



Full-Scale Test and Analysis Results of a PRSEUS Fuselage Panel to Assess Damage-Containment Features

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³NASA Langley Research Center

⁴Boeing Research & Technology

⁵Legacy Engineering

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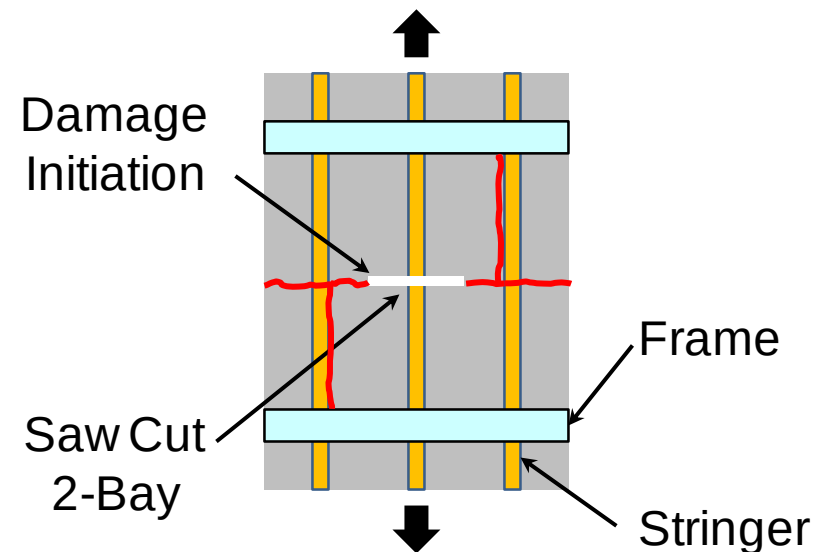
Outline

- Objective and Overview
- Experimental Procedure
 - Test Panel Configuration
 - Inspection and Monitoring Methods
 - Load History
- Results
 - Phase I: Pristine
 - Phase II: Barely Visible Impact Damage (BVID)
 - Phase III: Two-Bay Notch
- Summary & Conclusions

Overview

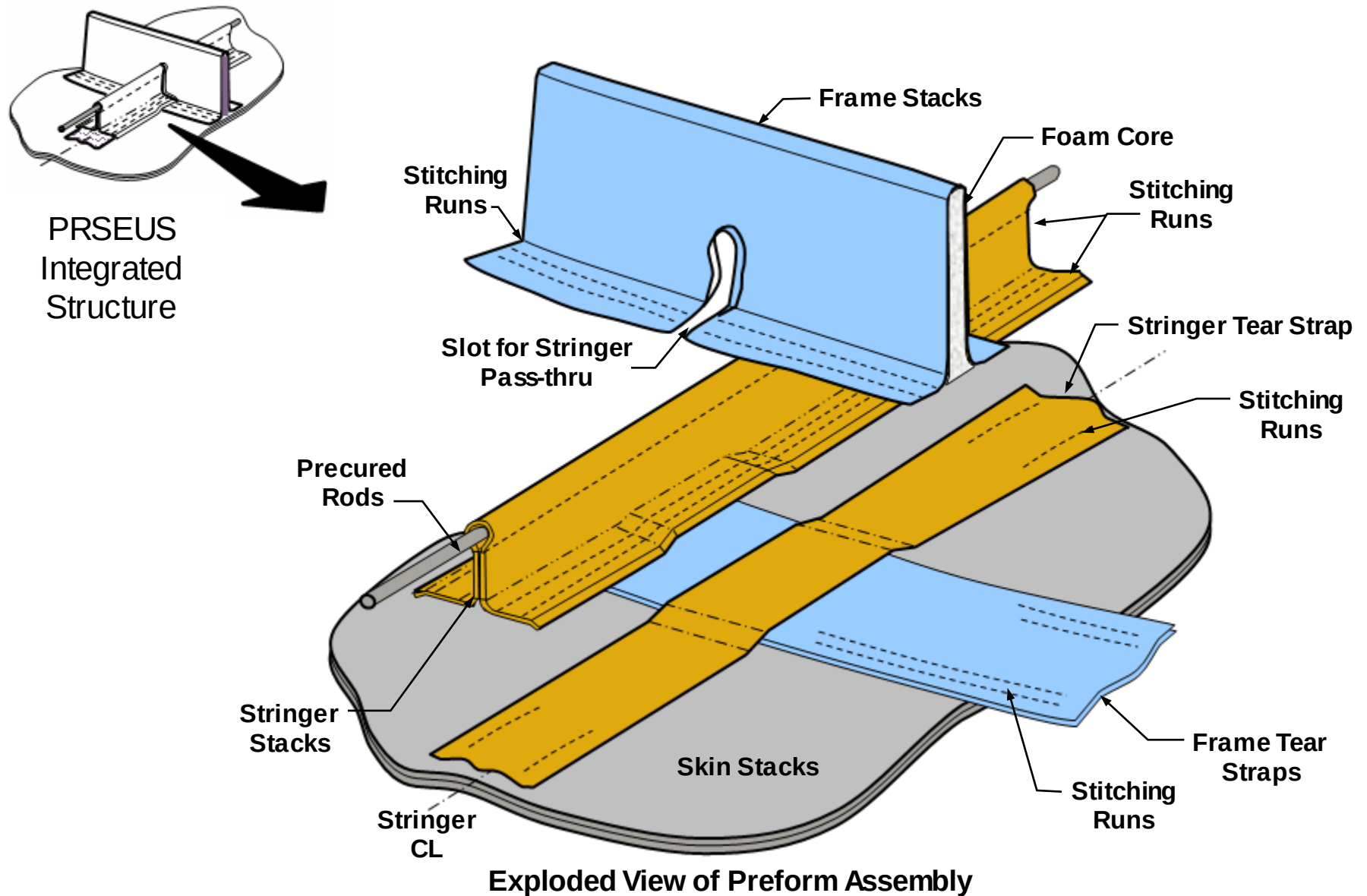
Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS)

- Objective: Assess damage containment
 - Demonstrate compliance with FAR part 25:
 - Strength, Deformation, Damage Tolerance
- Approach: Full-scale testing of a curved PRSEUS panel on the FASTER fixture using three test phases:
 - Pristine Panel
 - Impact Damage
 - Two-bay notch



Will a curved PRSEUS panel arrest damage?

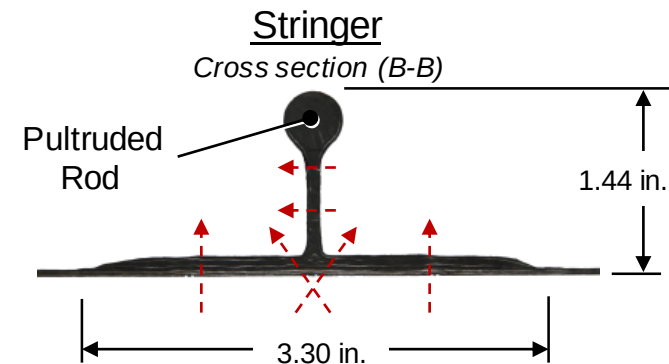
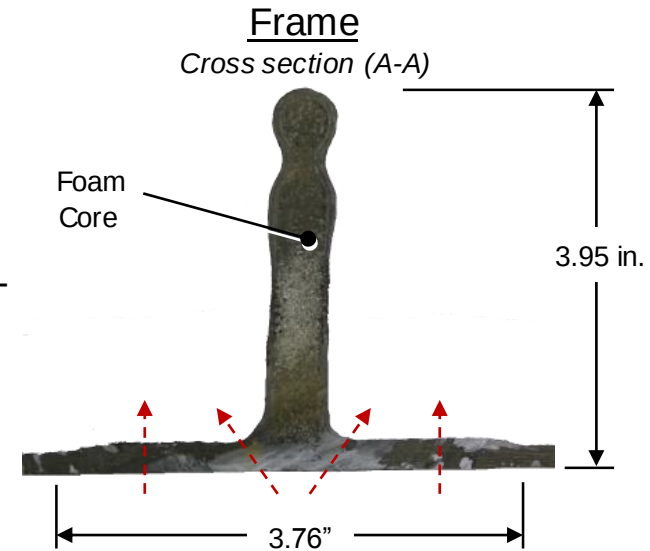
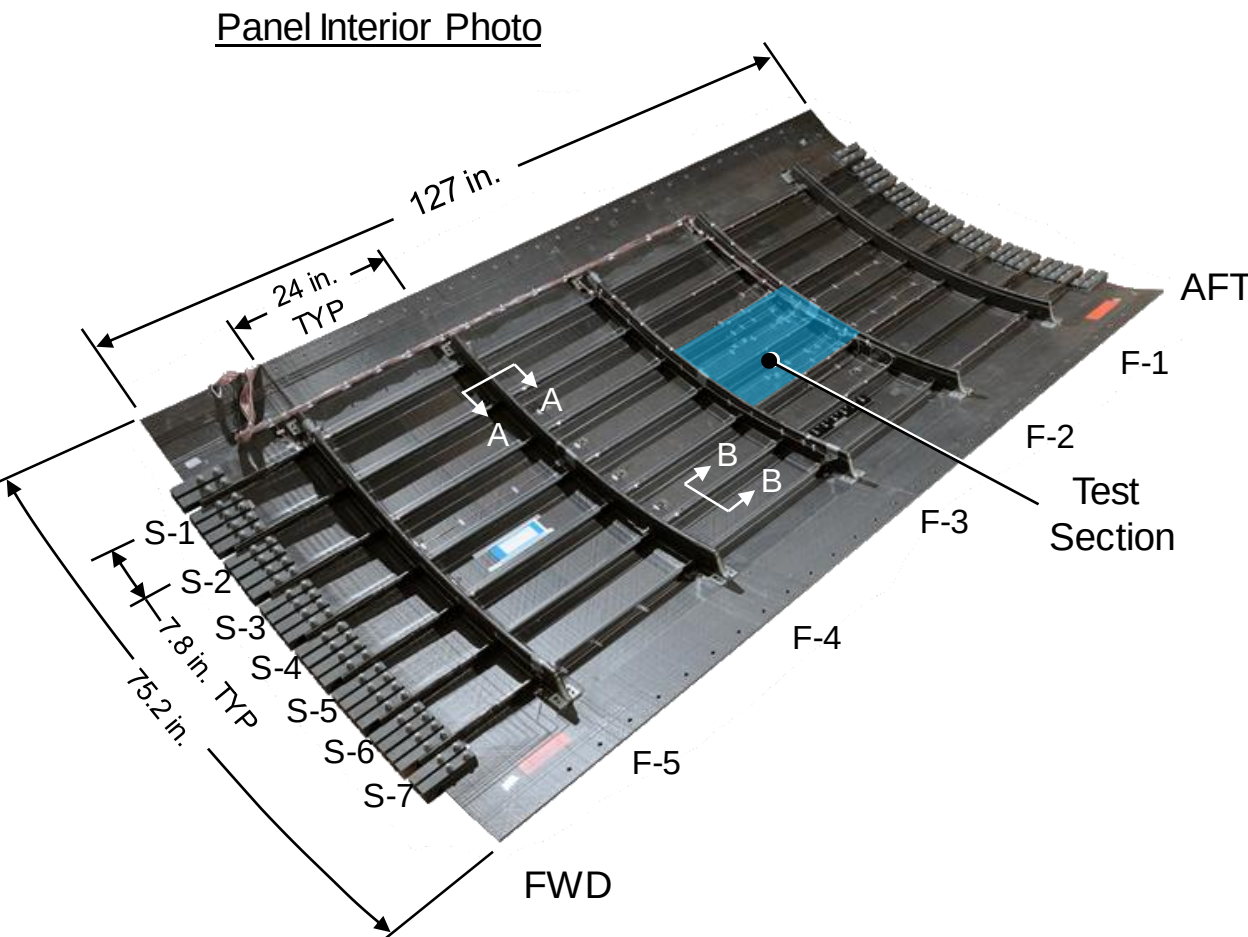
PRSEUS Structural Concept



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Test Panel Configuration

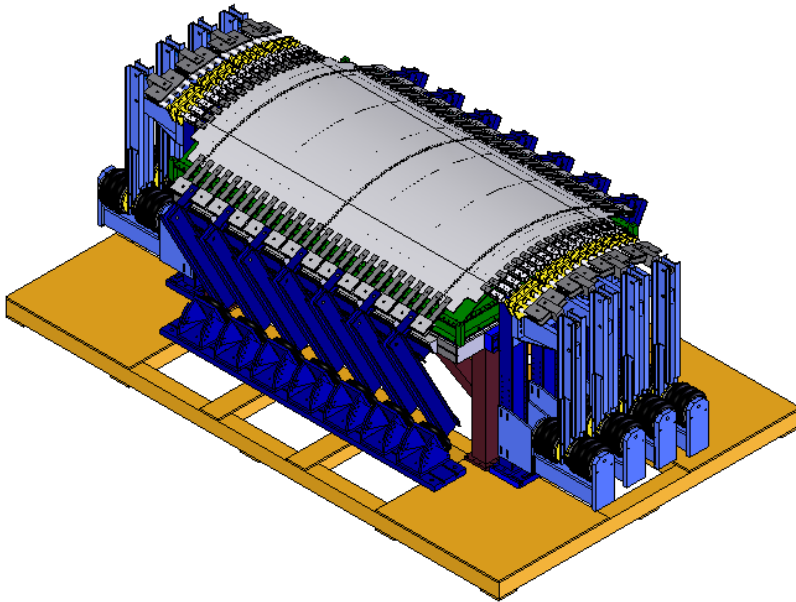


- 7 Stringers, 5 Frames
- Two-bay test section
- Skin thickness: 0.052 inch
- Combination of 0°, 45°, and 90° plies
- Test section skin layup: [+45/-45/0₂/90/0₂/-45/+45]

FASTER Fixture Modification

Existing Fixture

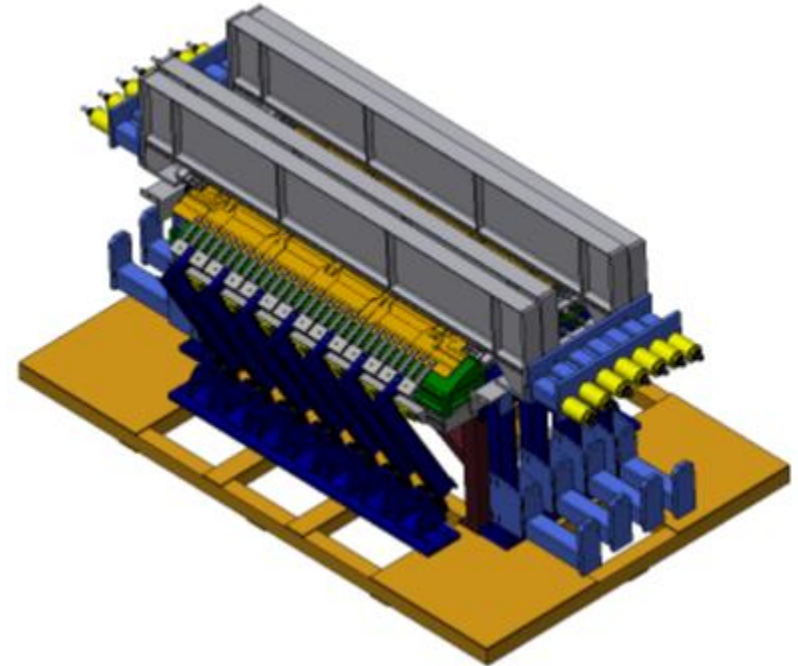
- 100 kip axial load capacity
- Axially *fixed* frame loaders
- Accommodates 74 in. radius panel



Before Modification

New Fixture

- 840 kip axial load capacity
- Axially *free* frame loaders
- Accommodates 90 in. radius panel



