Effects of **R**epair **P**rocedures on **B**onded **R**epairs of **C**omposite **S**tructures

2011 Technical Review

John Tomblin, PhD
Executive Director, NIAR

Lamia Salah
Sr. Research Engineer, NIAR

FAA Sponsored Project Information

- Principal Investigators & Researchers
  - Dr. John Tomblin, Wichita State University
  - Lamia Salah, Wichita State University
  - Mike Borgman, Spirit Aerosystems

- FAA Technical Monitor
  - Curtis Davies, Lynn Pham

- Other FAA Personnel Involved
  - Larry Ilcewicz, Peter Sheprykevich

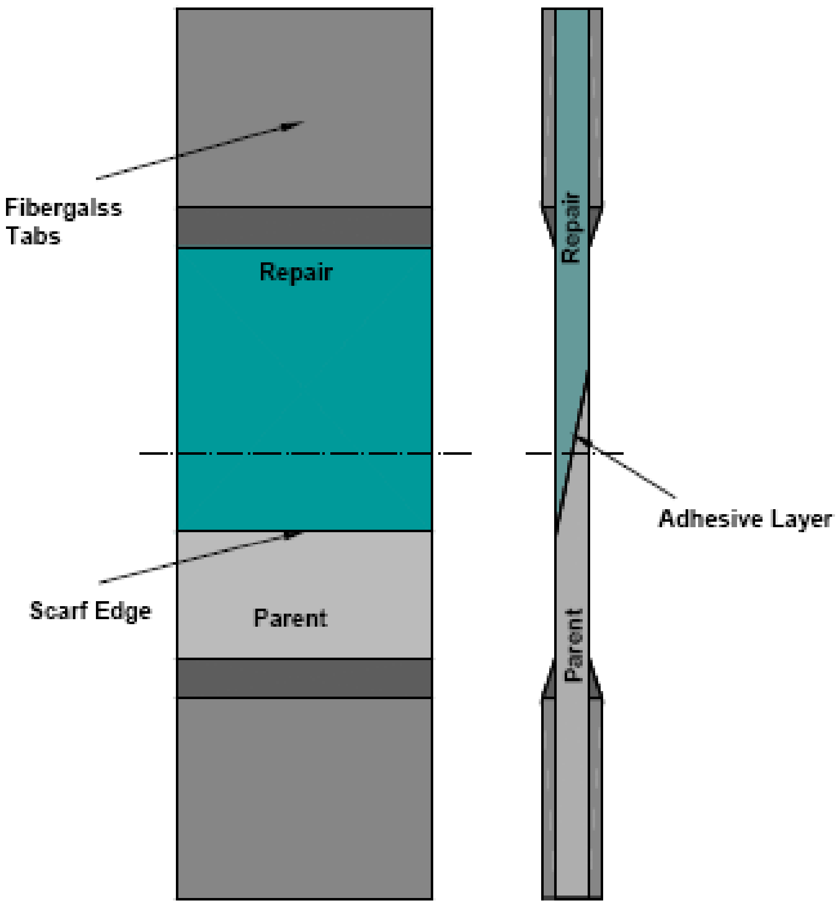
- Industry Participation
  - Mike Borgman, Spirit Aerosystems

Objective

To investigate different variables on the performance of repairs applied to moderately thick solid laminates

- To substantiate the strength and durability (mechanical loading) of OEM repairs applied to moderately thick composite laminates
- To substantiate the strength and durability (mechanical loading) of field repairs applied to moderately thick composite laminates
- To evaluate the ultimate strength of bonded repairs subjected to contamination prior to repair
- To evaluate the damage tolerance of repairs subjected to BVID inflicted at three different locations on the repair scarf joint
- To provide recommendations pertaining to process improvement to ensure repair bond repeatability and structural integrity

Laminate Repair Coupon Configuration



- Parent Substrate: highly toughened system, 350°F cure, autoclave processed
- Adhesive System: Cytec metalbond 1515, 350°F cure (OEM repair)
- Adhesive System: FM300-2, 250°F cure (Field repair)
- Repair Material, same as parent but processed under vacuum, cured at 350°F (OEM repair)
- Repair Material, ACG MTM45-1 processed under vacuum, cured at 250°F (Field repair)
- Single Scarf Joint, 4” wide to isolate the variables investigated

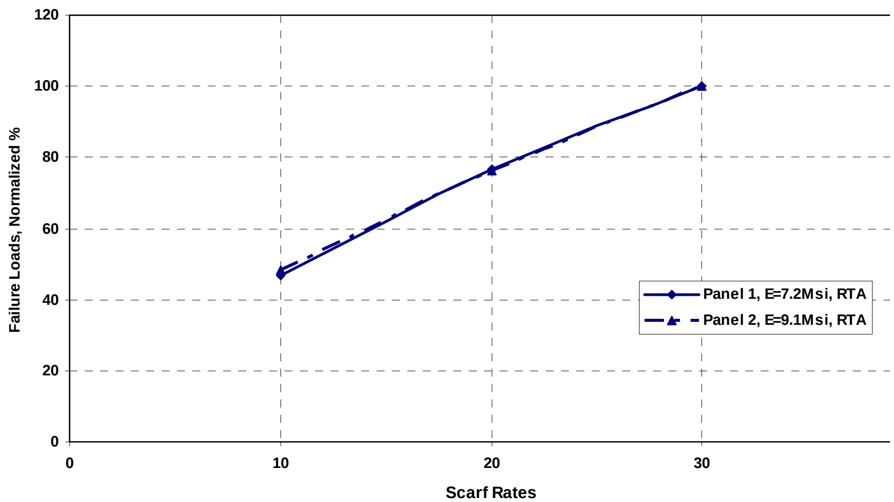
OEM Repair Material Evaluation

- To generate baseline repair data with the parent material used as the repair material (OEM repair), 96 coupons used for the investigation

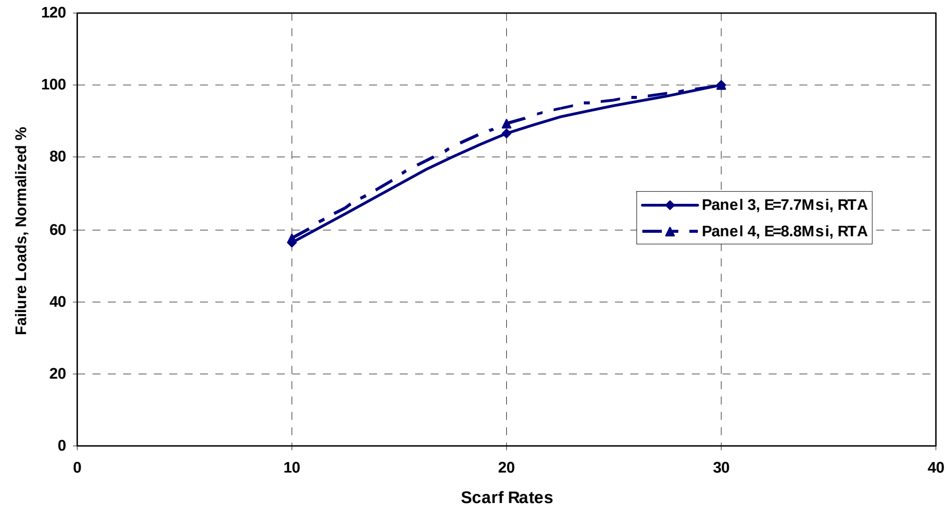
				STATIC	FATIGUE
Panel #	**Thickness (in)**	**E (Msi)**	**Scarf Rate**	RTA	RTA
1	0.1332	7.2	10	6	3
			20	6	3
			30	3	3
2		9.1	10	6	3
			20	6	3
			30	3	3
3	0.2368	7.7	10	6	3
			20	6	3
			30	3	3
4		8.8	10	6	3
			20	6	3
			30	3	3

OEM Repair Material Evaluation

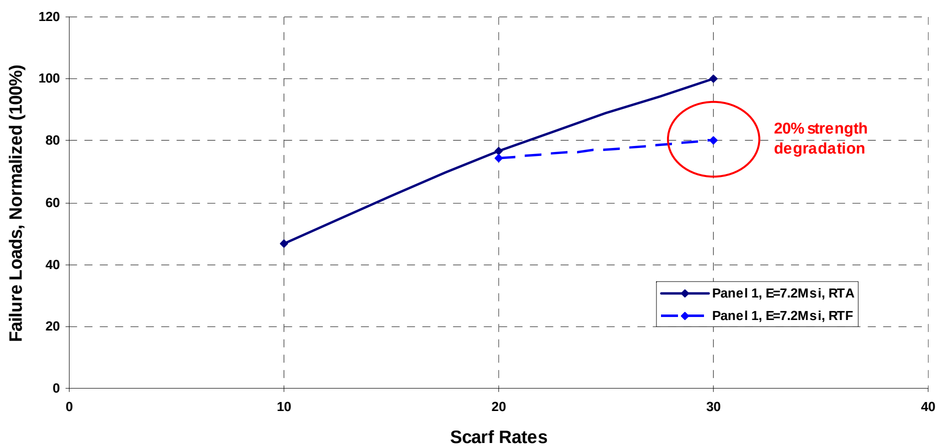
Failure Loads, normalized vs. Scarf Rates (Panels 1 & 2)



Failure Loads, Normalized vs. Scarf Rates (Panels 3 & 4)



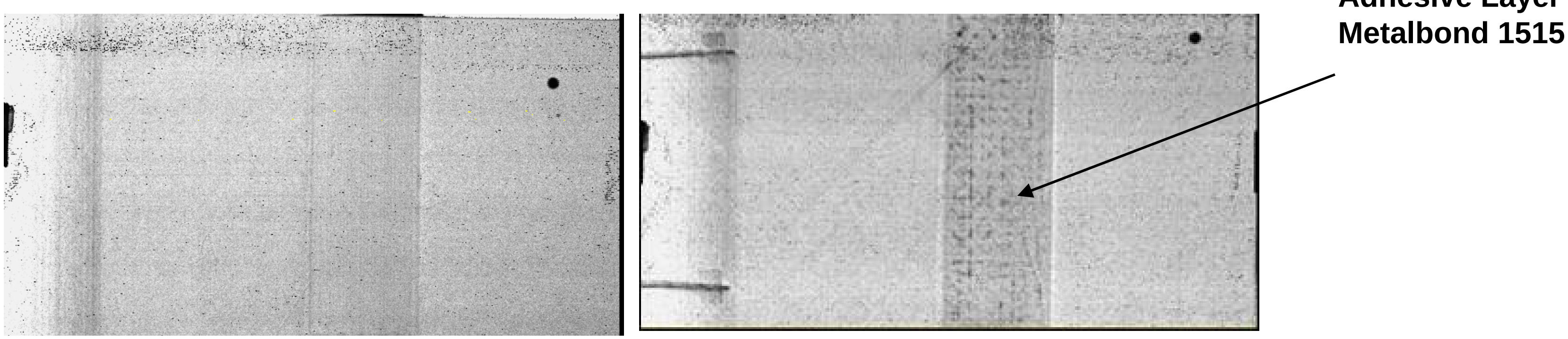
Static/ Residual Strength vs. Scarf Rates (Panel 1)



- 100% corresponds to the failure load of the -30 repairs
- increased load carrying capability with increased repair size

