Effects of Repair Procedures Applied to Composite Airframe Structures

National Institute for Aviation Research

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Research Team

- Principal Investigators & Researchers
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- FAA Technical Monitor
  - Peter Shyprykevich
- Other FAA Personnel Involved
  - Curtis Davies, Larry Ilcewicz
- Industry Participation
  - Spirit Aerosystems
  - Raytheon Aircraft
  - Adam Aircraft

Objective/ Overview

- To assess the effects of different variables on the strength and durability of repairs applied to composite laminate and sandwich structures
  - Substrate stiffness
  - Lap length
  - Thickness
  - Repair materials
  - Cure Temperatures
  - Static/ Fatigue Performance
- To evaluate the strength and durability of poorly bonded repairs that passed NDI
  - Poor Surface Preparation
  - Pre-bond Moisture
  - Improper Cure
  - Contamination
- To validate existing CACRC standards and provide recommendations pertaining to proper repair process implementation
- To develop an analysis method and corresponding failure criteria for structural sizing of bonded repairs

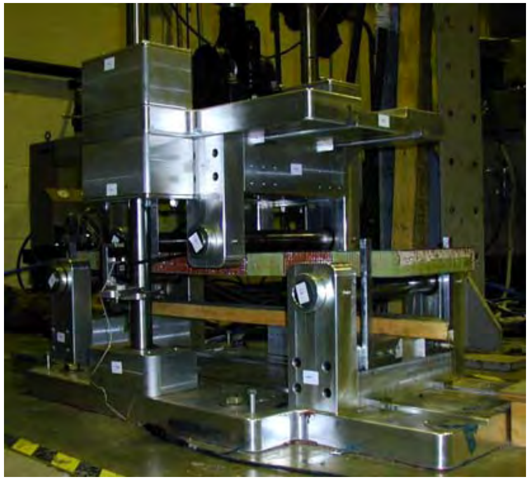
Research Methodology

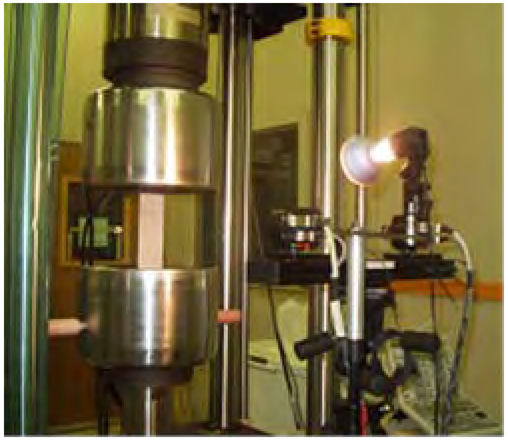
- Task1: to generate baseline static and fatigue repair data for both composite laminate and sandwich coupons using OEM repairs as well as field repairs. Laminate repaired coupons are tested in tension whereas sandwich repaired coupons are tested in compression

- Task 2: to evaluate the durability of “poor” bonded repairs that passed NDI (undetected weak repairs). Deviations in process parameters/ contamination will be induced during coupon repair and subsequent mechanical testing will be conducted to assess the static and residual strength after repeated loading.

- Task 3: task 2 results will be used to validate CACRC standards required for composite repair and inspection technicians and providing recommendations pertaining to repair process control to ensure repair bond structural integrity

- Task4: to validate experimental results using FEM





Relevance to FAA CS & CI

Current CS&CI Technical Thrust Areas Pursued by FAA and NASA

FAA

NASA

Advancements depend on close integration between areas

Material Standardization and Shared Databases

Damage Tolerance and Maintenance Practices

- Critical defects (impact & mfg.)
- Bonded structure & repair issues
- Fatigue & damage considerations
- Life assessment (tests & analyses)
- Quantitative NDE/Service POD
- Equivalent levels of safety

Structural Substantiation

- Advances in analysis & test building blocks
- Environmental effects
- Manufacturing integration

FAA and NASA R&D is currently active in most of these areas

Flammability & Crashworthiness

Support from cabin safety research groups

Bonded Joint Processing Issues

Advanced Material Forms and Processes

Significant progress, which has relevance to all aircraft products, has been gained to date

Relevance to FAA CS & CI In a number of Ways

Structural Substantiation:

- **Advances in Analysis & Test Building Blocks:**
  - Developing an analysis method and corresponding failure criteria
  - Building Block Substantiation Approach is the Ultimate Goal "big picture" of the Program
- **Environmental Effects**
  - Environmental Effects On Bonded Joint Strength Performance Included In Current Program Scope

Bonded Joint Processing Issues:

- Process and Repeatability issues as a result of producing 120 bonded repairs for 4 different material systems (480 bonds)
- Effects of process parameters (Poor surface preparation, pre-bond moisture, cure cycle deviations, contamination) included in the current program
- CACRC repair standard validation
- Tied With Other FAA Project: "Acceptability Of Surface Preparation For Subsequent Bond"

Damage Tolerance and Maintenance Practices:

- **Fatigue and Damage Considerations:**
  - Fatigue Effects On Bond Structural Performance Included In Plan
  - BVID Tolerance Of Scarf Joints Proposed As Extension Of Current Plan.

Laminate Baseline Repair Data

- Panels manufactured and supplied by the OEM

OEM Repair

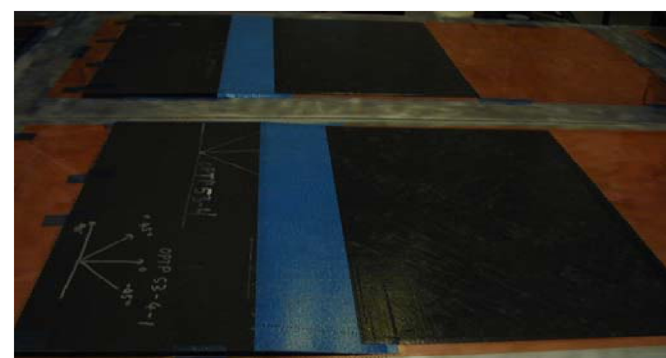
- Panels are machined into subpanels, scarfed and repaired using an OEM proprietary debulking procedure
- Repairs implemented using the laminate parent material as the repair material

Field Repair

ACG T800/MTM45 unidirectional prepreg with FM300-2U film adhesive

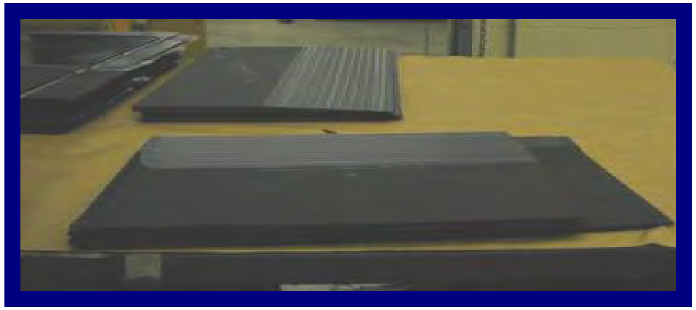
Hexcel M20 prepreg with Metalbond 1515-4 adhesive