After Modification

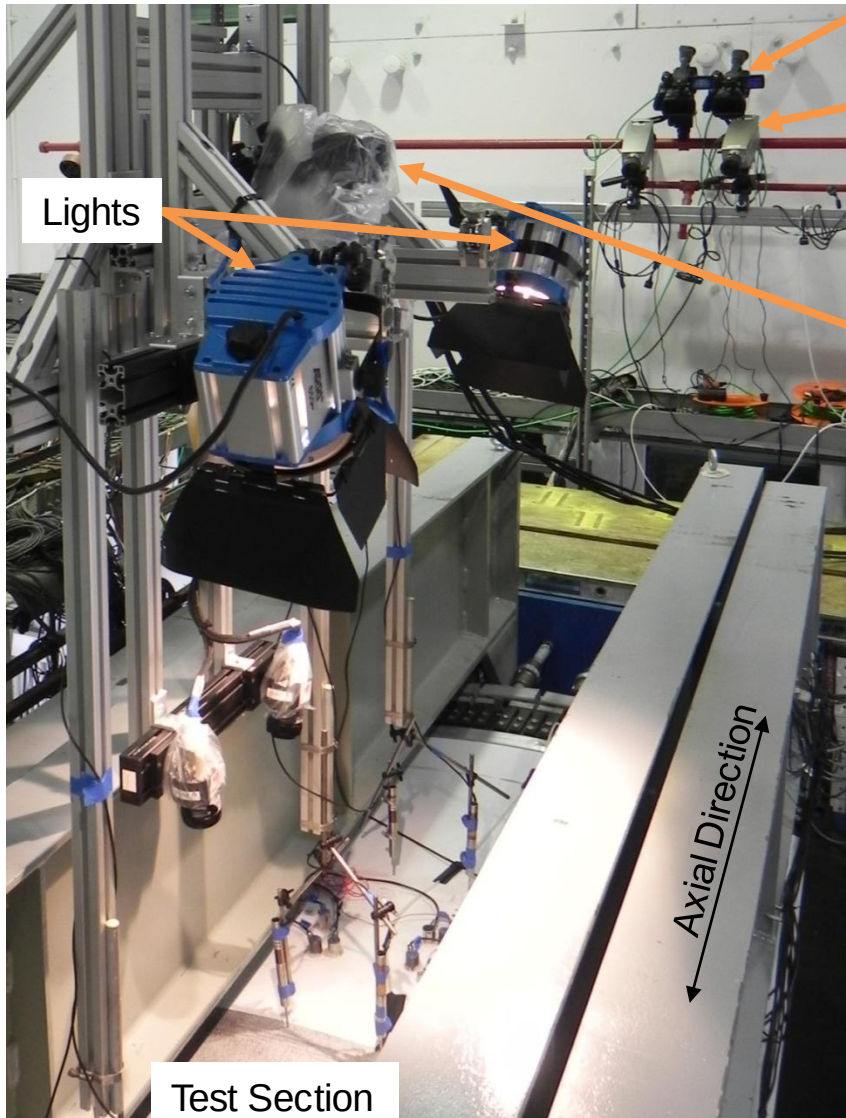


FASTER Fixture Modification

Video

Visual Monitoring

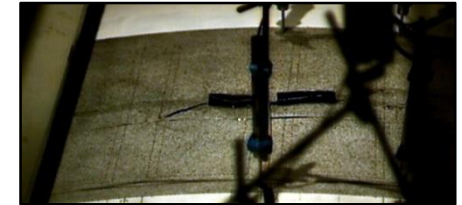
Exterior visual monitoring setup



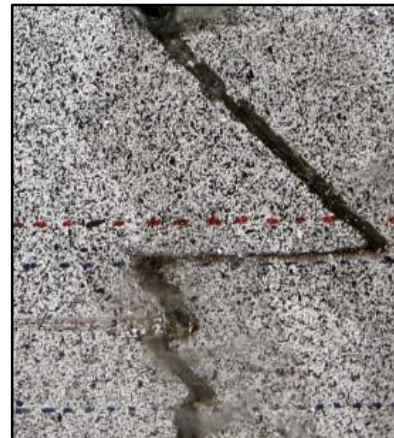
High definition video



High speed video



High resolution still



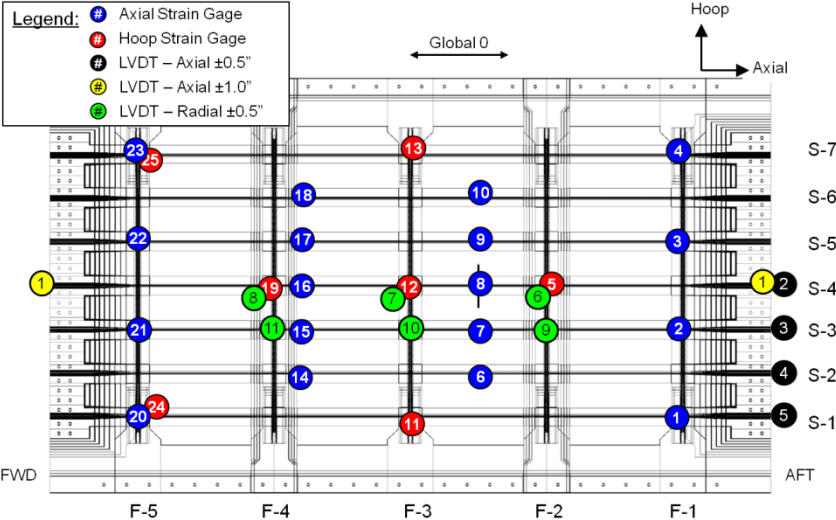
Underwater camera (not shown in a)



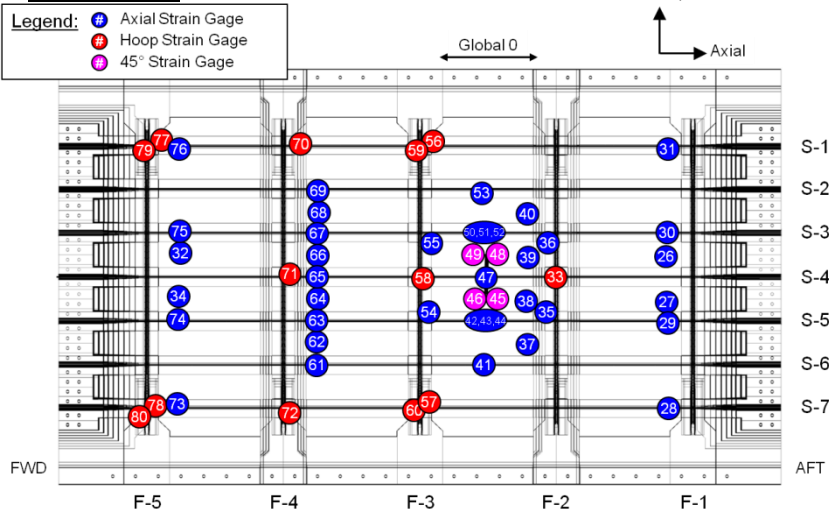
Strain & Displacement Monitoring

80 Strain gages (axial, hoop, and 45°)
11 LVDTs (axial, radial)

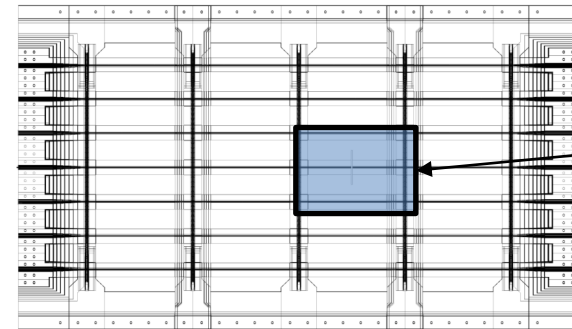
Exterior



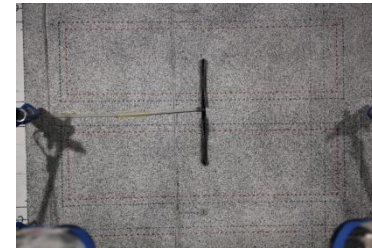
Interior



ARAMIS Digital Image Correlation (DIC) *Full-field deformation and strain*



Field of view:
two-bay region



Stochastic
pattern

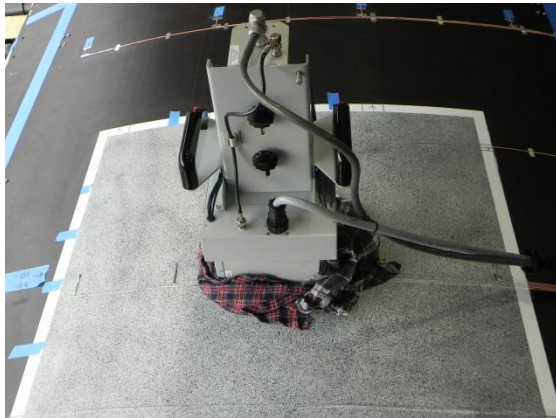


Two 4-MP
cameras

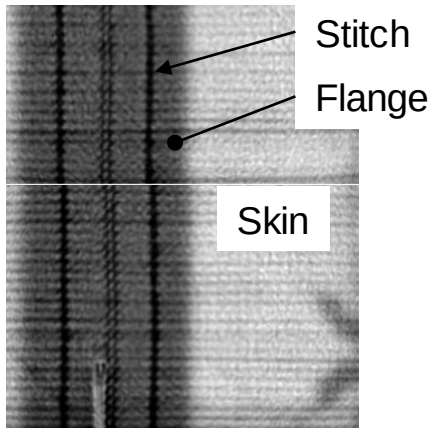
Damage Detection

Flash Thermography

Heat source and camera

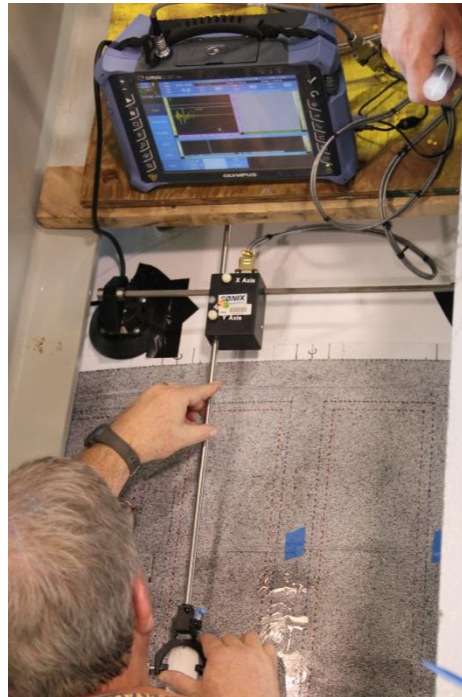


Sample result

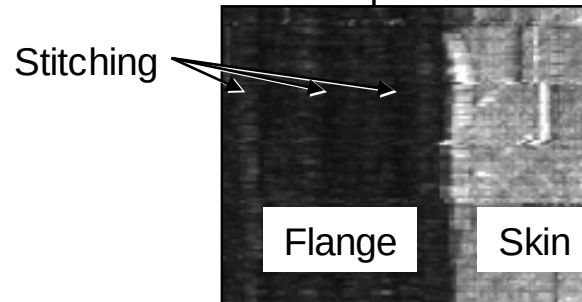


Ultrasound (C-Scan)

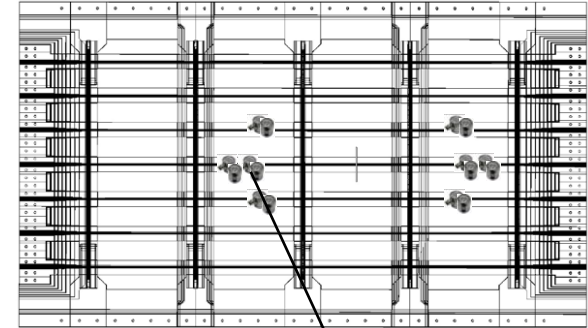
Data Acquisition



Sample result



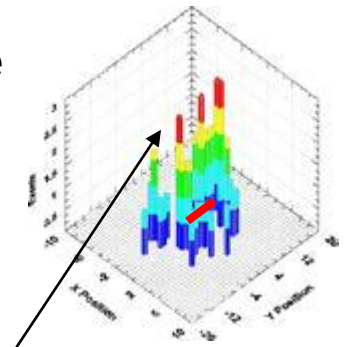
Acoustic Emission



Wideband & resonant sensors



Sample result



High amplitude event at notch tip

Load History

	Load Condition	Relative Applied Loads*		Absolute Applied Loads**			
		Axial	Pressure	Axial [lbf]	Hoop [lbf]	Frame [lbf]	Pressure [psi]
Phase I	Axial	100%DLL	-	32,473	0	0	0
	Combined	100%DLL	1P	36,436	11,423	2,390	9.2
	Pressure	-	1.33P	5,270	15,192	3,178	12.2
Phase II	Axial	100%DLL	-	32,473	0	0	0
	Pressure	-	1.33P	5,270	15,192	3,178	12.2
	Combined	100%DLL	1P	36,436	11,423	2,390	9.2
	Pressure	-	2P	7,925	22,844	4,780	18.4
	Axial	150%DLL	-	48,710	0	0	0
	Combined	150%DLL	1.5P	54,654	17,134	3,584	13.8
Phase III	Final	N/A	N/A	67,000	13,136	2,748	10.6

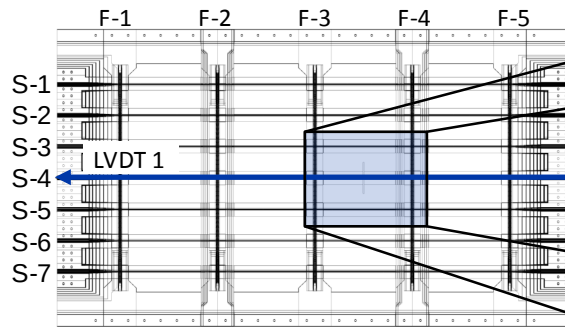
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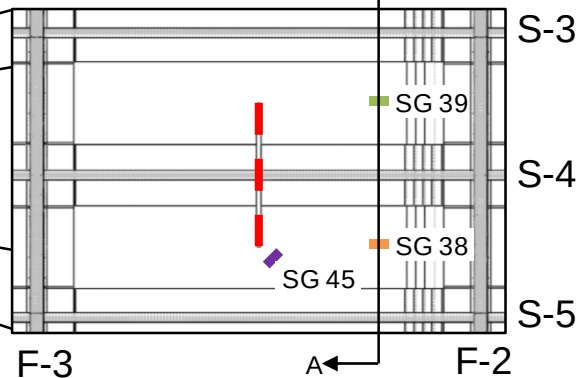
Phase I: Repeatability

Load: 0.5P + 50% DLL

Panel Interior

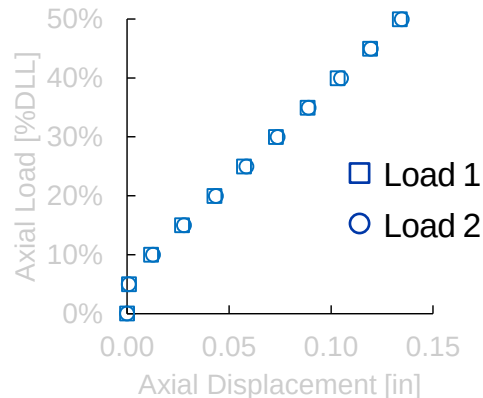


Detail View

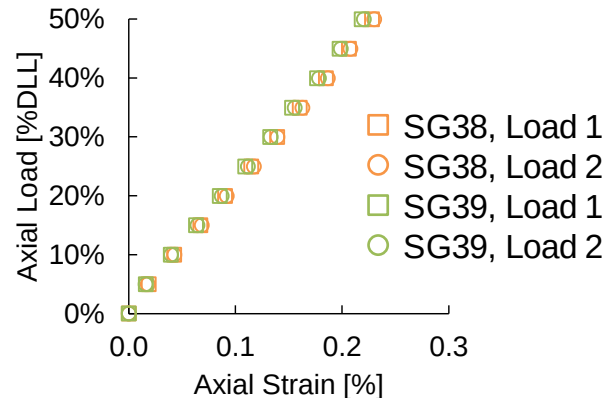


Hoop
↑
Axial
→

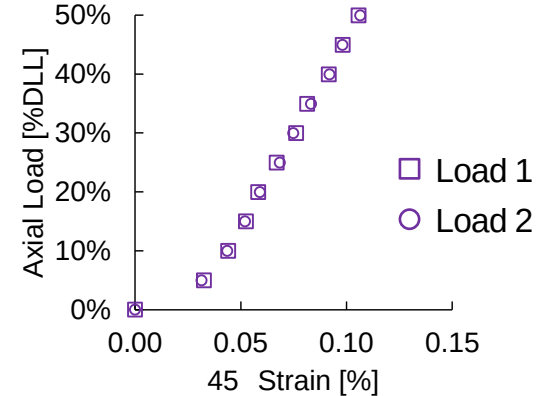
Axial Displacement



Interior Skin Axial Strain



Interior Skin 45° Strain

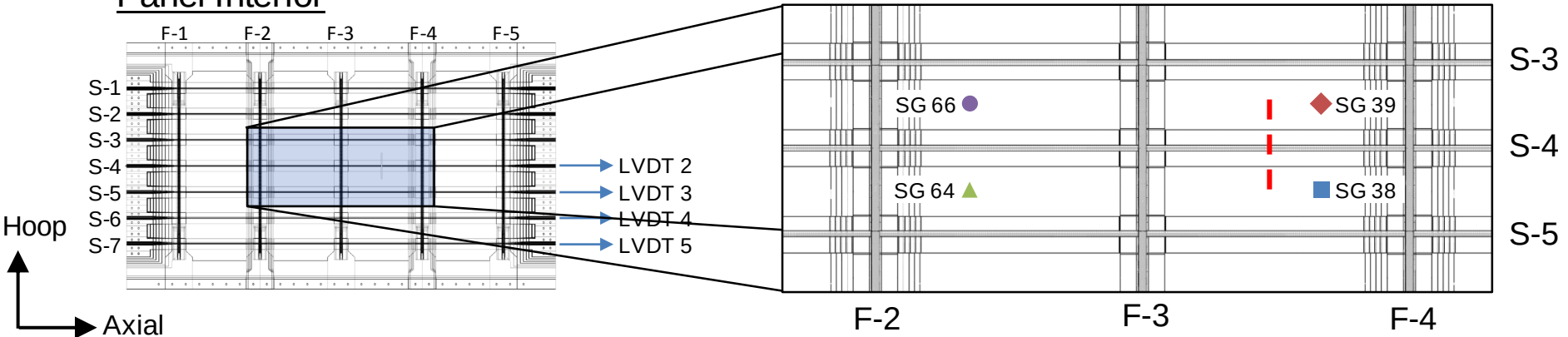


Results show linear and symmetric response

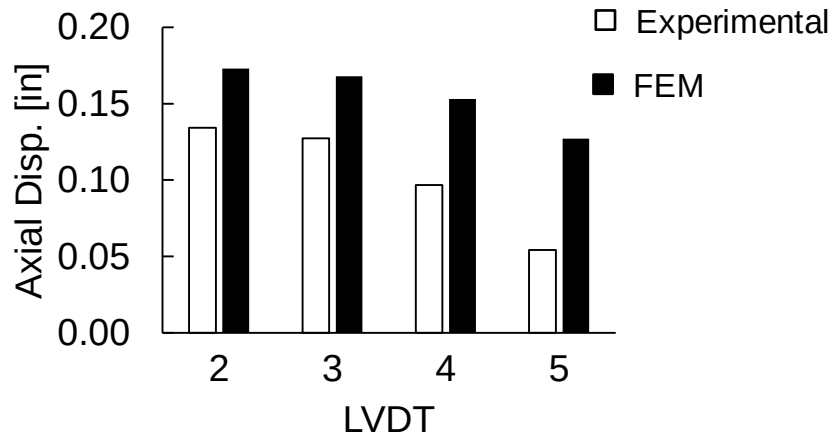
Phase I: Comparison with FEM

Load: 1P + 100% DLL

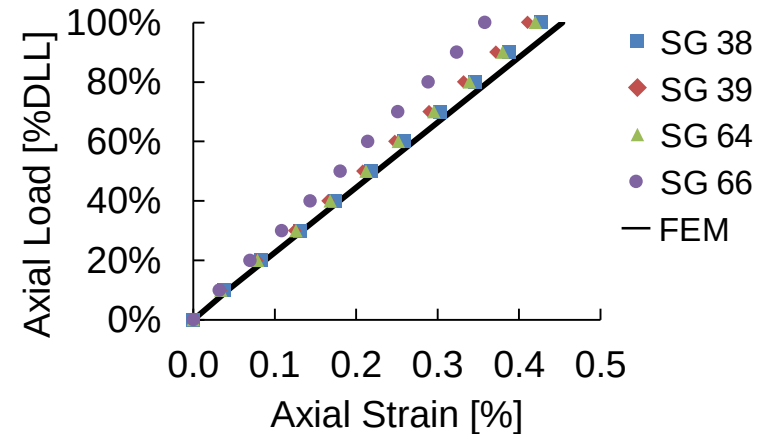
Panel Interior



Axial Disp. Distribution



Axial Strain



Phase I Comparison with FEM:

