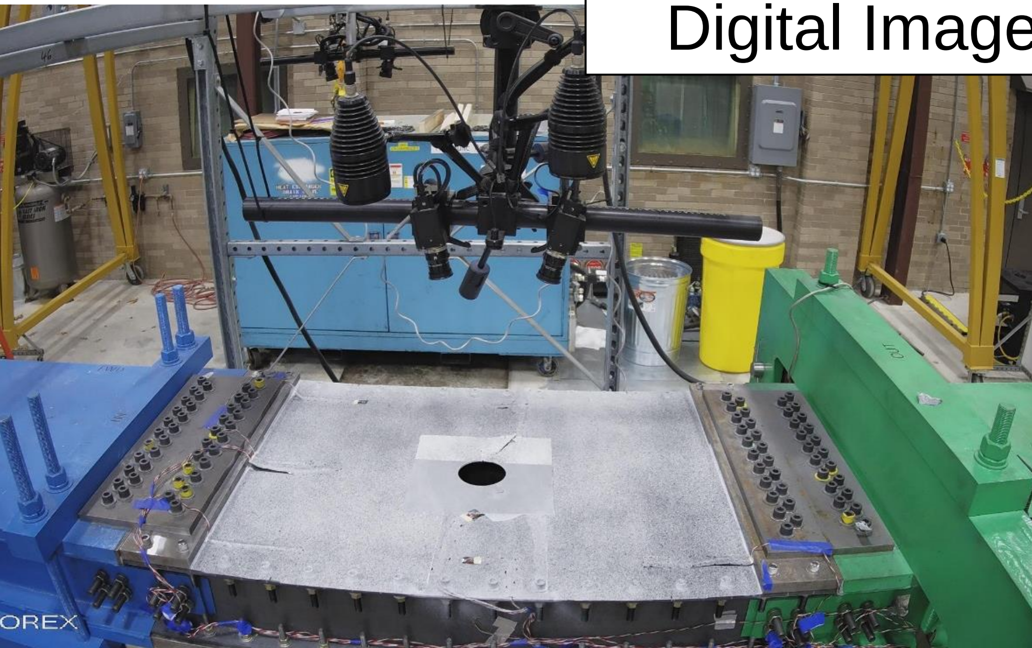
Bending moment applied to induce tensile strains

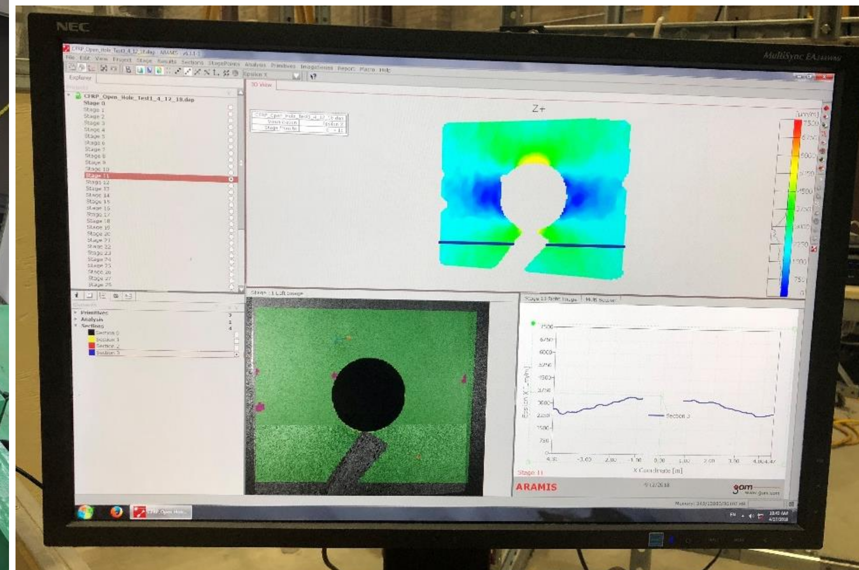


Constant Moment

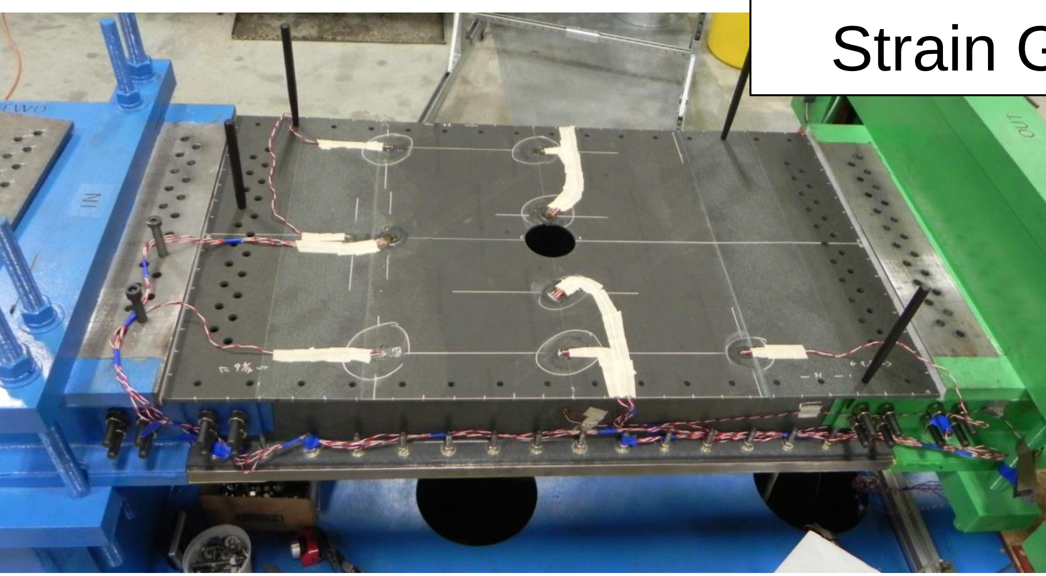
Instrumentation - Strains Measurement

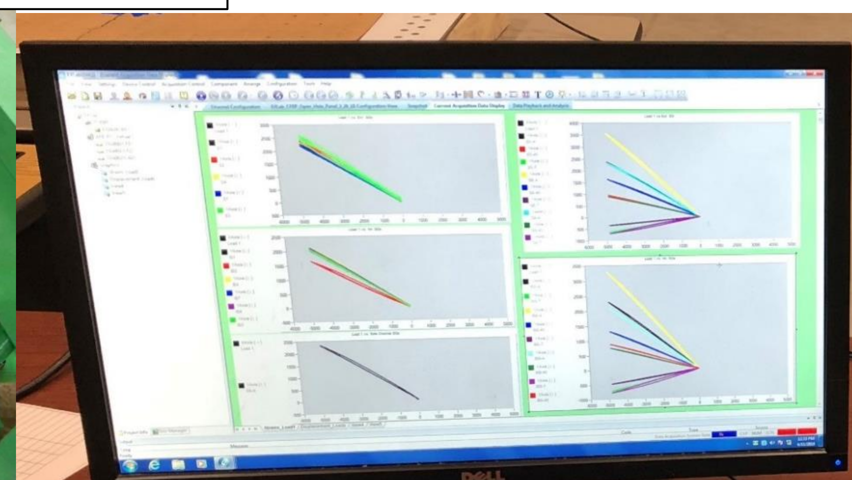
Digital Image Correlation (DIC)