AMS 2980 CACRC using G40-800 6k intermediate modulus fibers with Epocast 52A/B Laminating resin

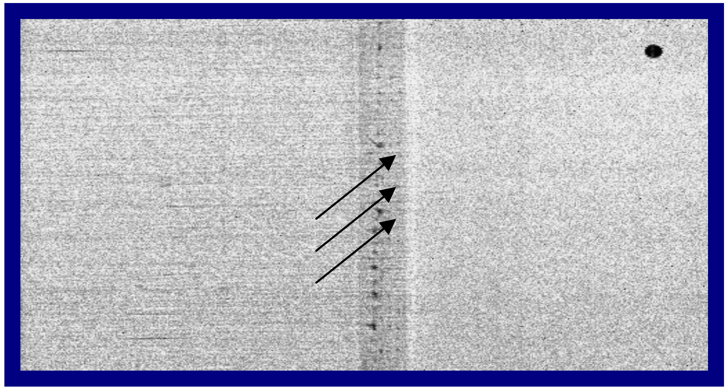


Baseline Repair Data

- 1-D Coupon used to isolate parameters/ effects studied

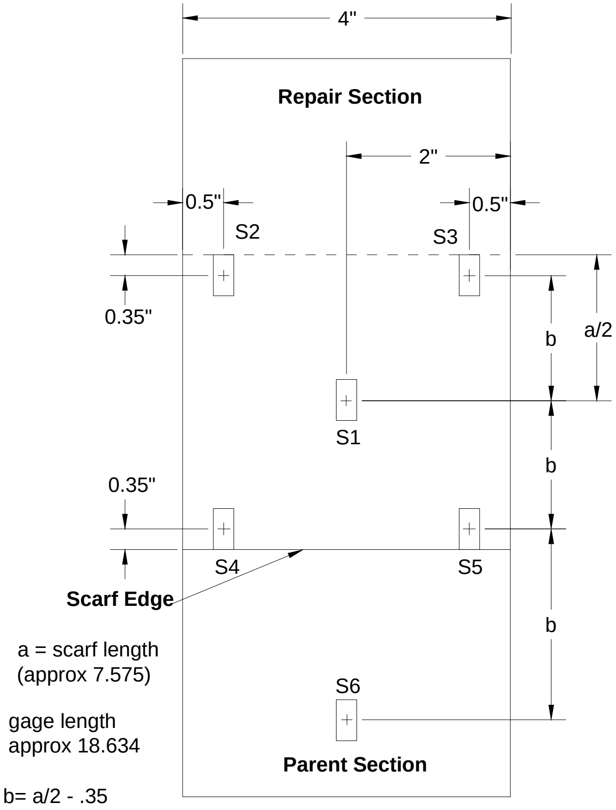


Panel Machining and Scarfing



Repair Panel NDI

Strain Gage Layout (-30 Scarf Rate Panel 5 & 6)

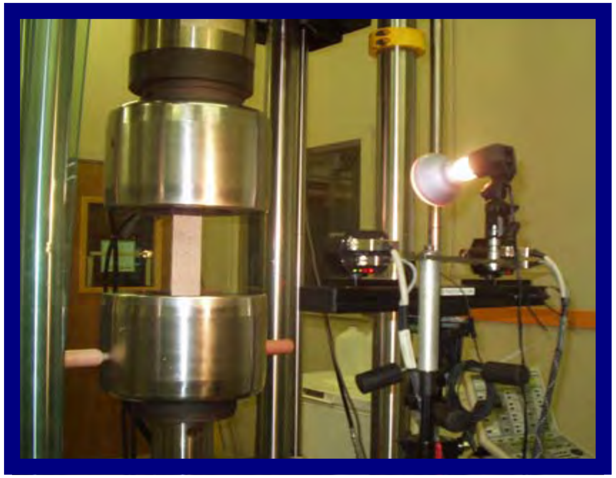


Strain Gage Layout

Test Matrix-Laminate

Test Matrix

- 288 coupons are being used to generate baseline static and fatigue data for OEM/field repairs
- photogrammetry system is being used to monitor specimen deformation/ strain concentrations in the repair
- ARAMIS strain data validated using strain gages
- Fatigue coupons are cycled for 165000 cycles and tested for residual strength to demonstrate repair acceptability.



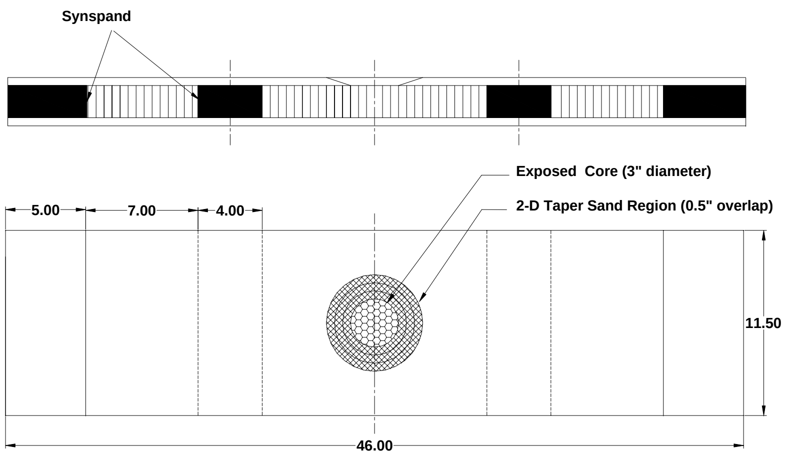
Mechanical Testing Strain Monitoring using ARAMIS

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

Test Matrix- Sandwich

Test Set-Up/ Test Matrix

- 45 coupons will be used to generate baseline static and fatigue data for OEM/ field repairs
- A four point bending beam fixture will be used for loading
- Fatigue coupons will be cycled for one lifetime equivalent to 150000 cycles and tested for residual strength to demonstrate repair acceptability.