- Displacements showed consistent trend
- Slight non-linearity in experimental strains

Phase I: Uniform Strain Distribution

Panel Exterior

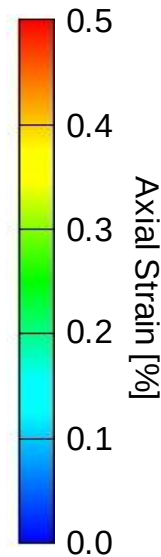
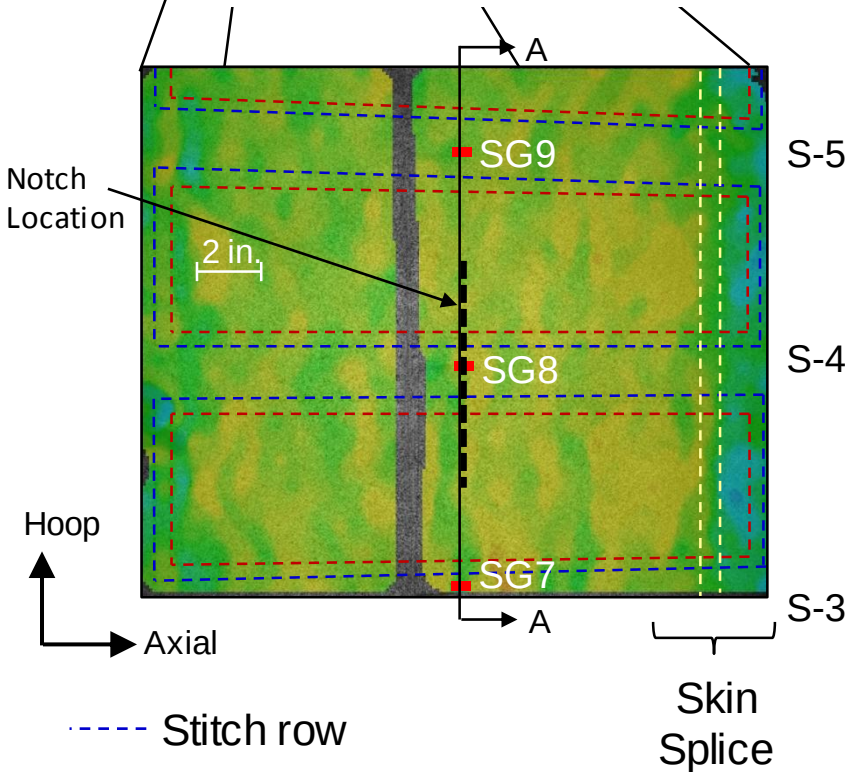
Load: 1P + 100% DLL

Phase I digital image correlation (DIC) results:

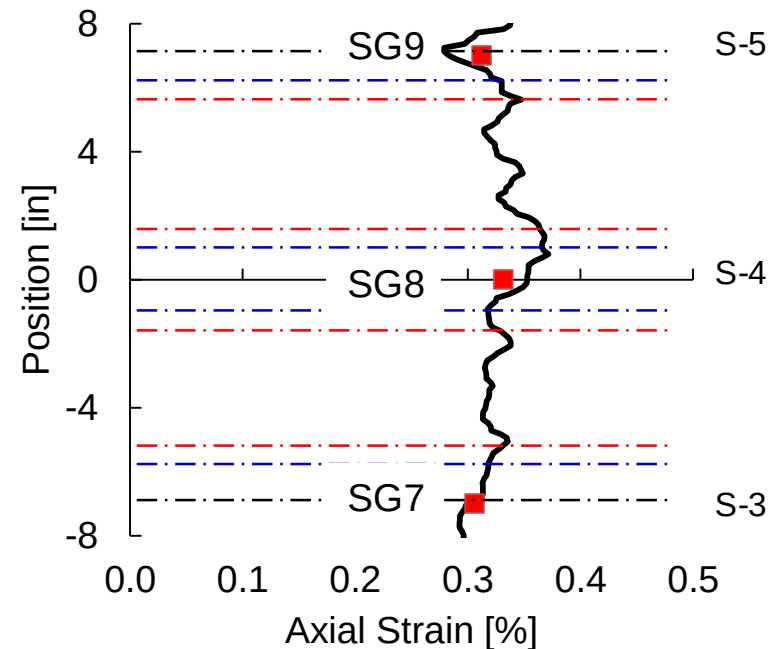
Good correlation with strain gage results

Uniform strain distribution in the test section

ARAMIS axial strain



Axial strain along section A-A



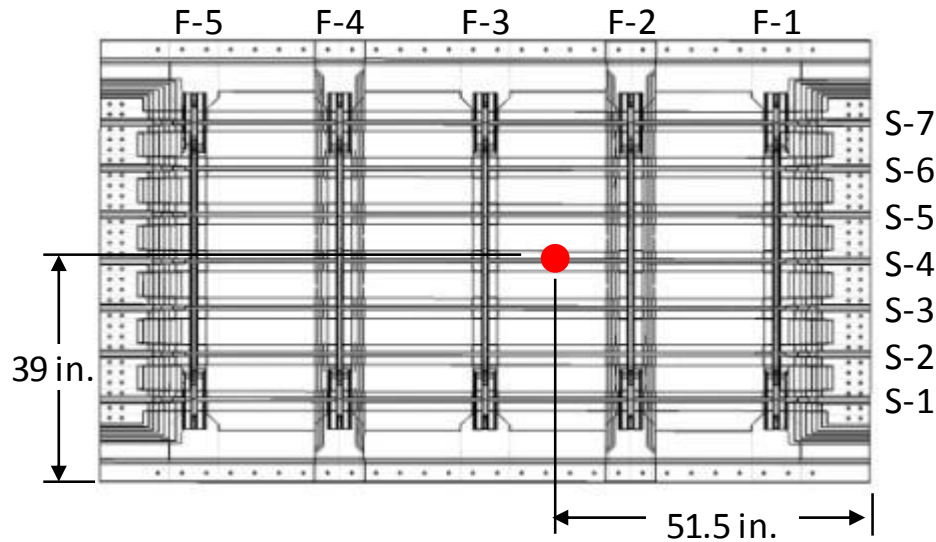
— ARAMIS ■ Strain Gage

Outline

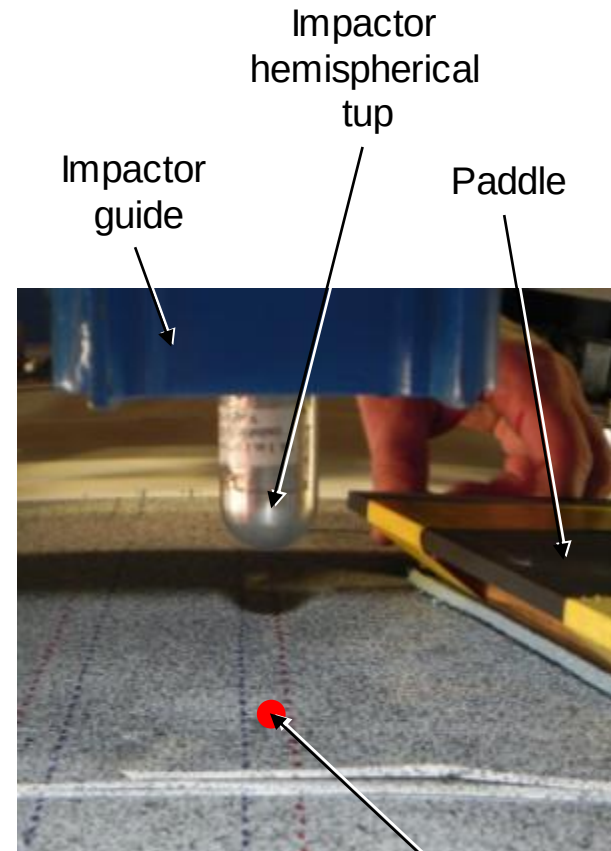
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Phase II: BVID

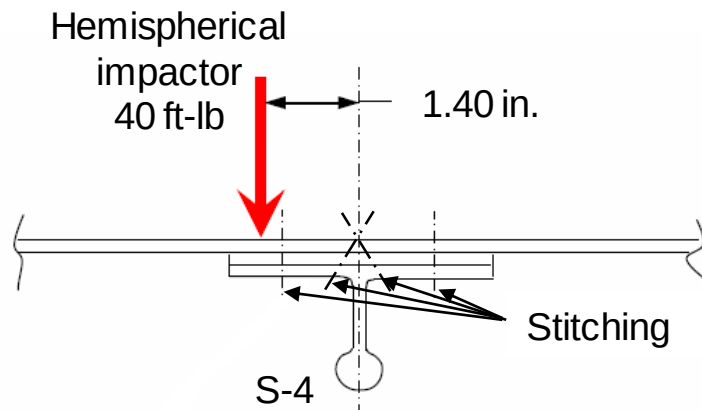
Impact Location, Panel Exterior



Impact Setup Photo



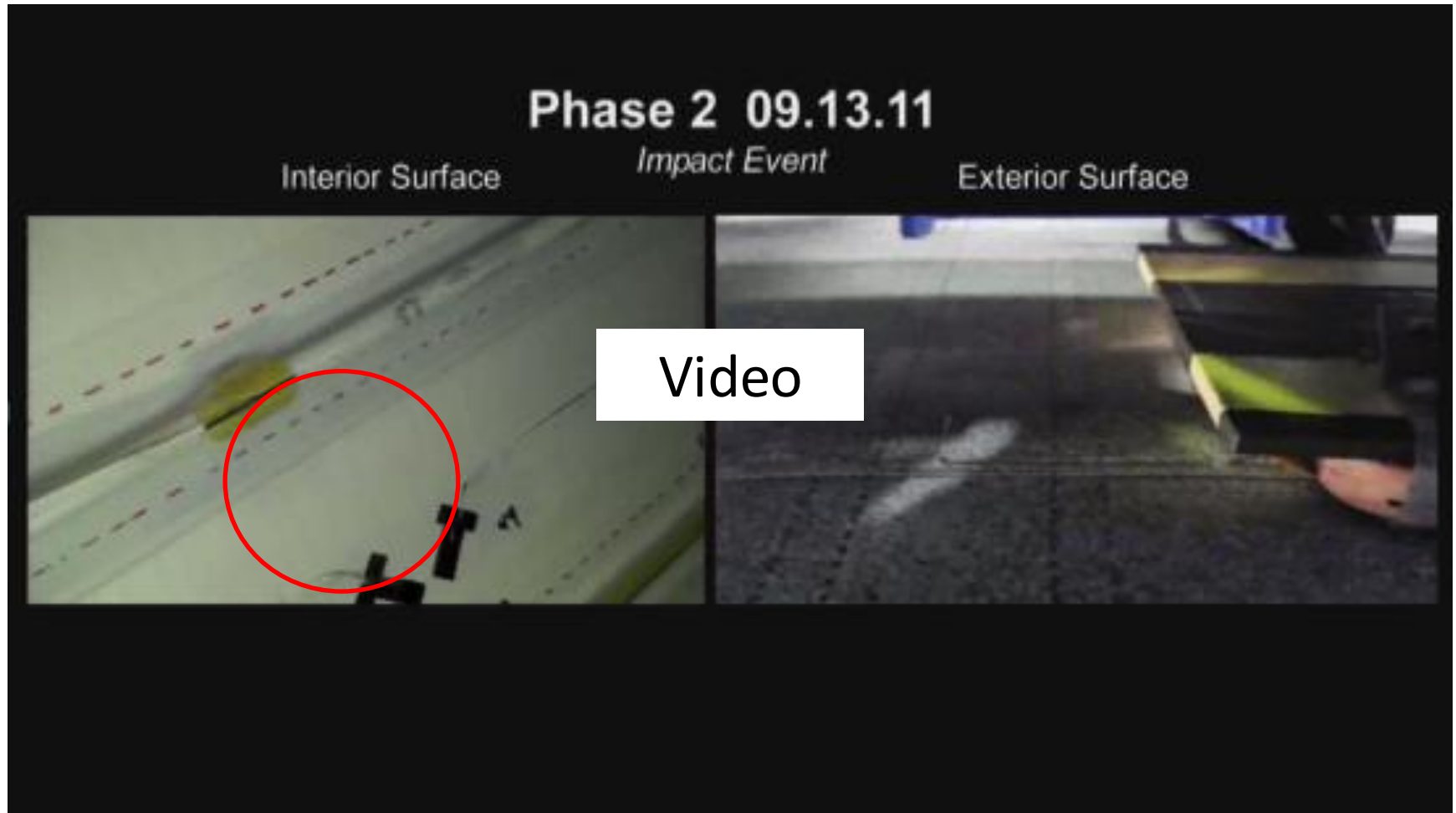
Impact Detail Schematic



S-4
Stitch
Flange
Impact location



Phase II: Impact Video





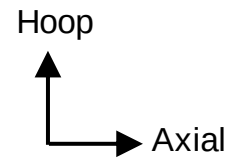
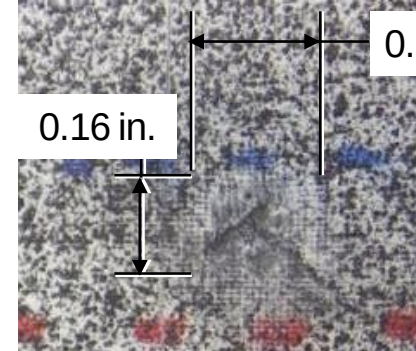
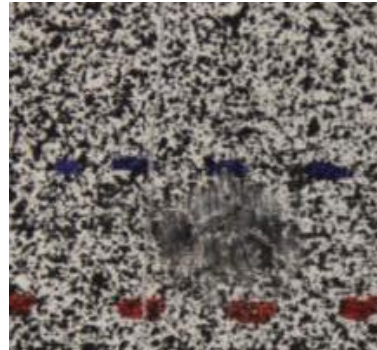
Phase II: Visual Inspection

Before Impact

After First Impact

After Second Impact

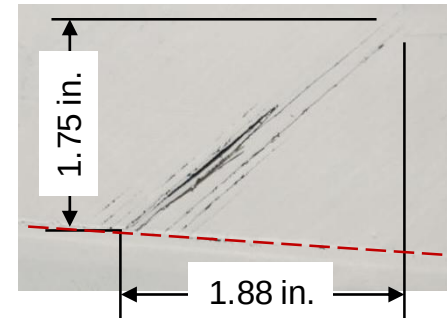
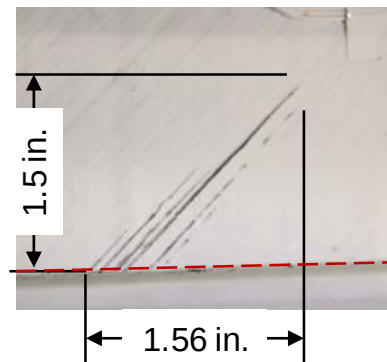
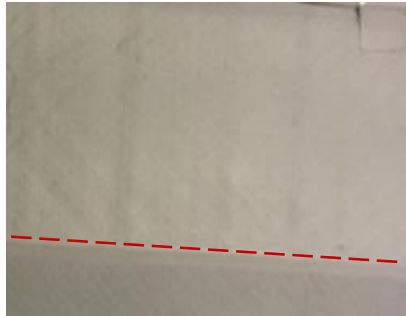
Exterior



Stitch

Flange Edge

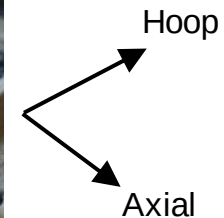
Interior



Flange Edge

Detail view

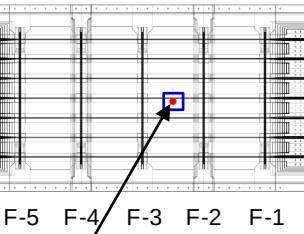
Broken
fiber



Clear Fiber Break Indicated BVID

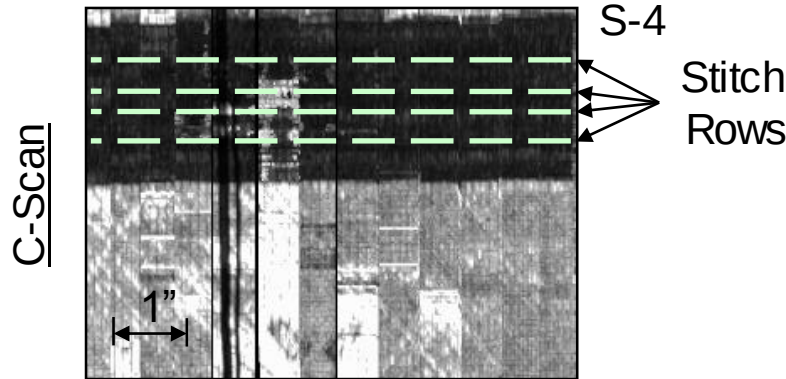
Phase II: NDI of Impacted Region

Panel Exterior

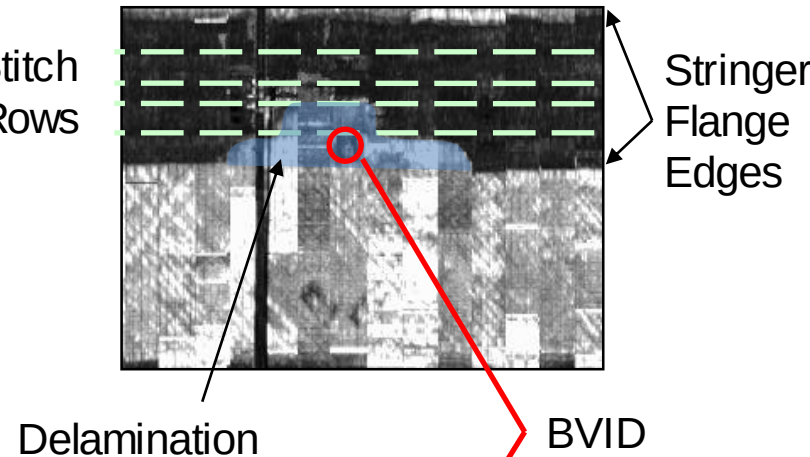


Impact Location

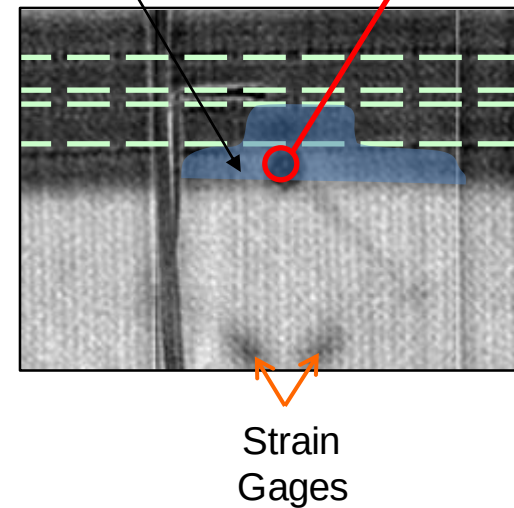
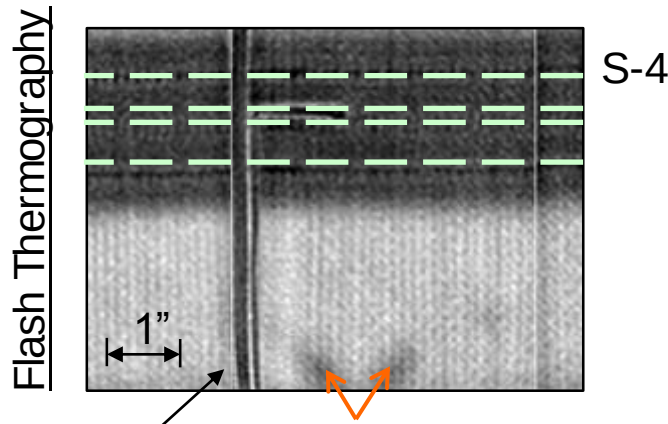
Before impact



