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# Lessons Learned from CACRC Depot Bonded Repair Round Robin Investigation


Presented by:

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NIAR – Wichita State University



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# CACRC Depot Bonded Repair Investigation

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  Boeing – Russell Keller
  Airbus – Francois Museux
  Lufthansa Technik AG – Jan Popp
  Delta – Ray Kaiser, Nathan Schulz
  United Airlines – Eric Chesmar, Dean Jerry
  Nordam – Suranga Nagendra
  Aviation Technology Associates – Marc Felice
  Hexcel – Justin Hamilton

# Introduction – Technological Challenges

*In-Service Damage, Courtesy Eric Chesmar, UAL [1]*

## Motivation / Key Issues

- Major Technological Advances using Composite Materials in the last 50 years (composite materials used for the first time in wing and fuselage load bearing structures)

## Technological Challenges

- Material fabrication and Processes, analysis methods, structural health monitoring, lightning strike protection, recycling, repair methods and standardization

## Important Considerations for continued airworthiness [2]

- Durability, environmental resistance (Brittle nature of polymers, weak interfacial bonds)
- Repairability, supportability (development of repair methods, in-service maintenance versus OEM environment, chemical and mechanical properties of materials)
- Maintainability (simple assemblies, easy access to hardware, clearly defined ADL,CDT early development of repair methods)


**References:**

1. **Chesmar, E. "Repair And Maintenance Implementation: Airline Experience, Problems, Concerns and Issues," Presented at FAA Bonded Workshop, 2004.**
2. **Design of Durable, Repairable and Maintainable Aircraft Components – SAE AE 27, 1997**

# Introduction – In Service Experience

**Lessons Learned:**

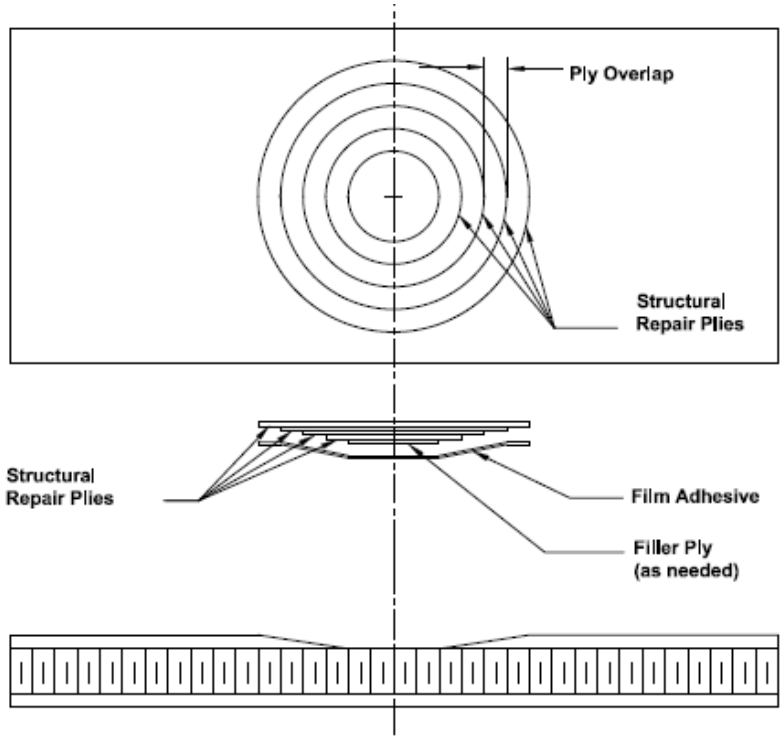
- Outstanding performance where reliable processes were used
- Numerous in-service failure with deficient processes
- Surface preparation yielding a clean chemically active interface resistant to degradation is necessary for a durable bond
- Adhesion failures are caused by deficient processes (pre-bond contamination, poor surface preparation, inadequate cure parameters that inhibit the formation of strong chemical bonds)
- Cohesion Failures are caused by poor design (thermal residual stresses, stiffness mismatch between adherends, poor material selection, inadequate repair overlap, porous bondlines)

- NDI methods cannot guarantee absolute bond integrity Rigorous bond quality management, repair definition and process execution is essential to achieve repeatable and structurally reliable bonded repairs.

**Complete Overhaul of a Composite Fan Cowl**

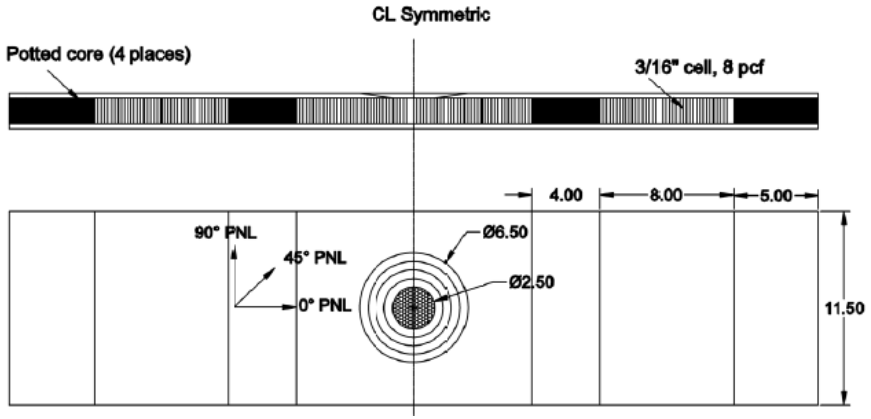
# Research Objectives

- Evaluate the existing CACRC standards and approved materials used for repair of composite structures
- Assess the repair process variability between depots, using the same repair document procedures (similar to industry standard repair manuals) using CACRC repair techniques and materials provided to all the depots
- Investigate the variability associated with technician training (minimal level of experience versus extensive experience) on the performance of the repair
- Compare strength of the different repairs (CACRC-R1/R2 field repairs vs OEM-R1/R2 repairs) to a set of control “pristine” panels and to a set of open-hole scarfed panels
- Evaluate the environmental effects on the static and residual strength after fatigue of these repairs

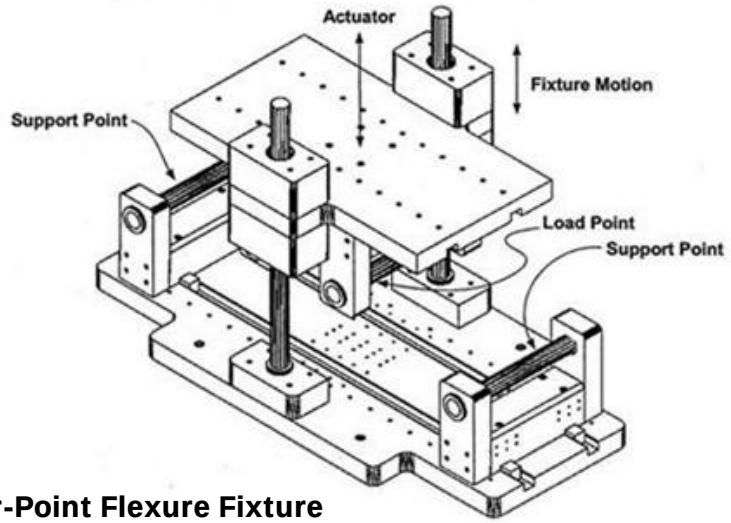



**Schematic of a Bonded Repair to a sandwich panel (no core restoration, facesheet repair only)**

# Research Approach / Methodology




**Sandwich CACRC Prepreg Repair Configuration**




**Four-Point Flexure Fixture**

**Sandwich Repair Element Configuration**
**Representative of production hardware / materials and processes**

- Large beams, 11.5” x 48” with the repair tested in compression and tension modes
- 2.5” hole diameter to maintain a W/D>4
- 2” thick core, 3/16” core cell size, 8 pcf, 4-ply facesheets
- No core restoration, facesheet repair only (FS2)

**Parent Material:**
T300/ 934 3KPW with FM 377S adhesive (OEM)

**Repair Materials:**
CACRC repair 1: Hexcel M20 PW (250°F cure) with EA9695 adhesive (AMS 3970)

CACRC repair 2 (wet lay-up): G904 D1070 TCT fabric with Epocast 52A/B laminating resin (AMS 2980)

OEM repair 1: using the parent system (350°F cure)

OEM repair 2 (wet lay-up): T300 fabric with EA9396 C2 laminating resin and EA9696 adhesive