Strain Gages

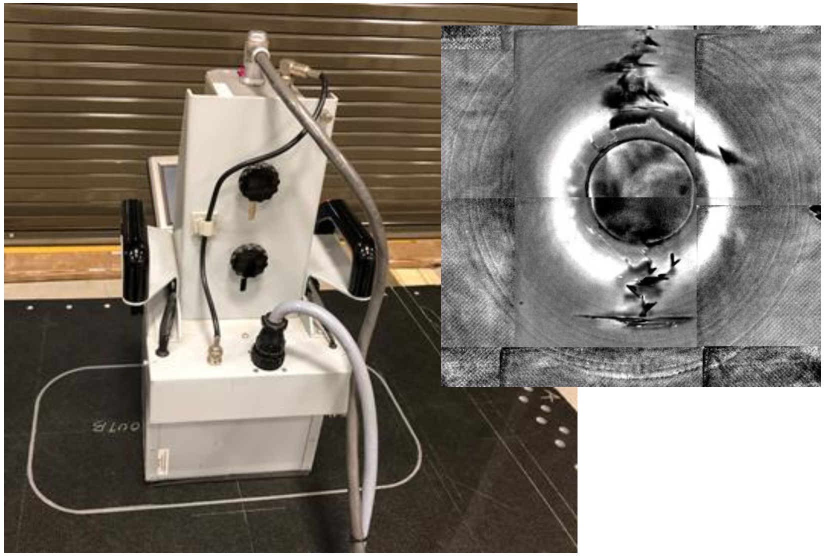




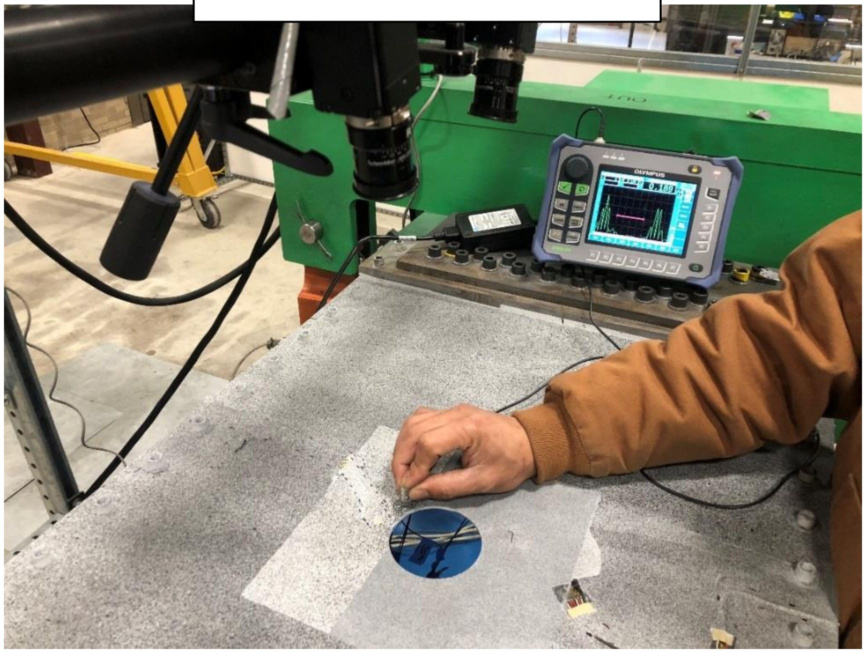
Non-Destructive Inspection (NDI) Methods

- Baseline using TT Ultrasonic System prior to testing (Boeing)
- Pulse Echo Ultrasonic during test
- Phased Array Ultrasonic during test
- Flash Thermography during test