OEM Repair Material Evaluation

- Bonded Repair performance is dependent on repair processes
- Overall increased static performance with increased repair size
- Stiffer panels tend to have a lower strength capability than panels with lower stiffness (more pronounced poisson's effects)
- All -20 and -30 repairs survived 165000 cycles of fatigue at 3000 microstrain demonstrating acceptability of these repairs at that strain level
- The thin panels residual strength after fatigue was 20% lower than their ultimate static strength capability due to a change in compliance/ stiffness after fatigue (adhesive plastic deformation)



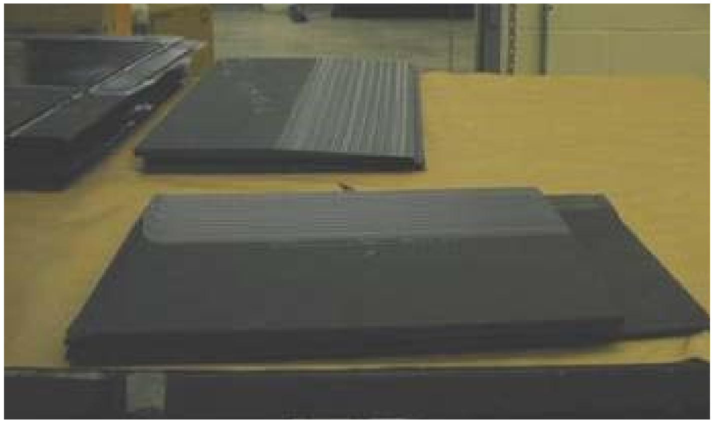
Field Repair Material Evaluation

- To generate baseline repair data for a candidate field repair material (ACG MTM45-1, 250°F vacuum cure system), 72 coupons used for this investigation

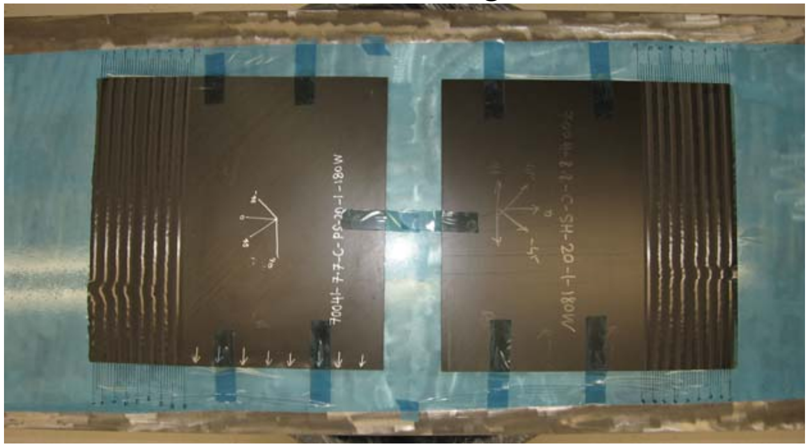
				STATIC	FATIGUE
Panel #	**T (in)**	**E (Msi)**	**Scarf Rate**	RTA	RTA
1	0.1332	7.2	10	3	3
			20	3	3
			30	3	3
2		9.1	10	3	3
			20	3	3
			30	3	3
3	0.2368	7.7	10	3	3
			20	3	3
			30	3	3
4		8.8	10	3	3
			20	3	3
			30	3	3

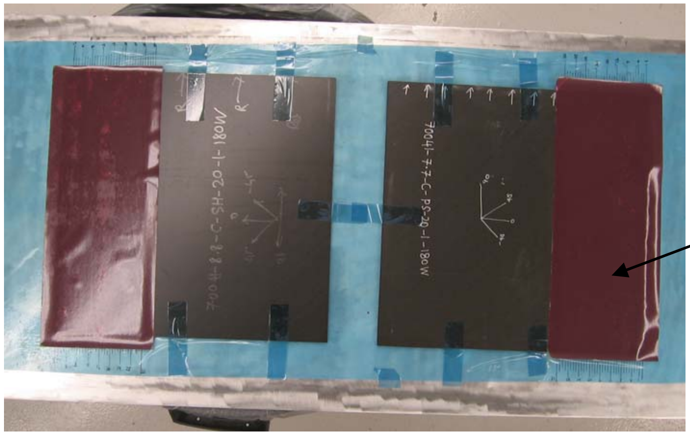
Field Repair Material Evaluation

Scarf Machining



Scarfed Panels

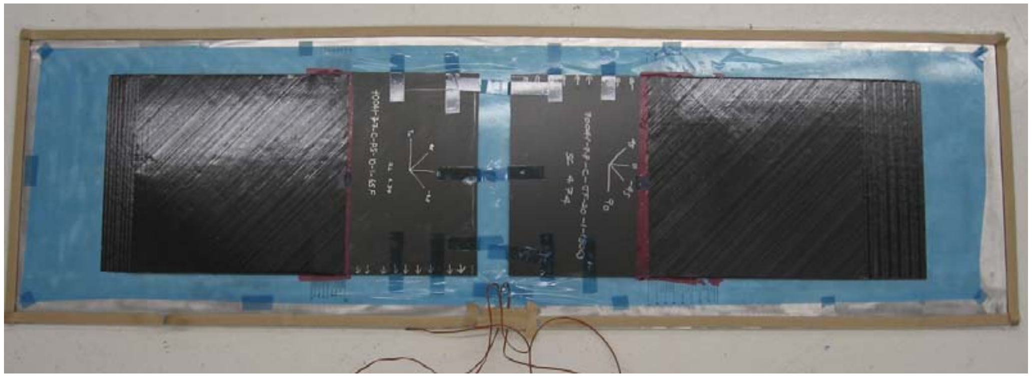


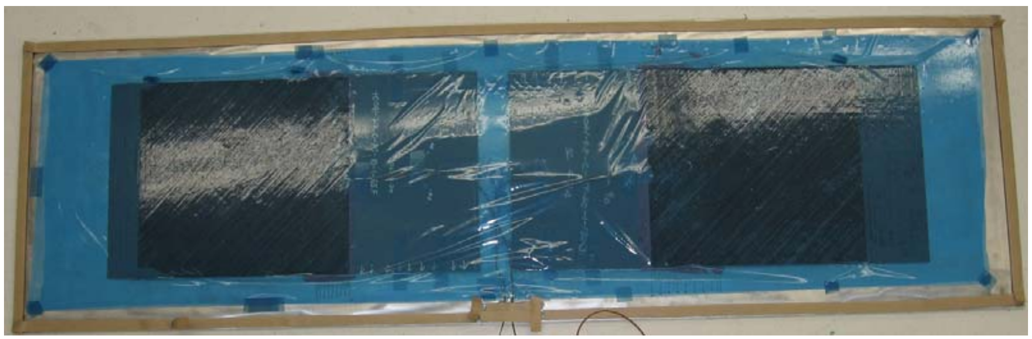


Adhesive Layer FM300-2

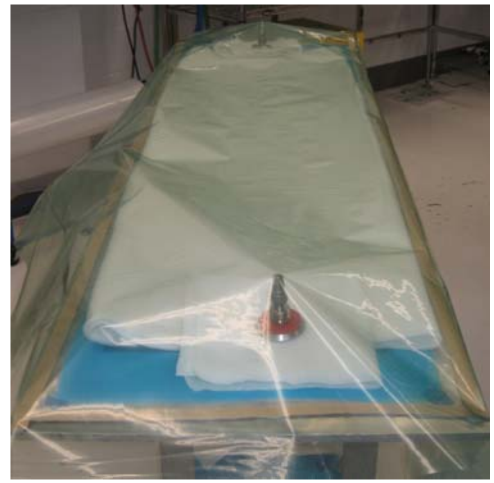
Repair Implementation

Field Repair Material Evaluation



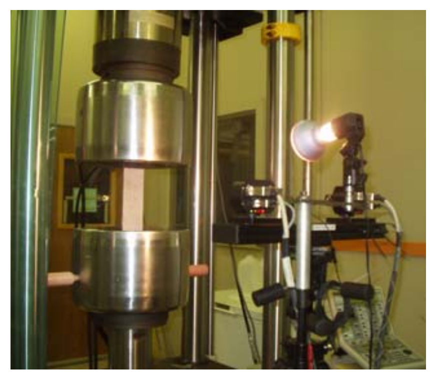


Repair Implementation



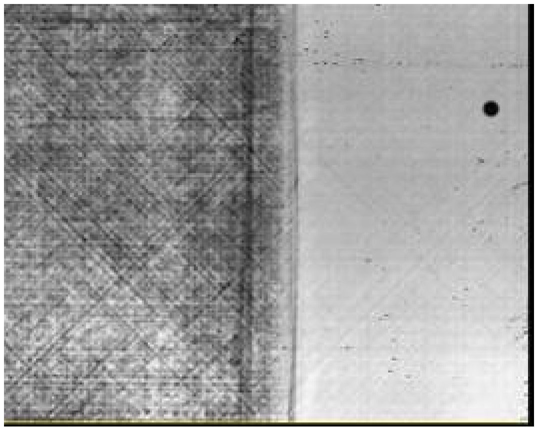
Repair Bagging

Tabbed Panel

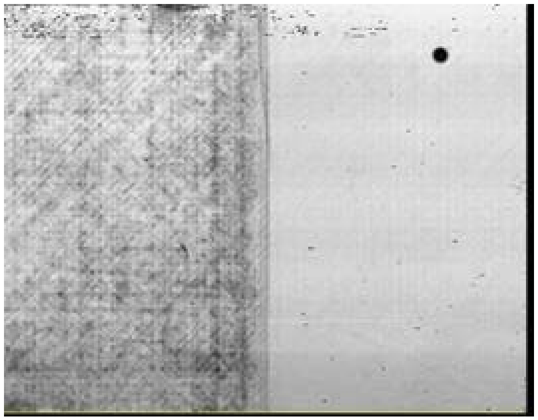


Mechanical Testing

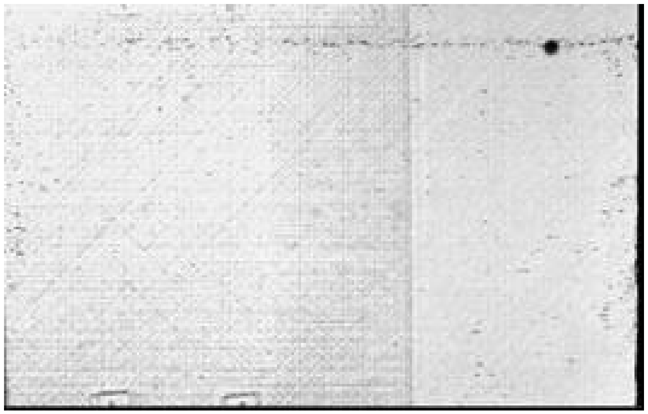
Methodology Field Repair Material Evaluation



ACG 2-1-10-RTA



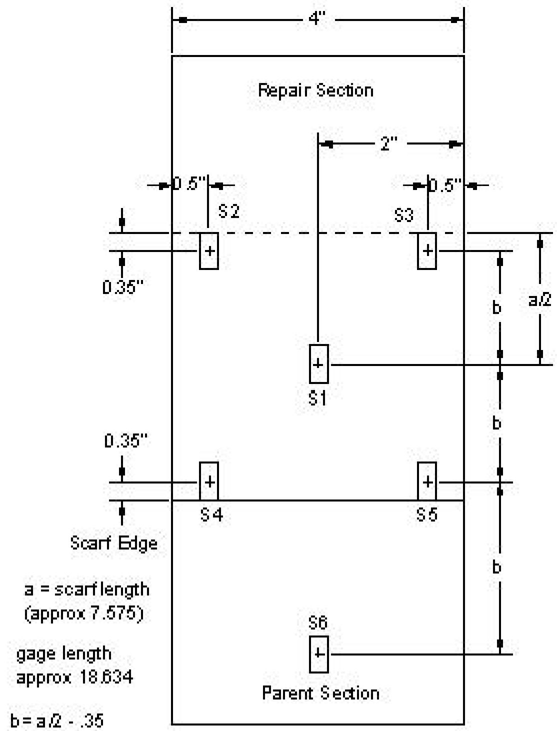
ACG 2-1-10-RTF



4-2-20-RTA

- Process yielded repairs with various levels of porosity as illustrated by the C-Scan images. Possible source of variability in the mechanical data