# Test Matrix

| Repair Station | Element Configuration | Repair Material | Loading Mode | Experience Level | Static RTA | Static ETW | Fatigue ETW |
|---|---|---|---|---|---|---|---|
| N/A | Pristine/ Undamaged | N/A | Compression | | 3 | 3 | 3 |
| N/A | Unrepaired /2.5" hole/Scarf | N/A | Compression | | | 3 | |
| OEM | Repair/ 2.5" hole/ 0.25" scarf overlap | OEM-R1 | Compression | M2 | | 3 | 3 |
| OEM | Repair/ 2.5" hole/ 0.5" scarf overlap | OEM-R1 | Compression | M2 | | 2 | |
| NIAR | Repair/ 2.5" hole/ 0.5" scarf overlap | OEM-R2 | Compression | M2 | | 3 | 3 |
| NIAR | Repair/ 2.5" hole/ 0.5" scarf overlap | OEM-R2 | Tension | M2 | | 3 | 3 |
| NIAR | Repair/ 2.5" hole/ 0.5" scarf overlap | CACRC-R1 | Compression | M2 | | 3 | 3 |
| NIAR | Repair/ 2.5" hole/ 0.5" scarf overlap | CACRC-R1 | Tension | M2 | | 3 | 3 |
| NIAR | Repair/ 2.5" hole/ 0.5" scarf overlap | CACRC-R2 | Compression | M2 | | 3 | 3 |
| NIAR | Repair/ 2.5" hole/ 0.5" scarf overlap | CACRC-R2 | Tension | M2 | | 3 | 3 |
| Field Station 1 | Repair/ 2.5" hole/ 0.5" scarf overlap | CACRC-R1 | Compression | M1 | | 3 | |
| Field Station 1 | Repair/ 2.5" hole/ 0.5" scarf overlap | CACRC-R2 | Compression | M1 | | 3 | |
| Field Station 1 | Repair/ 2.5" hole/ 0.5" scarf overlap | CACRC-R1 | Compression | M2 | | 3 | |
| Field Station 1 | Repair/ 2.5" hole/ 0.5" scarf overlap | CACRC-R2 | Compression | M2 | | 3 | |
| Field Station 2 | Repair/ 2.5" hole/ 0.5" scarf overlap | CACRC-R1 | Compression | M1 | | 3 | |
| Field Station 2 | Repair/ 2.5" hole/ 0.5" scarf overlap | CACRC-R2 | Compression | M1 | | 3 | |
| Field Station 2 | Repair/ 2.5" hole/ 0.5" scarf overlap | CACRC-R1 | Compression | M2 | | 3 | |
| Field Station 2 | Repair/ 2.5" hole/ 0.5" scarf overlap | CACRC-R2 | Compression | M2 | | 3 | |
| Field Station 3 | Repair/ 2.5" hole/ 0.5" scarf overlap | CACRC-R1 | Compression | M1 | | 3 | |
| Field Station 3 | Repair/ 2.5" hole/ 0.5" scarf overlap | CACRC-R2 | Compression | M1 | | 3 | |
| Field Station 3 | Repair/ 2.5" hole/ 0.5" scarf overlap | CACRC-R1 | Compression | M2 | | 3 | |
| Field Station 3 | Repair/ 2.5" hole/ 0.5" scarf overlap | CACRC-R2 | Compression | M2 | | 3 | |
| Field Station 4 | Repair/ 2.5" hole/ 0.5" scarf overlap | CACRC-R1 | Compression | M1 | | 3 | |
| Field Station 4 | Repair/ 2.5" hole/ 0.5" scarf overlap | CACRC-R2 | Compression | M1 | | 3 | |
| Field Station 4 | Repair/ 2.5" hole/ 0.5" scarf overlap | CACRC-R1 | Compression | M2 | | 3 | |
| Field Station 4 | Repair/ 2.5" hole/ 0.5" scarf overlap | CACRC-R2 | Compression | M2 | | 3 | |
| Field Station 5 | Repair/ 2.5" hole/ 0.5" scarf overlap | CACRC-R1 | Compression | M1 | | 3 | |
| Field Station 5 | Repair/ 2.5" hole/ 0.5" scarf overlap | CACRC-R2 | Compression | M1 | | 3 | |
| Field Station 5 | Repair/ 2.5" hole/ 0.5" scarf overlap | CACRC-R1 | Compression | M2 | | 3 | |
| Field Station 5 | Repair/ 2.5" hole/ 0.5" scarf overlap | CACRC-R2 | Compression | M2 | | 3 | |

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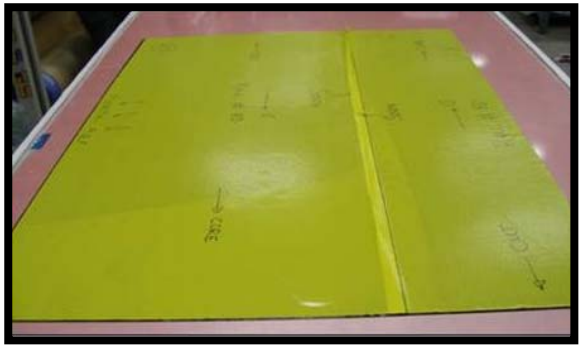
| | | | |
|---|---|---|---|
| OEM-R1 | T300/934 w FM377 adhesive | CACRC- R1 | M20PW with EA9695 adhesive |
| OEM-R2 | EA 9396 C2 wet lay-up w EA9696 | CACRC- R2 | Epocast 52A/B wet lay-up |
| M1 | Minimal level of Experience | RTA | Room Temperature Ambient |
| M2 | Experienced Mechanic | ETW | Elevated Temperature (180°F) Wet |

# Parent Panel Manufacture Assembly I

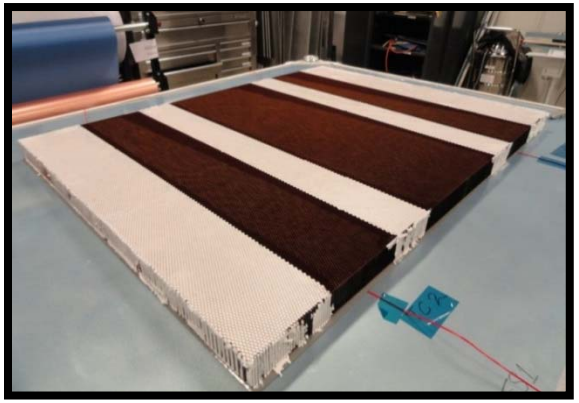
- Parent materials provided by the OEM
- Panel manufacture conducted at NIAR/NCAT using OEM approved processes verified by OEM quality assurance inspectors (40 large panels)
- Assembly 1 (uncured facesheet1(FS1) and potted core) co-cured at 350°F for 120 minutes at 45 psi



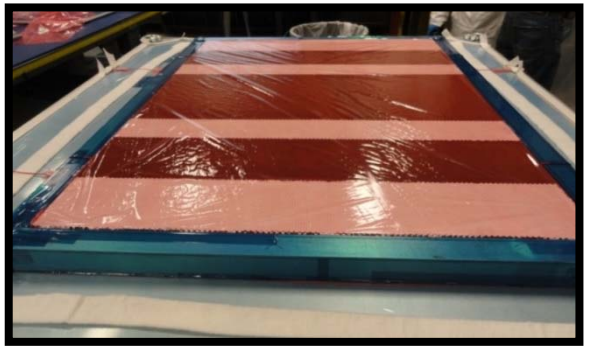
Facesheet 1 (FS1) lay-up

Film Adhesive Application

Corfil Application

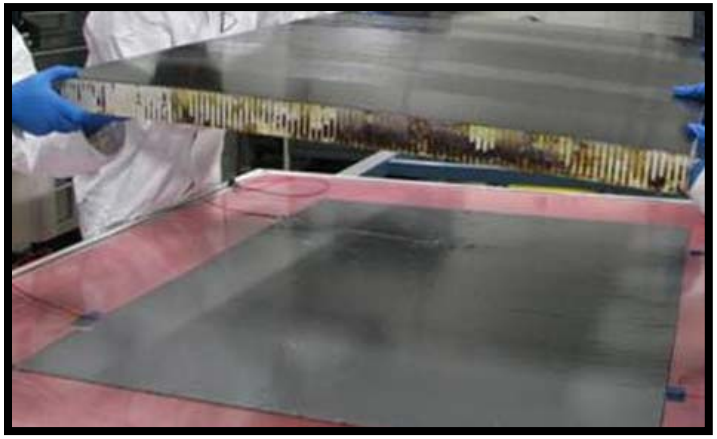


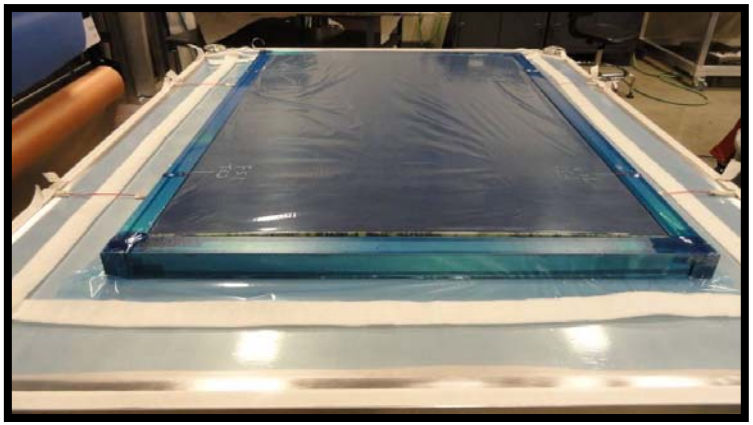
Core Application onto facesheet 1 (FS1)



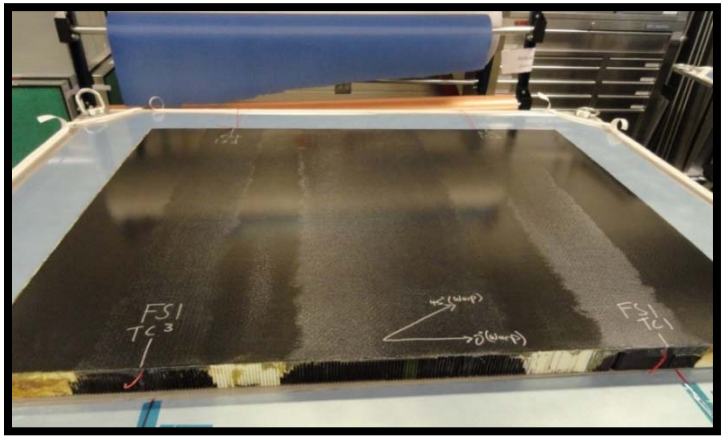
Assembly 1 Bagging and preparation for cure

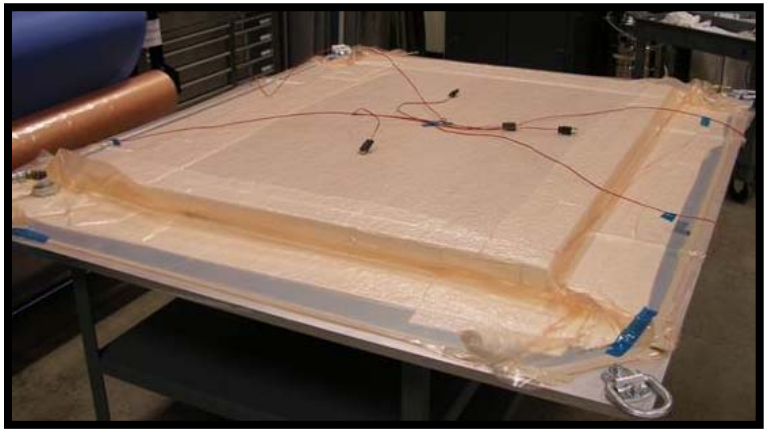
# Parent Panel Manufacture
# Final Assembly