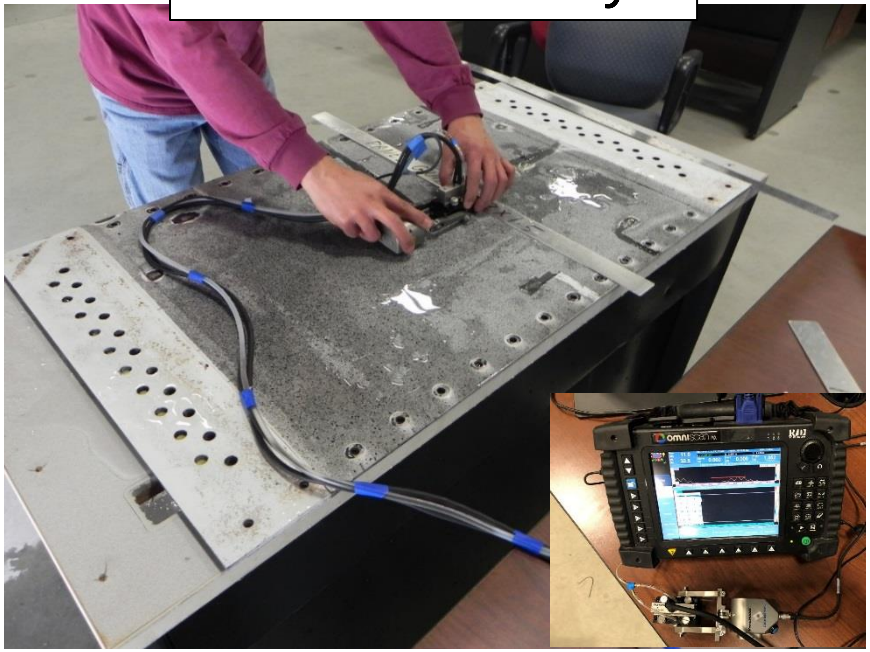
Thermography



Pulse Echo



Phased Array



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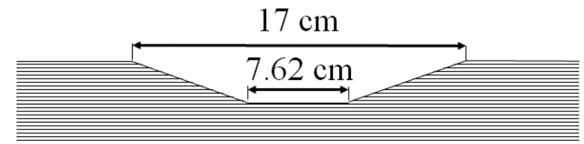
3	Partial-Depth Scarf (PDS)	Baseline Residual Strength	
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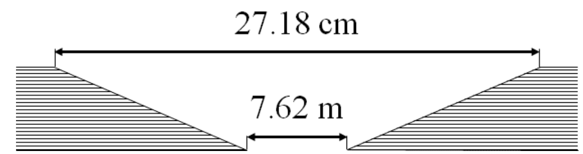
4	Full-Depth Scarf (FDS)	Baseline Residual Strength	
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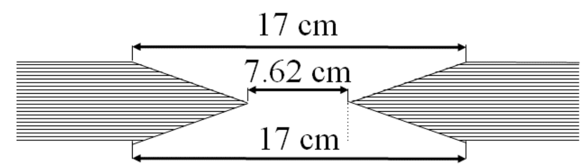
7	Double-Sided Scarf (DDS)	Baseline Residual Strength	
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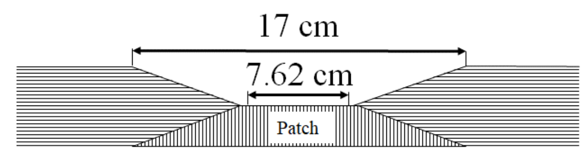
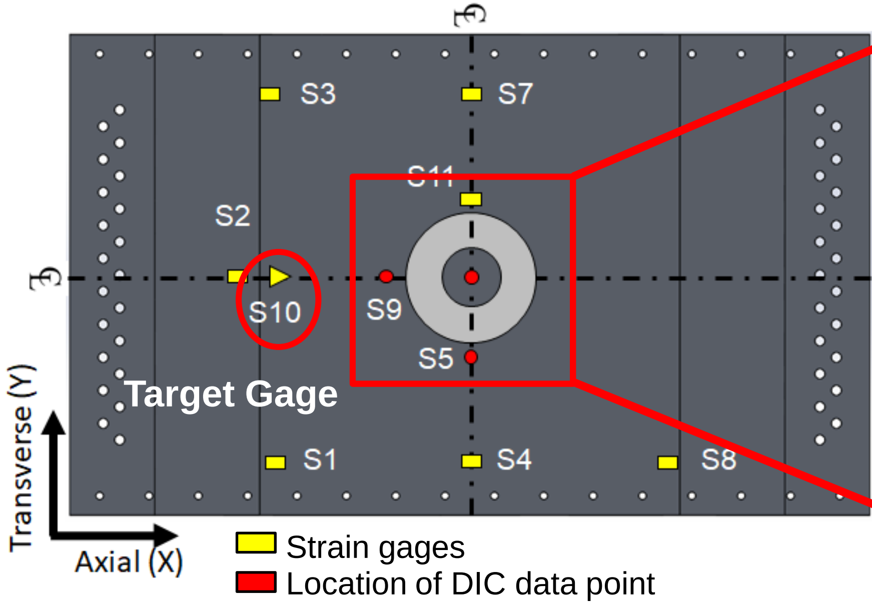
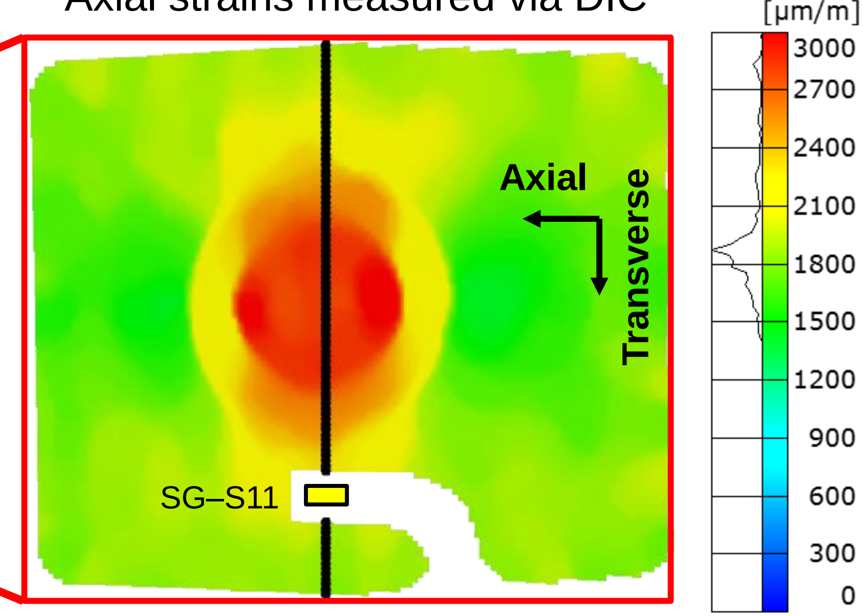
9,10 and 11	Double-Sided Scarf with Single-Sided patch	Baseline Residual Strength: Compare with Partial Depth Scarf	

Panel 3, Partial Depth Scarf – Static Test

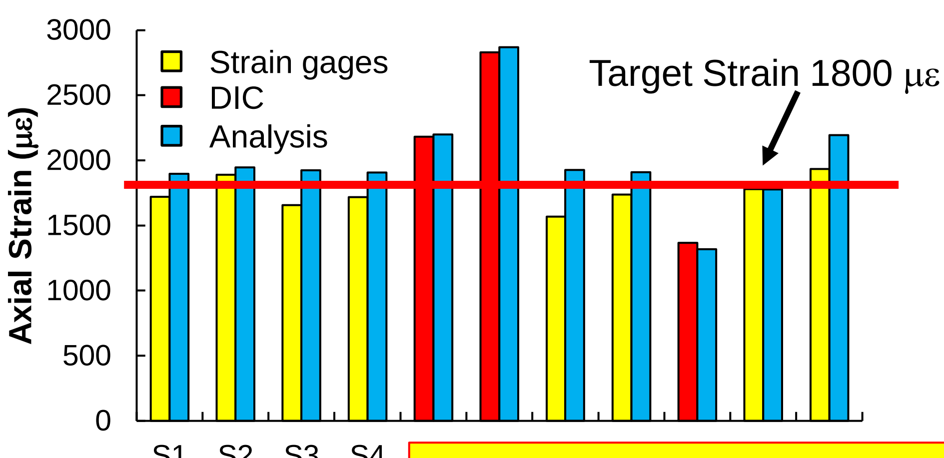
Partial Depth Scarf configuration
and location of strain gages