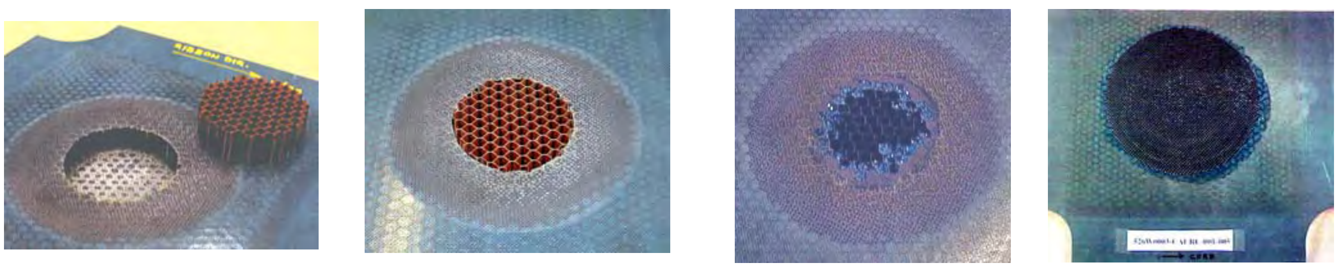


Repair Configuration	Core Cell Size	Repair Material	Repair Type	Scarf Overlap (in)	Static (RTA)	Fatigue (RTA)
2-D Compression	3/16	Toray T700/2510 PW Prepreg	Baseline undamaged	N/A*	3	6
			Flush Scarf Repair	0.50	3	6
			External Patch	0.50	3	6
	3/16	CACRC Wet lay-up Repair	Flush Scarf Repair	0.50	3	6
			External Patch	0.50	3	6

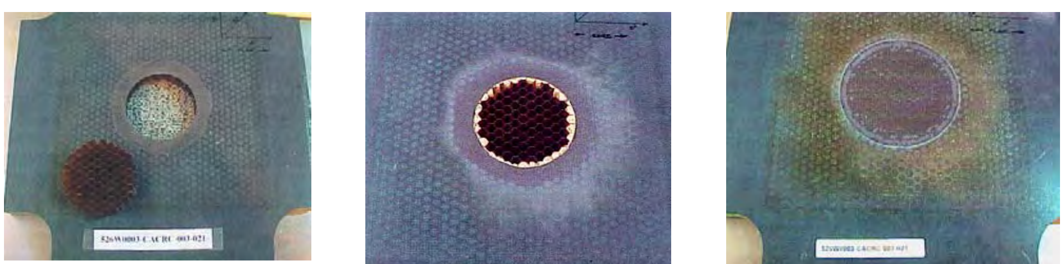
*Baseline undamaged unrepaired coupon

Effects of Process Parameters

- The quality of training and experience of repair technicians is directly associated with the technician's successful implementation of a repair
  Ref. John Tomblin et. al "Bonded Repairs of aircraft composite sandwich structures." FAA AR 03-74
- Process deviation directly affects the strength of the repair
- To investigate the performance of OEM/ field repairs using different methods

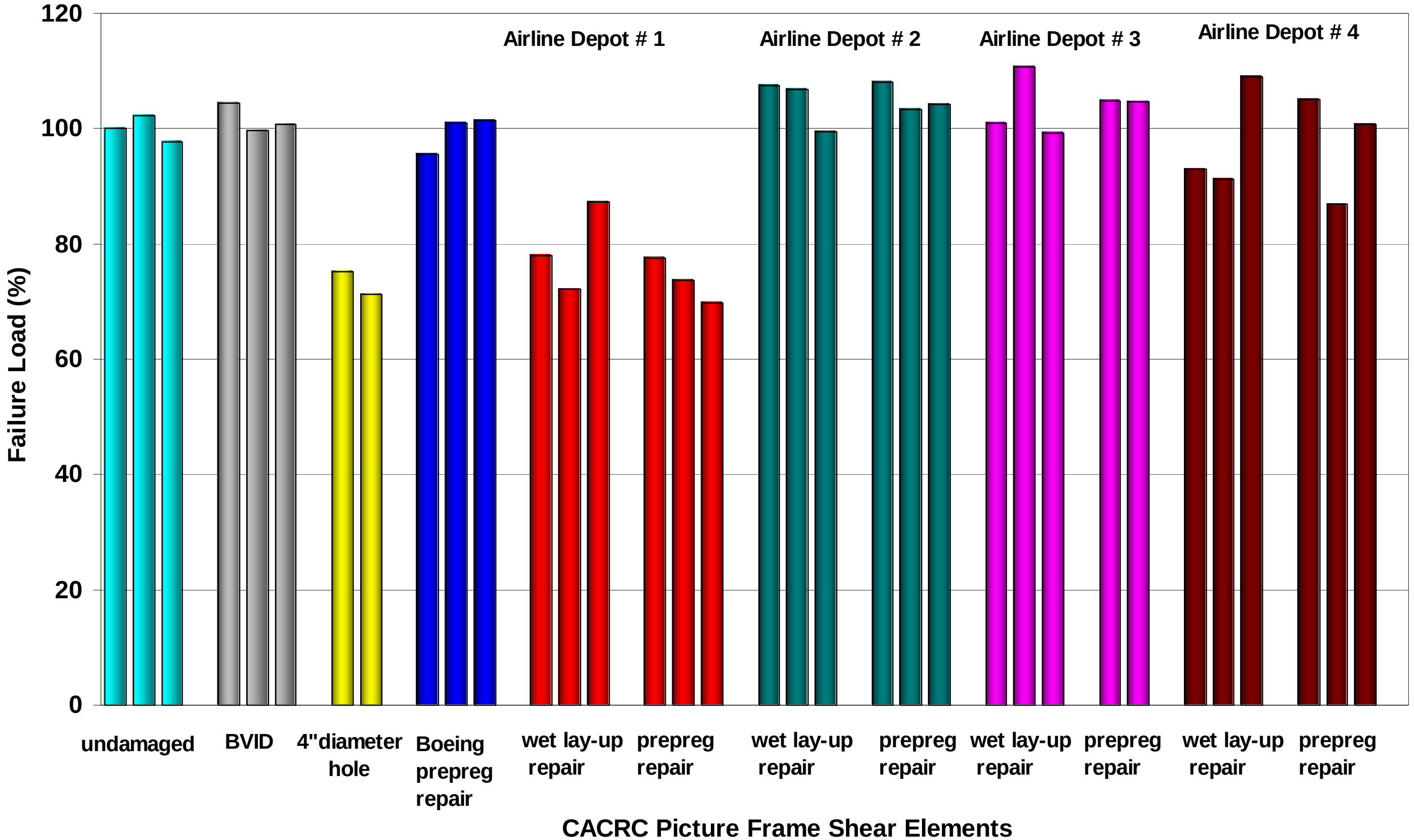


CACRC Method



OEM Method

Effects of Process Parameters



Surface Free Energy by contact Angle Measurement

- A surface with a high surface free energy will produce a good bond
- Surface Free energy can be measured by measuring surface contact angle
- Screening study was conducted to determine surface free energy of contaminated surfaces ready for repair (Dr. Bill Stevenson)