After impact



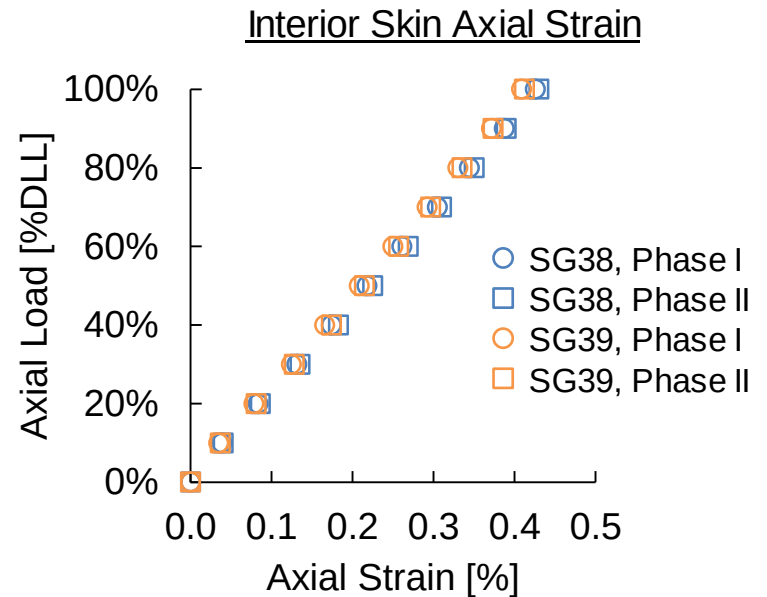
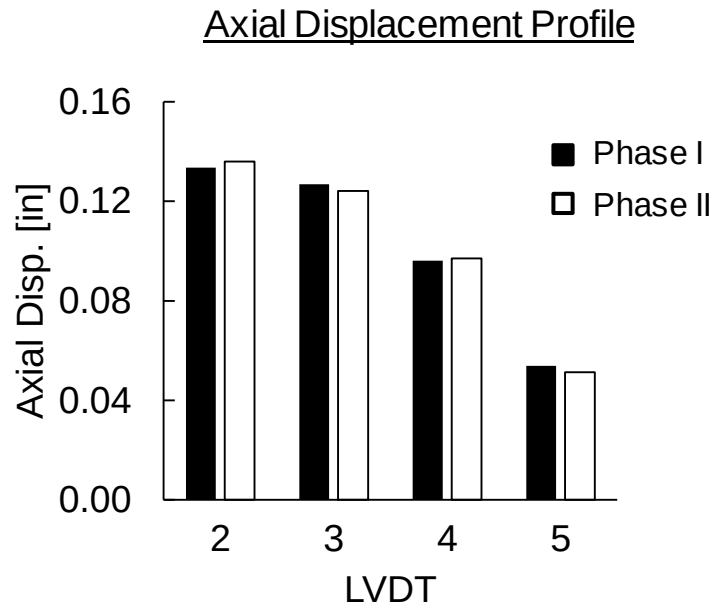
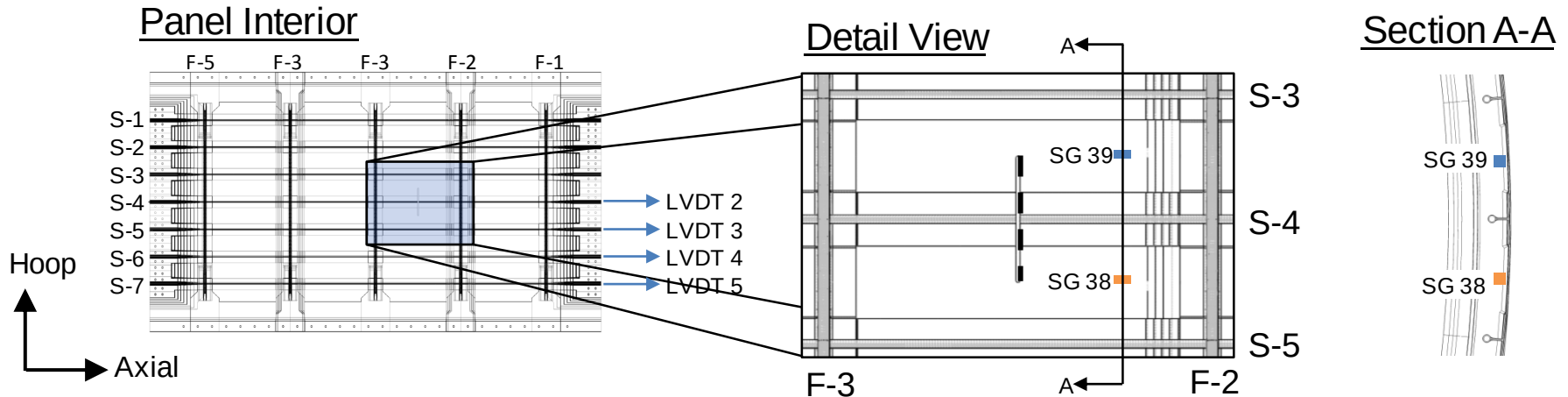
Hoop
↑
↓
Axial →



Flange Delaminated from Skin Due to BVID

Phase I & II Comparison

Load: Combined Limit (1P + 100% DLL)



Consistent Response Indicates No Load Redistribution

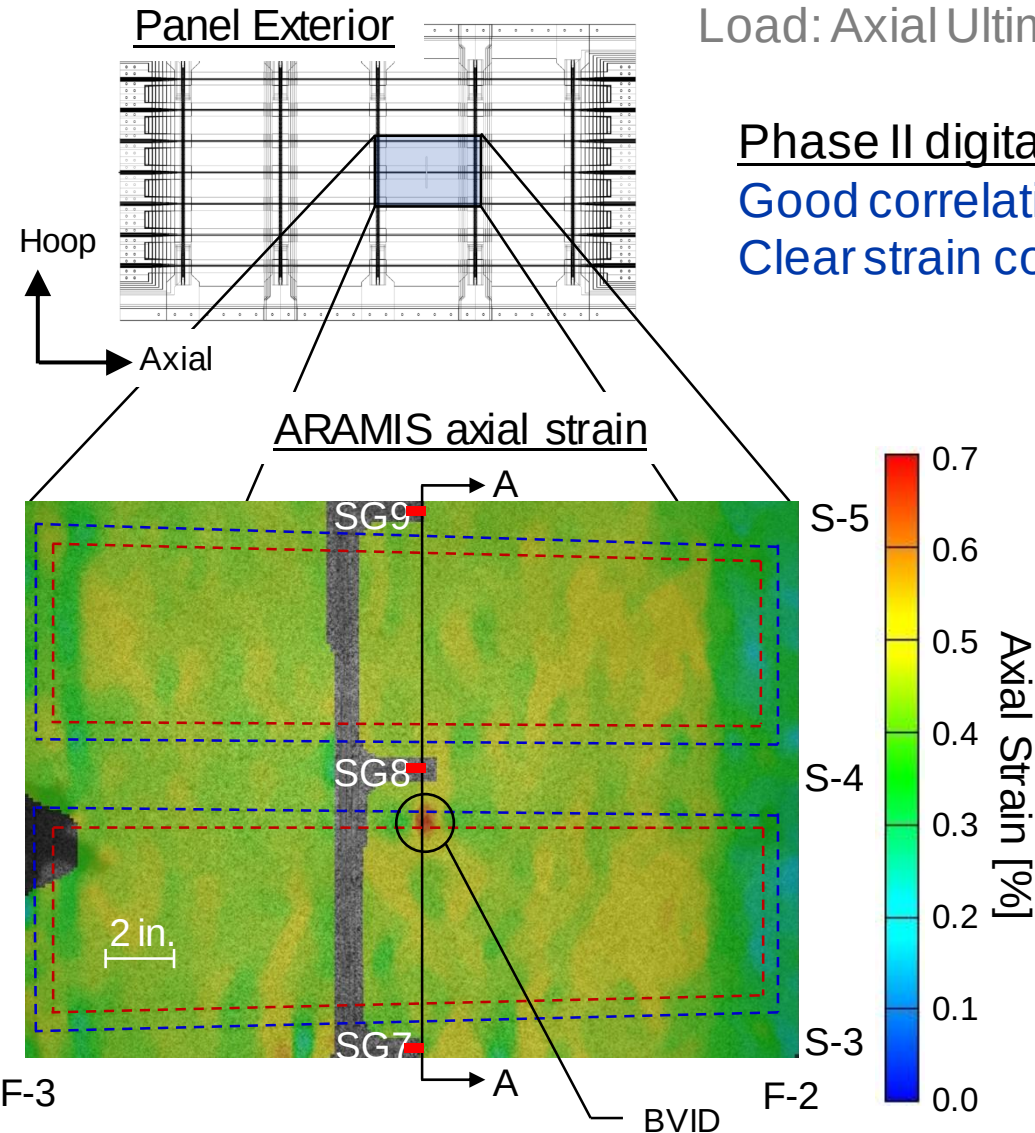
Phase II: Local Strain Distribution

Load: Axial Ultimate (150% DLL)

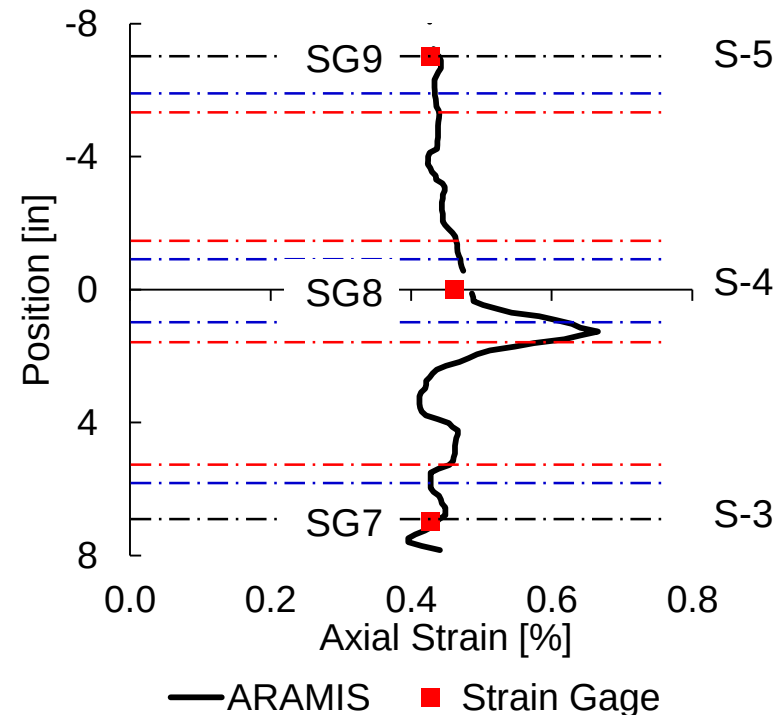
Phase II digital image correlation (DIC) results:

Good correlation with strain gage results

Clear strain concentration at BVID location



Axial strain along section A-A



Local Strain Concentration below Material Failure Strains



Phase II: No Growth of BVID

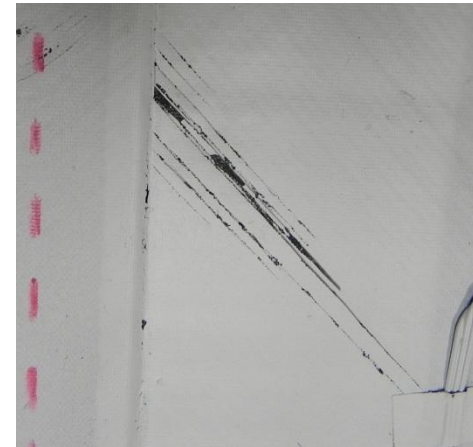
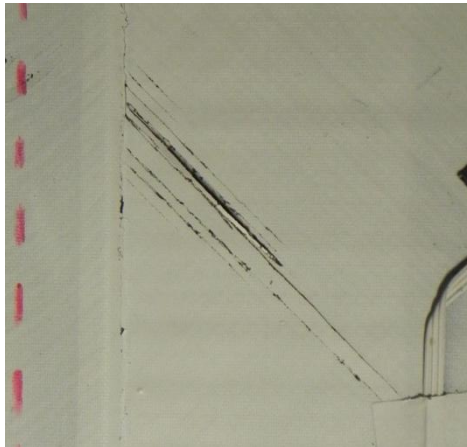
Before Loading

After Loading

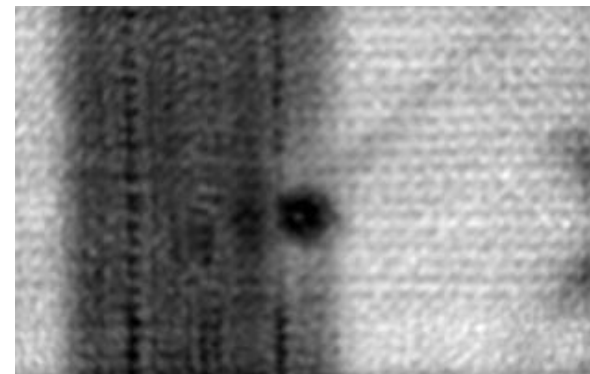
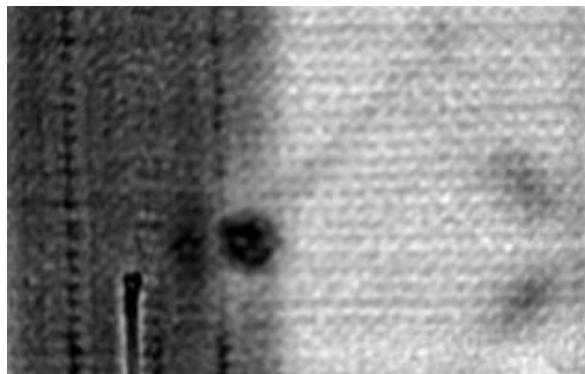
Exterior
Photo



Interior
Photo



Flash
Thermography

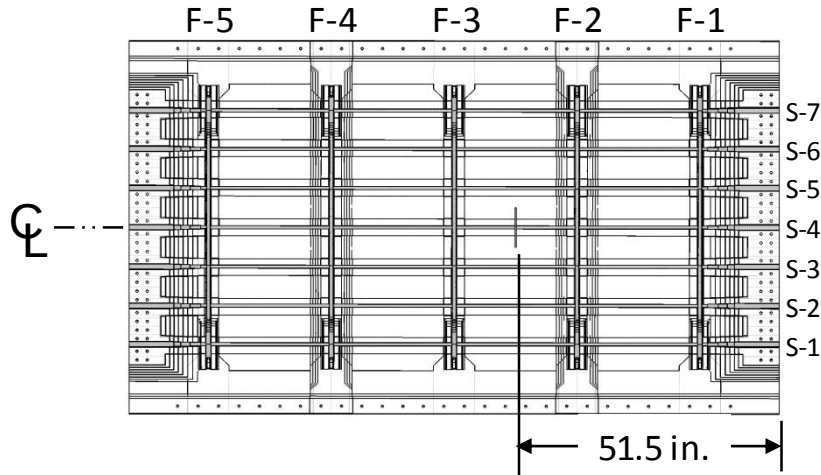


Outline

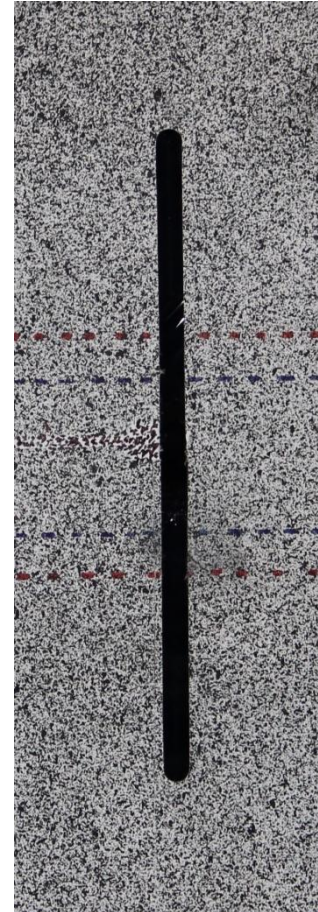
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Phase III: Two-Bay Notch