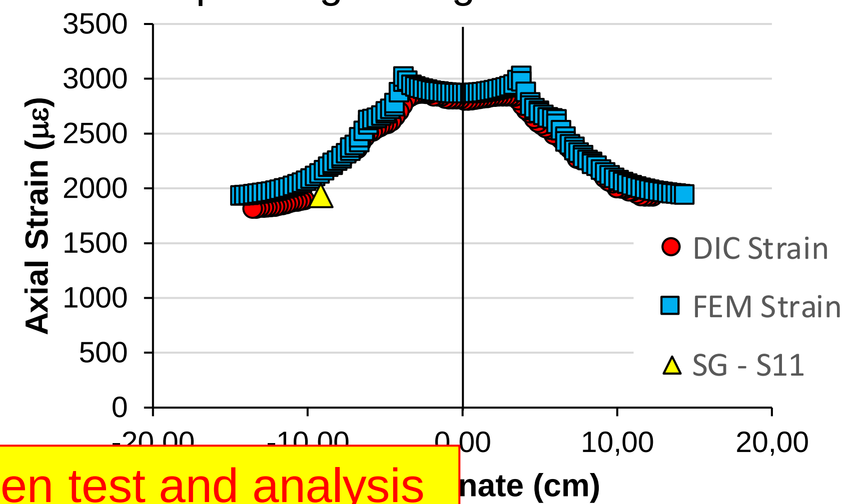
Axial strains measured via DIC



Test and Analysis Correlation

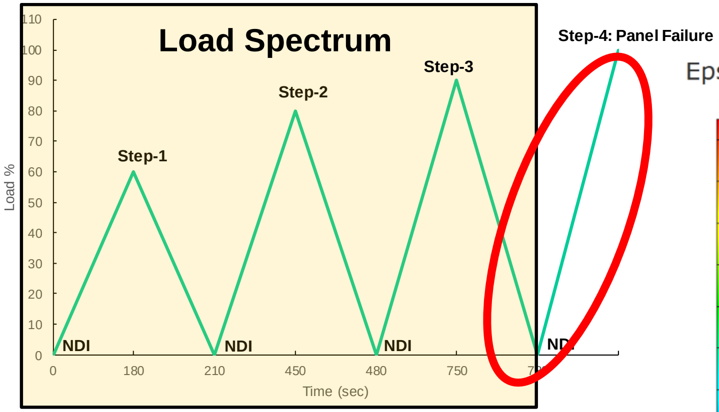


Axial strains along the Y-Coordinate
passing through the center

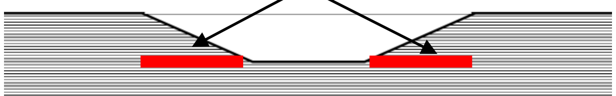


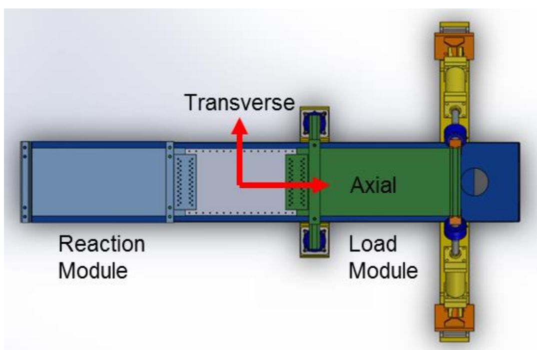
Excellent correlation between test and analysis

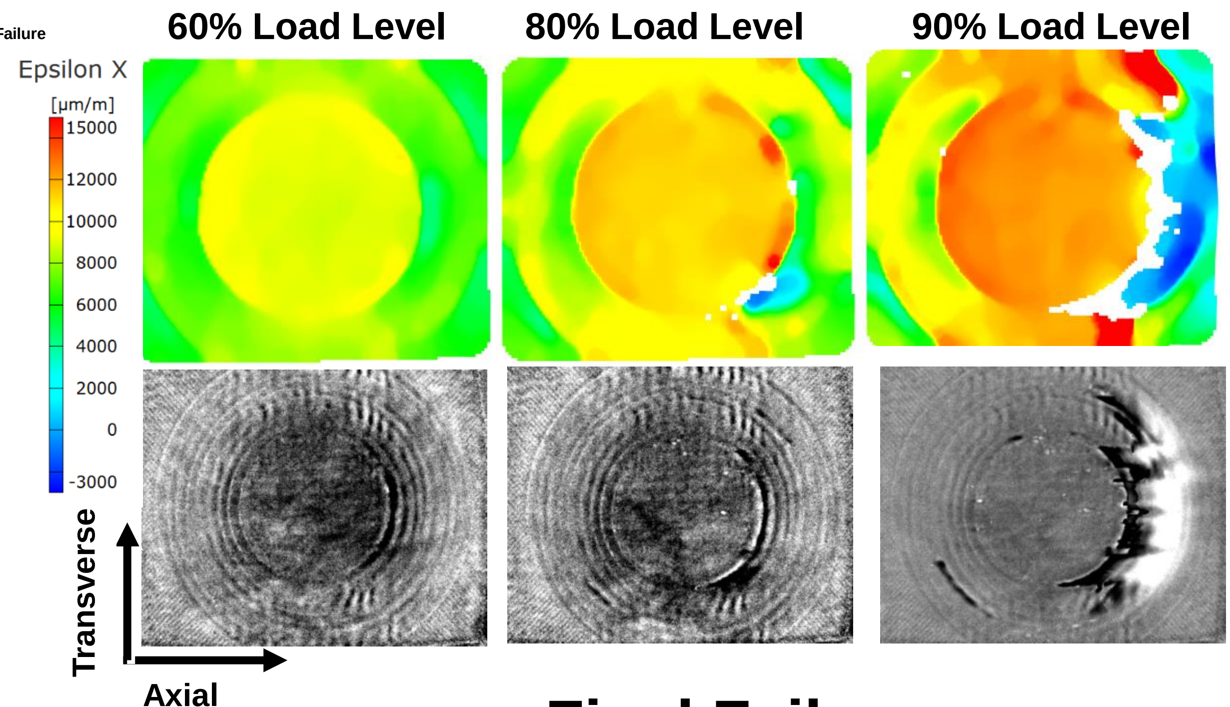
Panel 3, Partial Depth Scarf – Residual Strength

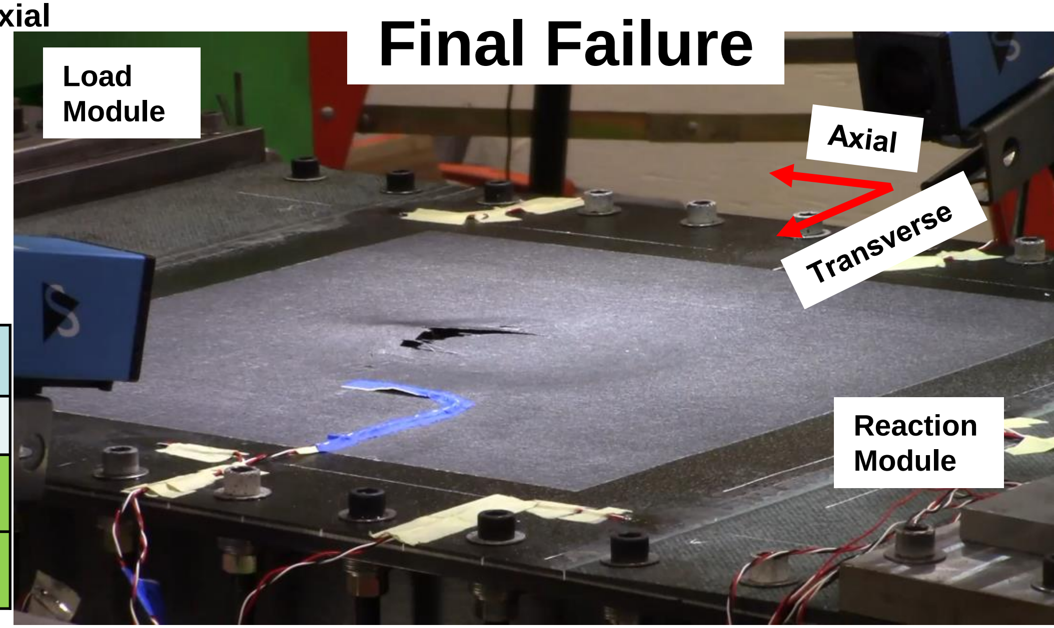


Scarf delamination









Test Description	Failure Load Level	
	Actuator 1 & 2	Actuator 3 & 4
Predicted Critical Load	-89.5 KN	126.6 KN
Measured Failure Load	-89 KN	125.1 KN