Results Field Repair Material Evaluation



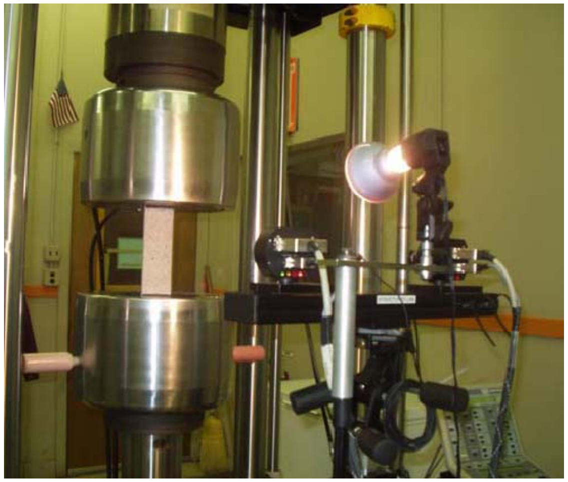
- ARAMIS

a non-contact optical 3-D deformation measuring system that uses two high resolution cameras to monitor strain concentrations in a test article

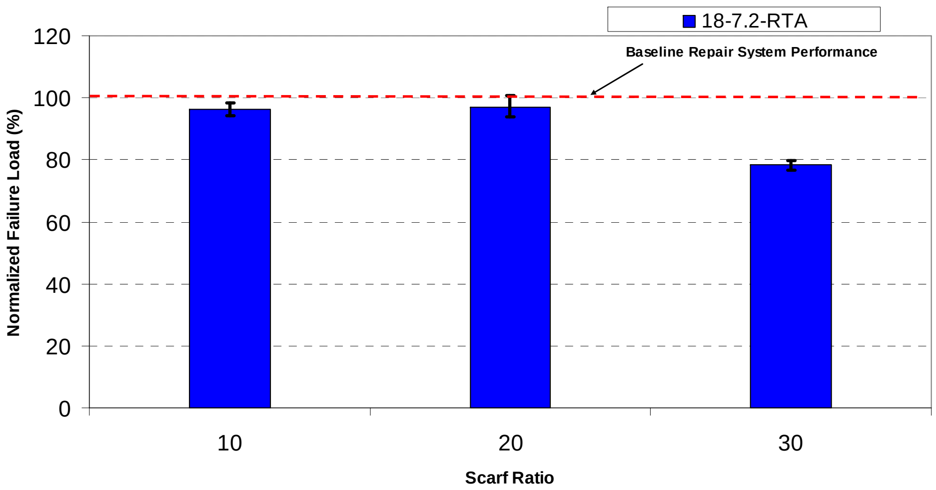
the test article is sprayed with a random pattern prior to loading

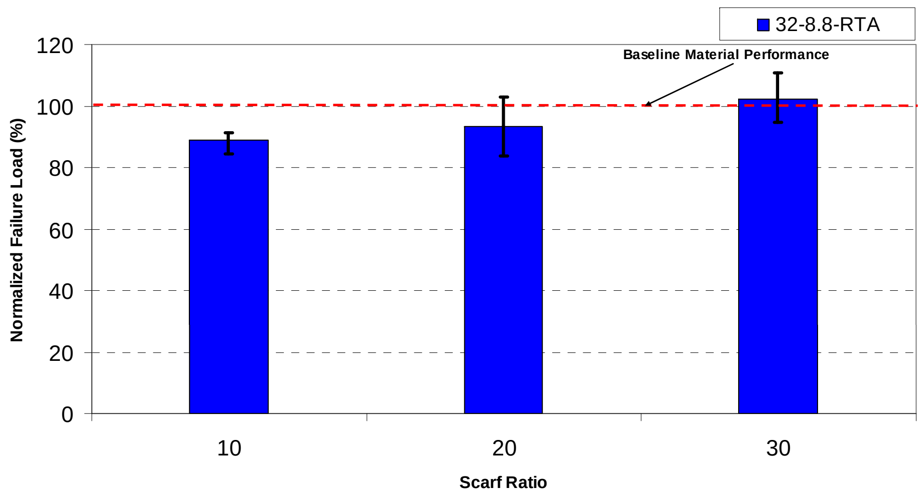
measurements are taken at different load levels,

changes in displacements and rotations between stages are recorded, from which strains can be calculated



Field Repair Material – Results





At least 80% baseline repair strength was restored at room temperature

At least 89% baseline repair strength was restored at room temperature

Baseline repair (350°F cure material, same material as the parent, processed under vacuum)

Methodology - Field Repair Material Evaluation- Summary

- Field repair material cured at 250°F under vacuum
- At least 89% of RTA baseline joint strength was restored for most cases
- A few low data points (porosity, process variability)
- A higher strength knockdown with respect to baseline repair material performance was observed for CTD and ETW specimens
- The thicker specimens 32 ply and 48 ply repairs survived 3DSO in fatigue for all RTD specimens
- For the 18 ply repairs, the -30 all survived 3DSO (165000) in fatigue at RTA

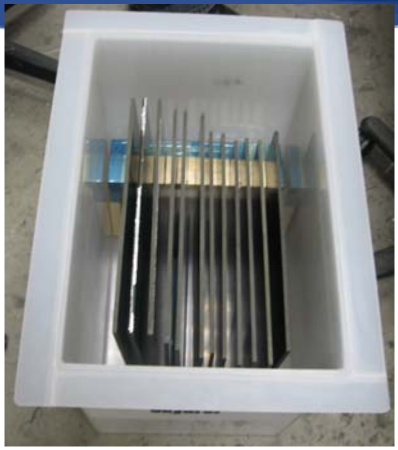
Contamination Study - Objectives

➢ To evaluate the strength of contaminated repairs applied to laminate configurations. Five different contaminants are considered: Hydraulic oil (skydrol), jet fuel (JP8), paint stripper, water and perspiration. The effects of each one of the contaminants is being evaluated according to the proposed test matrix. A total of 168 contaminated coupons are being used for this evaluation.

Modulus	scarf rate	Test Condition	**Contamination**													
			Skydrol		Jet Fuel		Paint Stripper		Water							
									75%		50%		25%		0%	
7.7	10	RTA	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	20	RTA	3	3	3	3	3	3	3	3	3	3	3	3	3	3
8.8	10	RTA	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	20	RTA	3	3	3	3	3	3	3	3	3	3	3	3	3	3

Contamination Study - Overview

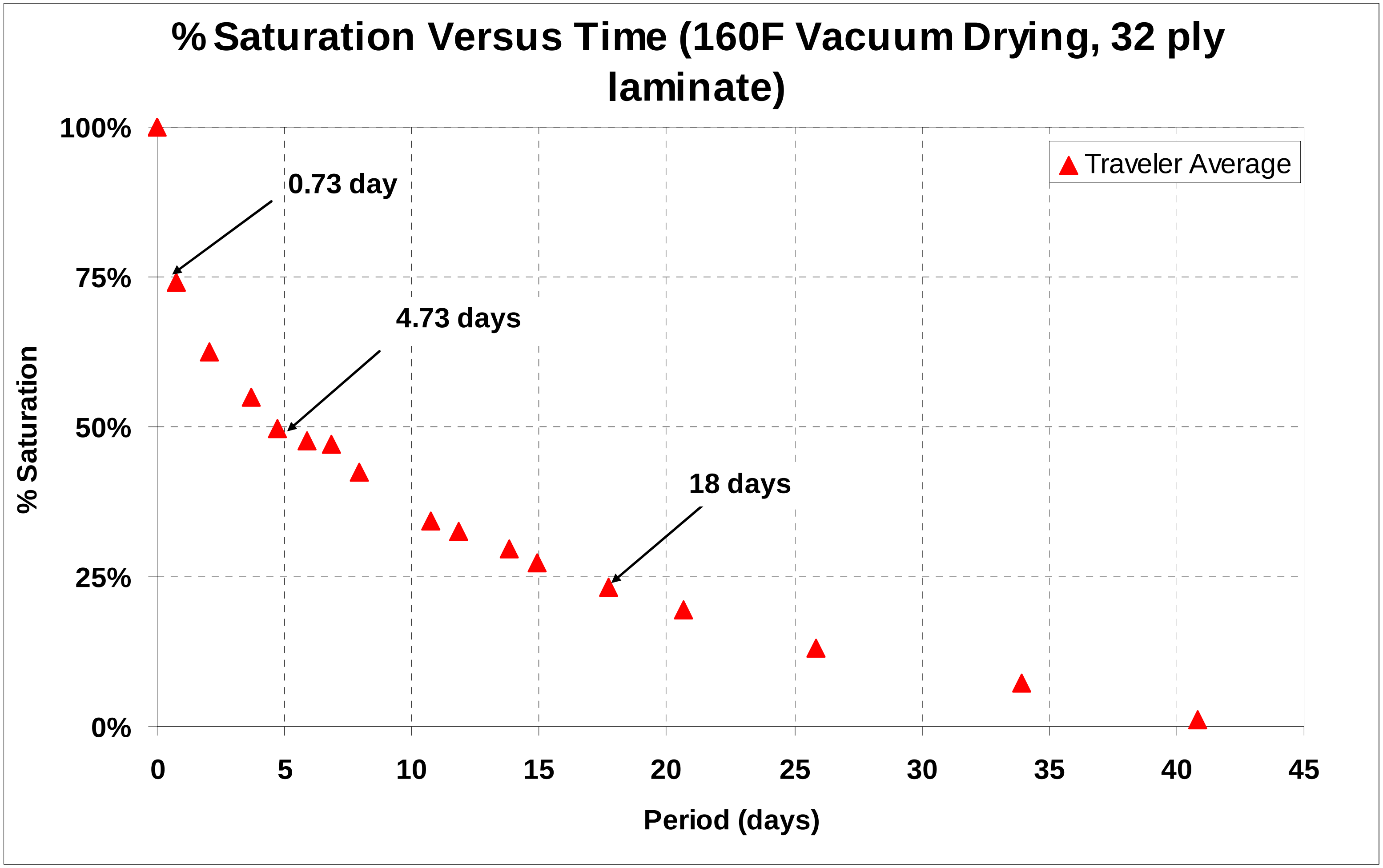
Exposure to Water and Skydrol



Contaminant	Minimum Soak Time
Jet Fuel, JP8	30 days
Paint Stripper	6 days
Skydrol	30 days
Water	30 days

After reaching moisture equilibrium, coupons were dried to achieve saturation levels of 0%,25%,50%, 75% and 100%