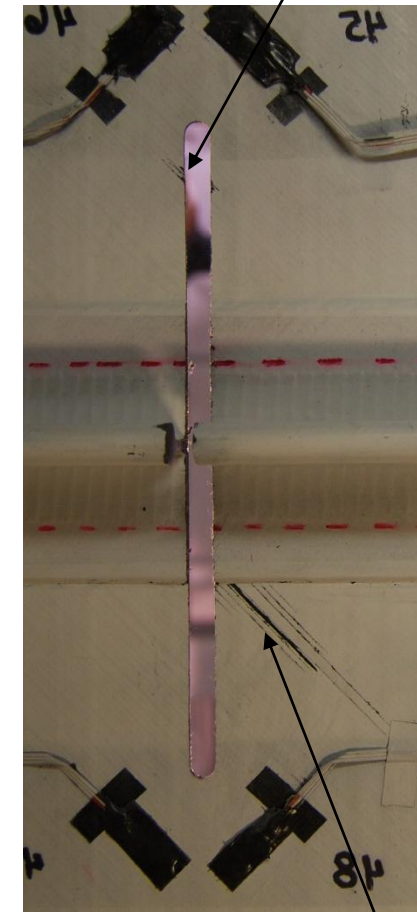
Panel Exterior



Exterior



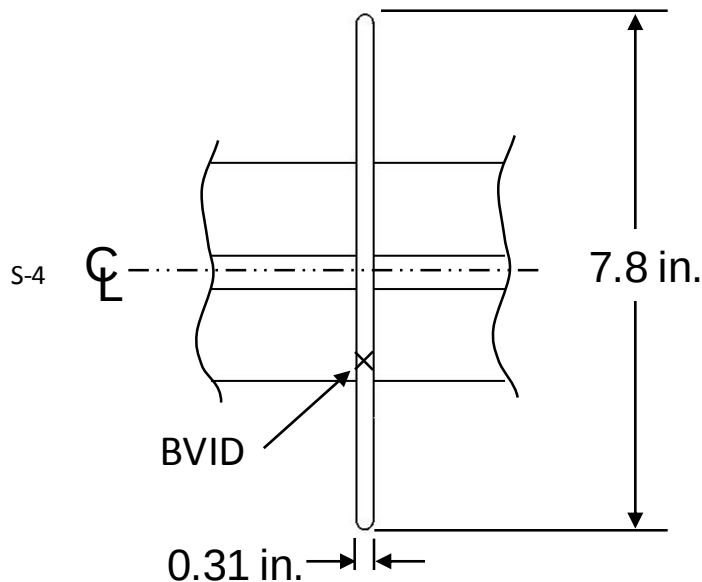
Interior



Breakout during machining

BVID Damage

Notch detail schematic

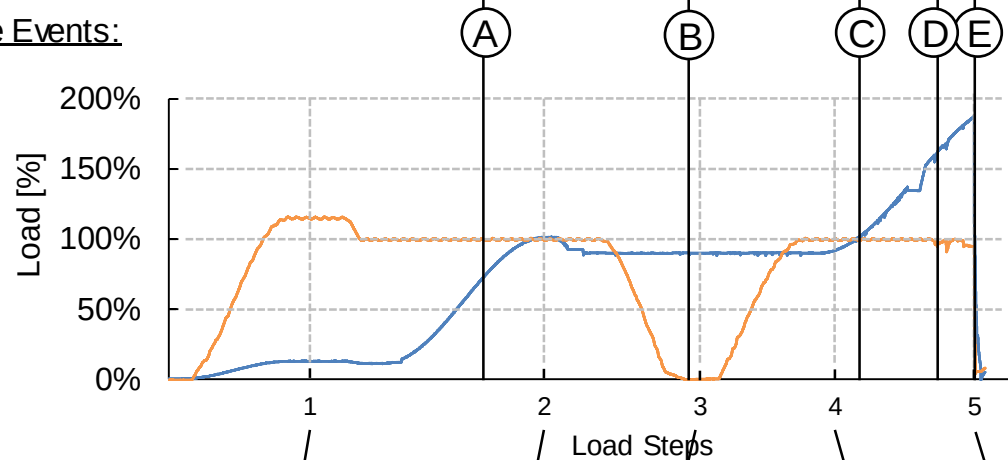


Notch Severed Central Stringer and Adjacent Skin

Phase III: Load History

	Load Target				
Observations	1.15P	1P + DLL	DLL	1P + DLL	↑ Axial
Failed Strain Gages		●			●
Damage Containment	2-Bay Region				
Damage Propagation		■	■	■	■

Damage Events:



1) Pressure (1.33P)

2) Combined (1P + 100%DLL)

3) Axial (100%DLL)

5) Inc. Axial to Failure
(1P + 184%DLL)

4) Combined (1P + 100%DLL)

Key Damage Events

(A) Visual Damage Formation

(B) Cont'd Damage Propagation

(C) Cont'd Damage Propagation

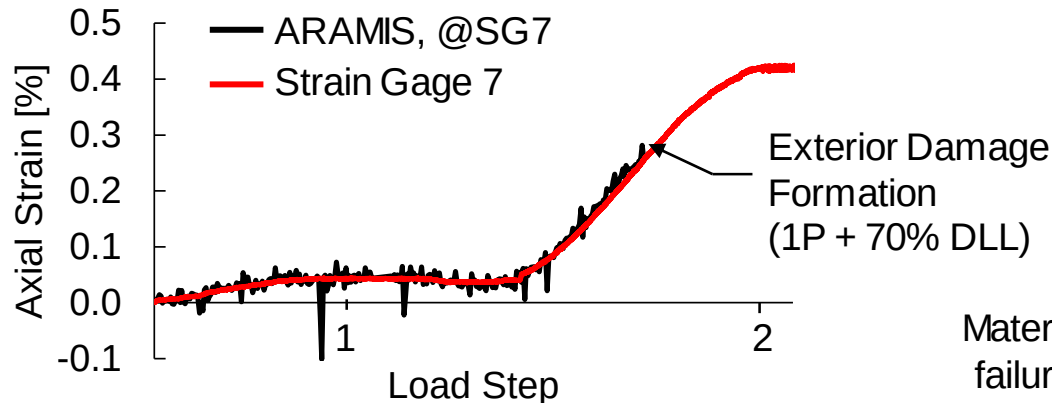
(D) Damage Propagation
beyond two-bay region

(E) Catastrophic Failure

Panel Never Completely Unloaded to Prevent Damage Due to Unloading

Load Step 2: Combined Limit Load Pre-Failure Strain Distribution

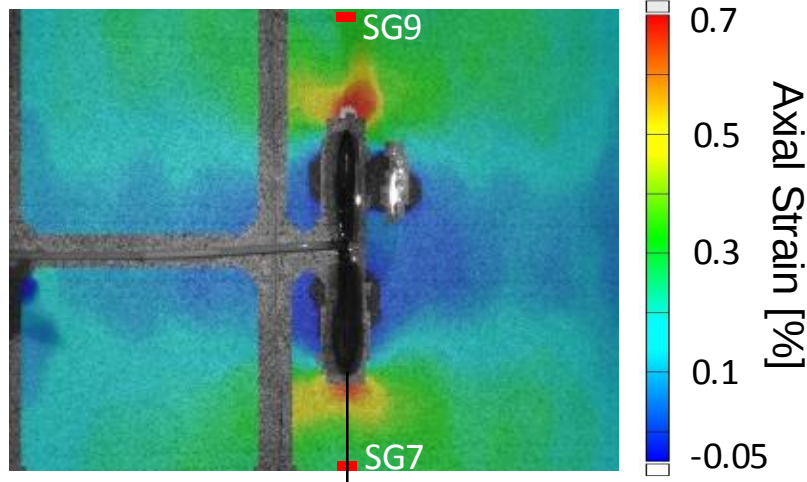
Strain History at SG7



Observations

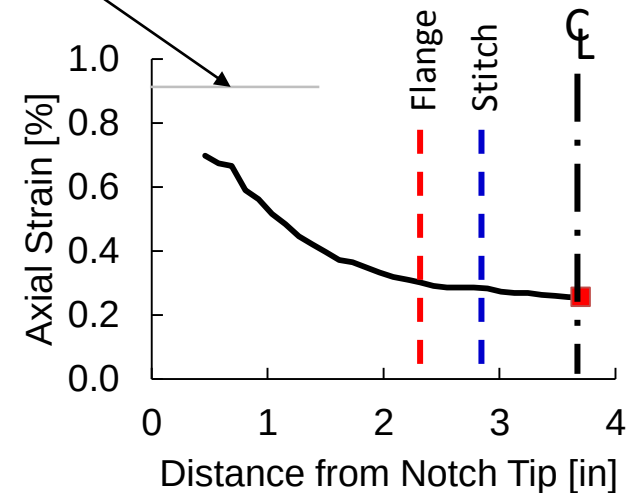
- Excellent Correlation between ARAMIS and strain gage results
- No ARAMIS results after damage formation due to water leakage

Load: 70%DLL + 1P



Material failure strain

Notch Strain Gradient



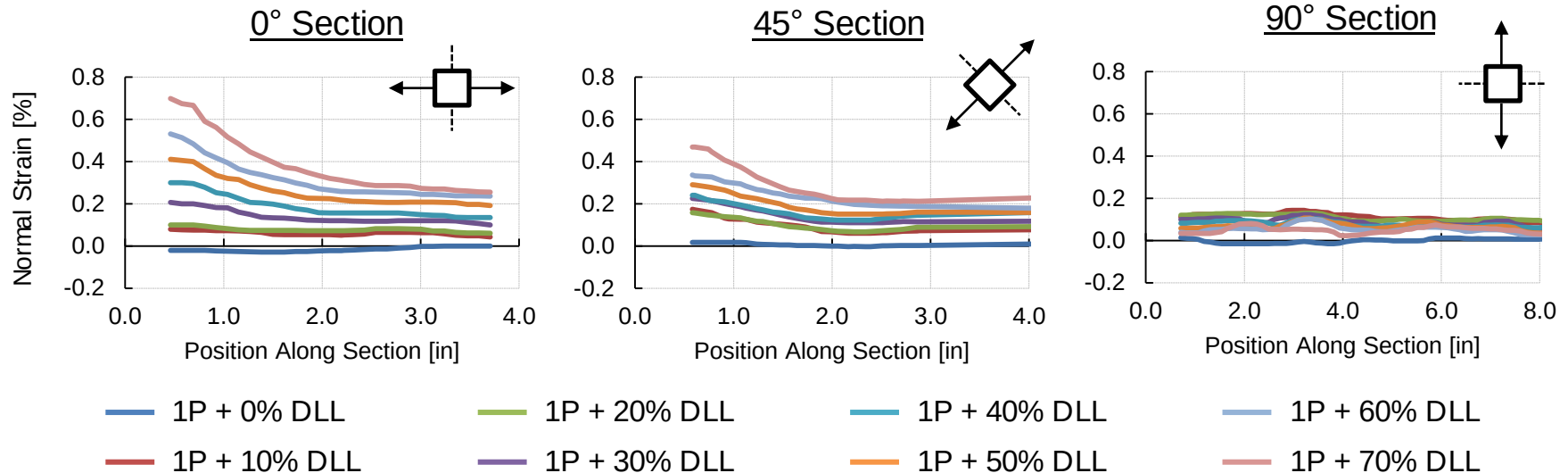
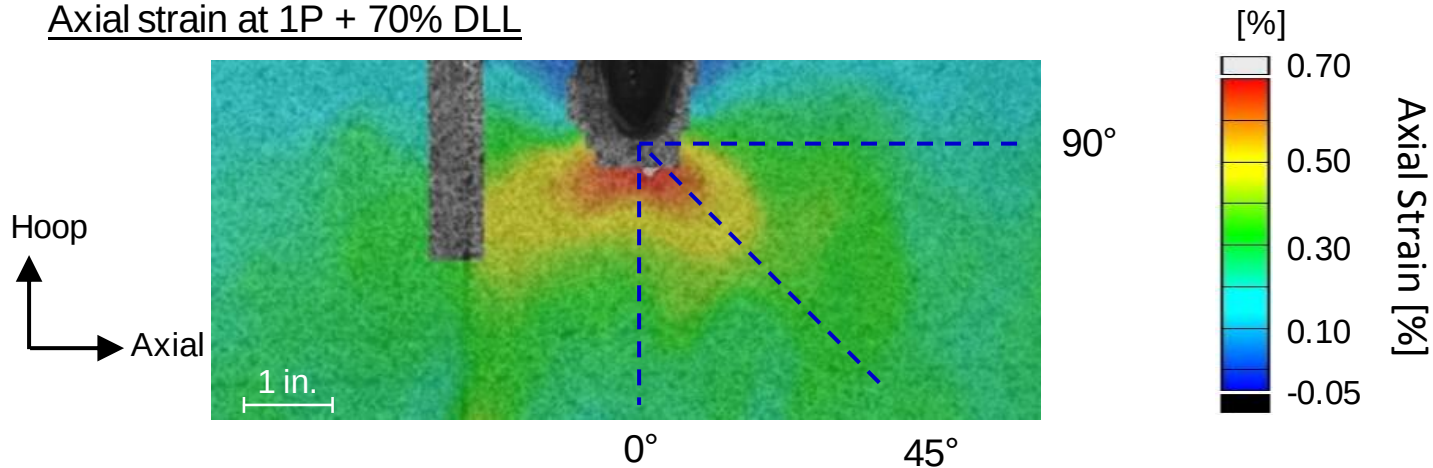
— ARAMIS, 7 ■ Strain Gage 7

Notch Tip Axial Strain Approached Material Failure Strain at Visual Damage Initiation

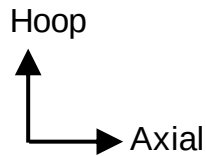
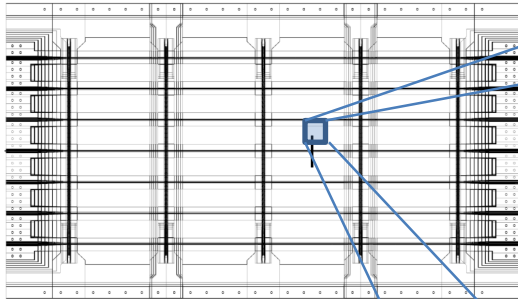
Load Step 2: Combined Limit Load

Notch Tip Strain Gradients

Axial strain at 1P + 70% DLL



Dominate Notch Tip Strains were Axial Strains



1P +
54% DLL



1P +
67% DLL



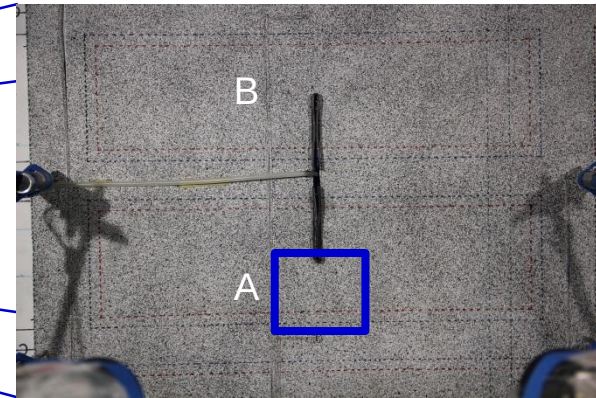
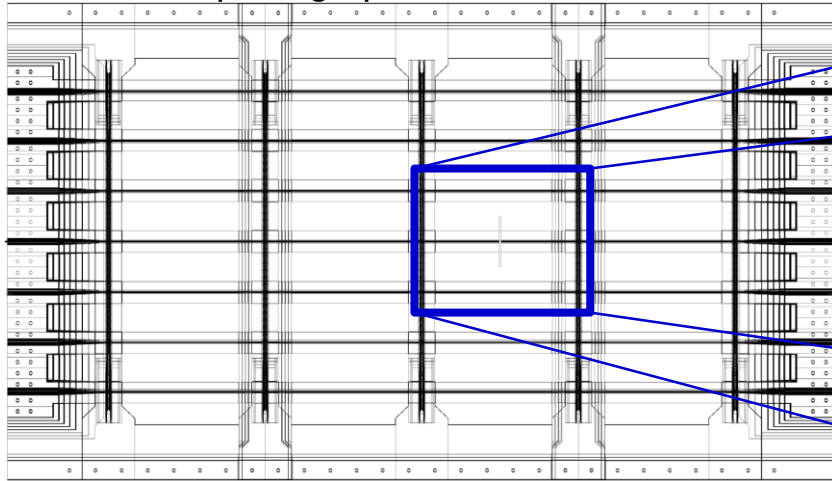
1P +
100% DLL



- Damage initiation: 1P + 54% DLL (interior first)
- Damage propagation slow and stable at 45° (surface ply dir.)
- Failure by matrix splitting