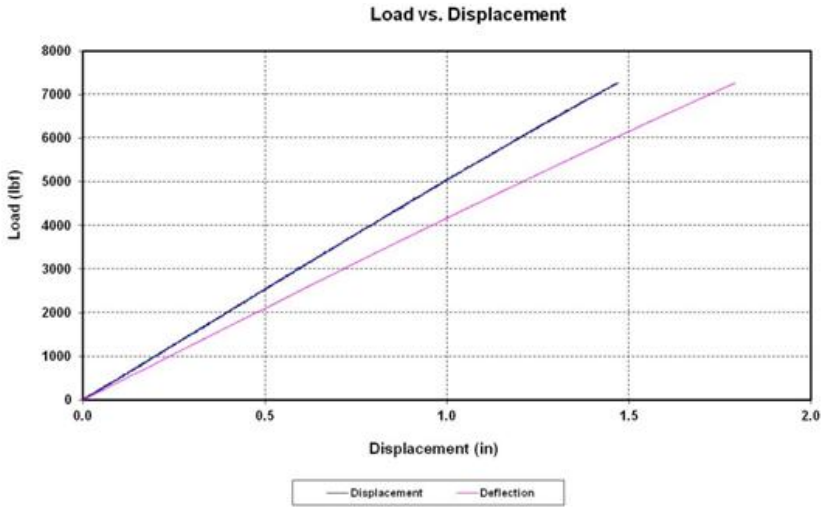
Uncured Assembly 2 (facesheet 2 and adhesive) co-bonded to cured assembly 1

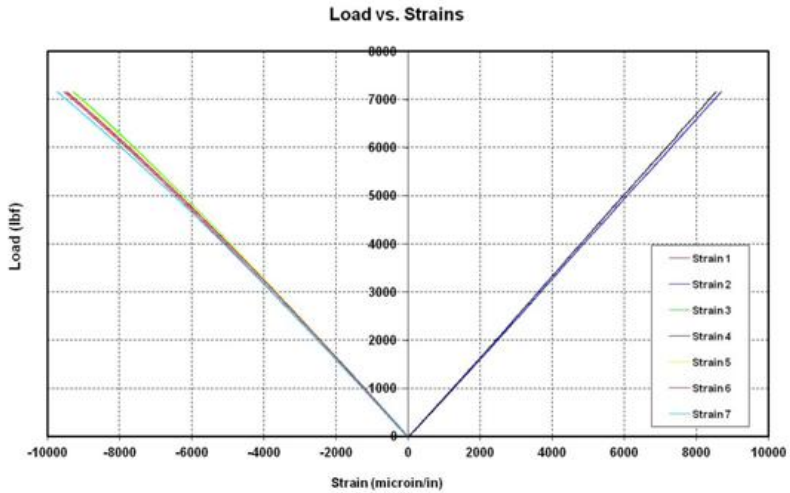




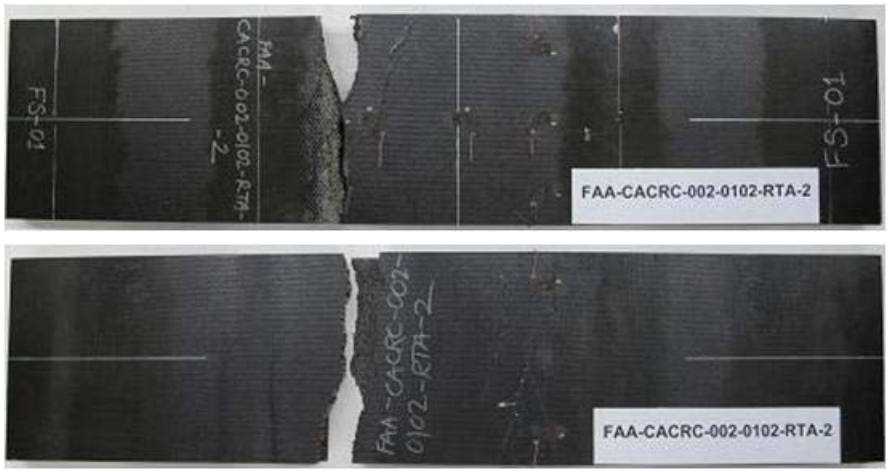
Assembly Bagging in preparation for cure

# Sandwich Repair Element Design Validation



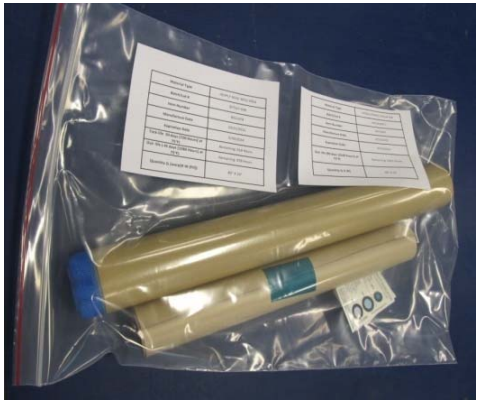




- 3 undamaged-pristine beams were tested to establish the undamaged parent element capability at RTA
- Good correlation between experimental results and predictions
- Average failure strains (-9335με -compression and 8492με -tension )

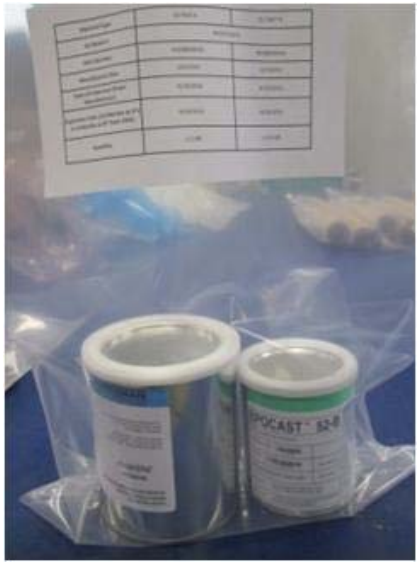



Typical Failure Modes – Undamaged beams

# Repair Instructions and Kit preparation



CACRC Prepreg Kit



CACRC Wet Lay-Up Resin

- A detailed Repair Document procedure (similar to industry standard repair manuals) referencing the relevant SAE CACRC standards was reviewed and approved by the technical monitors, industry POCs and participating airline depots before performing the repairs
- Repair process checklists with inspection points for both wet lay-up and prepreg repairs were provided to the repair personnel along with the CACRC standards (detailed process documentation)

Repair kits (using CACRC approved materials) were prepared and shipped to all participating depots

- Hexcel M20/G904 prepreg
- EA9695 NW 0.05 psf film adhesive
- Hexcel G904 D1070 TCT, PW dry fabric, 193 g/m$^2$ using Tenax Fibers
- Huntsman Epocast 52A/B resin
- Peel ply and perforated film for wet lay-up bagging

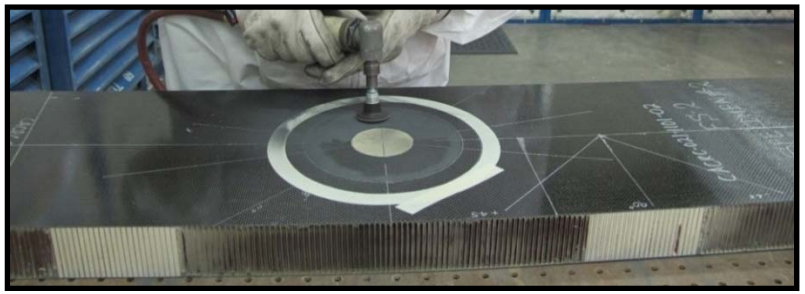
Notes:

- Difficulties in material procurement, long lead times and difficulty obtaining small quantities
- CACRC Materials not commonly called out today in composite repairs

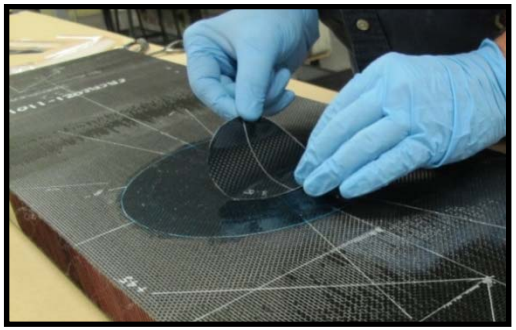
# CACRC Repairs - Depot #1

- Depot 1 performed repairs with CACRC materials (CACRC-R1 and CACRC-R2) only as defined in test matrix table

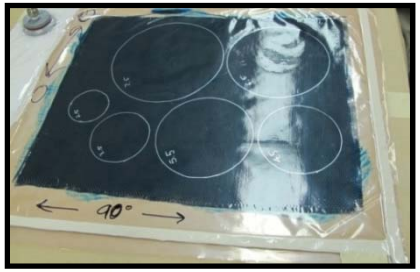
CACRC Repair Element Masking in Preparation for Scarf Sanding