  Deicing Fluid
  Skydrol
  Hydraulic Fluid
  Jet Fuel
  Water

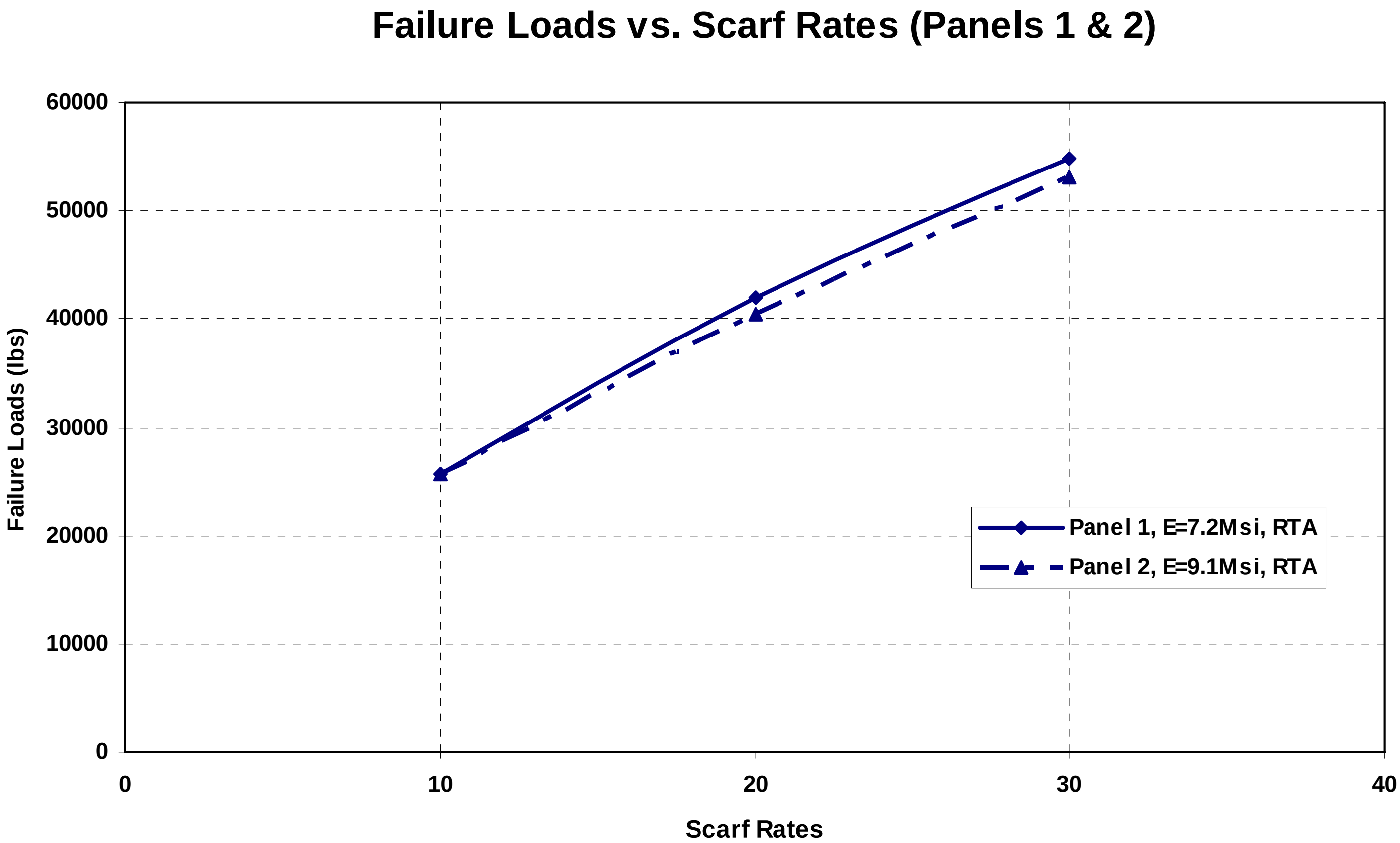
Contaminant	Exposure	Surface Free Energy (mN/m)
None	N/A	55.16
Deicing Fluid	30 days @ RTD	56.29
Skydrol	30 days @ RTD	43.83
Jet Fuel JP-8	30 days @ RTD	51.74
Water (85% @145°F)	Saturation	46.4
Salt Water	30 days@ RTD	56.41

Effects of Process Parameters- Test Matrix

- Mechanical Tests will be conducted to assess the effects of process deviations on these repairs

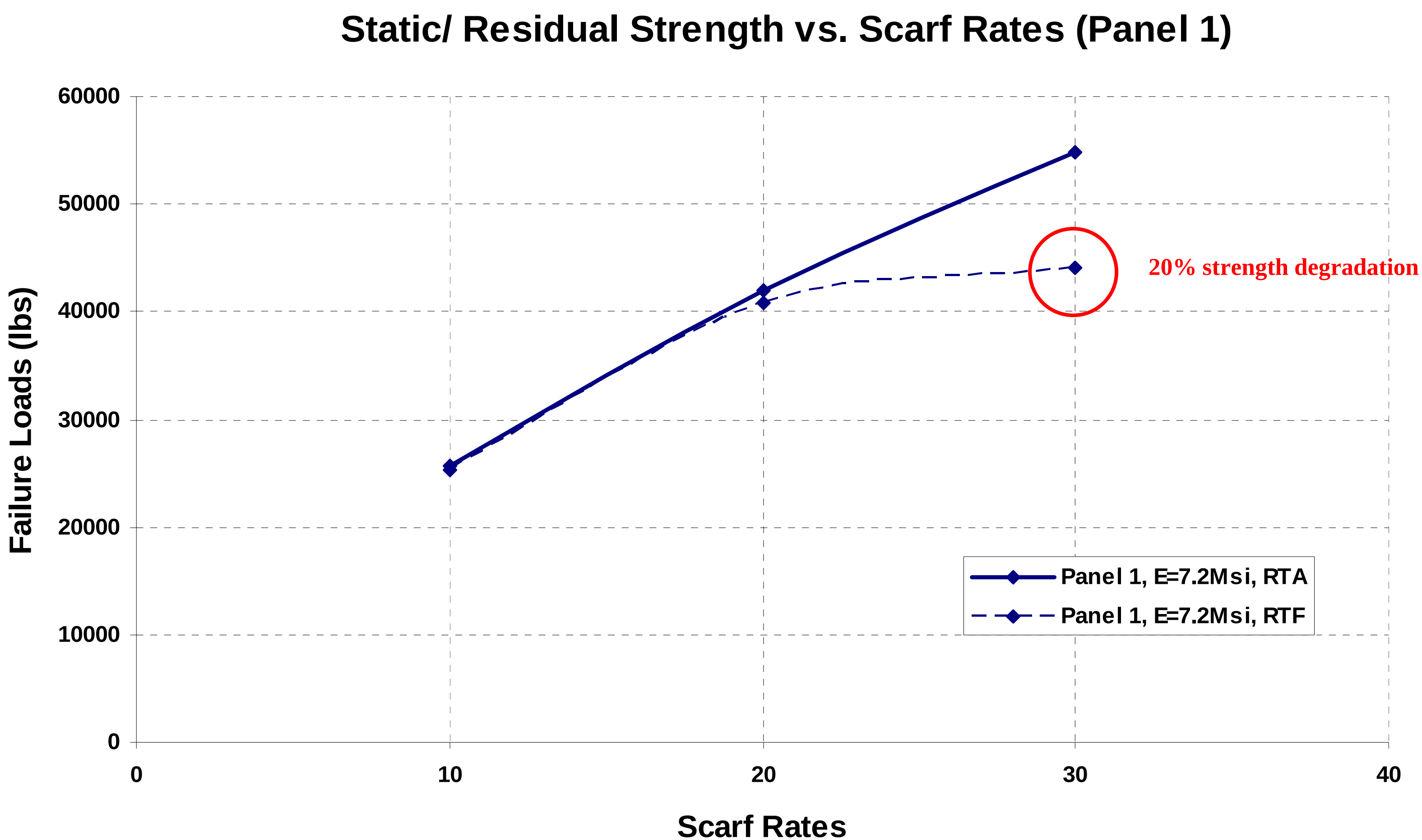
Load Mode	Process Parameters	Laminate Thickness	Scarf Rate	Quantity of Test OEM Repair	
				Static (RTA)	Repeated Loading (RTA)
Tension	Effects of Poor Surface Preparation	0.1332	20	6	6
		0.2368	20	6	6
	Effects of Improper Cure	0.1332	20	6	6
		0.2368	20	6	6
	Effects of Surface Contaminant 1	0.1332	20	6	6
		0.2368	20	6	6
	Effects of Surface Contaminant 2	0.1332	20	6	6
		0.2368	20	6	6
	Effects of Pre-bond Moisture	0.1332	20	6	6
		0.2368	20	6	6