Phase 3 – Test Matrix

- **Solid Laminate: 18-ply quasi-isotropic**
  $[\pm 45_{fabric}/-45°/90°/45°/0°/-45°/90°/45°/0°]_s$
- **Scarf Configurations: Partial, Full and Double**
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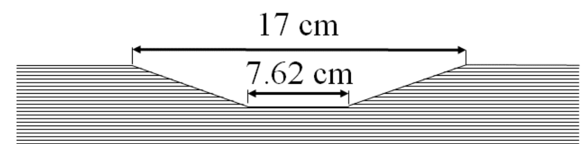
<table>
<tr><th>Panel No.</th><th>Scarf Configuration</th><th>Test Description</th><th></th></tr>
<tr><td>3</td><td>Partial-Depth Scarf (PDS)</td><td>Baseline Residual Strength</td><td rowspan="3">
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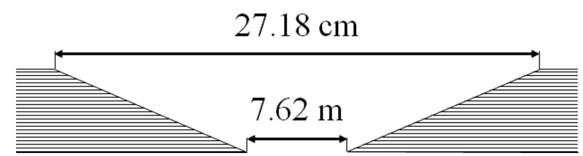
<tr><td>4</td><td>Full-Depth Scarf (FDS)</td><td>Baseline Residual Strength</td><td rowspan="3">
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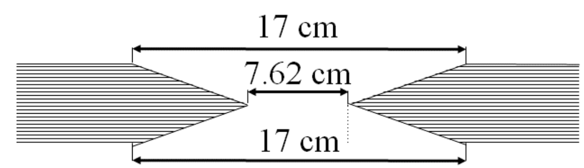
<tr><td>Post-Fatigue Residual Strength</td></tr>
<tr><td>7</td><td>Double-Sided Scarf (DDS)</td><td>Baseline Residual Strength</td><td rowspan="3">
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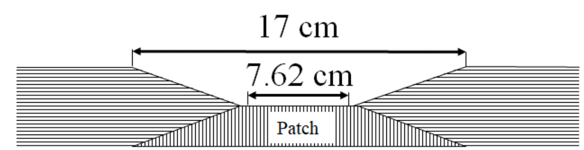
<tr><td>9,10 and 11</td><td>Double-Sided Scarf with Single-Sided patch</td><td>Baseline Residual Strength: Compare with Partial Depth Scarf</td><td>
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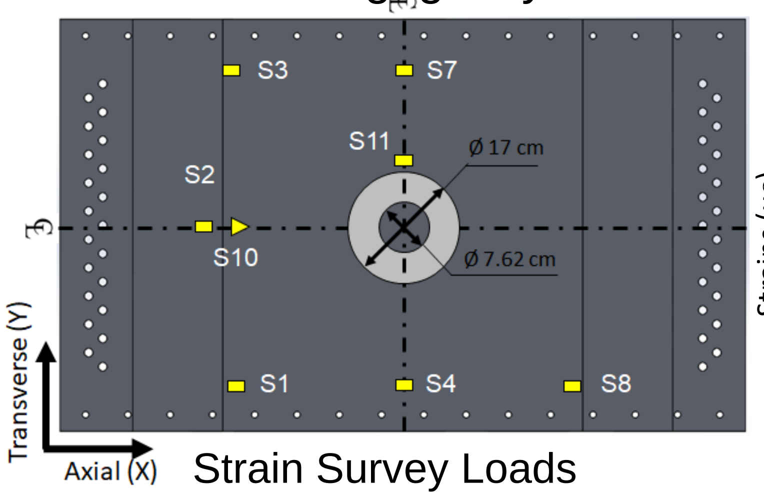
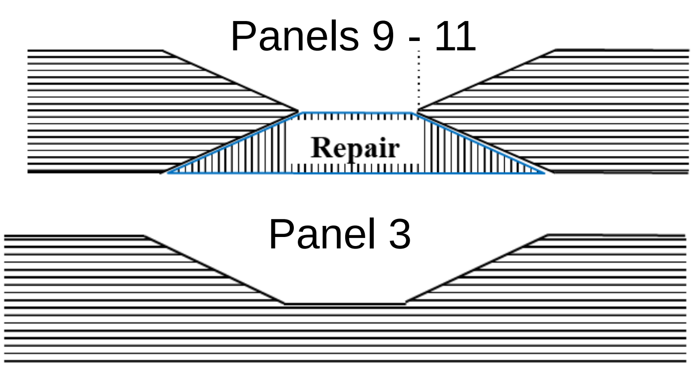
Comparison of Double-Sided Scarf w/ Repair and Half-Depth Scarf