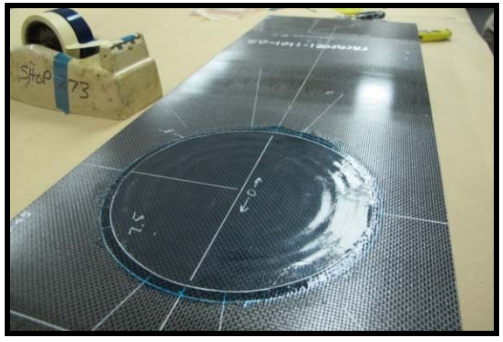
Scarf/Taper Sanding



Wet lay-up repair ply application

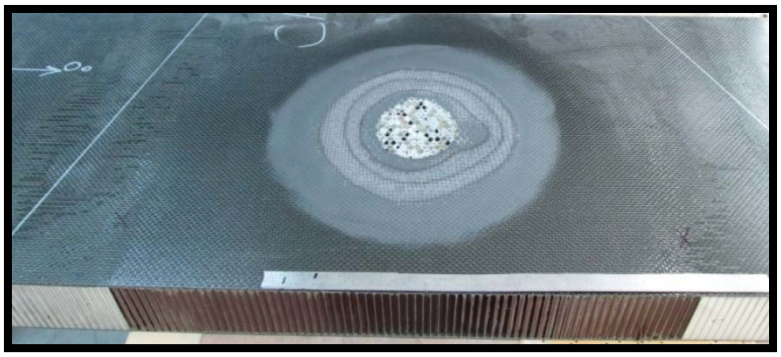


Wet lay-up resin impregnation

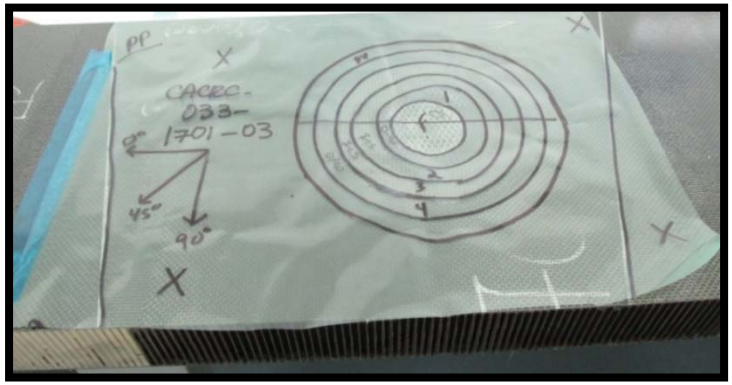


# CACRC Repairs - Depot #2

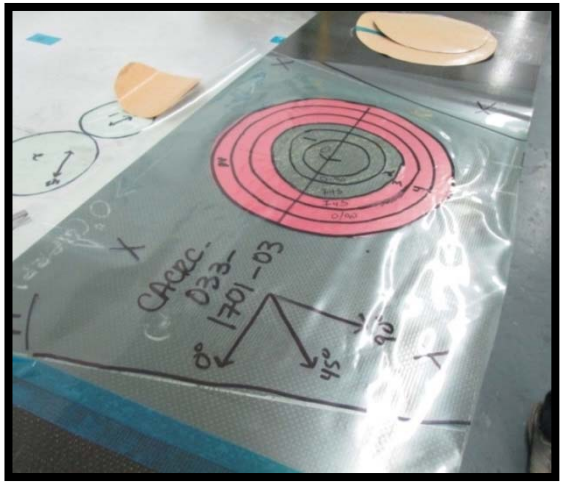
- Depot 2 performed repairs with CACRC materials (CACRC-R1 and CACRC-R2) only as defined in test matrix table



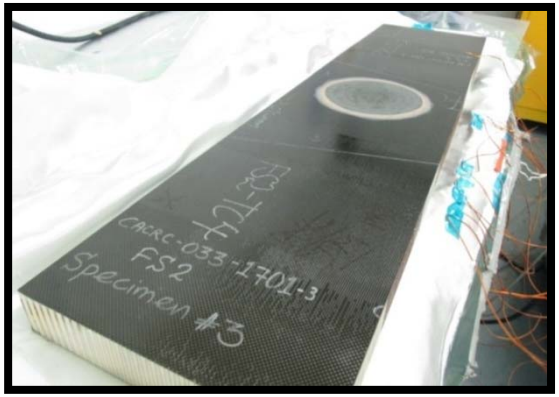
Element scarf sanded in preparation for repair




Repair Ply Template



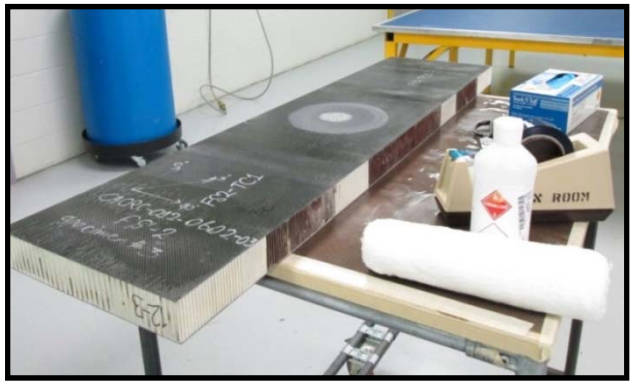

Repair Ply Application



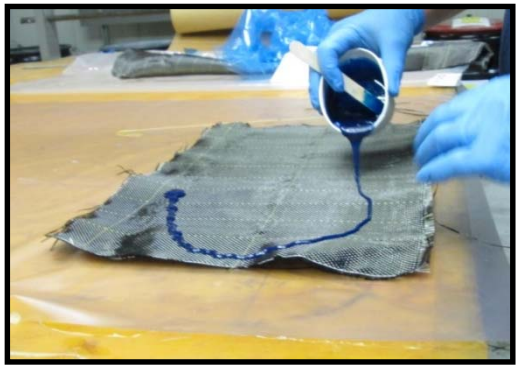

Cured Repair

# CACRC Repairs - Depot #3

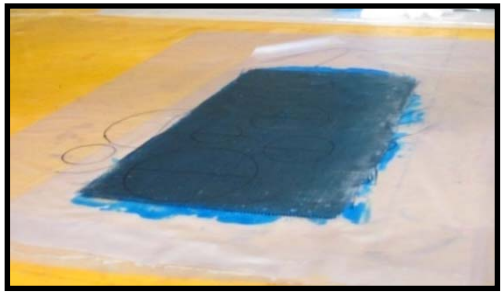
- Depot 3 performed repairs with CACRC materials (CACRC-R1 and CACRC-R2) only as defined in test matrix table