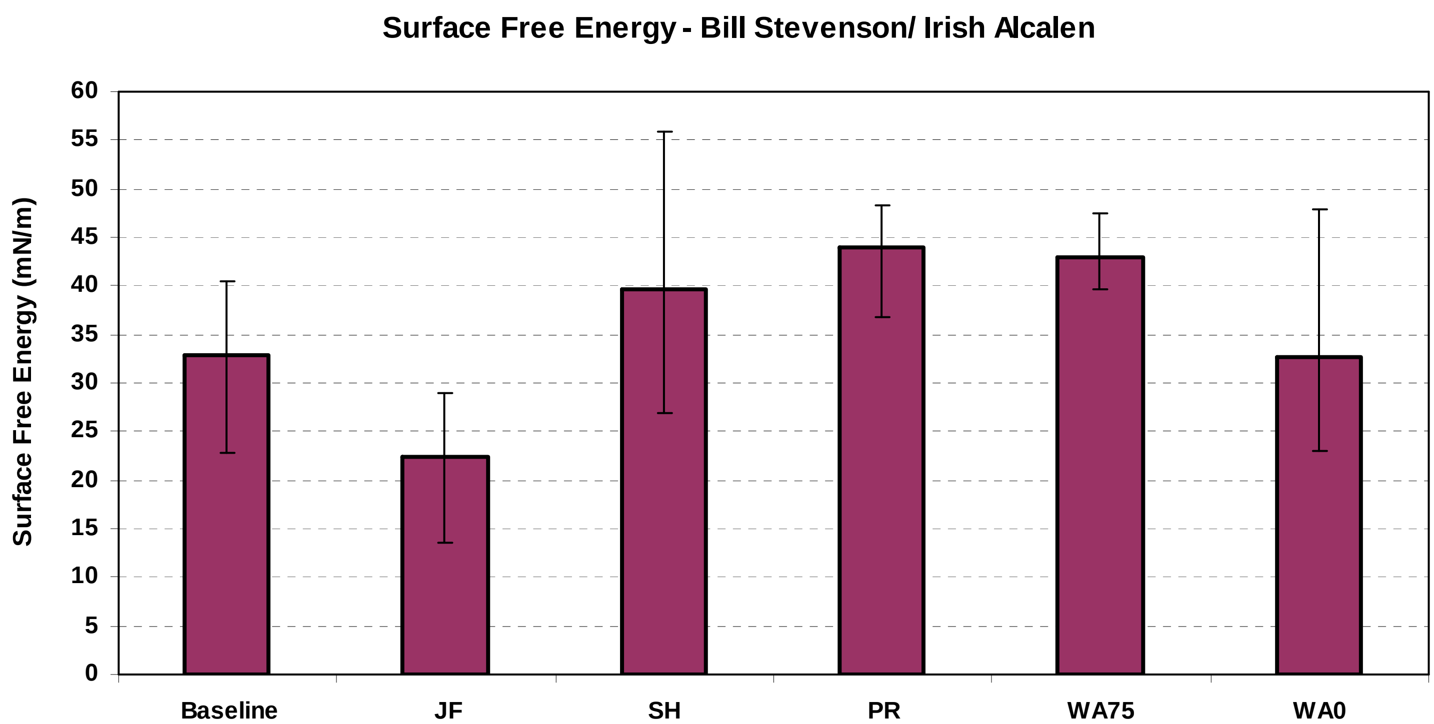
Contamination Study



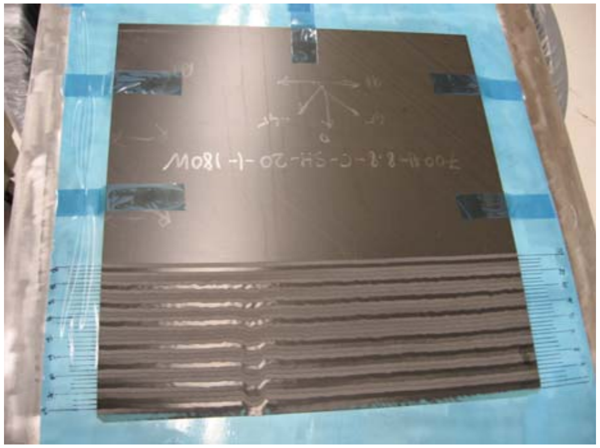
Contamination Study – Surface Analysis

Surface Analysis: Dr Stevenson/ Irish Alcalen

- High surface free energy = efficient wetting before cure
- High surface free energy DOES NOT NECESSARILY EQUAL a good bond
- A surface contaminated with polar compounds analyzed with water will yield a high SFE

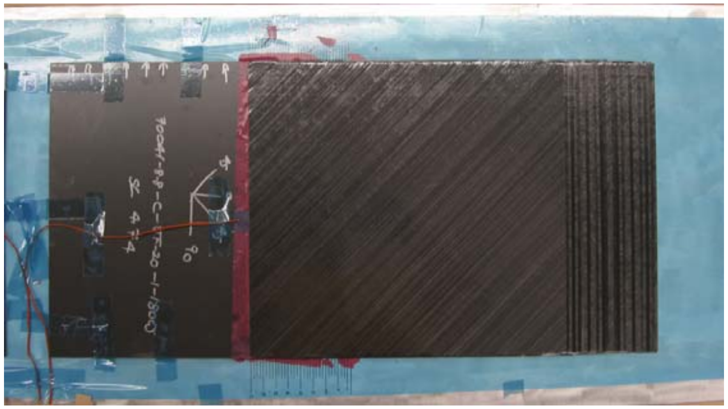


Repair after Contaminant Exposure



Individual Ply Location Marking

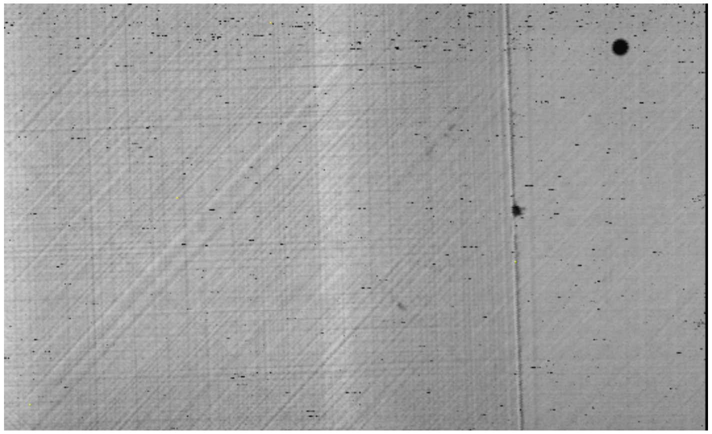
Adhesive Application



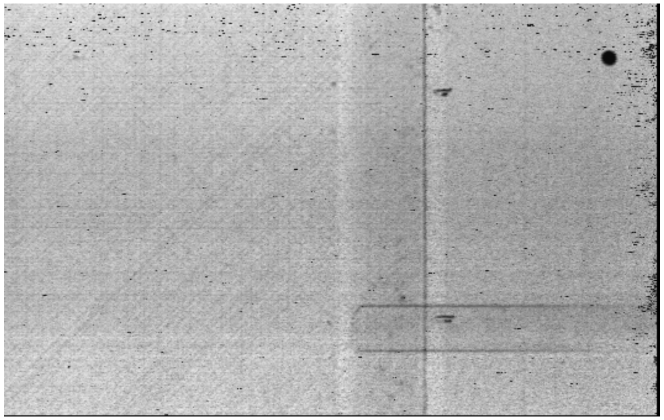
Repair Lay-up/ Thermocouple Installation