Laminate Mechanical Test Data
Static Test Results



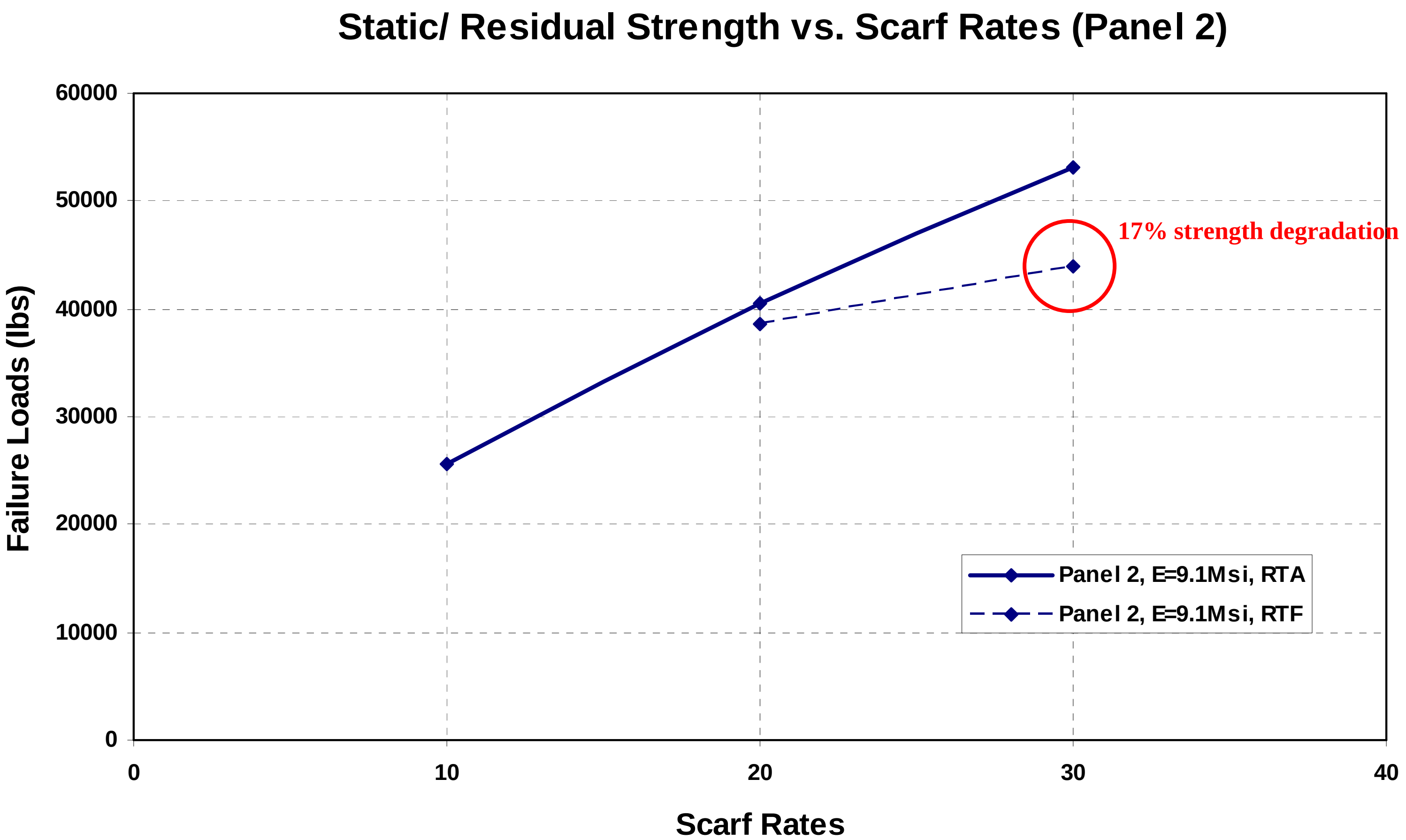
Slight increase in load carrying capability for panel 1 compared to panel 2

Laminate Mechanical Test Data
Initial Results



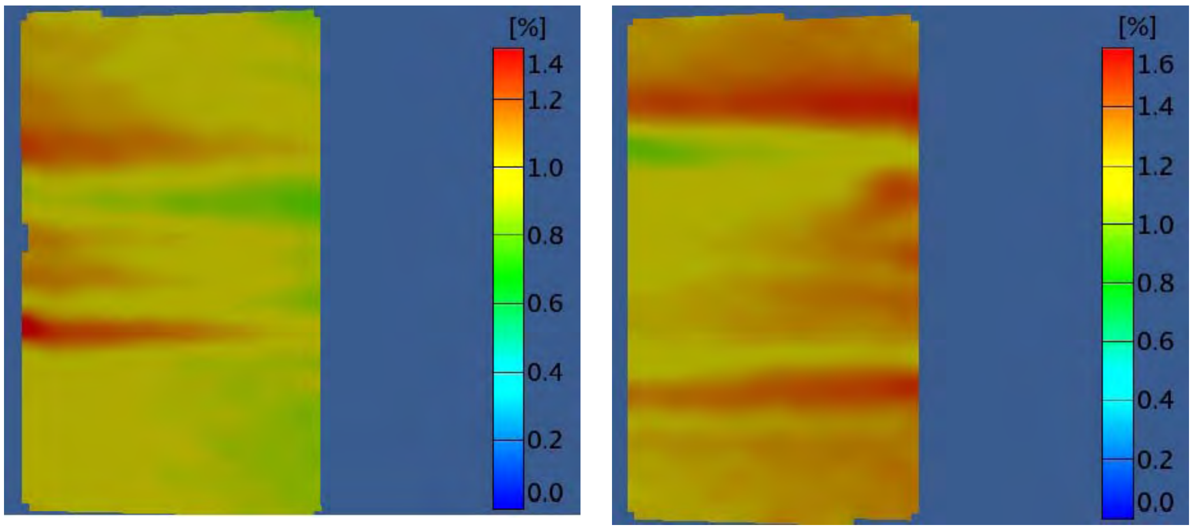
Coupons fatigued at a strain level equivalent to 3000 microstrain for 165000 cycles