Strain gage layout

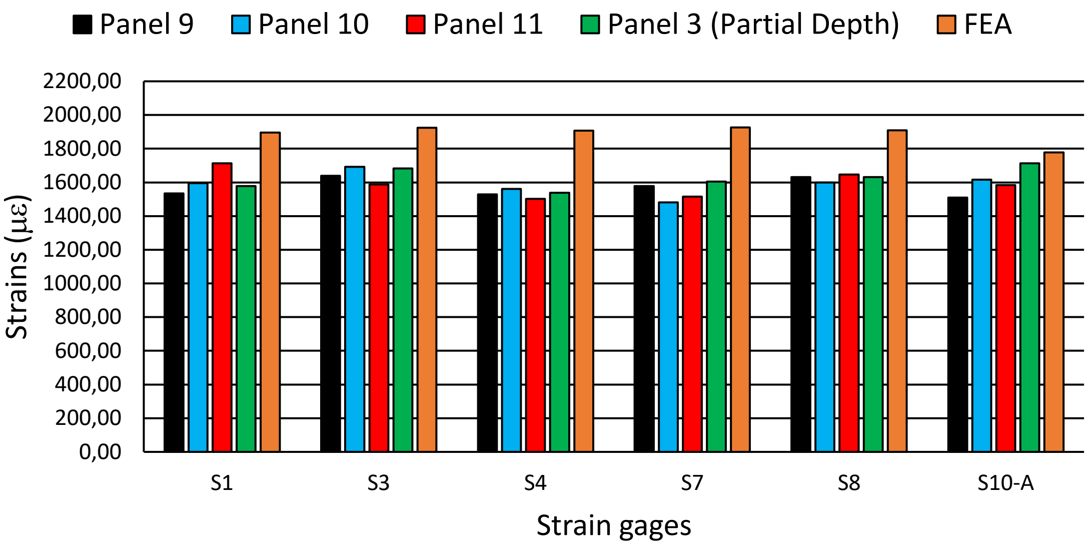


Strain Survey Loads

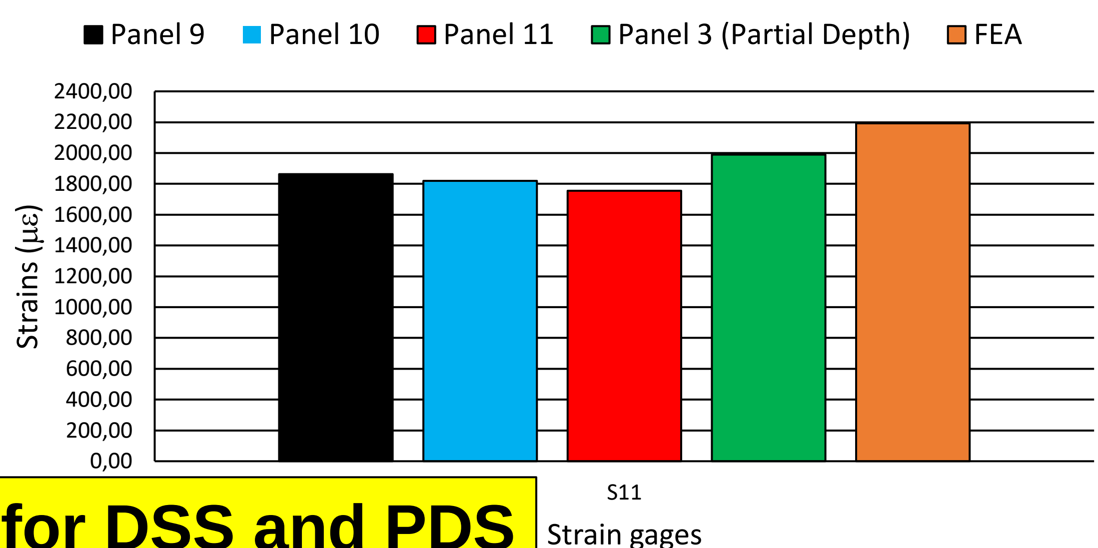
Actuators 1 & 2	Actuators 3 & 4
-16 KN	***22.5 KN***



Far-field strains

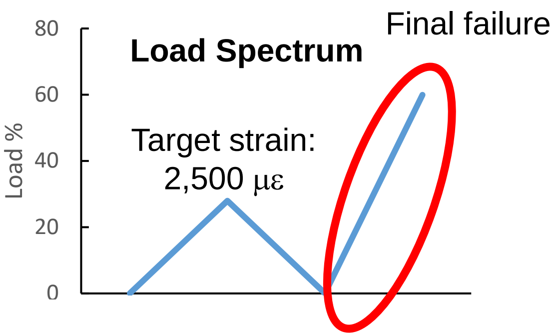


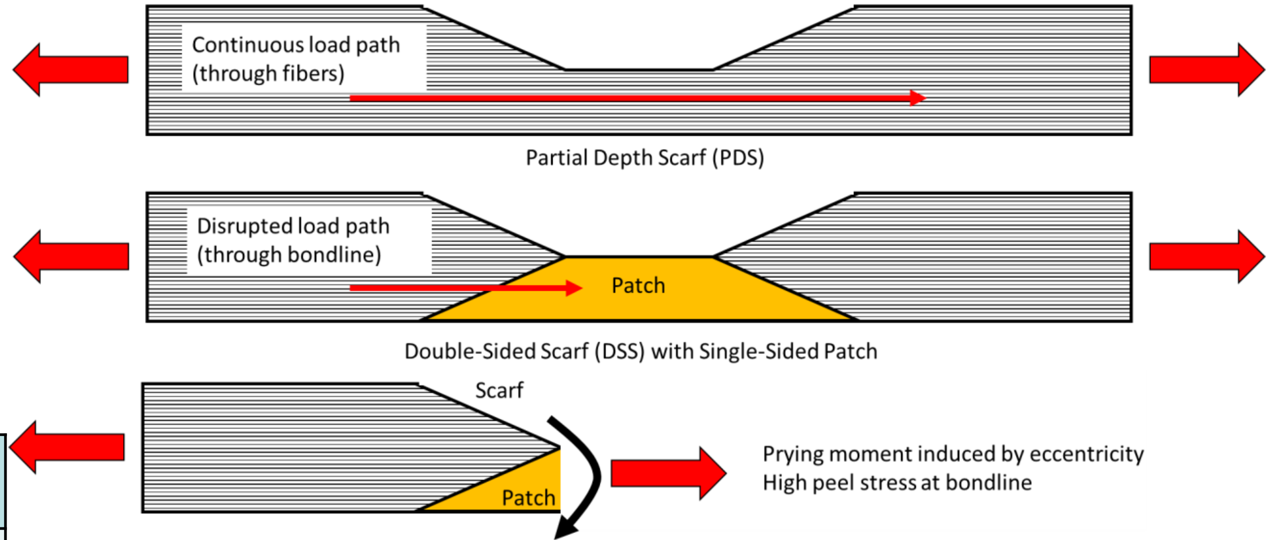
Strains in the vicinity of the scarf



Strain surveys similar for DSS and PDS

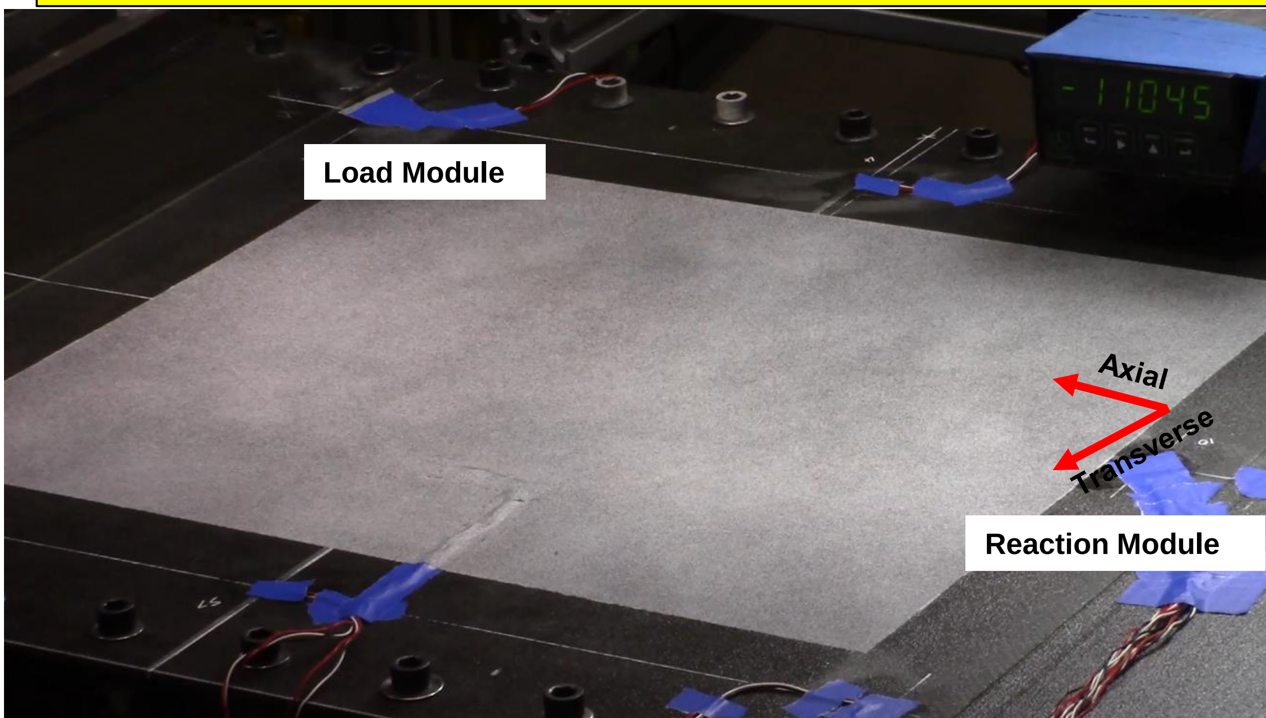
Double Sided Scarf (DDS) with patch: Residual Strength