Repair Bagging

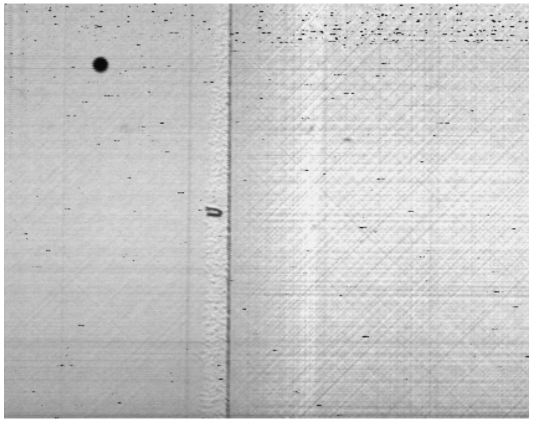
TTU Non-Destructive Inspection



Jet Fuel Contaminated Panel

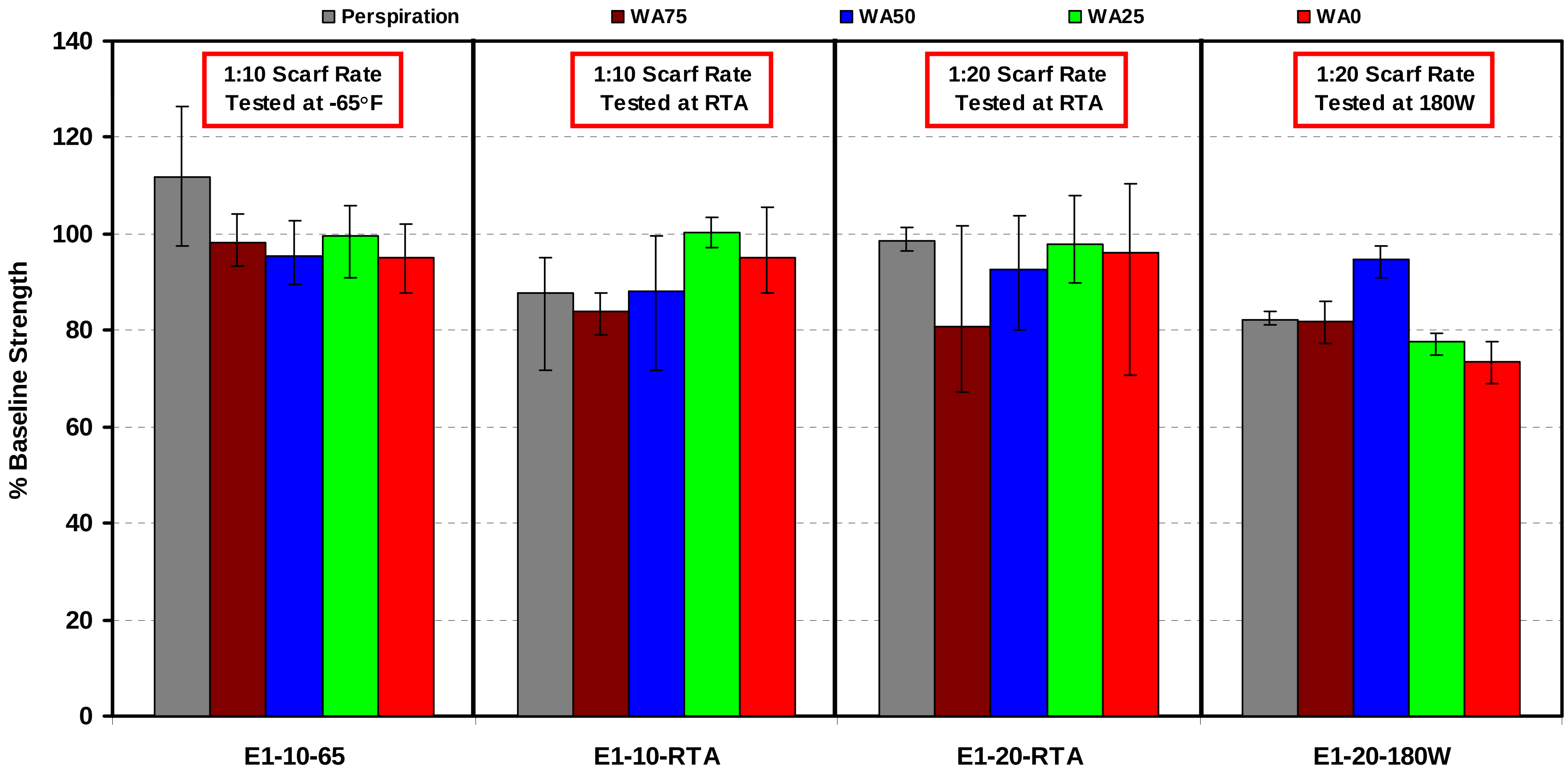


Skydrol Contaminated Panel

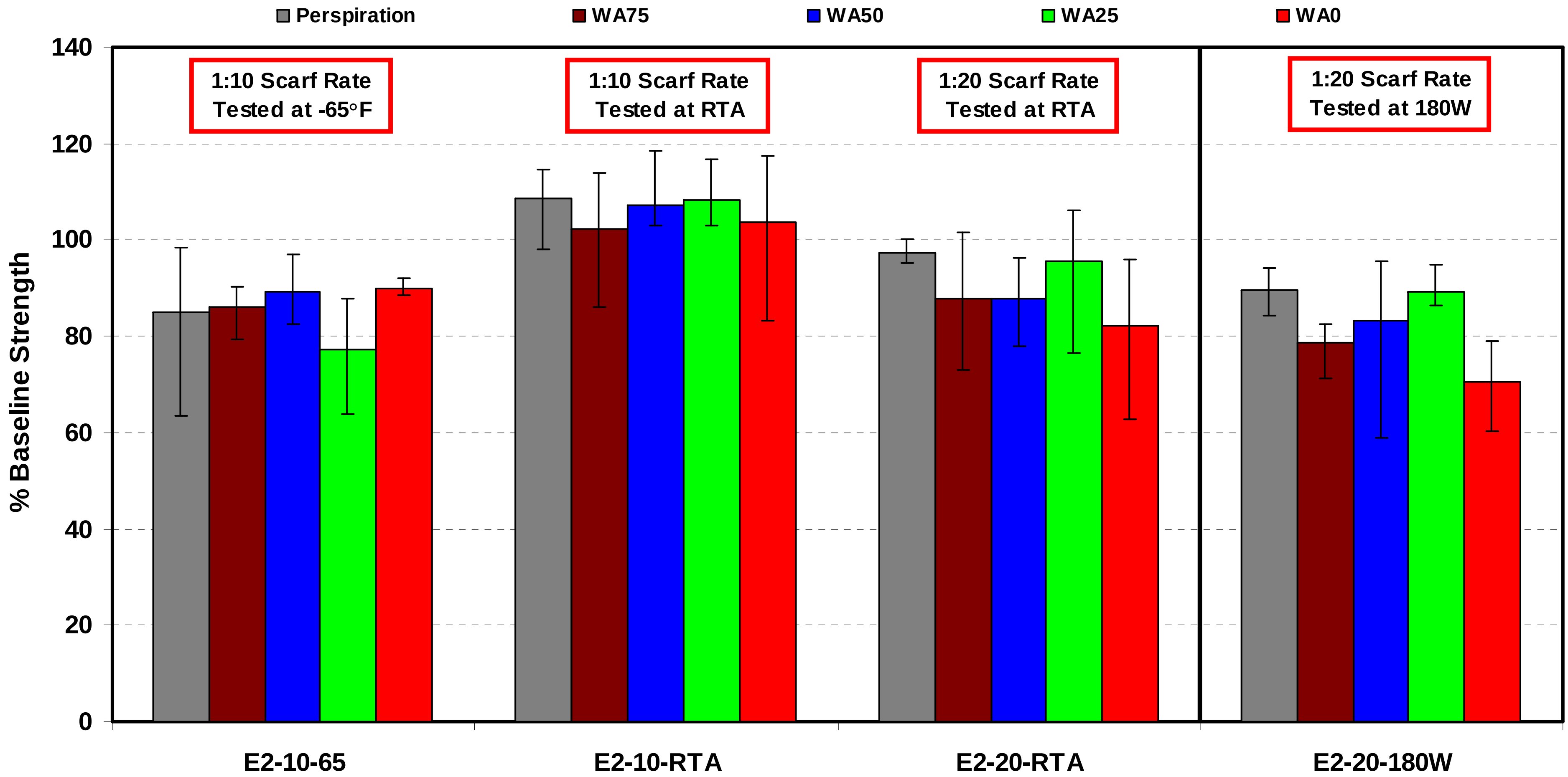


Water Contaminated Panel

Contamination Study- Results



Contamination Study- Results



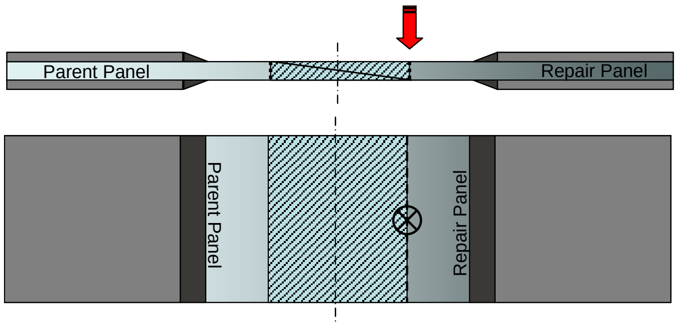
Contamination Study- Summary

- Static data showed a lower strength performance for panels contaminated with PR, WA75%, WA 50%, WA 25%, WA 0%
- RTA Static data showed minor strength degradation for panels contaminated with JF, SH and PS
- Environmental durability and effects of cyclic loading have to be considered. Later studies demonstrated lower fatigue life for contaminated JF and SH coupons.

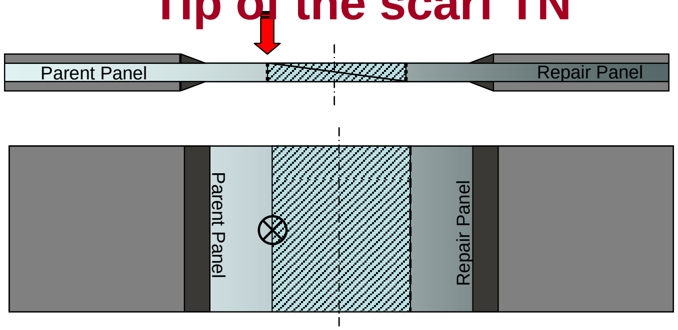
Impact Damage Study - Objectives

- To evaluate the strength, durability and damage tolerance of scarf repairs applied to laminate structures (To substantiate the effects of different impact sites on bonded repairs and their effect on residual strength)

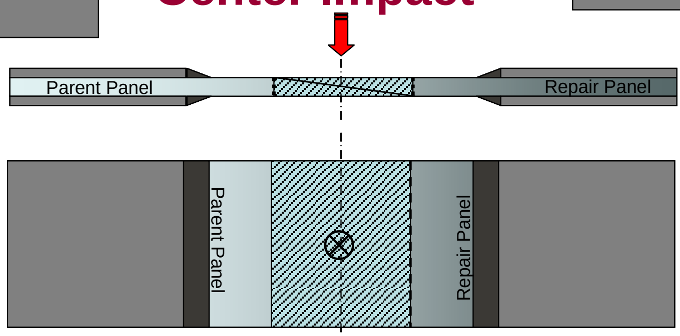
Tip of the scarf far side TF



Tip of the scarf TN



Center Impact



Reference CMH17-3G Chapter 12 Damage Resistance, Durability and Damage Tolerance: Damage tolerance provides a measure of the structure's ability to sustain design loads with a level of damage or defect and be able to perform its operating functions. Consequently, the concern with damage tolerance is ultimately with the damaged structure having adequate residual strength and stiffness to continue in service safely until the damage can be detected by scheduled maintenance inspection (or malfunction) and be repaired or until the life limit is reached. The extent of damage and detectability determines the required load level to be sustained. Thus, safety is the primary goal of damage tolerance.

Impact Damage Study – Summary

Plies	Modulus	scarf rate	Test Condition	Impact Site TN	Impact Site TF	Impact Site CN
18	7.2	10	RTA	3	3	3
			RTF	3	3	3
		20	RTA	3	3	3
			RTF	3	3	3
	9.1	10	RTA	3	3	3
			RTF	3	3	3
		20	RTA	3	3	3
			RTF	3	3	3
48	7.2	10	RTA	3	3	3
			RTF	3	3	3
		20	RTA	3	3	3
			RTF	3	3	3
	9.1	10	RTA	3	3	3
			RTF	3	3	3
		20	RTA	3	3	3
			RTF	3	3	3

Variables Investigated:

- Three impact sites on scarf joint (TN, TF or CN)
- Substrate thickness, Moduli, Scarf rate
- Same normalized energy level for all con figurations
- Tension Loading mode (ultimate strength, residual strength after fatigue
- Parent material used as repair (processed under vacuum)

18 ply configurations (1.2" impactor)

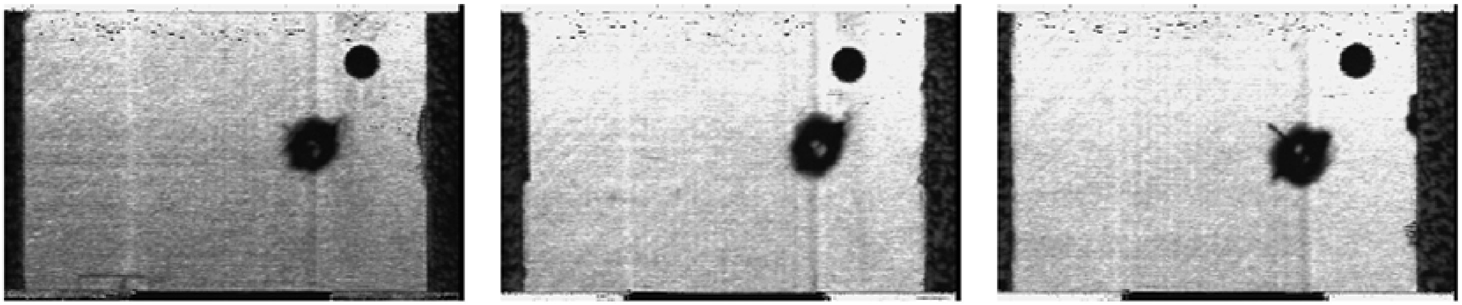
Impact Energy Level 200 in-lbs, Depth: 0.01"

48 ply configurations (1.2" impactor)

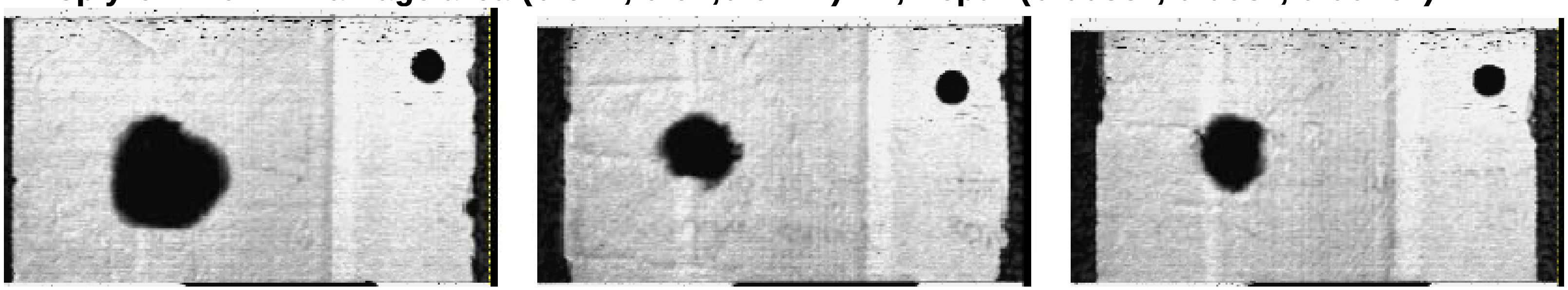
Impact Energy Level 400 in-lbs, Depth: 0.01"