Laminate Mechanical Test Data Results



Coupons fatigued at a strain level equivalent to 3000 microstrain for 165000 cycles

ARAMIS Strain Maps
Preliminary Data

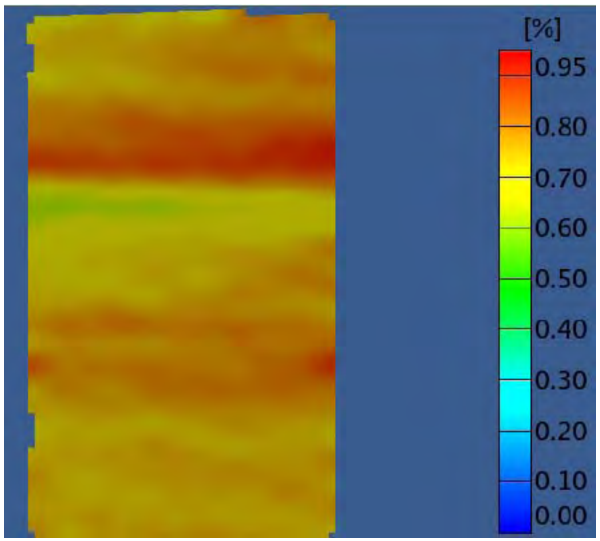


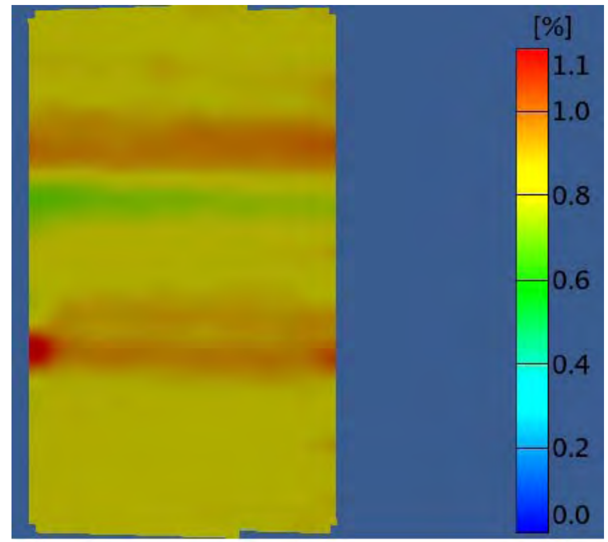
Y-Strain Distribution for varying scarf rates -20, -30
Panel 1, 18 ply, RTD

Increased strain capability with an increase in scarf overlap, maximum strains achieved for the -30 panels

(average far field strain = 9500 microstrain, peak strain = 16000 microstrain)

ARAMIS Strain Maps
Preliminary Data





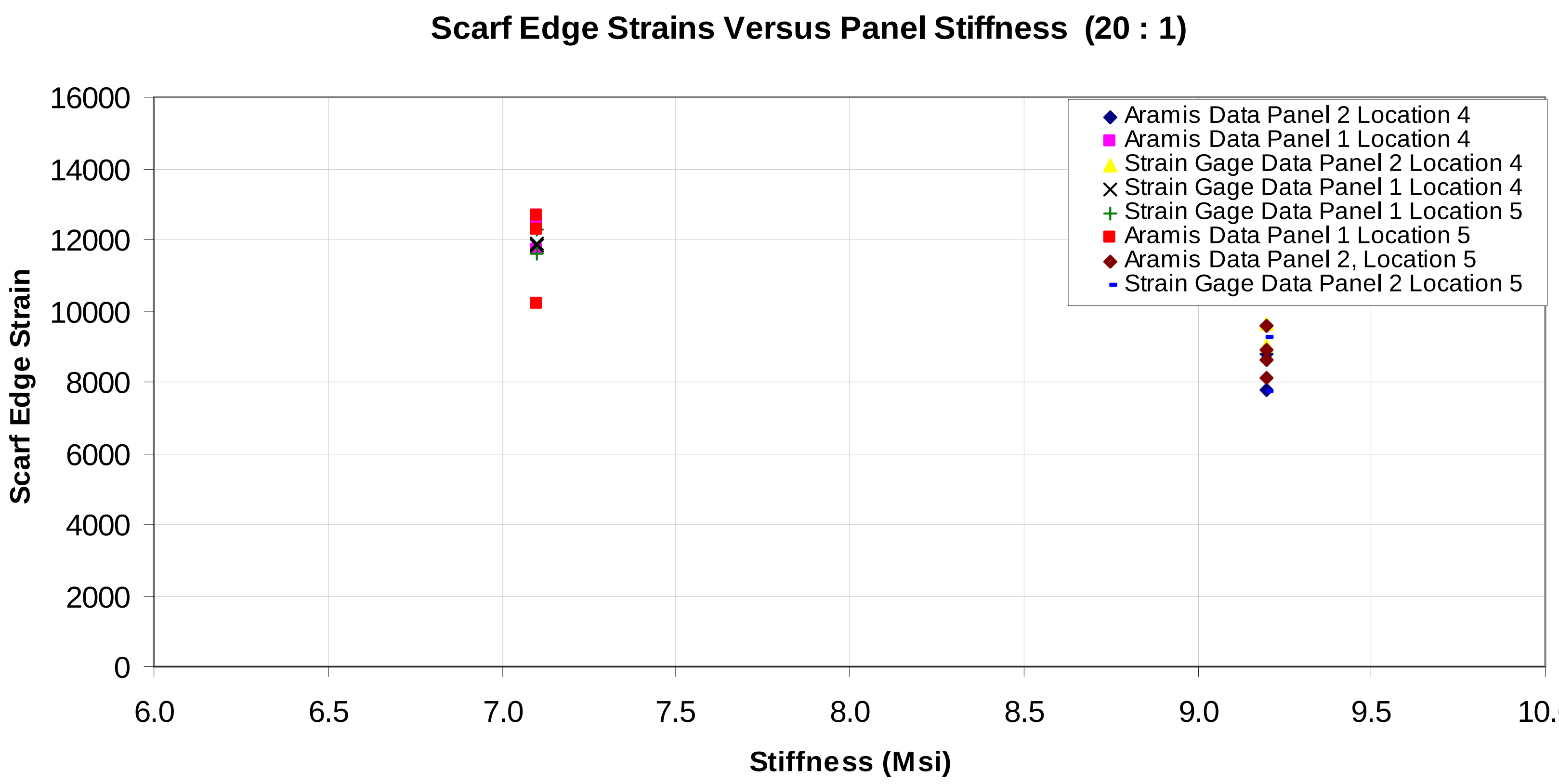
Y-Strain Distribution for varying scarf rates -20, -30
Panel 2, 18 ply, RTD