Load Step 2: Combined Limit Load Exterior Visual Damage Propagation

Location of photographs



S-3

S-4

S-5

F-3

F-2

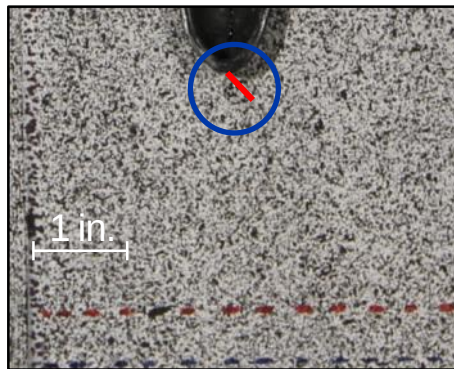
1P + 70% DLL

1P + 88% DLL

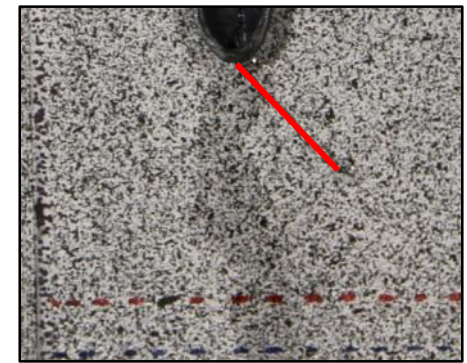
1P + 100% DLL

Hoop
↑
↓
Axial
→

Flange Edge
Stitch row



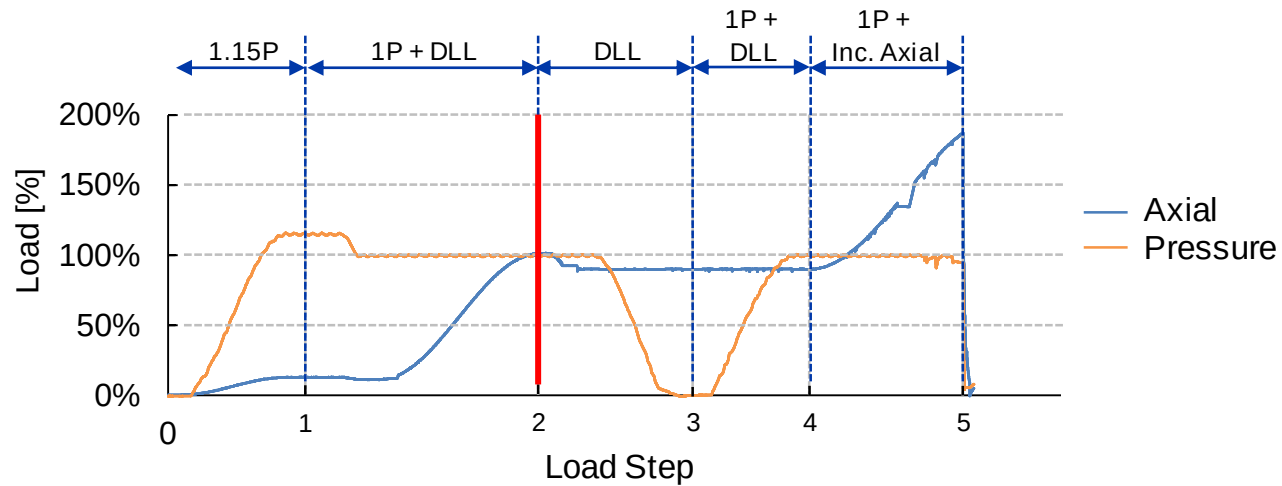
Damage Event A



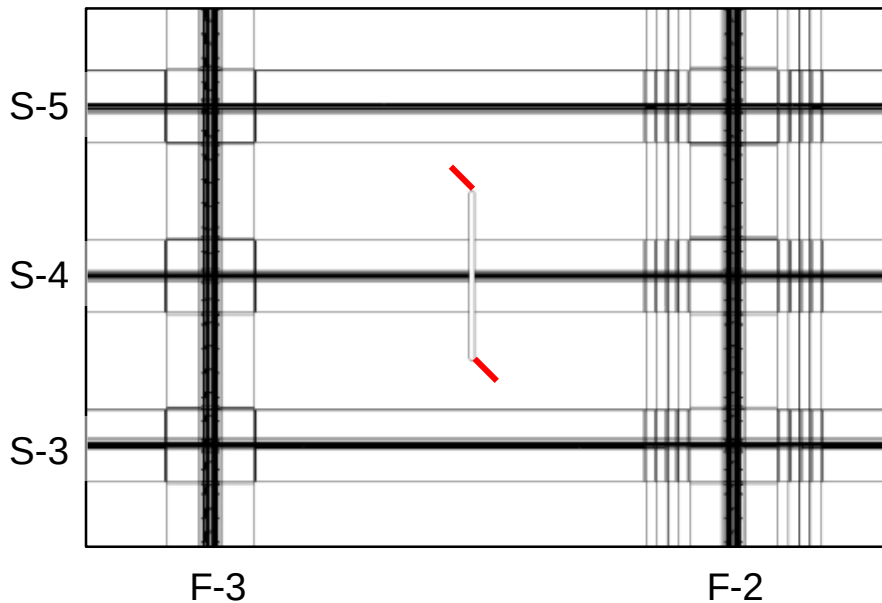
Damage on Exterior Skin was 45° Splitting Propagating Slowly & Stably



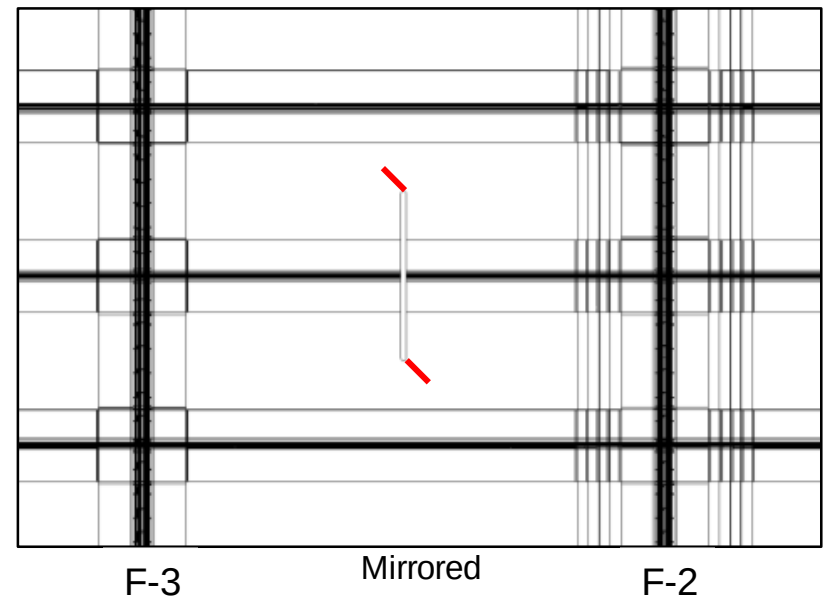
Damage State – Load Step 2



Exterior



Interior



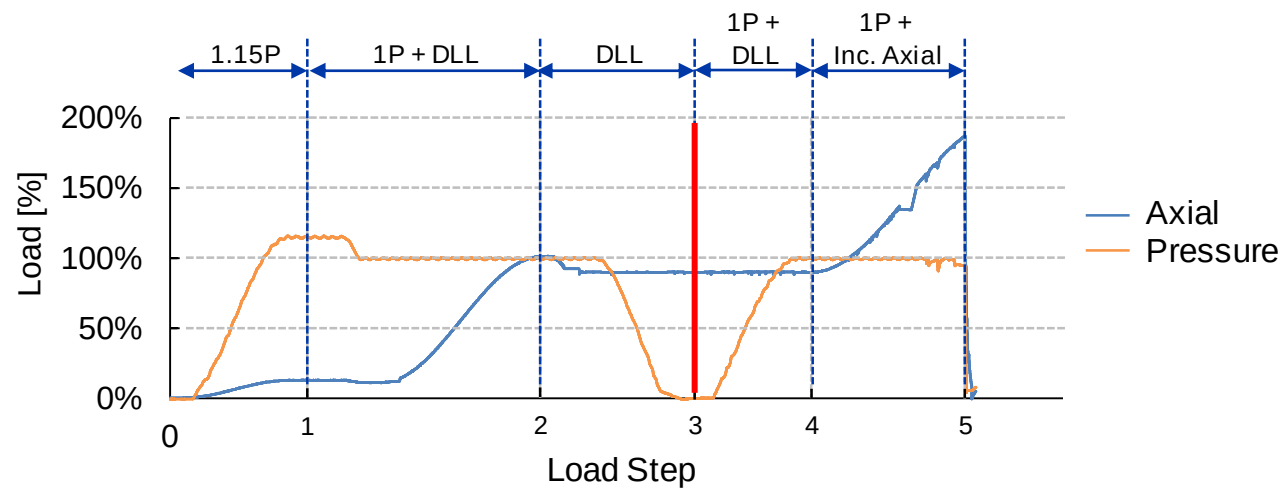
Load Step 3: Axial Limit Load Interior Visual Damage Propagation



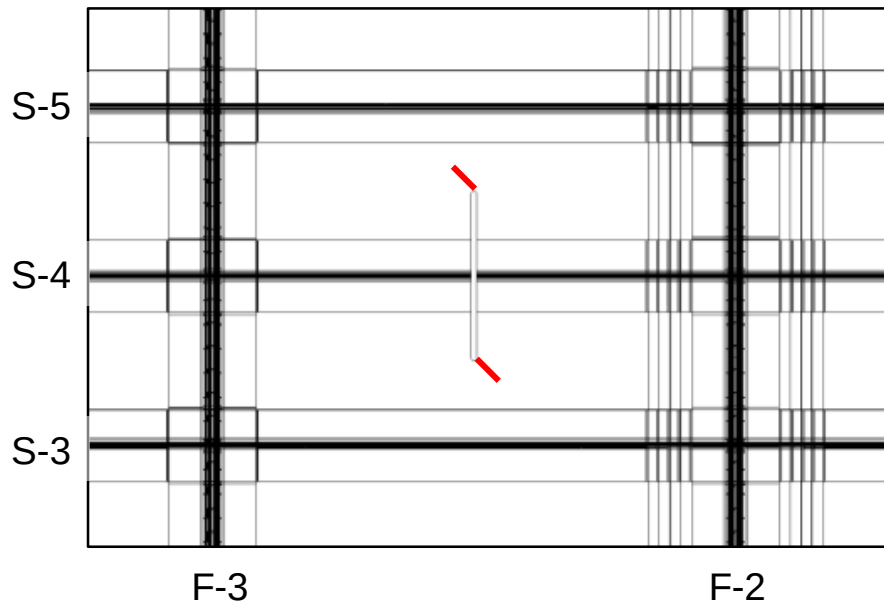
Axial Only Limit-Load Case was the Most Severe Load Condition



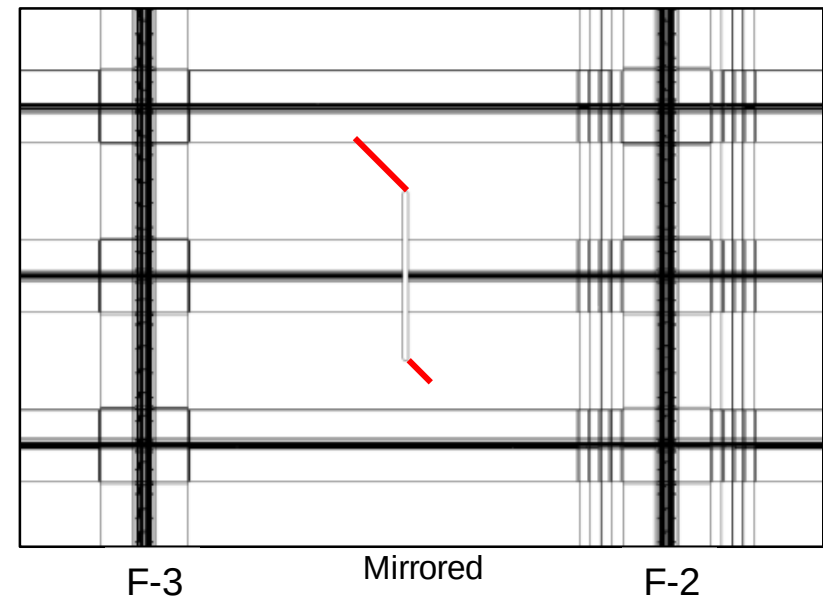
Damage State – Load Step 3



Exterior



Interior



Load Step 5: Catastrophic Failure (1P + Inc. Axial)

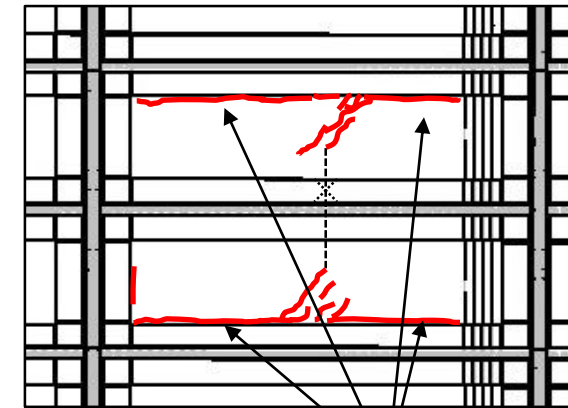
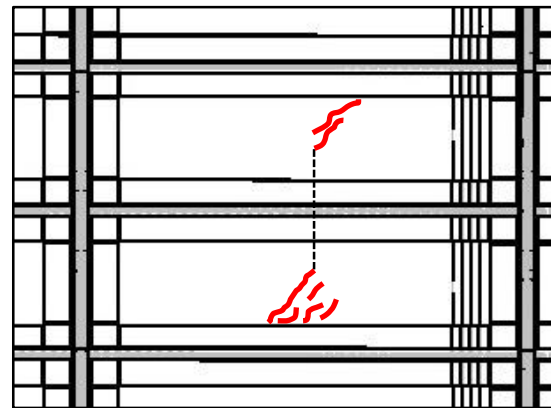
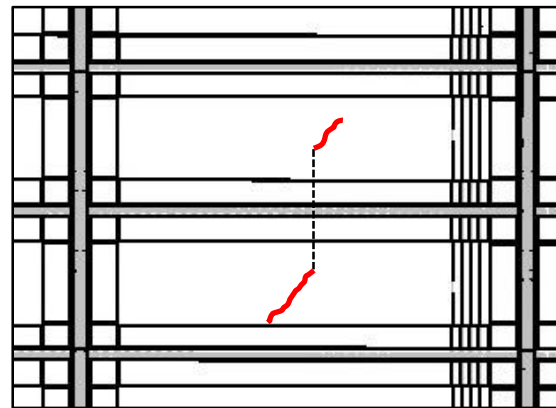
Interior Surface Schematic of Damage Propagation

Test Section (Interior)

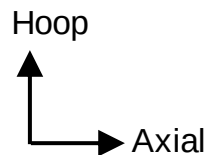
1P + 100% DLL

1P + 138% DLL

1P + 140% DLL



Delaminations
between skin &
stringer flange



Slow, stable
damage
accumulation

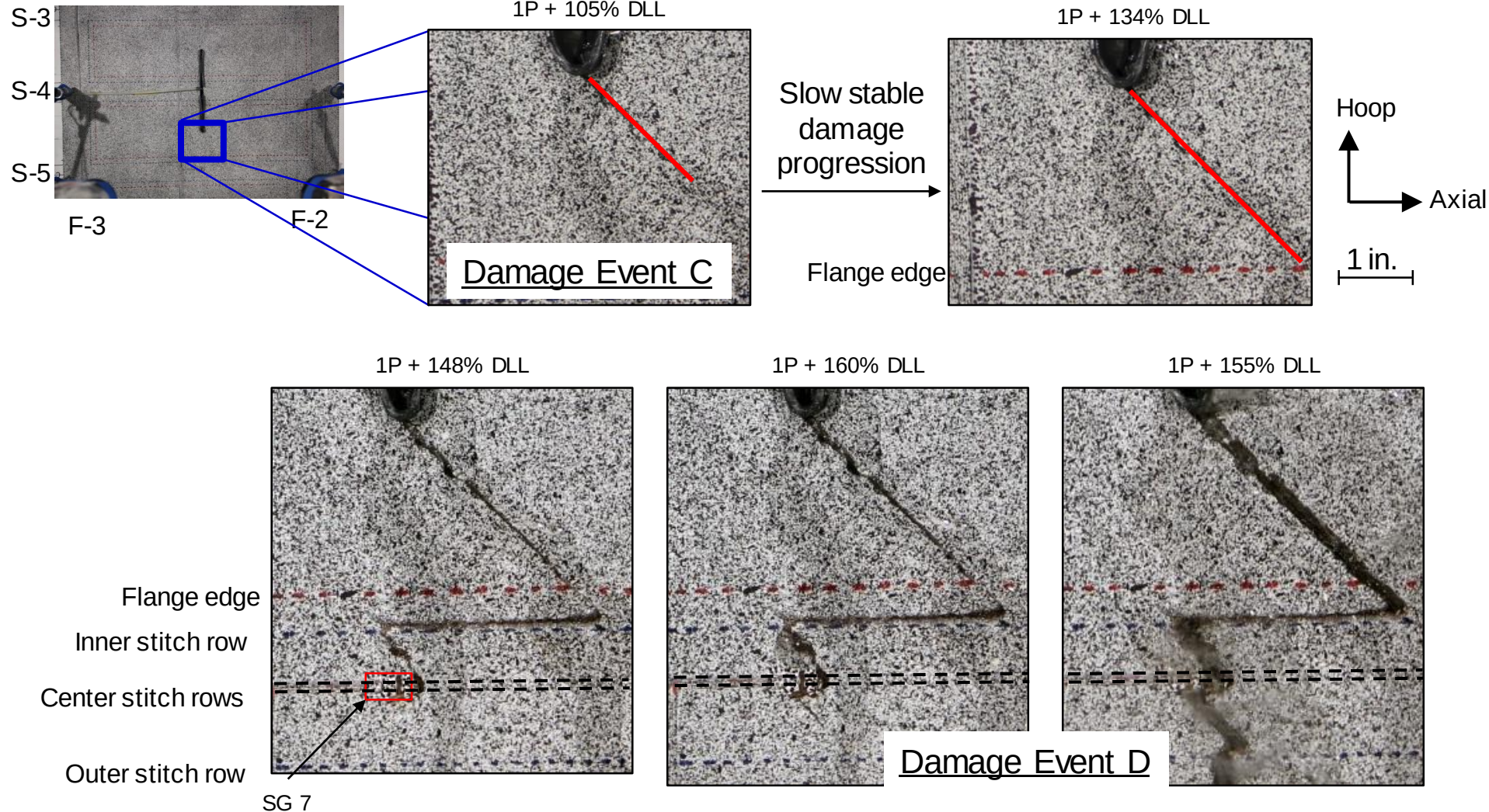
Unstable
damage
propagation

Visible damage was more widespread on the interior surface

Load Step 5: Catastrophic Failure (1P + Inc. Axial)