Impact Damage Study – NDI Results

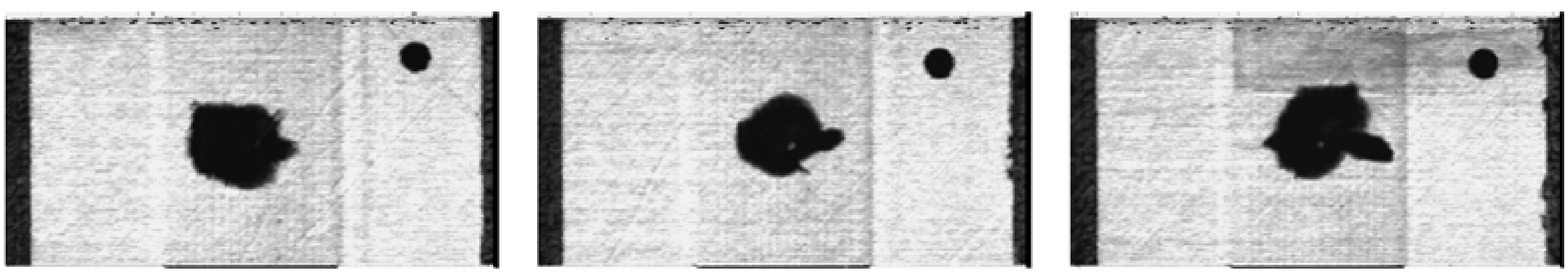
Same impact energy level yielding different damage sizes depending on impact site (TN, TF or CN)



18ply-9.1-20-TN Damage area (0.642, 0.61,0.6444) in^2, Depth (0.0085", 0.008", 0.0075")



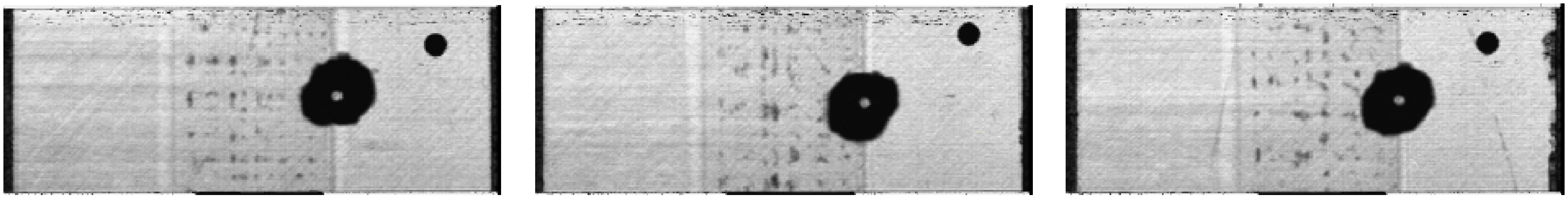
18ply-9.1-20-TF Damage area (2.28, 0.96, 0.95) in^2, Depth (0.0095", 0.0095", 0.008")



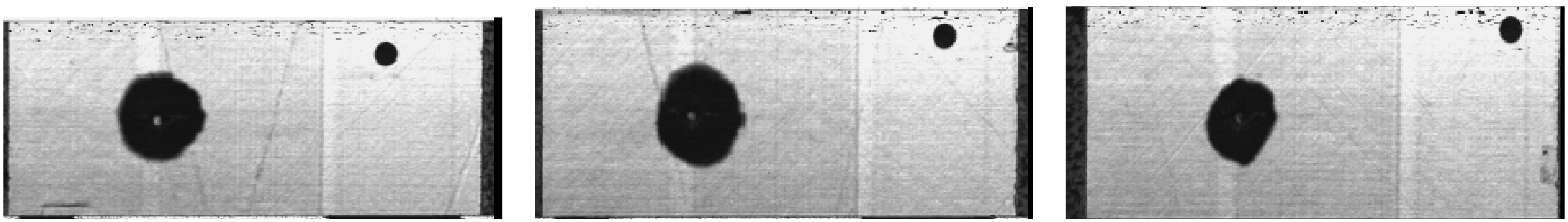
18ply-9.1-20-CN Damage area (1.8852, 1.5352, 2.1032) in^2, Depth (0.009", 0.007", 0.0075")

Impact Damage Study – NDI Results

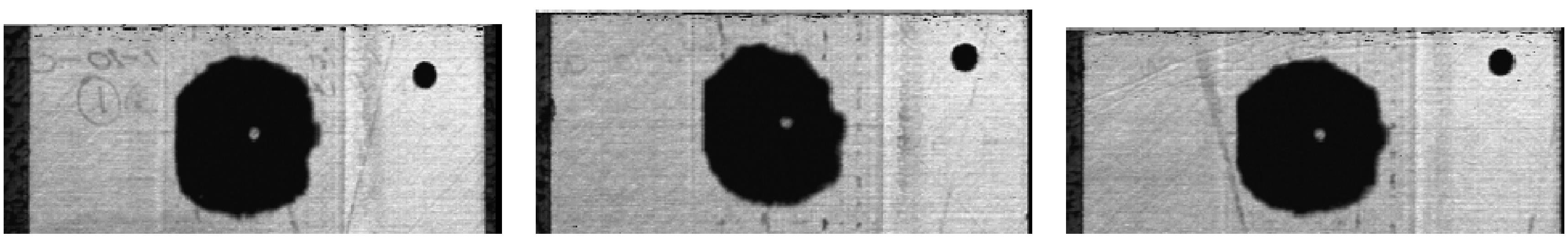
Same impact energy level yielding different damage sizes depending on impact site (TN, TF or CN)



48ply-9.1-10-TN Damage area (1.905, 1.878,1.869) in^2, Depth (0.0085”, 0.011”, 0.0085”)

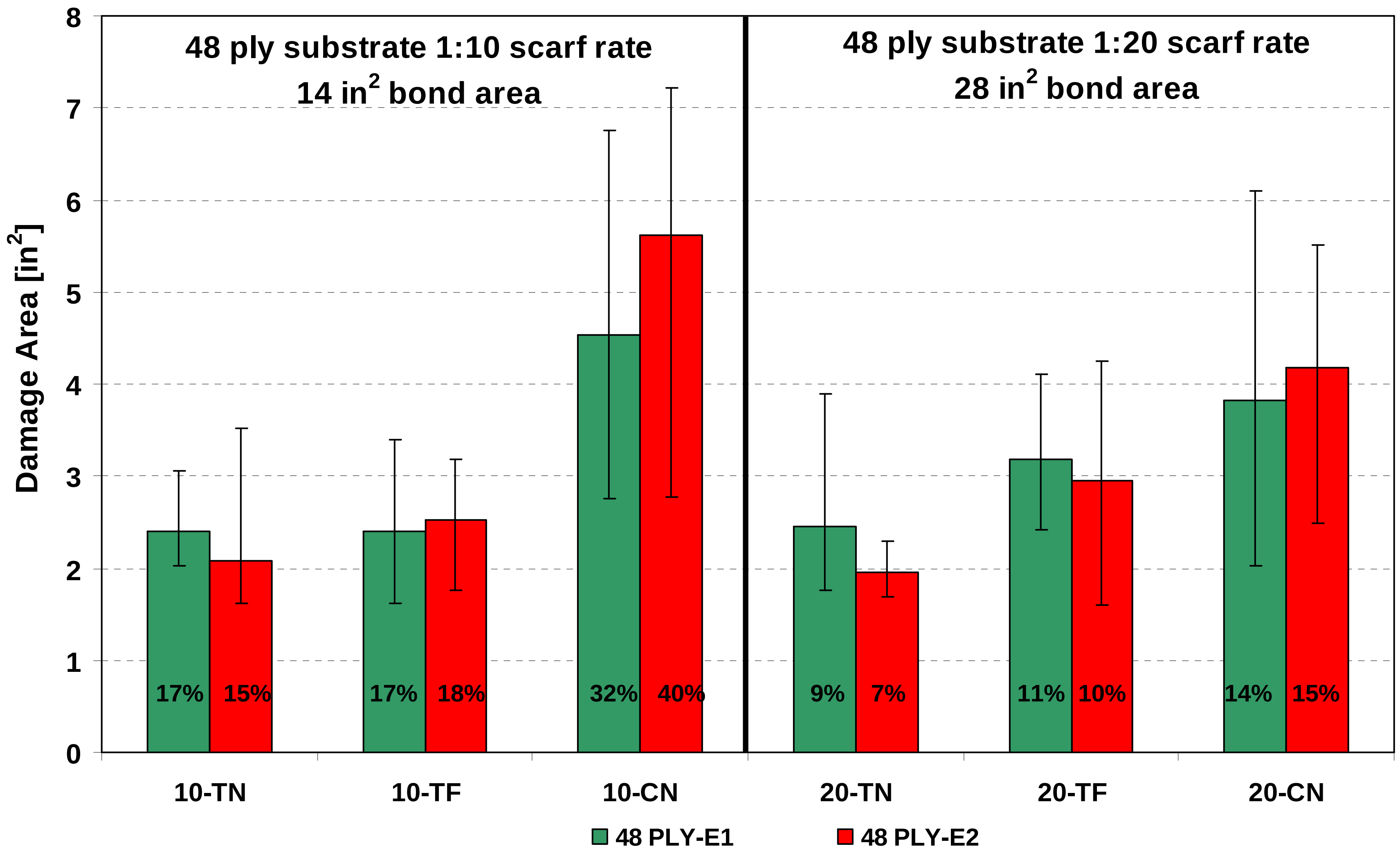


48ply-9.1-10-TF Damage area (2.5648, 2.9164,1.7528) in^2, Depth (0.011”, 0.009”, 0.013”)