Increased strain capability with an increase in scarf overlap, maximum strains achieved for the -30 panels

(average far field strain = 8500 microstrain, peak strain = 11000 microstrain)

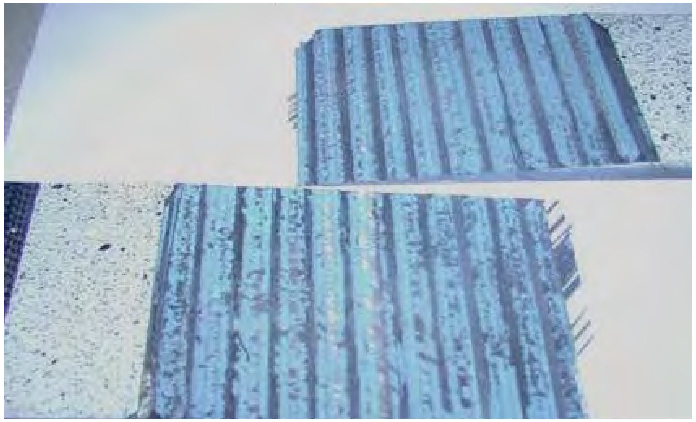
Stiffer panel (panel 2) has lower strain to failure than the softer panel (panel 1)

Strain Variation vs Stiffness (Scarf Edge)



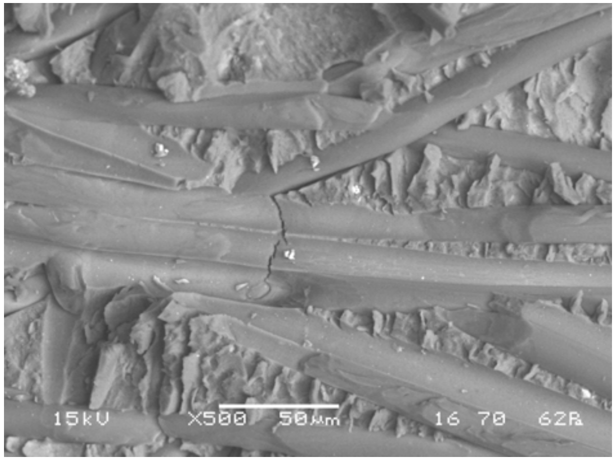
Failure Modes/ Fractography

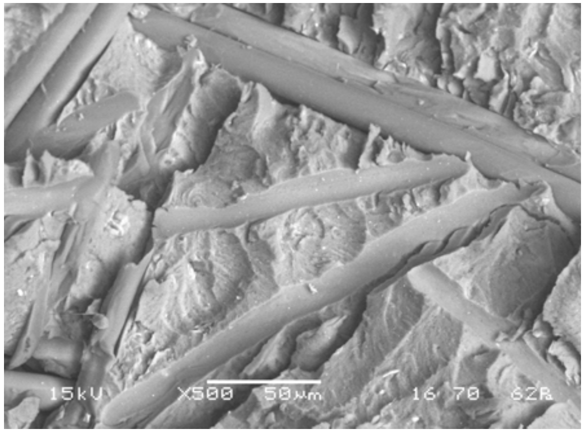
- **SEM Analysis**



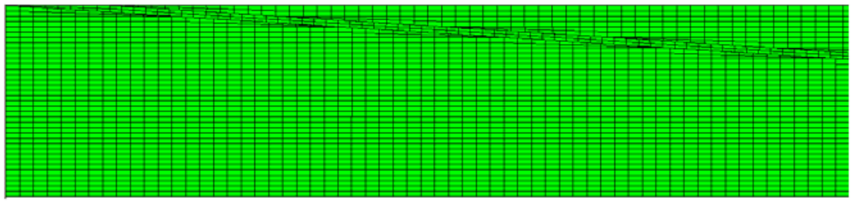
Failure Mode: combination of a cohesive failure of the adhesive and interlaminar facing failure of the laminate indicative of a strong bond

SEM analysis shows fiber fracture, brittle/ shear failure of the adhesive

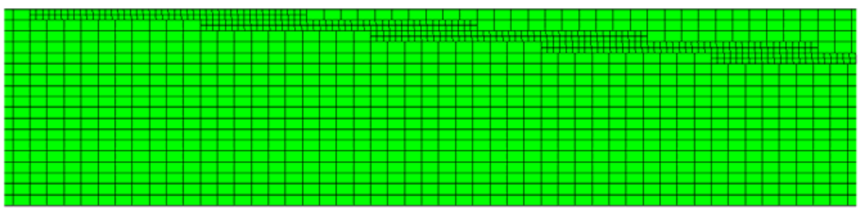




Analytical Validation
2-D FEA



Scarf Joint

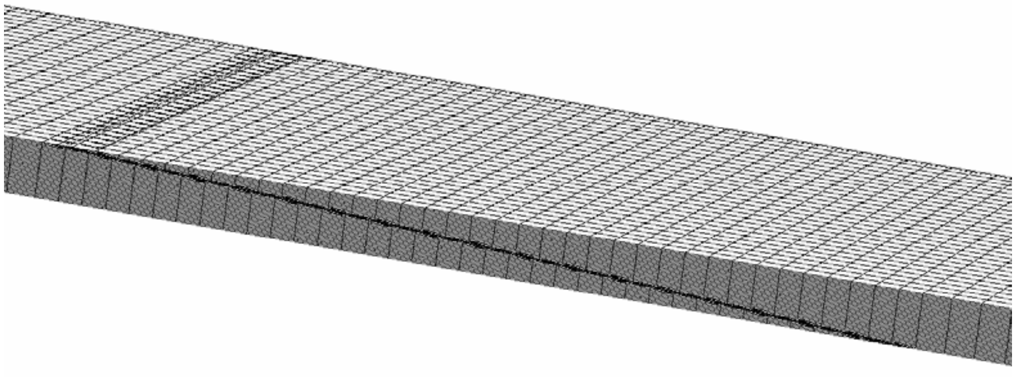


Stepped Joint

- 2-Dimensional Dynamic Finite Element Models
- Adhesive Failure Criterion: Equivalent Plastic Strain=0.25
- 90-Deg Ply Failure Criterion: von Mises Equivalent Stress = 19 ksi