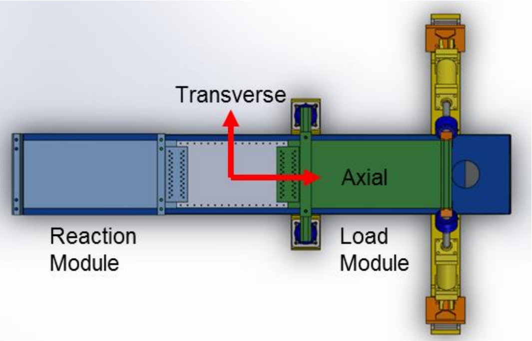




Test Description	Failure Loads	
	Actuator 1 & 2	Actuator 3 & 4
Panel 9 (DSS)	-49.1 KN	69.4 KN
Panel 10 (DSS)	-52 KN	73.5 KN
Panel 11 (DSS)	-51.2 KN	72.4 KN
Panel 3 (PDS)	-89 KN	125.1 KN

Residual Strength of DSS 43% Lower than PDS

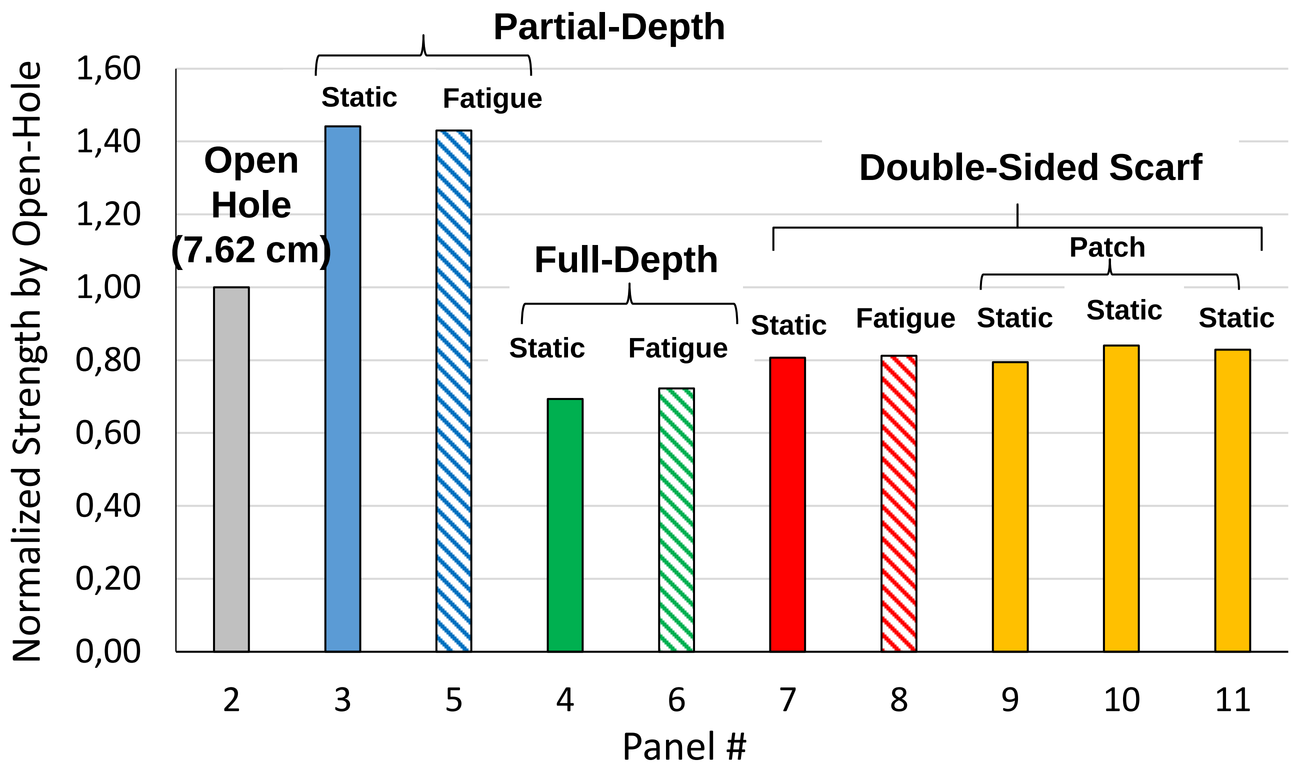




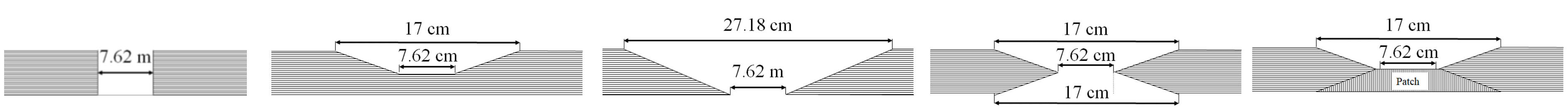
Summary of Residual Strength Tests

Effect of notch geometry on strength - Comparison made against 3" inner scarf diameter