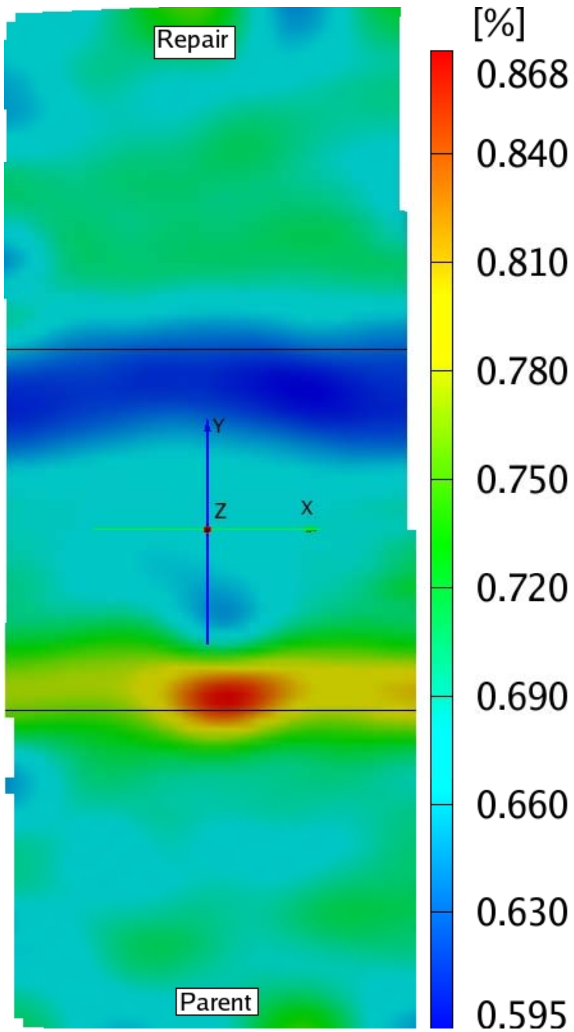


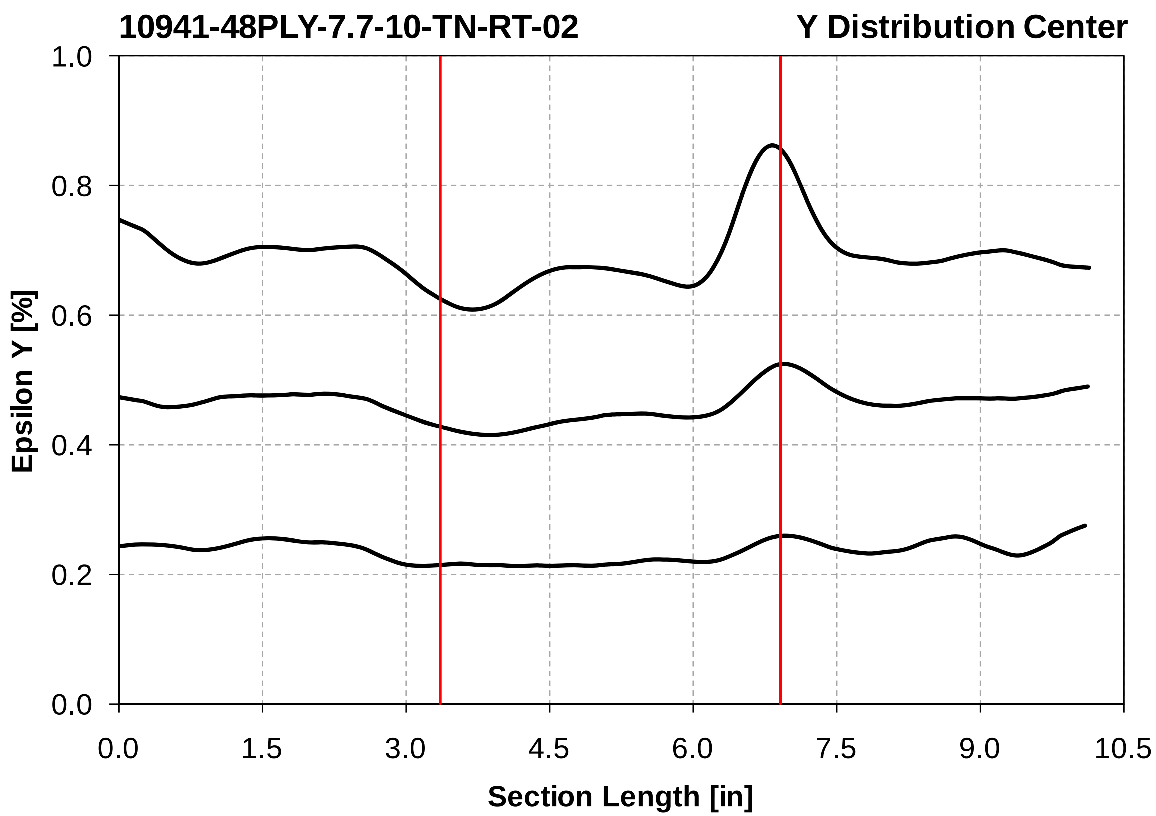
48ply-9.1-10-CN Damage area (7.218, 6.30,6.9596) in^2, Depth (0.008”, 0.008”, 0.008”)