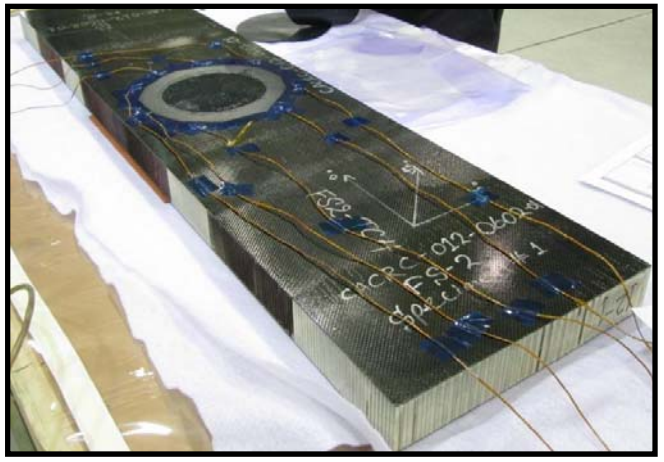


Element scarf sanded in preparation for repair

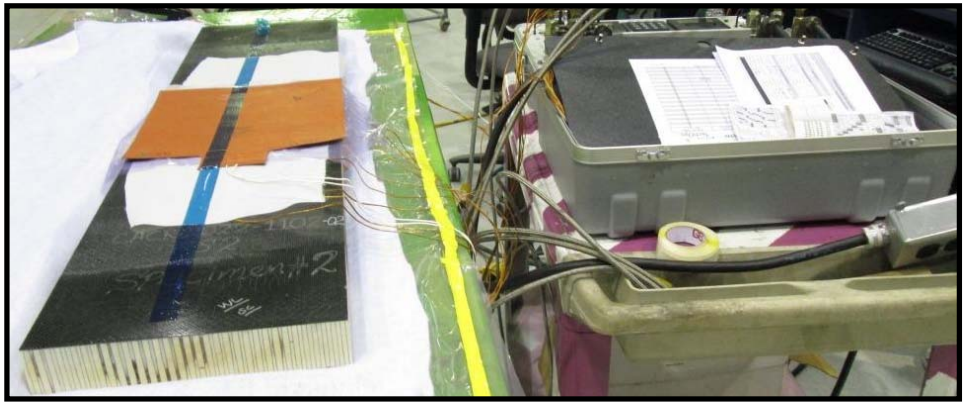


Wet lay-up resin impregnation



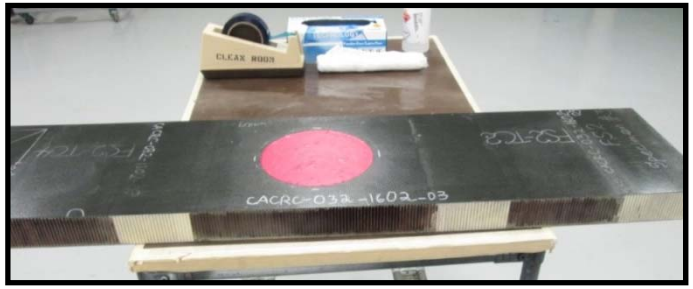


Wet lay-up repair application

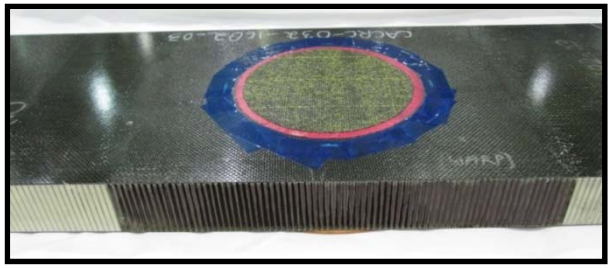


Repair Bagging in preparation for cure

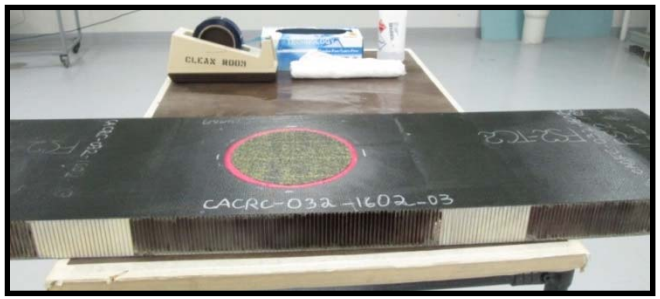
# CACRC Repairs - Depot #3



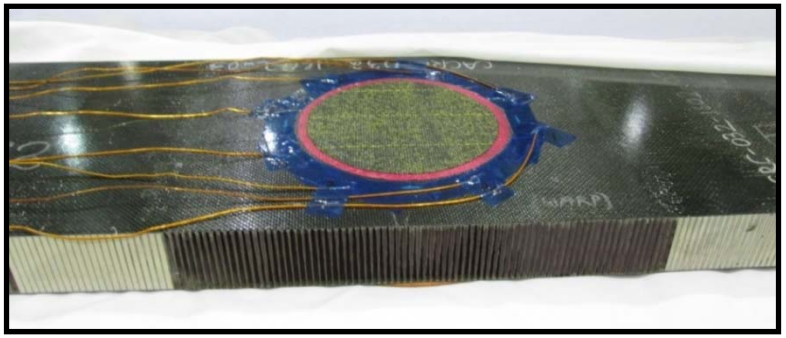

Adhesive application – prepreg repair



Repair Masking – prepreg repair




Repair application – prepreg repair



Thermocouple Application – prepreg repair

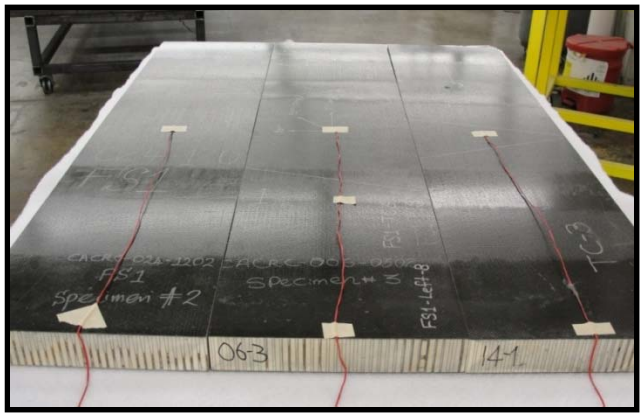
Repair Bagging

Cured repair

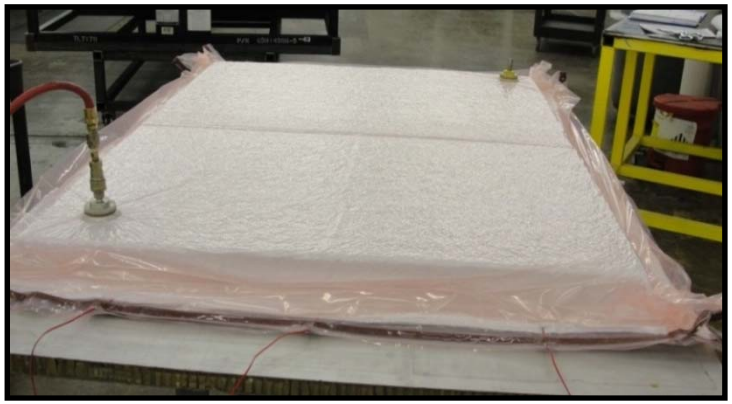
# CACRC Repairs - Depot #4

- Depot 4 performed repairs with CACRC materials (CACRC-R1 and CACRC-R2) only as defined in test matrix table

Repair Element Scarf Sanded in Preparation for Repair



Repair Elements Scarfed and prepared for Drying

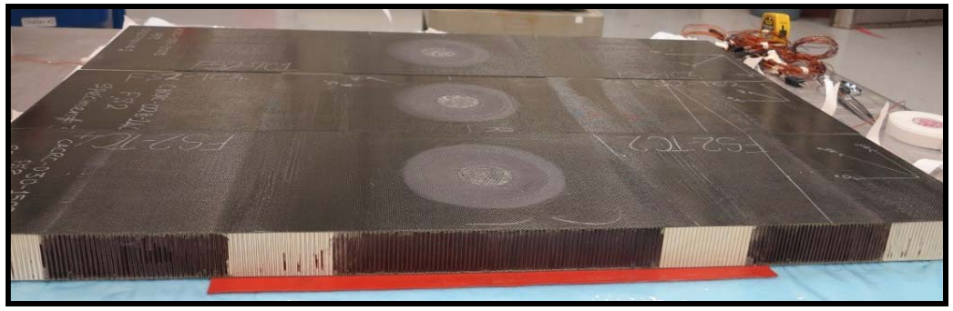


Repair Element Drying

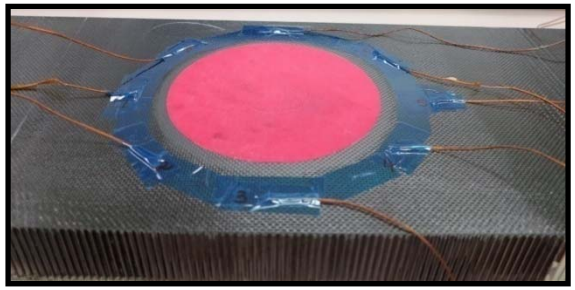
Repair Application

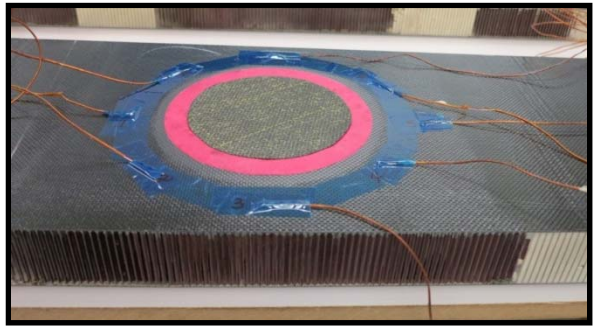
# CACRC Repairs - Depot #5

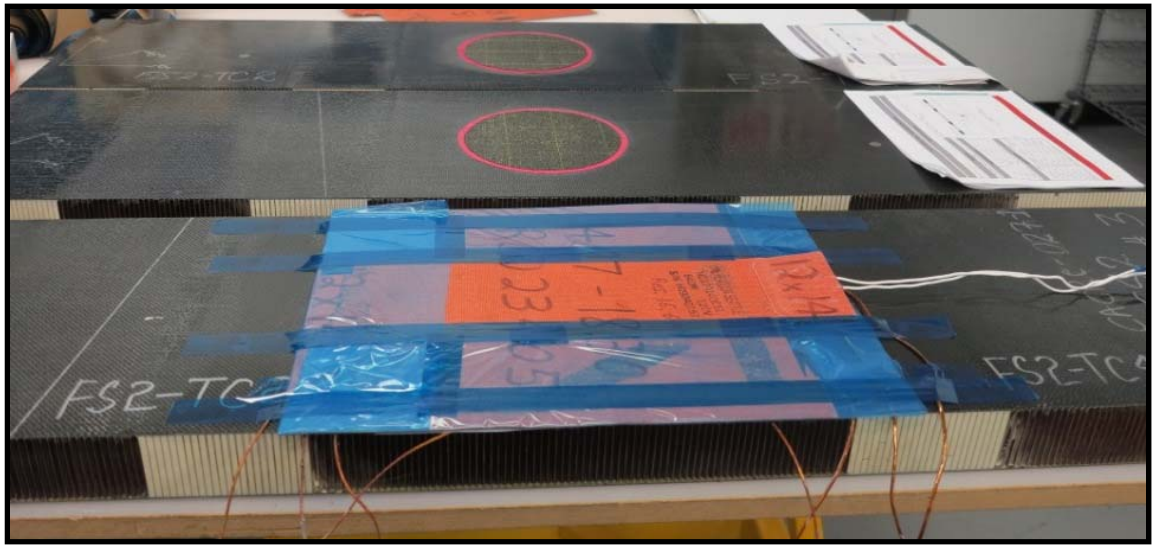
- Depot 5 performed repairs with CACRC materials (CACRC-R1 and CACRC-R2) only as defined in test matrix table