[±45_{fabric}/-45°/90°/45°/0°/-45°/90°/45°/0°]$_s$

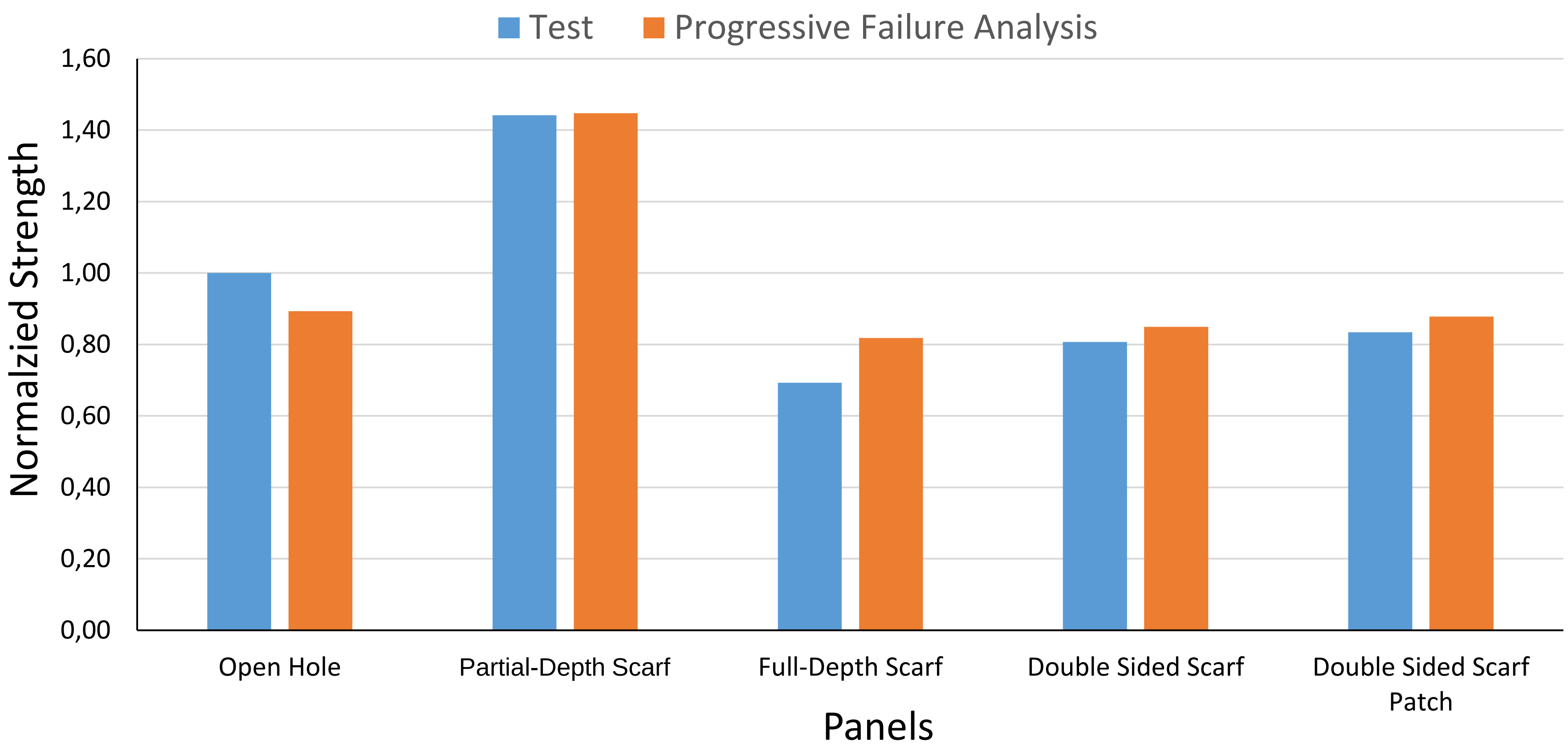


Open-hole	Patrial-Depth Scarf (Panels 3, 5)	Full-Depth Scarf (Panels 4, 6)	Double-Sided Scarf (Panels 7, 8)	Double-Sided Scarf with Repair (Panels 9,10,11)

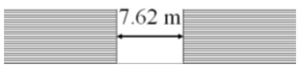


Residual Strength Test and Analysis Correlations

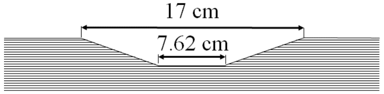
$[\pm 45_{fabric}/-45°/90°/45°/0°/-45°/90°/45°/0°]_s$



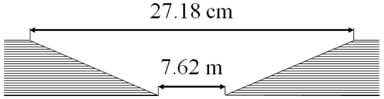
Open-hole



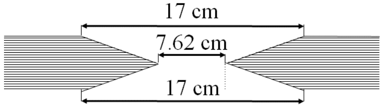
Partial-Depth Scarf (Panels 3, 5)



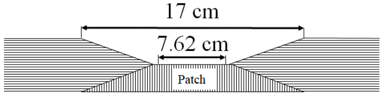
Full-Depth Scarf (Panels 4, 6)



Double-Sided Scarf (Panels 7, 8)



Double-Sided Scarf with Repair (Panels 9,10,11)



Outline

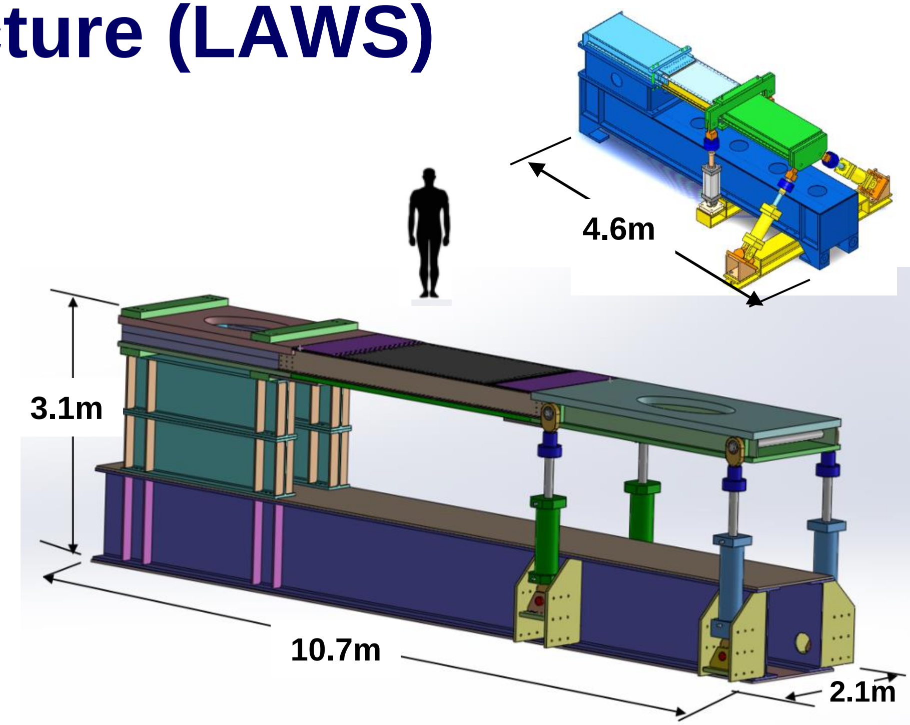
- Background and Objectives
- Experimental Procedure
- Results
- Summary
- Future Work

Summary

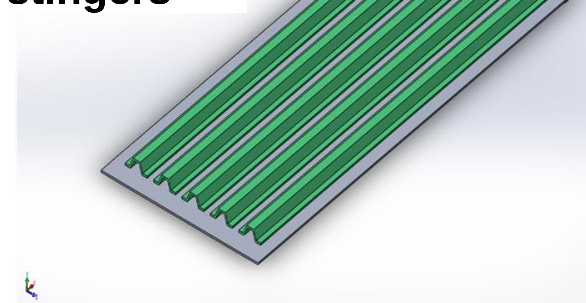
- **Collaborative effort to assess fatigue and damage tolerance of bonded repairs**
- **Bonded Repair Size Limits Studies - Characterize limit load residual strength for partial and fully failed scarf repair configurations for solid laminates:**
  - Increase in the residual strength capability of a repair by keeping parent material intact during the removal process (i.e., a partial-depth scarf is stronger than a full-depth scarf).
  - No reduction in strength due to fatigue after 3 DSGs in all panels and scarf configurations tested.
  - A single-sided repair patch in a double-sided scarf panel tested in this program cannot be credited for restoring the strength - early bondline failure due to eccentricities
  - Methods for bonded repair residual strength predictions correlated well with test results

Large Airframe Wing Structure (LAWS) Fixture- Future

- **Shear, Bending and Torsion loading capability**
- **Up to 15080 KN anticipated load in the panel**
- **Based on typical widebody mid-span wing panel**
- **Sized for residual strength testing:**
  - 10000 microstrain compression
  - 10000 microstrain tension axially
  - 4000 microstrain shear
- **Fatigue spectrum test capability**
- **Future Considerations:**
  - Large damage – two bay
  - Impact damage
  - Repairs in proximity to other repairs
  - Effect of substructure
  - Hot/wet and cold conditioning



Configured Panels:
3.9m Long x 1.5m Wide
Containing 5 stingers



Thank You