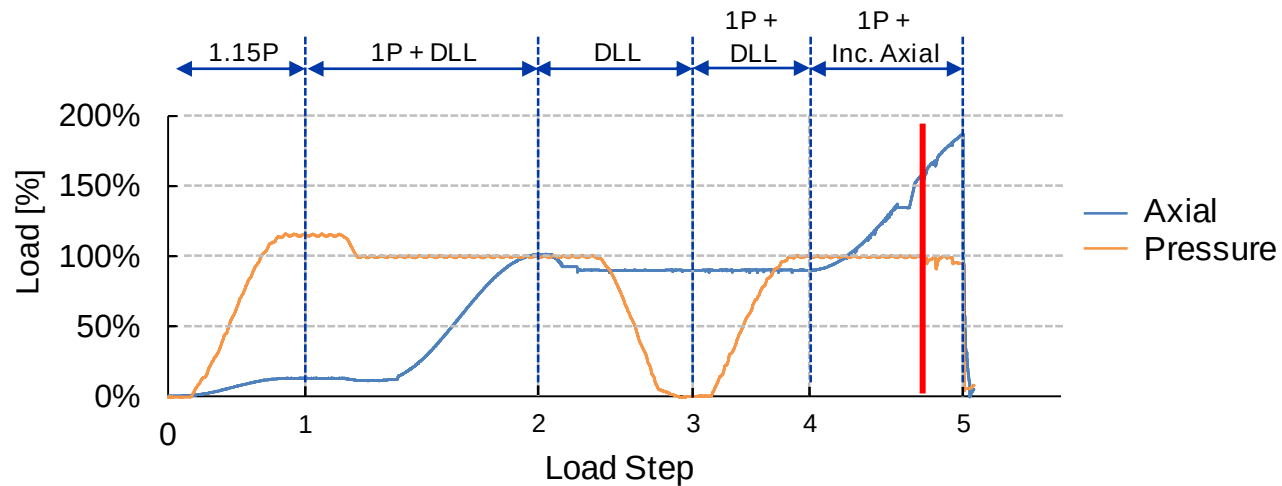
Visual Damage Propagation

Test Section (Exterior)

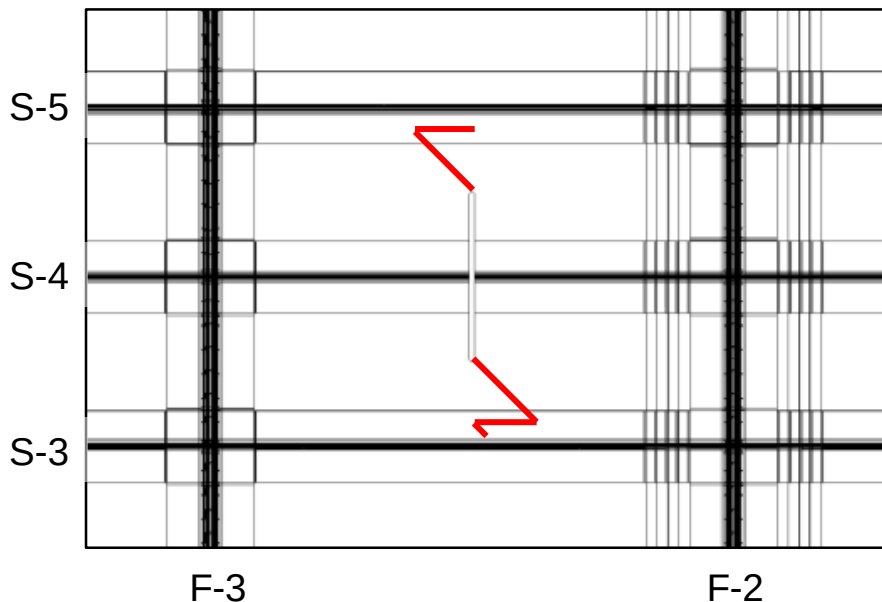


Damage was arrested by the stitches before propagating beyond the two-bay region

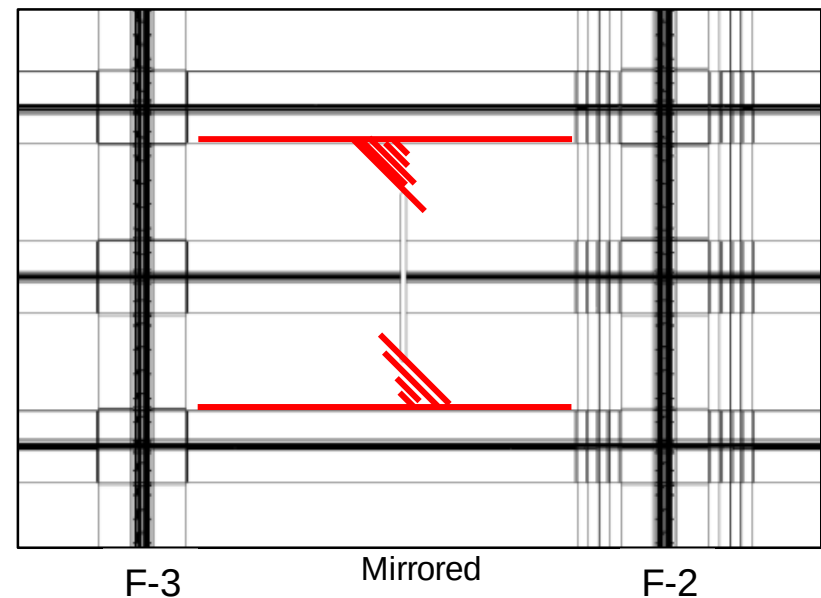
Damage State – Before Damage Event D



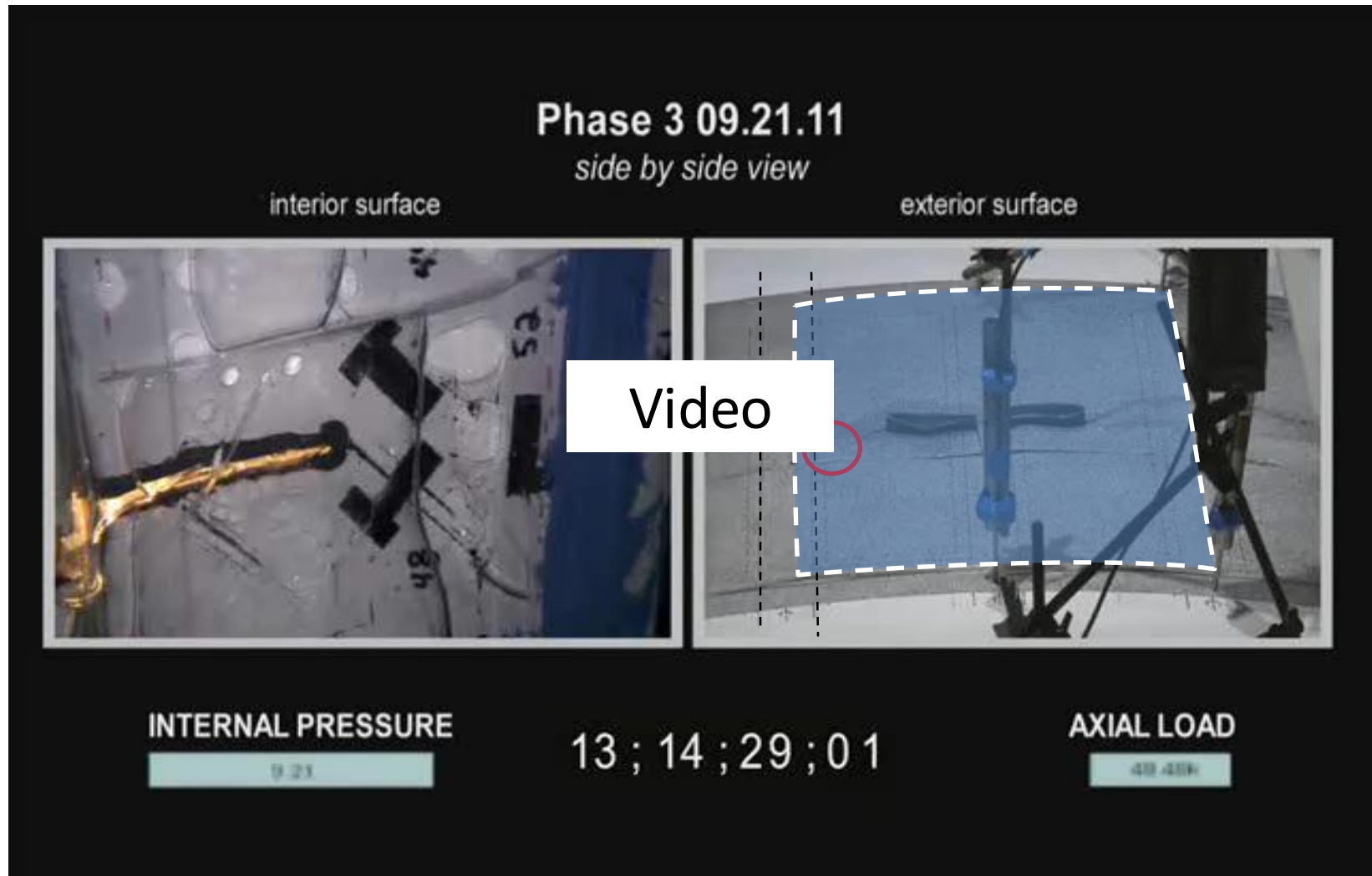
Exterior



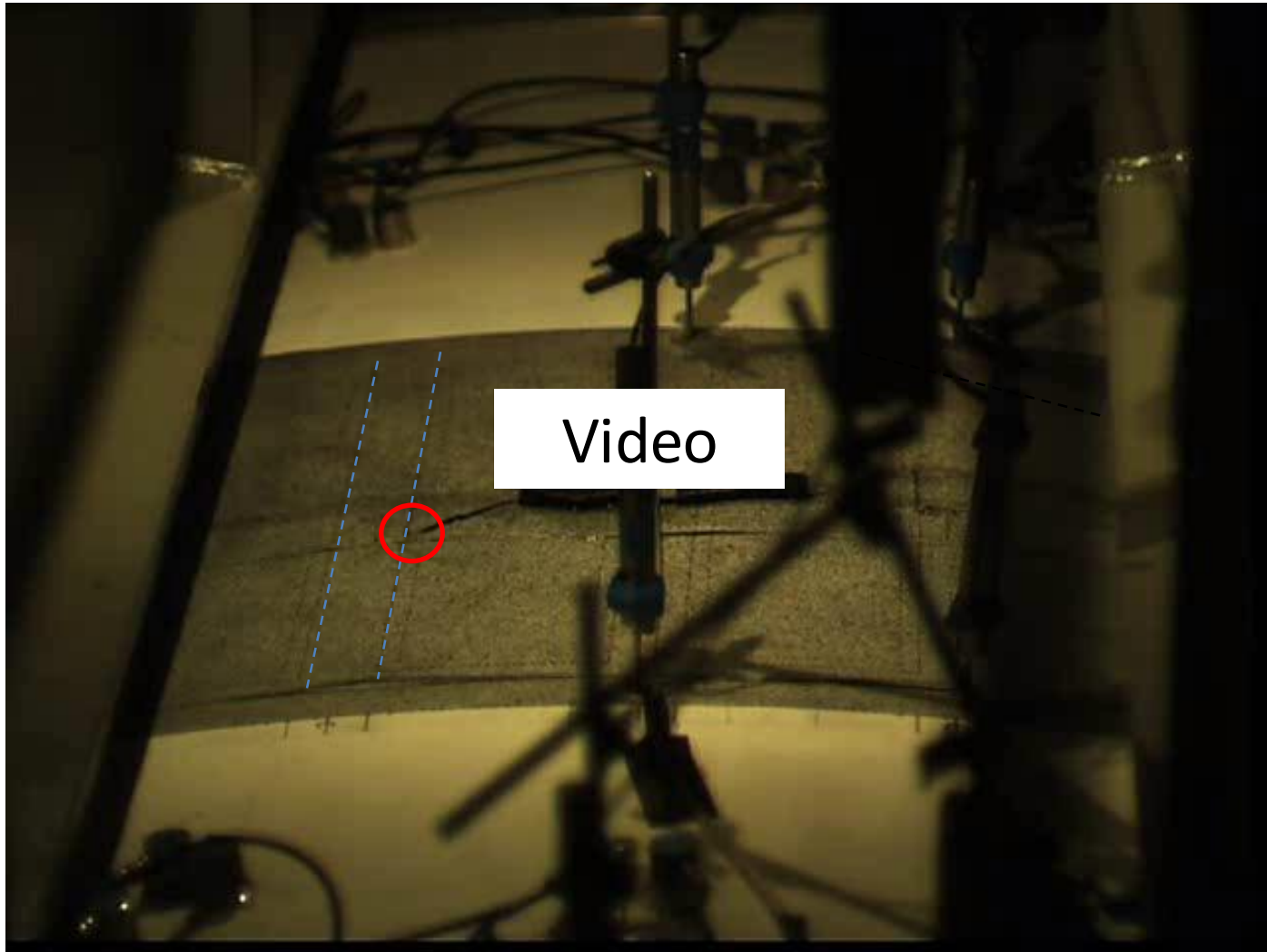
Interior



Damage Event D: Exterior Video



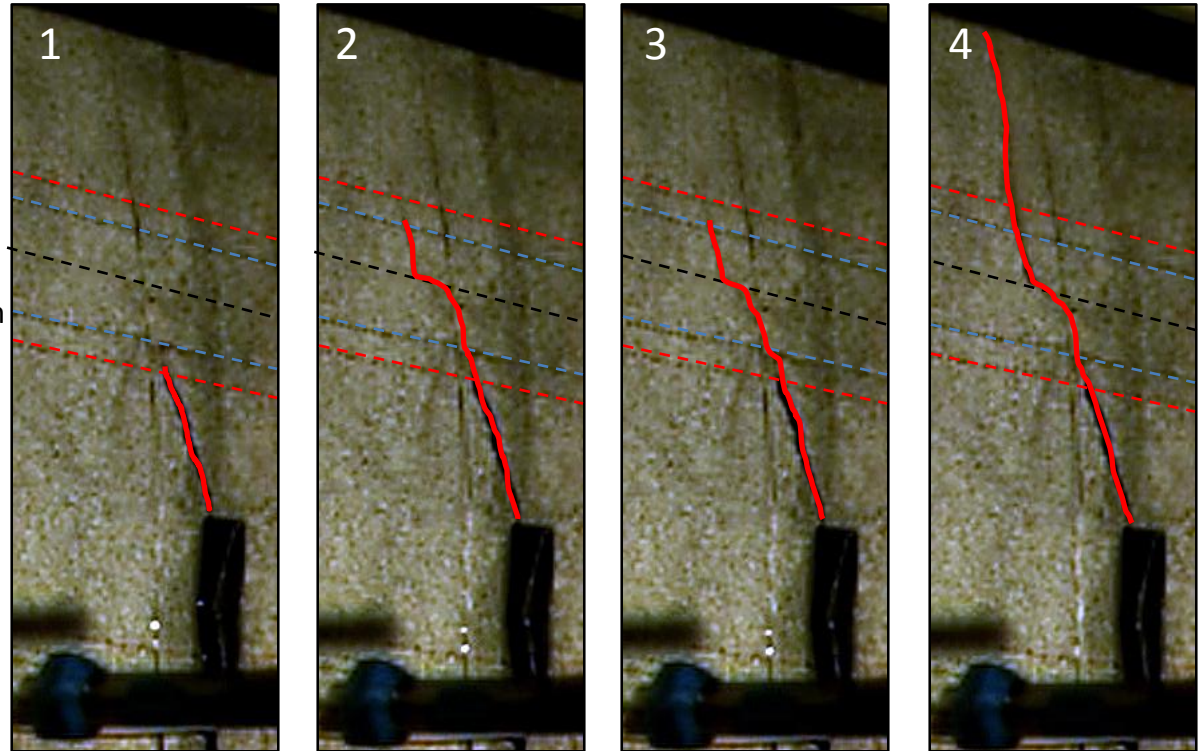
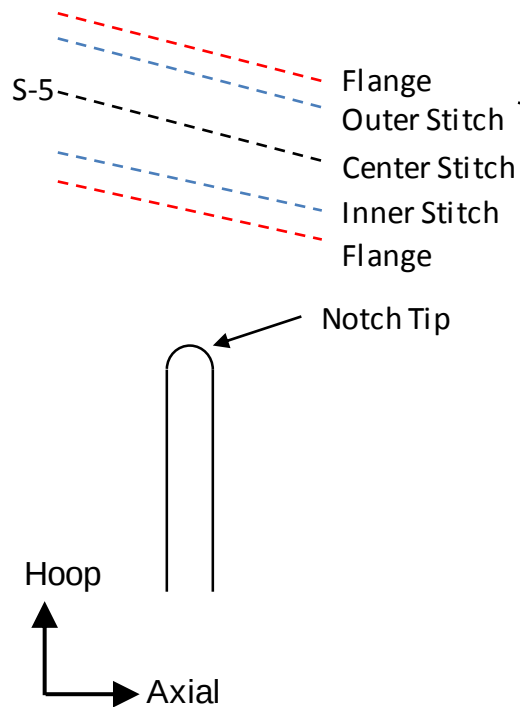
Damage Event D: Exterior High-Speed Video



Damage Event D: High Speed Video Frames

Sequential frames captured with an Olympus-i3
High Speed Video Camera at 5000 FPS