Scarfed Elements
prepared for drying

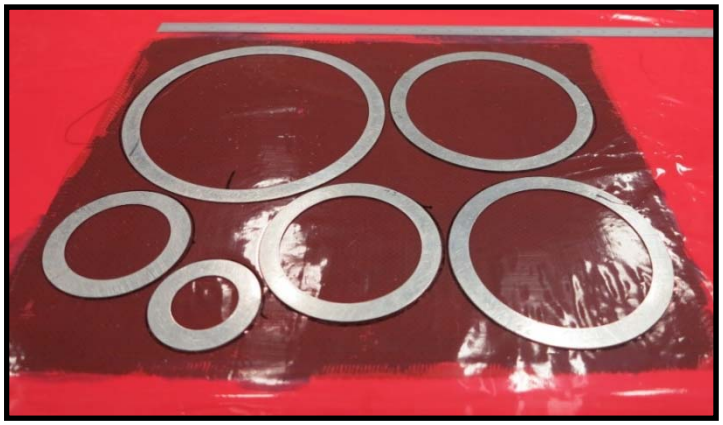




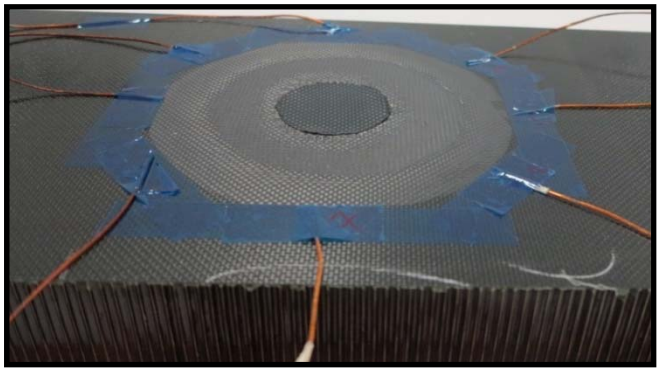



Prepreg Repair Application

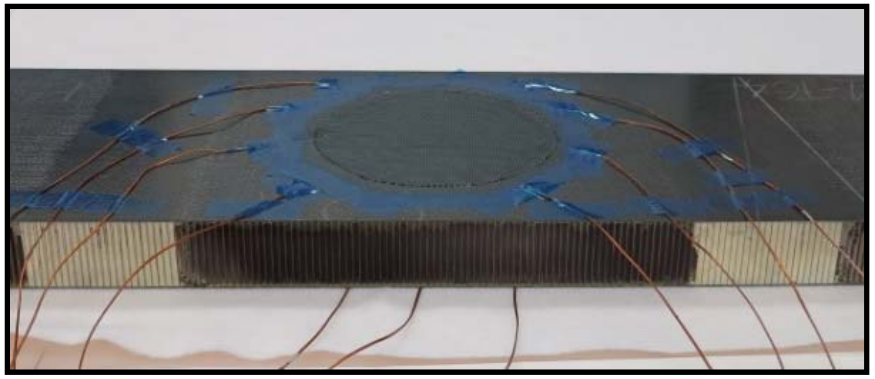
# CACRC Repairs - Depot #5



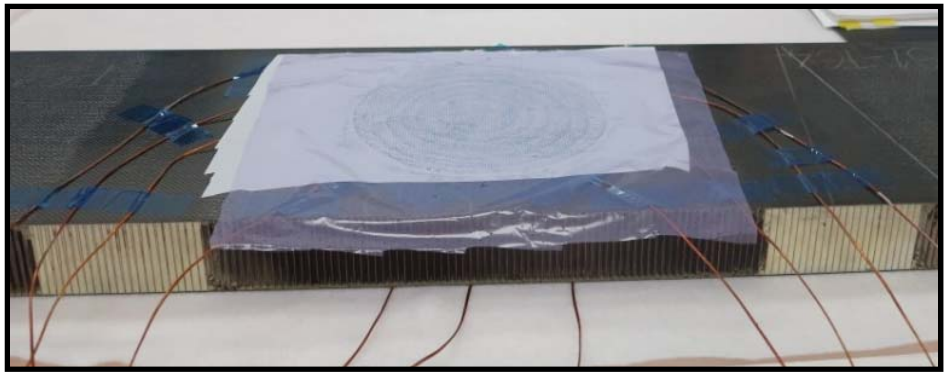
Wet lay-up ply impregnation



Wet lay-up repair application

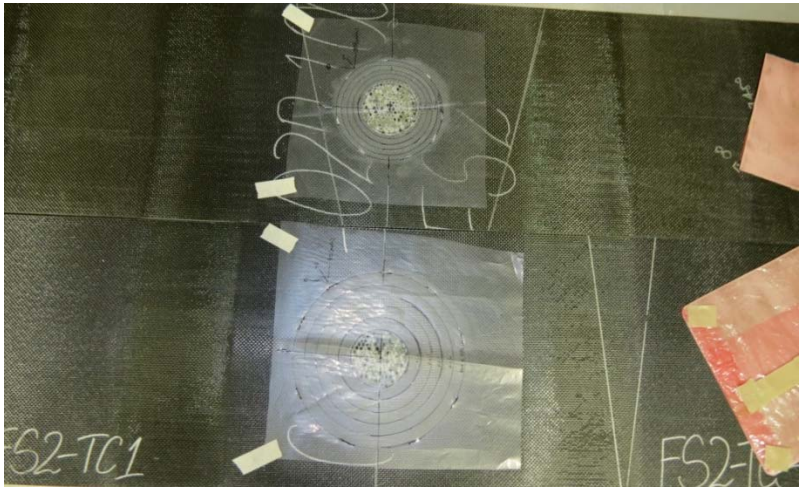


Wet lay-up repair application

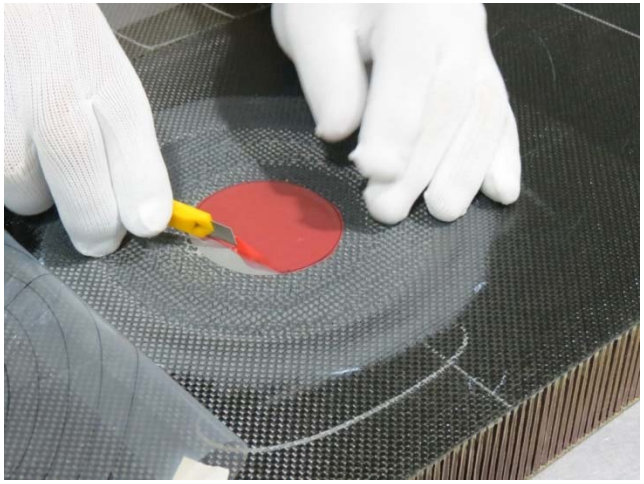


Wet lay-up repair bagging in preparation for cure

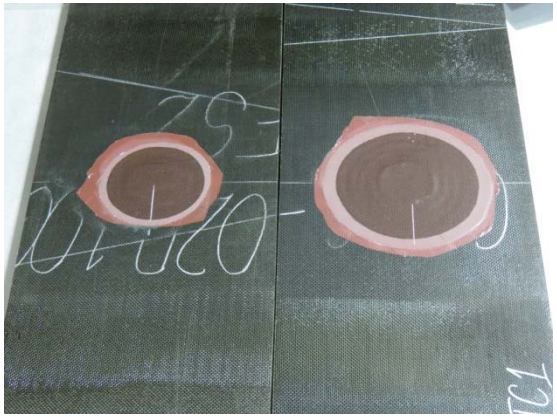
# OEM-R1 Prepreg Repairs



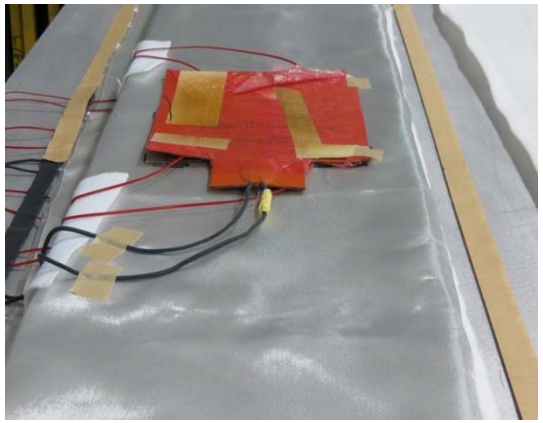

Scarfed panel ready for repair



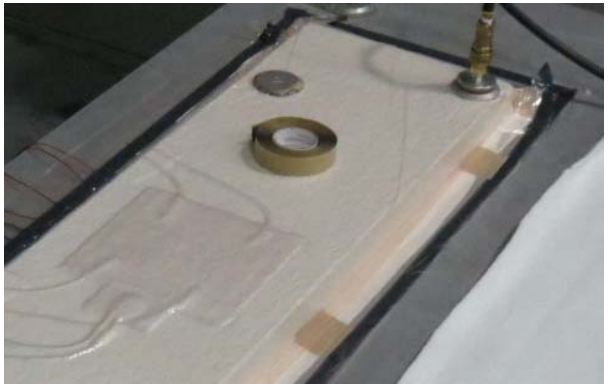
Repair Adhesive Application



Repair Application

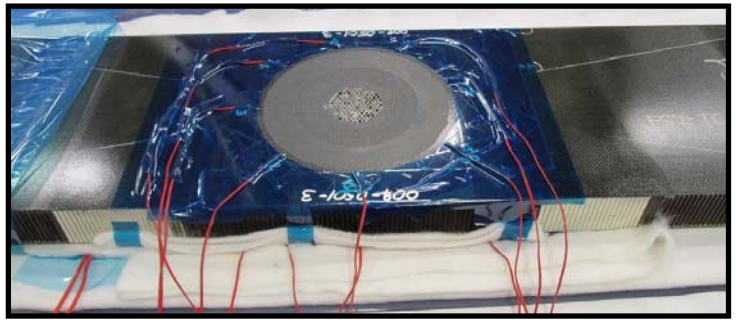


Heat Blanket Application

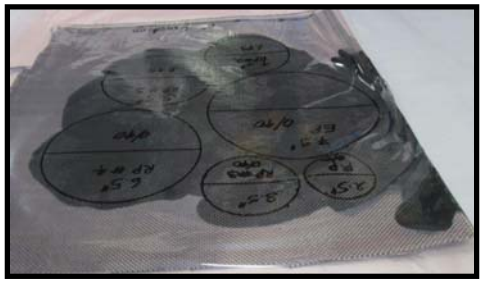


Panel Curing

# OEM-R2 Wet Lay-Up Repairs

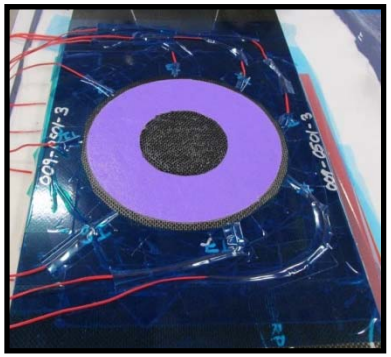


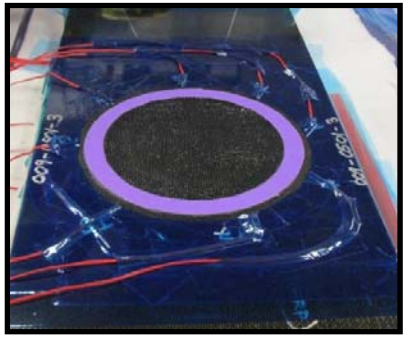
Scarfed panel ready for repair

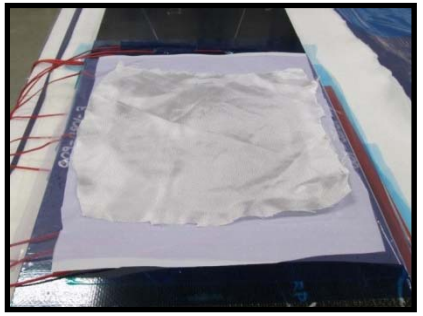


Wet Lay-up Fabric Impregnation

Wet lay-up
Repair ply
application

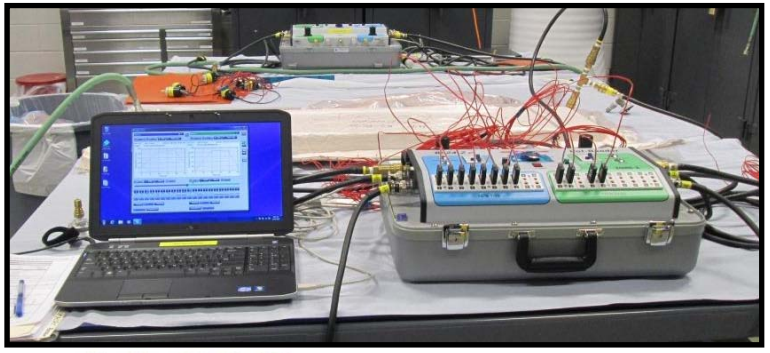






Wet lay-up
repair bagging

Heat Blanket
Application



Repair panel cure

# Prepreg Repair Checklist Review and Findings

- Repair Timeframe (December 2012, February 2013, March 2013, June 2013, October 2013)
- Repair station environment – not documented in some cases, temperature exceeds 70°F
- Prepreg Material within shelf life
- Material Out time, M20 prepreg (10 days AMS 3970)
- Material Out time, EA9695 adhesive (10 days AMS 3970)
- Adhesive material close to shelf life limit/ maximum out time in some cases (AMS 3970)
- Same batch of prepreg used, 2 adhesive batches used
- Time lag between drying and final cure (1 month time lapse in some cases)