OPT53 2D Models	Test (lbf)	ABAQUS Data	Deviation %
OPT53-1 Scarf	29,089.3	30,186.1	3.8
OPT53-1 Stepped		29,653.6	1.9
OPT53-2 Scarf	25,292.0	27,006.5	6.8
OPT53-2 Stepped		23,930.8	-5.4
OPT53-3 Scarf	56,768.3	55,901.2	-1.5
OPT53-3 Stepped		49,062.7	-13.6
OPT53-4 Scarf	54,765.6	54,773.3	0.1
OPT53-4 Stepped		49,751.6	-9.2
OPT53-5 Scarf	77,678.3	71,102.0	-8.5
OPT53-5 Stepped		74,264.6	-4.4
OPT53-6 Scarf	71,333.3	75,899.5	6.4
OPT53-6 Stepped		75,036.5	5.2

Analytical Validation

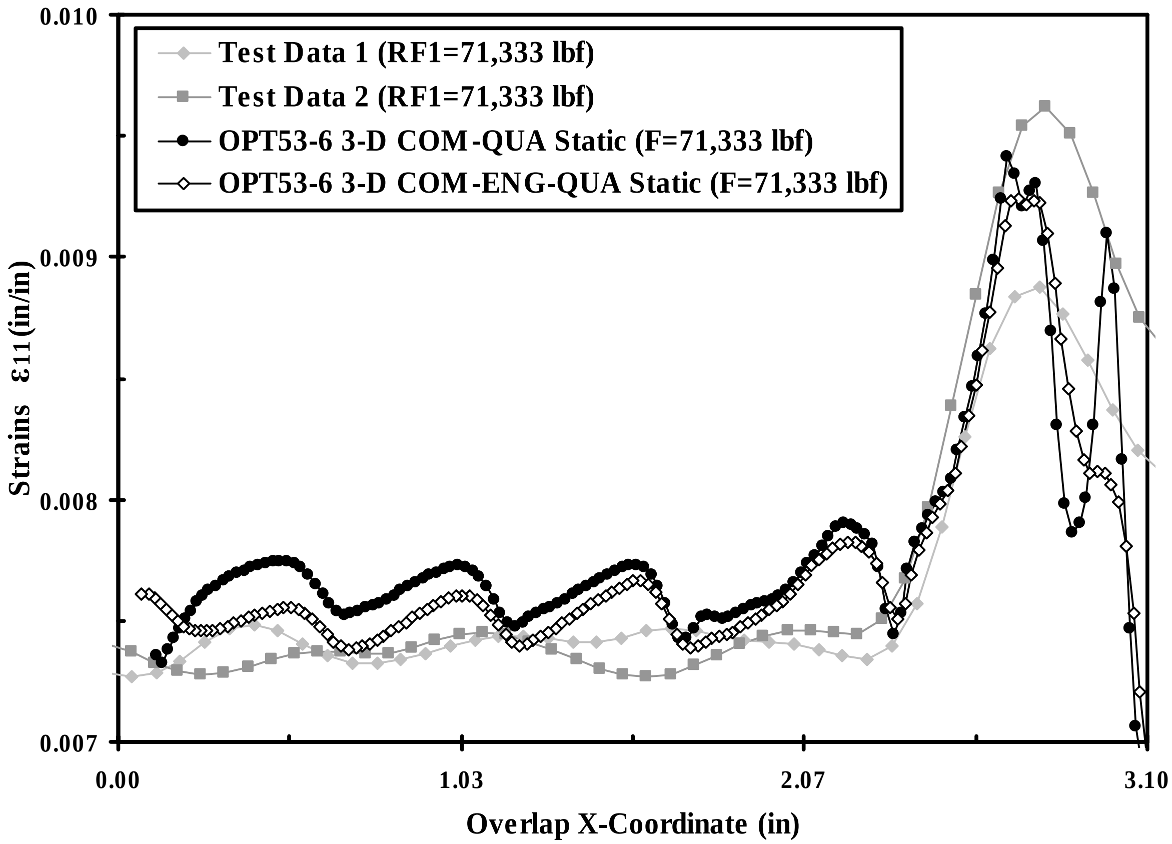


3-D Finite Element Model of a Scarf Joint

- **3-D FEA used to show edge effects and initiate failure around the scarf edge**

	Total Elements	Total Nodes
OPT53-1	30,090	35,824
OPT53-2	36,900	44,448
OPT53-3	69,300	79,136
OPT53-4	65,655	75,680
OPT53-5	114,855	129,504
OPT53-6	128,535	144,800

Analytical Validation



Surface Strain Comparison between 3-D FE Model and ARAMIS Data (OPT53-6)

Analytical Validation

- 90-degree plies modeled as isotropic since ABAQUS only offers stress failure criteria for isotropic materials

90-degree Ply Failure (Effective Stress Limit =19,000 psi) Adhesive Shear Failure PEEQ = 0.285				
	Test Data	ABAQUS Data	Deviation %	ν90
OPT53-1 COM-QUA	29,089.3 lbf	24,635.4 lbf	-15.3	0.200
OPT53-2 COM-QUA	25,292.0 lbf	24,472.2 lbf	-3.2	0.150
OPT53-3 COM-QUA	56,768.3 lbf	57,532.4 lbf	1.3	0.017
OPT53-4 COM-QUA	54,765.6 lbf	54,444.6 lbf	-0.6	0.017
OPT53-5 COM-QUA	77,678.3 lbf	71,041.0 lbf	-8.5	0.015
OPT53-6 COM-QUA	71,333.3 lbf	66,171.2 lbf	-7.2	0.017
90-degree Ply Failure (Effective Stress Limit =15,000 psi) Adhesive Shear Failure PEEQ = 0.285				
	Test Data	ABAQUS Data	Deviation %	ν90
OPT53-3 COM-QUA	56,768.3 lbf	55,998.0 lbf	-1.4	0.017
OPT53-4 COM-QUA	54,765.6 lbf	52,149.0 lbf	-4.8	0.017

Status To Date

- Laminate mechanical Testing to generate baseline repair data for various repair materials in progress
- Laminate repair using ACG MTM45/T800 in progress
- Panel Machining to generate mechanical data for contaminated coupons is in progress
- Screening panels for the sandwich configuration have been tested and are being resized to induce failure in the repair
- Improved analytical test results correlation with experimental data (3D FEM model)

A Look Forward/ Future Plans

Benefits To Aviation:

- **To assess the effects of surface contamination and process variations on the performance of bonded repairs**
- **To develop rigorous repeatable repair processes that ensure structural integrity of bonded repairs**
- **To gain confidence in bonded structural repairs**
- **To provide guidance for analytical modeling of repairs**