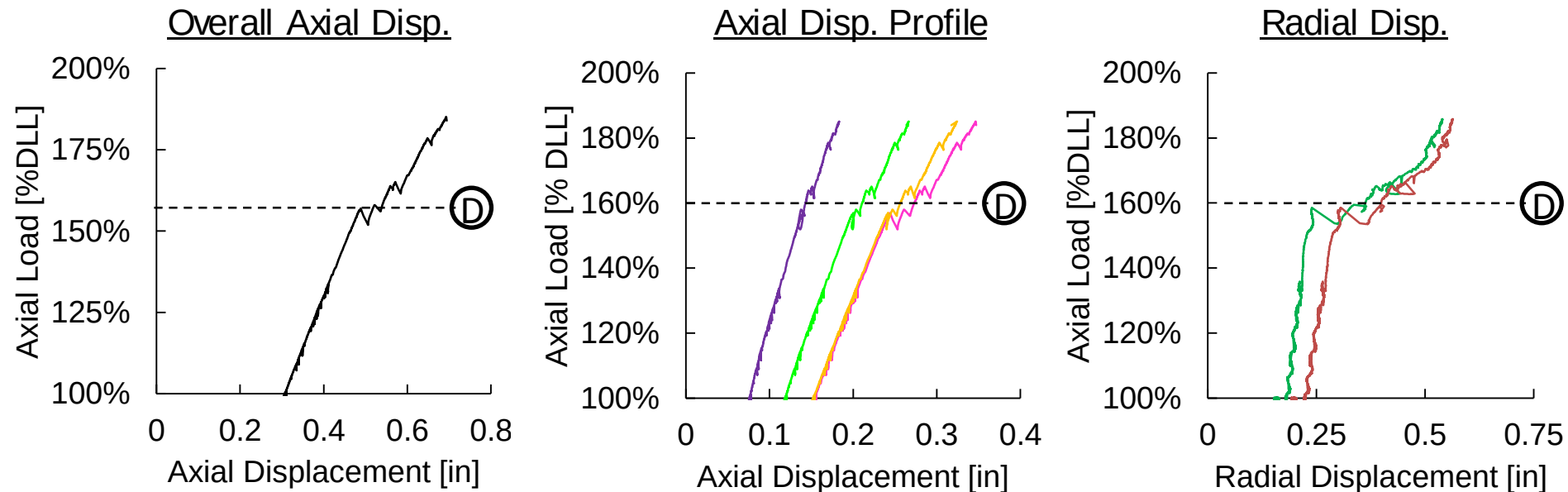
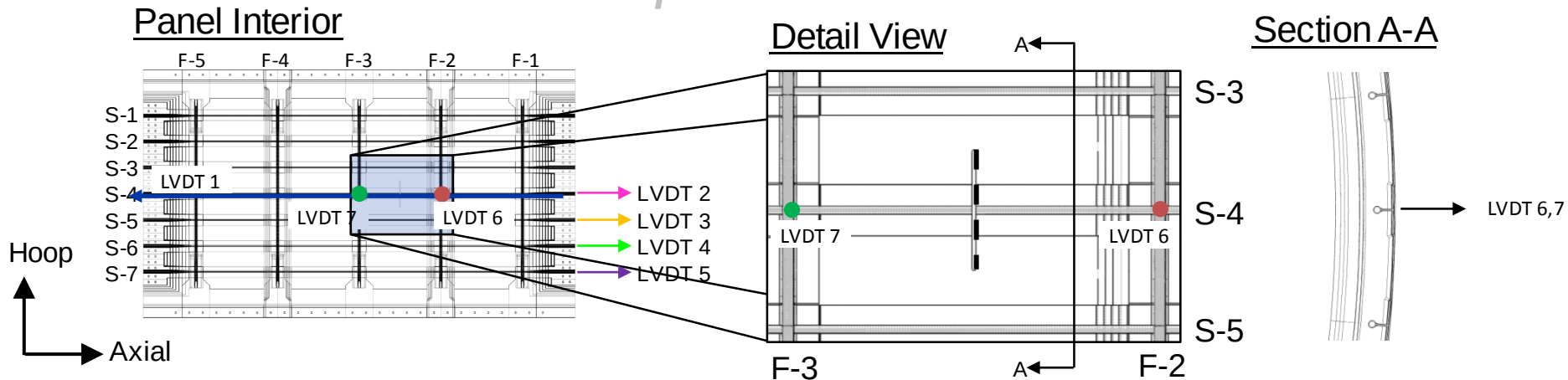
Notch Tip Schematic



*Damage Temporarily Arrested as it
Progressed Beyond the Adjacent Stringer*

Load Step 5: Catastrophic Failure (1P + Inc. Axial)

Displacements

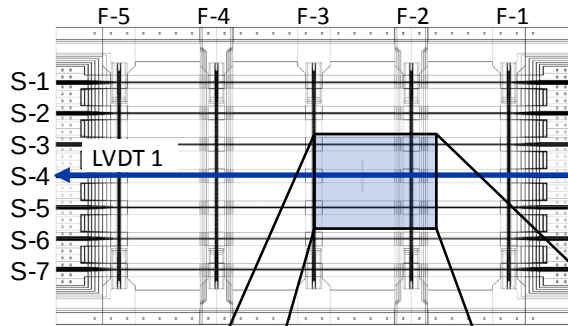


A Significant Displacement Discontinuity Occurred at Damage Event D

Load Step 5: Catastrophic Failure (1P + Inc. Axial)

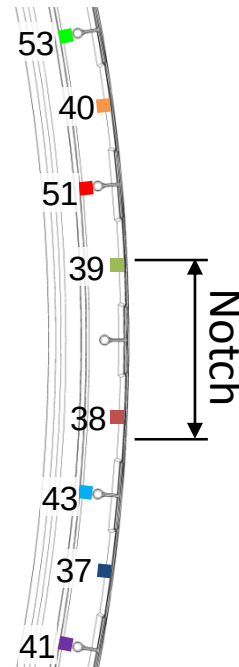
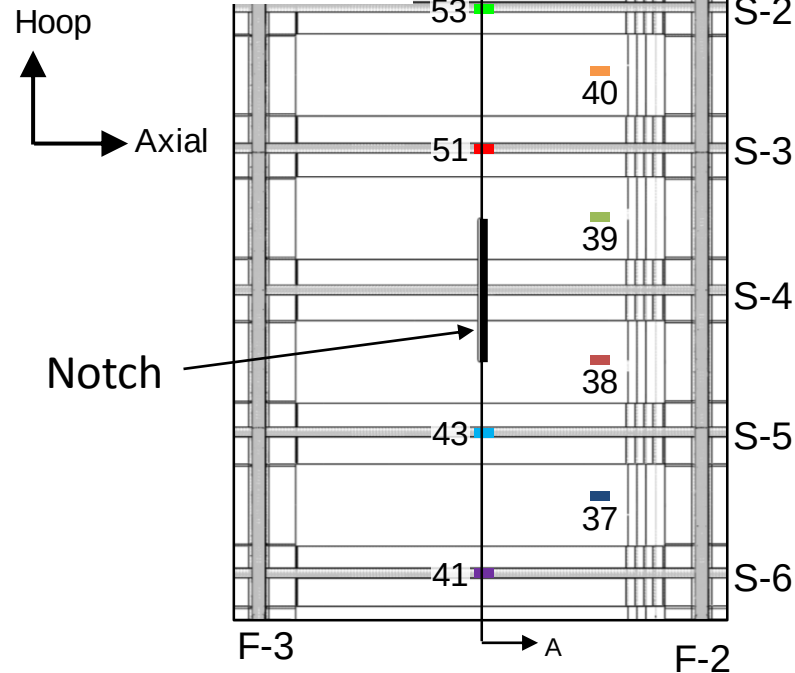
Strain Redistribution

Panel Interior

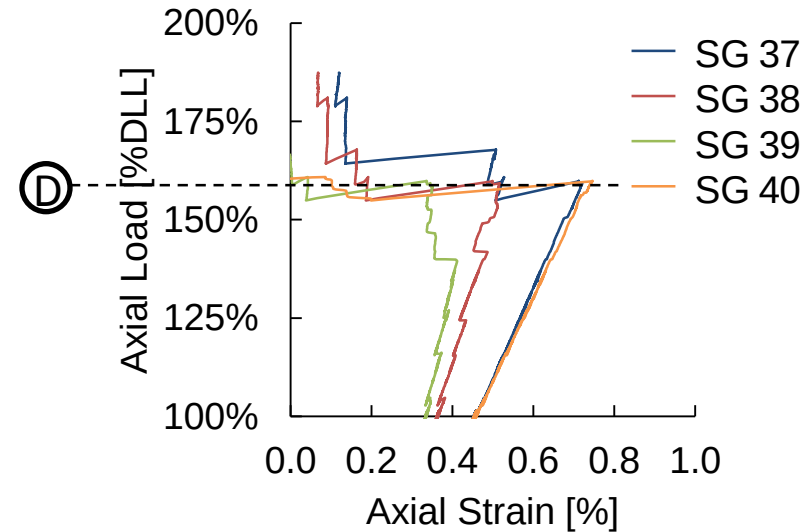


Section A-A

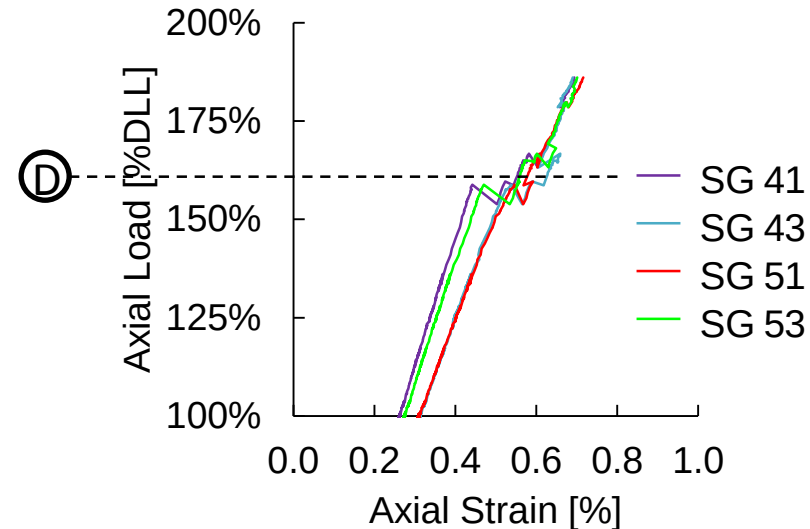
Detail View



Interior Skin Strain



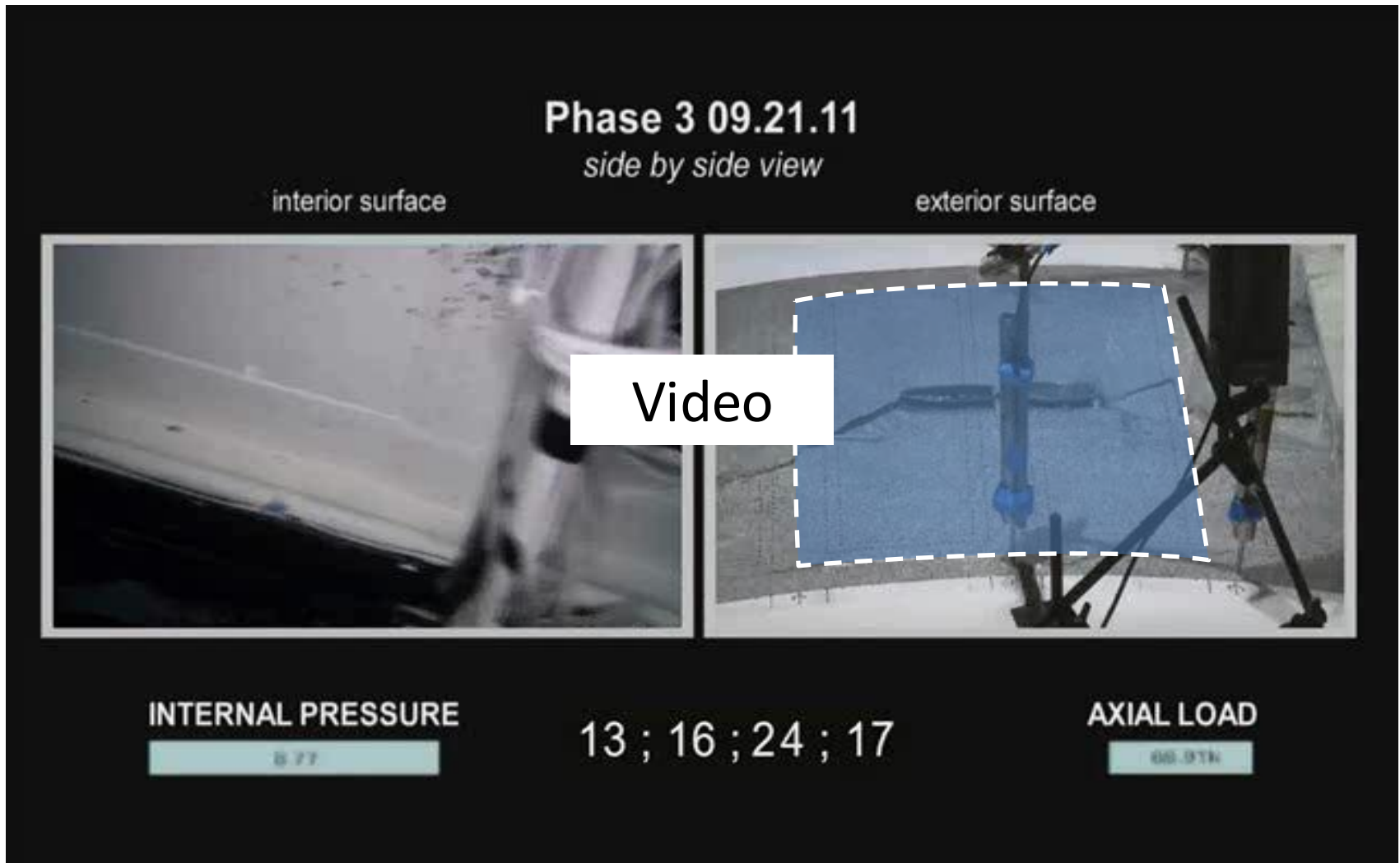
Stringer Strain



After Damage Event D, The Stringers Held Load, Bridging the Failed Skin



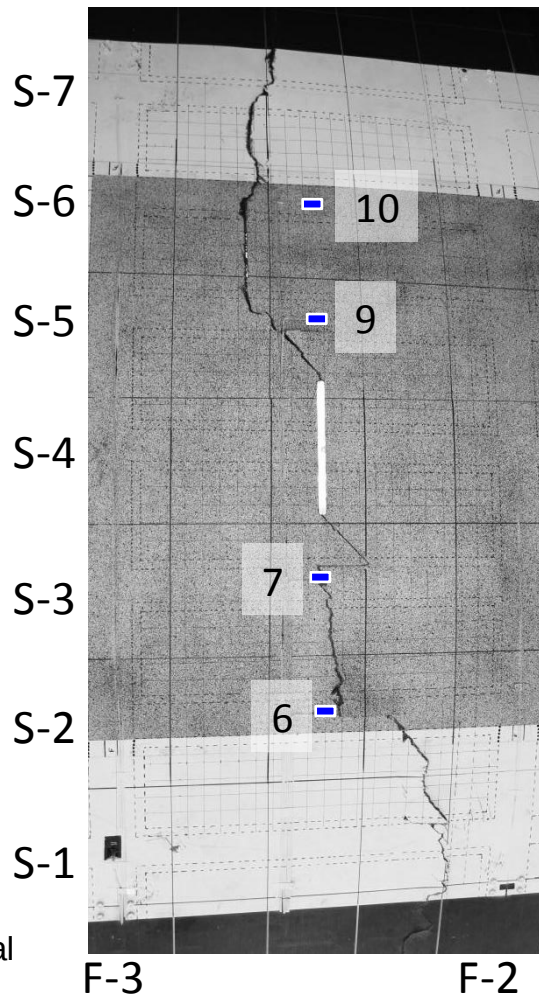
Damage Event E: Catastrophic Failure



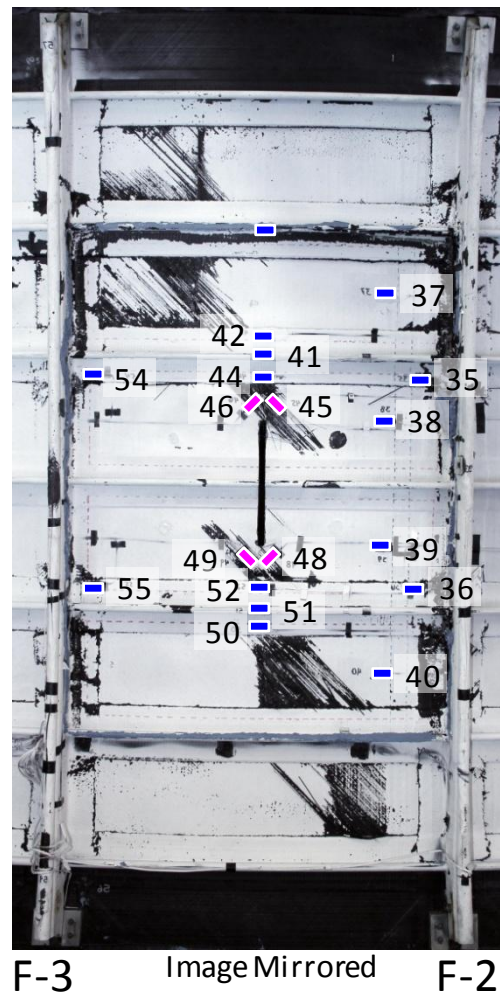


Post Failure Inspection

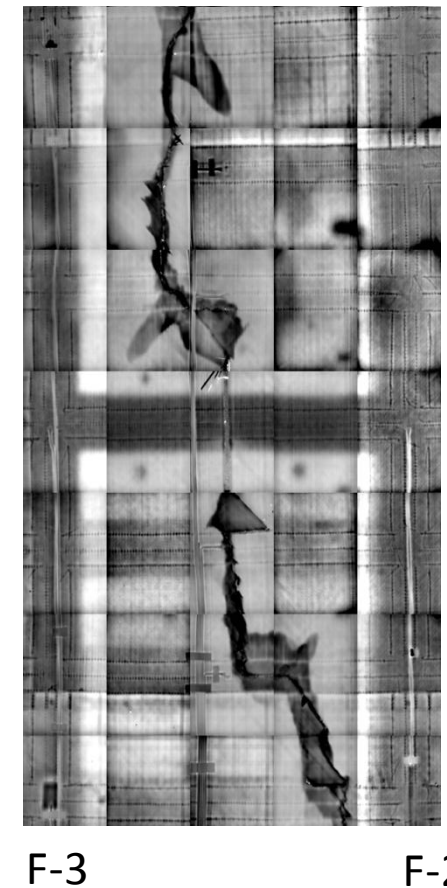
Exterior



Interior



Flash Thermography



Damage Widespread and Path Altered at Stitch Rows

Summary

❖ Phase I

- Good repeatability demonstrated at 50% load levels
- Linear strains and displacements observed

❖ Phase II

- Panel impacted with 40 ft-lb impactor
- No damage growth observed after ultimate loads were applied

❖ Phase III

- Inserted 7.8 in. through thickness notch, severed central stringer
- Damage formation observed at 1P + 70% DLL
- Damage contained with 2-bay region to 1P + 160% DLL
- Catastrophic failure at 1P + 184% DLL

Conclusions

- ❖ Successful test
- ❖ Fixture performed as designed
- ❖ Panel failure load well above expected failure
- ❖ Damage containment demonstrated on curved PRSEUS panel

Future Work

- Post test Non-Destructive and Destructive Evaluation
 - Objective: Identify failure mechanisms for use in evaluating future progressive failure analyses
 - Approach: Notch tip region evaluations using ultrasonic, thermography, and microscopy techniques
- FEM based progressive failure analyses



Acknowledgements

- Yongzhe Tian
- Jeff Panco
- Pat Sheehan
- Pat Johnston

Questions?



PRSEUS Fuselage Panel Test Team 9/15/11