Comments: "concerning repair station environment information, all 3 prepreg panels were prepared at the same time up to step 10. From that point on, steps 10-14 each panel was handled individually. Because of holidays vacation and local work demands for other products, these panels sat covered with solid release til scheduling allowed." "cure for spec 3 was cancelled 15 min after cure because I discovered that I did not put solid release in the lay-up"

- Bagging scheme (vertical bleed method was used for one set of prepreg repairs, instructions specify no bleed method)
- Ramp up rate varied between 3-5°F
- Soak time varied between 180-240 minutes
- Vacuum varied between 22-27in Hg

# CACRC Depot Repairs – Technicians Experience

**Experience**

- 16 Repair Participants took the survey
- 75% of all mechanics had an airframe or an A&P license
- Varying levels of experience and competency with composite materials
- OJT (Wet Lay-Up Repairs, Prepreg Repairs)

**Technicians' Perspective**

- More accessibility to engineering documentation and data
- Training with OEM documents and SRMs, training to particular repair manual (differences between aircraft to aircraft)
- No one standard structural repair manual ("2 years to get familiar with one SRM")
- Need for standardized SRMs and for material standardization (more robust processes, improved efficiency "5 days spent gathering repair information and tooling/ 5 hours to complete the repairs")
- Importance of training for a better understanding of the repair process for more effective and repeatable repairs and to minimize rework

# CACRC Depot Repairs – Observations/ Considerations

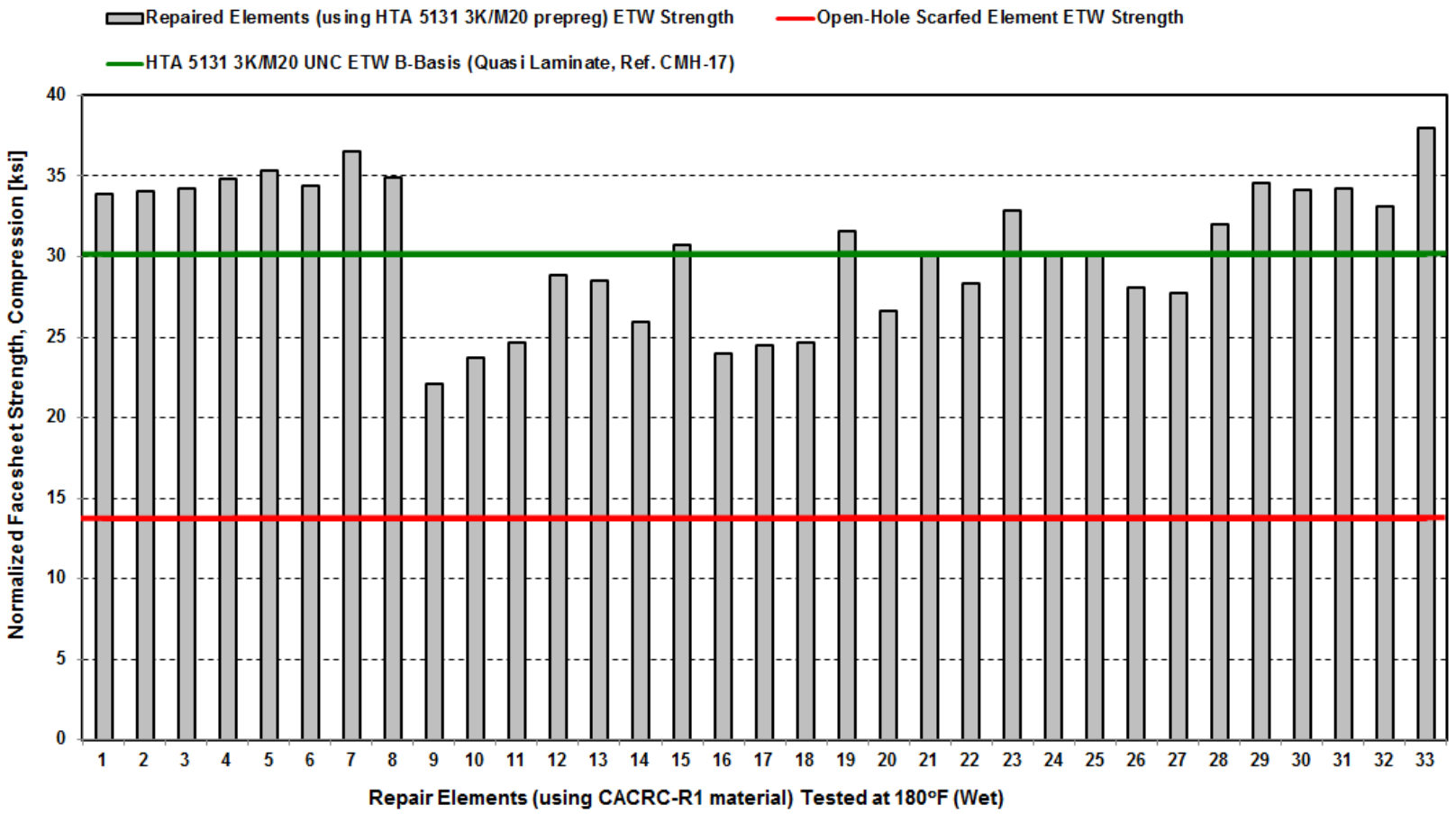
**OEM / Repair Station or MRO**

- Many repairs are performed on similar parts at an OEM, whereas at an airline depot a mechanic may only repair a given part occasionally (practice/training needed on the same part)
- Constraints to perform the repair within a limited timeframe (AOG), Continuity between shifts

**CACRC Standards**

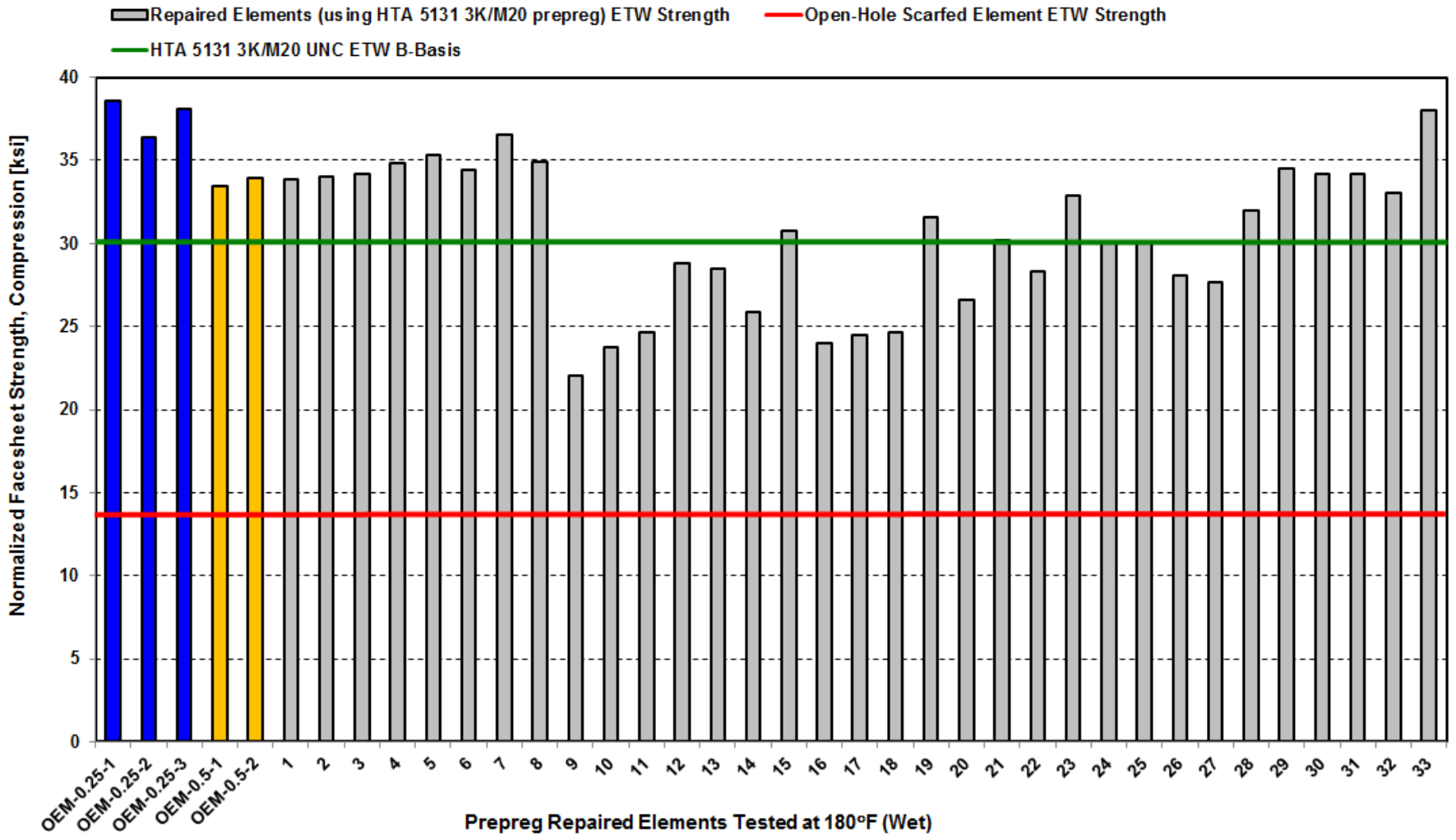
- CACRC standards cannot be used as a sole document without a detailed repair document, can be used along with an SRM
- Best practices/ techniques for repair (repair designer's responsibility to select which ones to use)
- Part specific document required (Ideally a part specific SRM)
- Difficulties interpreting the standards (wet lay-up repair standard, mixing ratios in ARP 5256), missing or incomplete information as well as unfamiliar nomenclature (mushroom sanding disk holder)