Impact Damage Study - Results

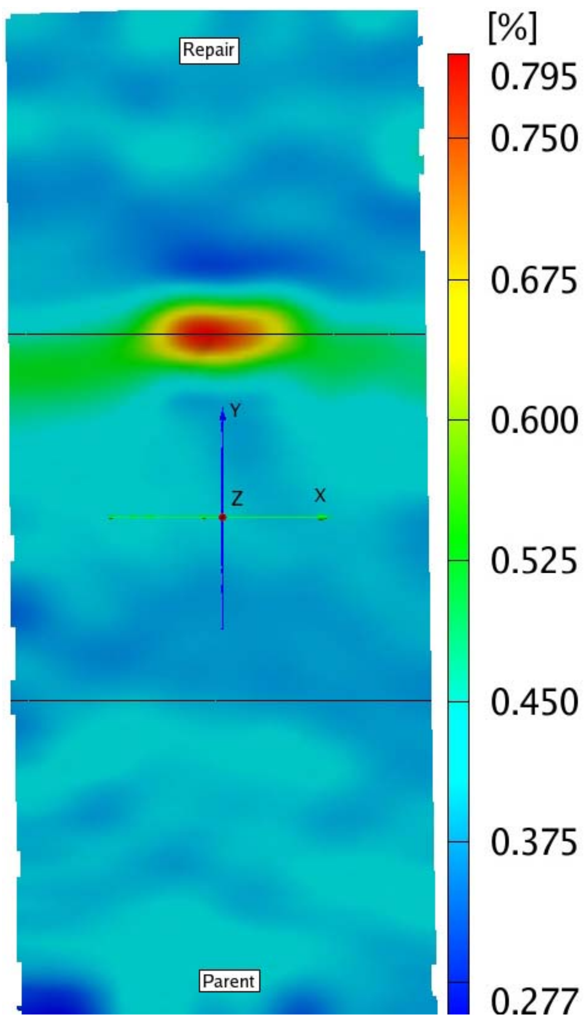


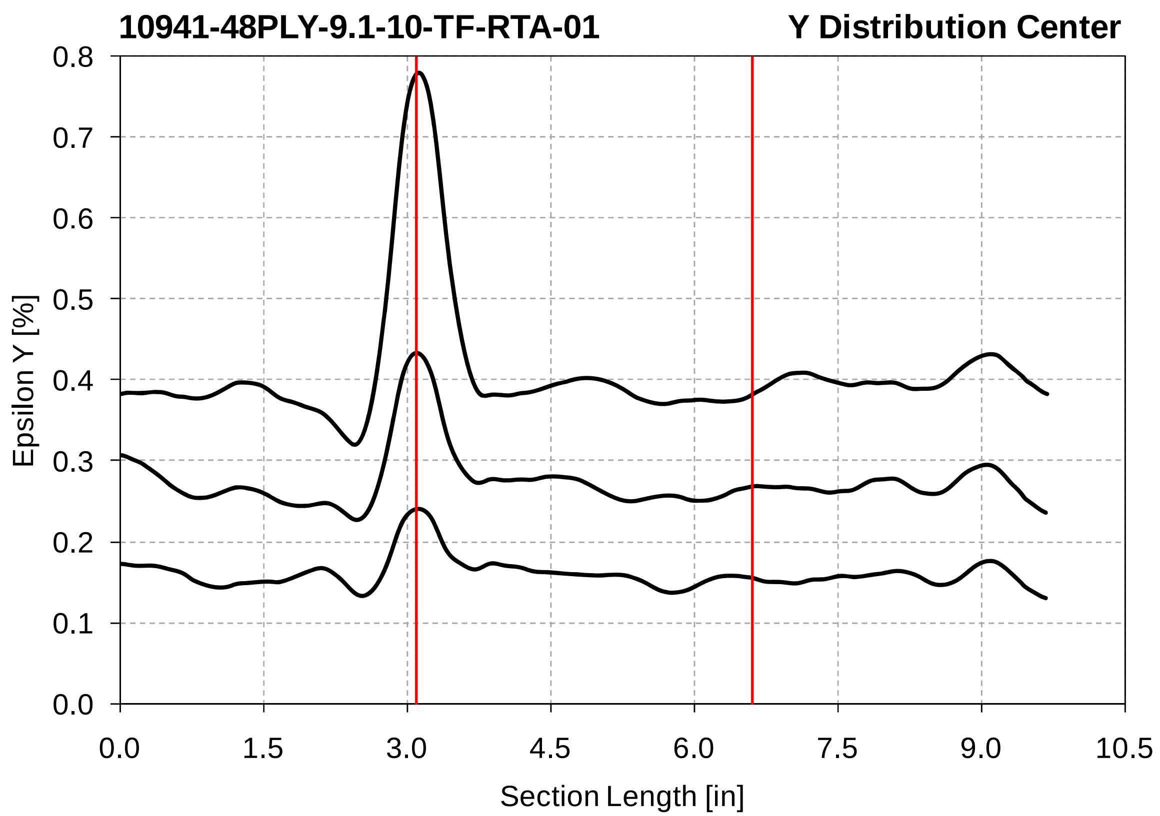
Impact Damage Study - Results



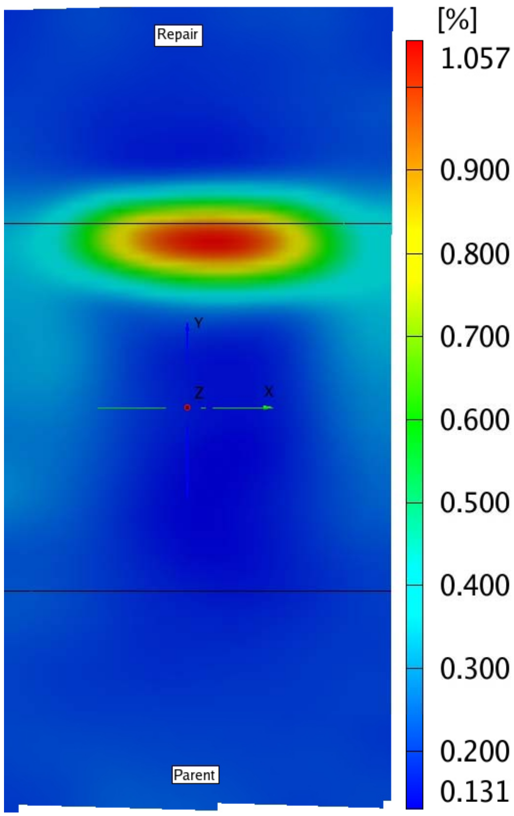


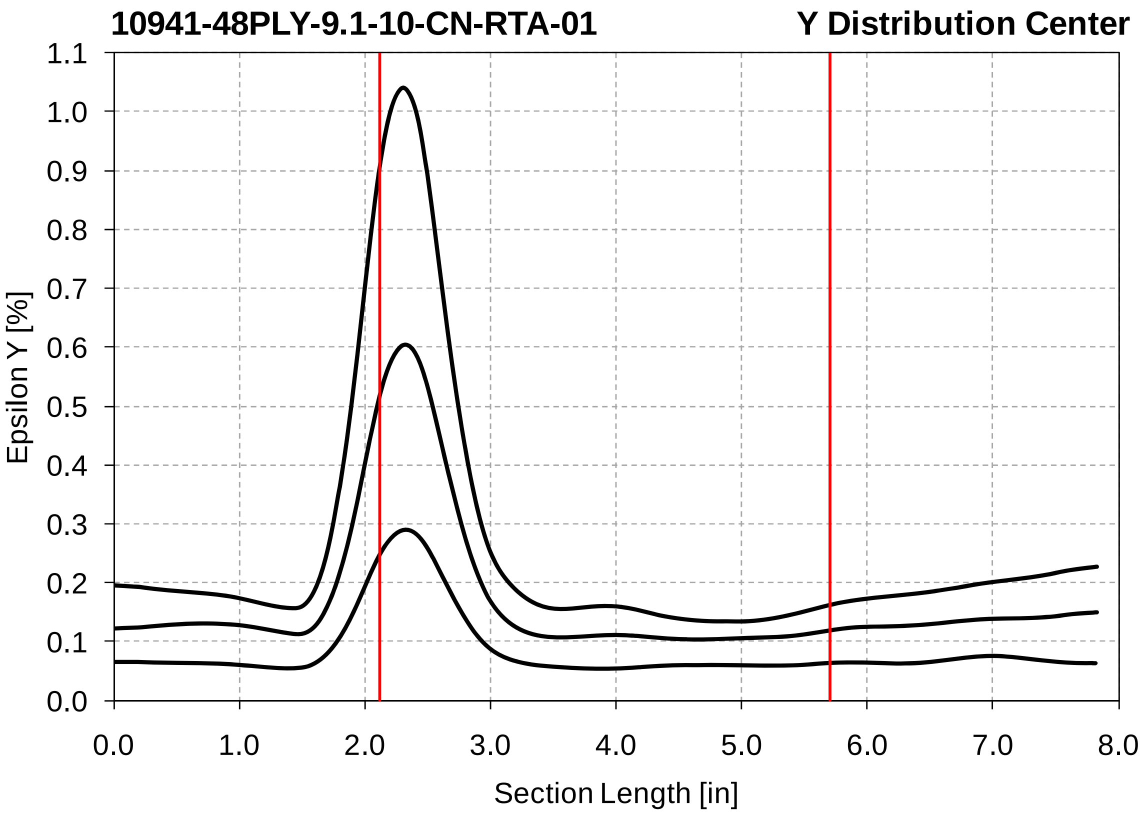
Impact Damage Study - Results



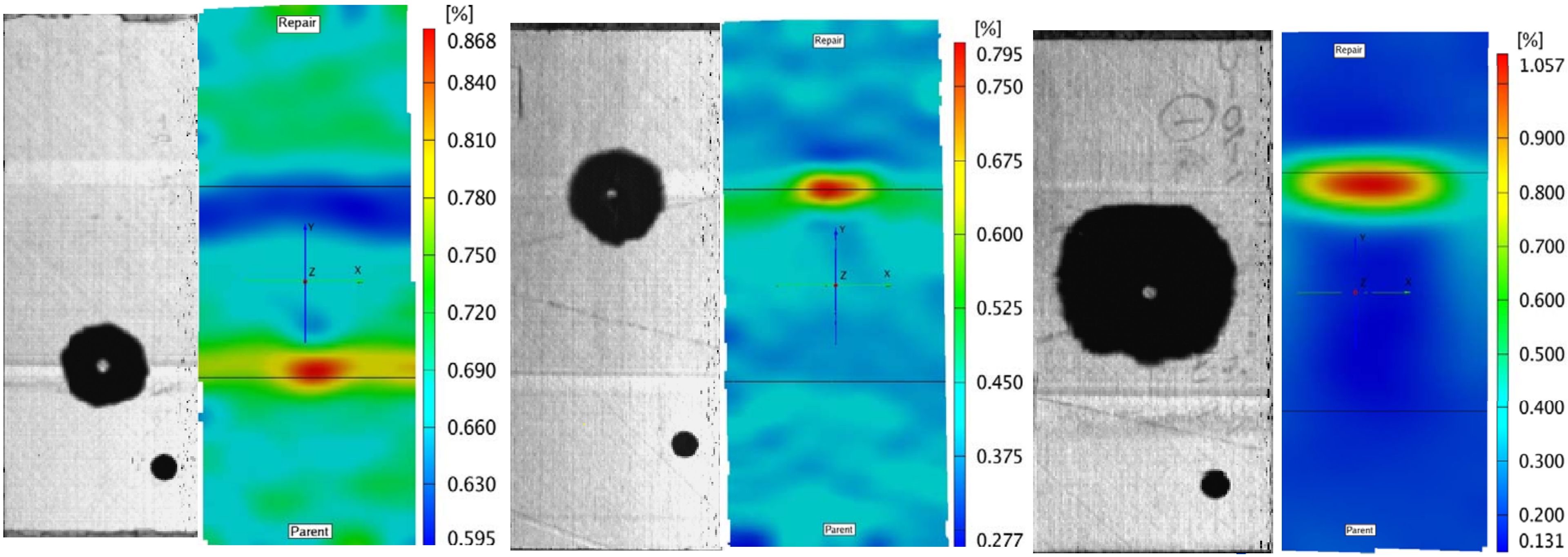


Impact Damage Study - Results



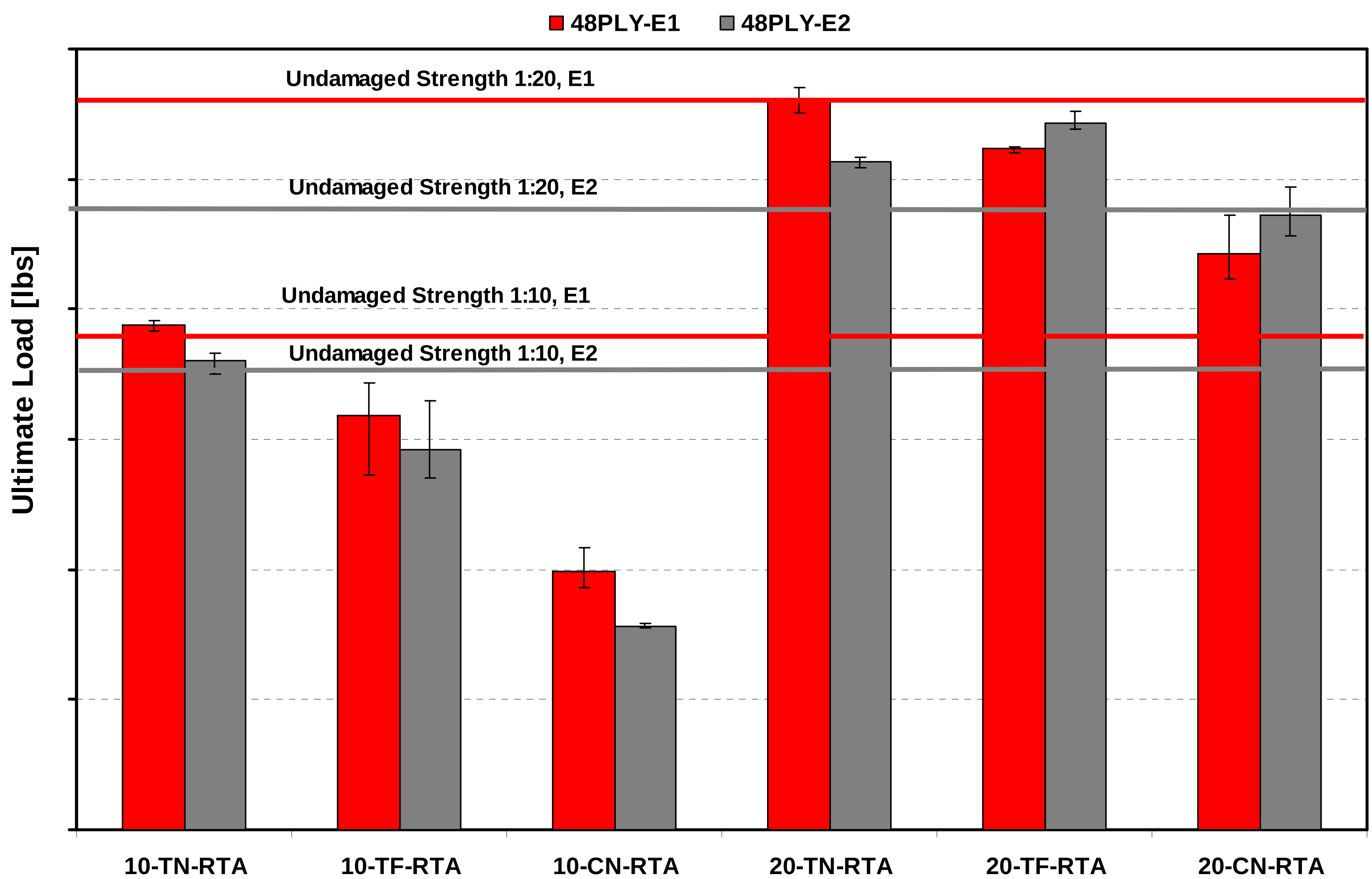


Impact Damage Study - Results



TN - Damage Area 2.054 in^2, depth 0.0095 in **TF - Damage Area 2.5648 in^2, depth 0.011 in** **CN - Damage Area 7.2184 in^2, depth 0.011 in**

Impact Damage Study - Results



Impact Damage Study – Durability Results

Panel Configuration	Specimen ID	Fatigue Cycles	Fatigue Strain (microstrain)
48PLY-E1-10-TN-RTF	1	36873	3000
	2	165000	2000
	3	165000	2500
48PLY-E1-10-TF-RTF	1	3540	3000
	2	165000	2000
	3	9754	2500
48PLY-E1-10-CN-RTF	1	249	2000
	2	36875	1000
	3	7005	1500
48PLY-E1-20-TN-RTF	1	165000	3000
	2	165000	3000
	3	165000	3000
48PLY-E1-20-TF-RTF	1	165000	3000
	2	165000	3000
	3	165000	3000
48PLY-E1-20-CN-RTF	1	122540	3000
	2	165000	3000
	3	165000	3000
48PLY-E2-10-TN-RTF	1	519	3000
	2	24519	2000
	3	165000	1500
48PLY-E2-10-TF-RTF	1	4	3000
	2	5538	2000
	3	165000	1500
48PLY-E2-10-CN-RTF	1	165000	1500
	2	2829	1750
	3	17514	1500
48PLY-E2-20-TN-RTF	1	143402	3000
	2	165000	3000
	3	106129	3000
48PLY-E2-20-TF-RTF	1	78087	3000
	2	106538	3000
	3	165000	3000
48PLY-E2-20-CN-RTF	1	64713	3000
	2	111840	3000
	3	50450	3000

- Target fatigue life 165000 cycles
- Durability and damage tolerance should be evaluated at the most aggressive environments the structure will be subjected to

Methodology Damage Effects Summary

- Strength degradation is a function of damage area
- The same impact energy level applied to various locations in the scarf joint yielded different damage areas
- Coupons impacted at the center of the scarf repair, yielded the largest damage area and the lowest static strength
- The residual strength is also dependent on the "residual" bond area. The largest repairs were observed to be more "damage tolerant" than the smaller repairs
- Conclusions are based on specimens tested at room temperature.

A look Forward/Benefits to Aviation

- To generate repair data for OEM/ factory materials that can be used to demonstrate acceptability of alternate materials to use for repair when the parent material is not available or cannot be used for repair

- To generate data that correlates contamination and process parameter deviation to the performance of bonded repairs

- To provide information on repair damage tolerance depending on damage location

- To identify the crucial steps in bonded repair that can be used to develop rigorous repeatable repair processes

- To gain confidence in bonded structural repairs