# Results – CACRC Prepreg Repairs using M20 PW / EA9695

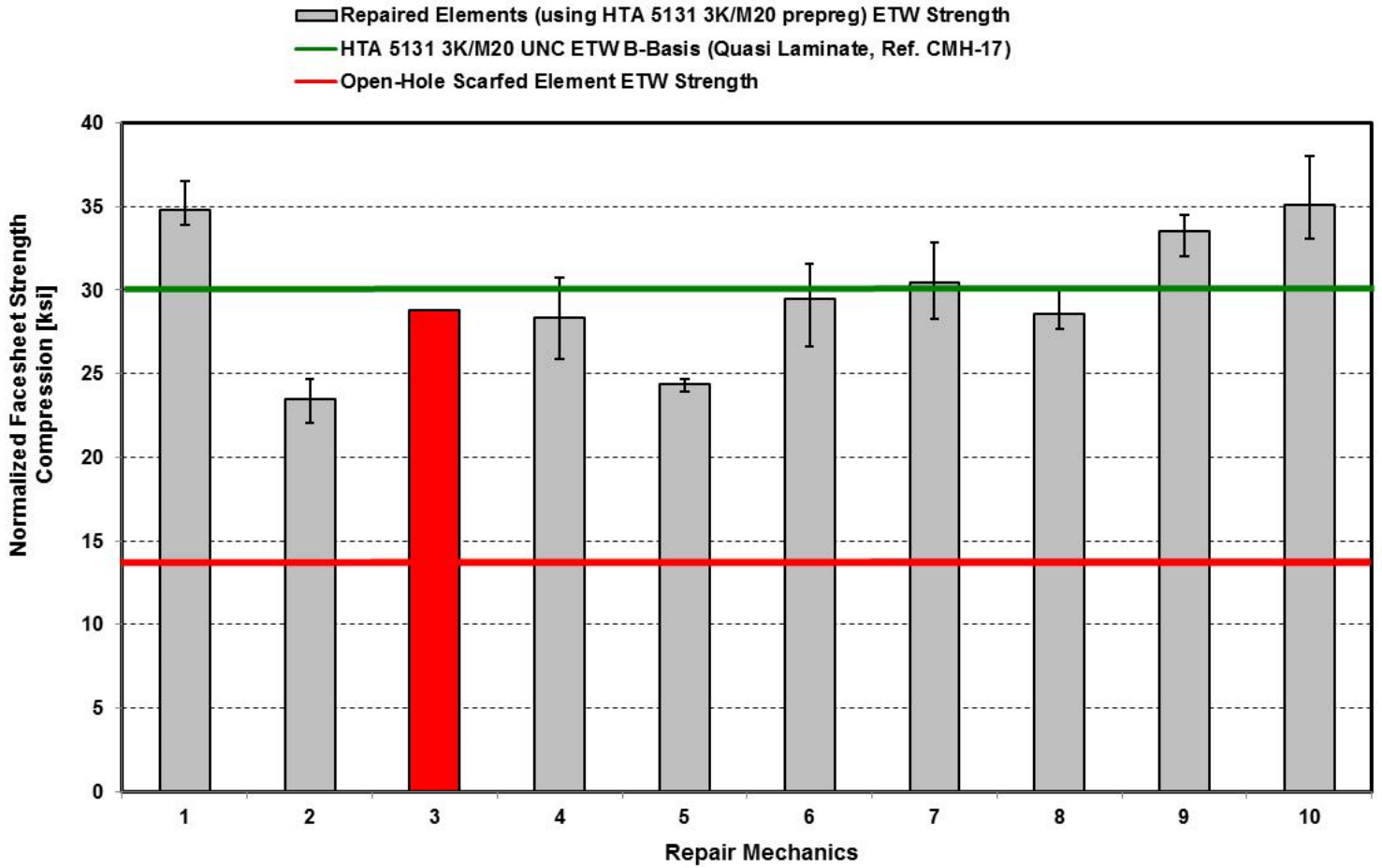



- 33 data points (instead of 39): 5 repairs not completed, 1 element damaged during testing
- Repair Element Average Strength: 30.5ksi Min=22.1ksi, Max=38.0 ksi, CPT=0.0083", COV 14.1%
- Undamaged Element Strength: 35.4ksi Min=32.9 ksi Unrepaired Open-Hole Scarf Strength:13.7 ksi
- M20 Laminate Compression QI OHC/UNC B-Basis Value (CMH-17)24 ksi/ 30.1 ksi

# Prepreg Repairs Data Summary



# Results – CACRC Prepreg Repairs using M20 PW / EA9695

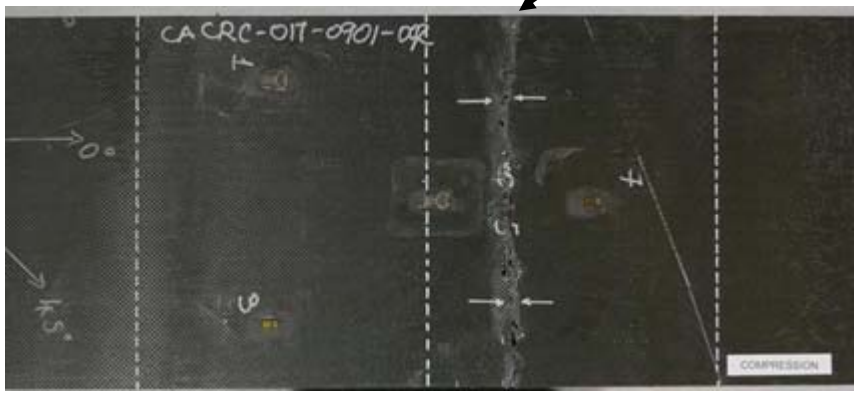



- Repair data (CACRC-R1), repair elements tested at 180°F (Wet)
- Participant#3 performed only one CACRC-R1 prepreg repair

# Results – CACRC Prepreg Repairs – Representative Failure Modes

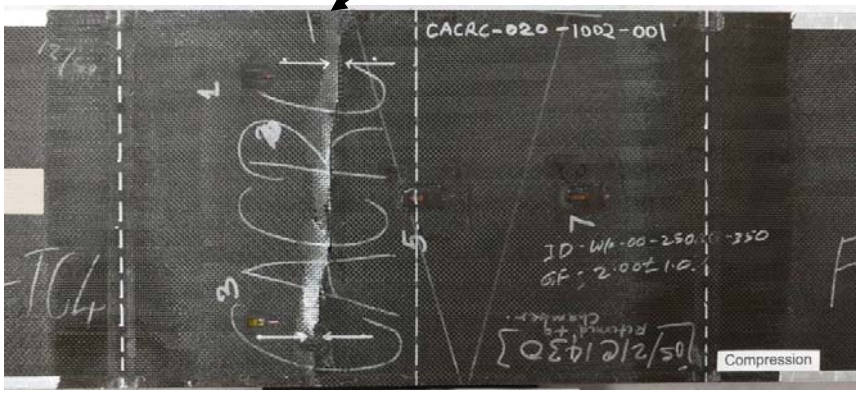
All baseline/ Undamaged Elements yielded facesheet compression failures in the gage section

Failure Location



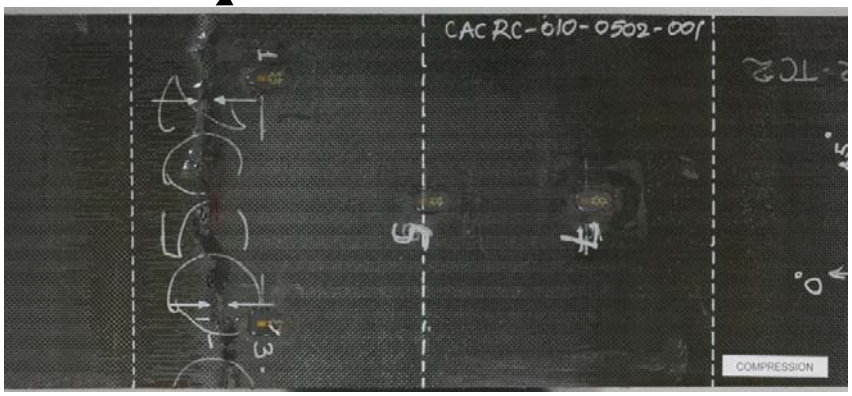

Gage Section

Failure Location




Gage Section

Failure Location

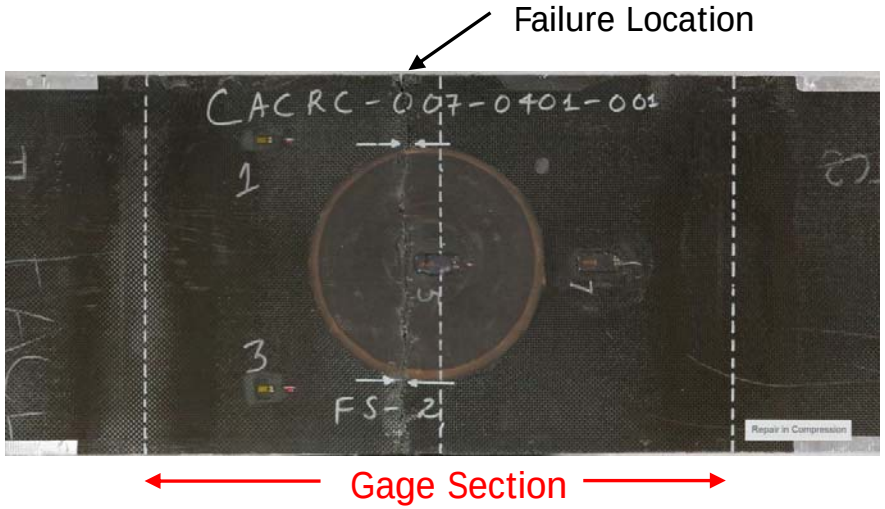


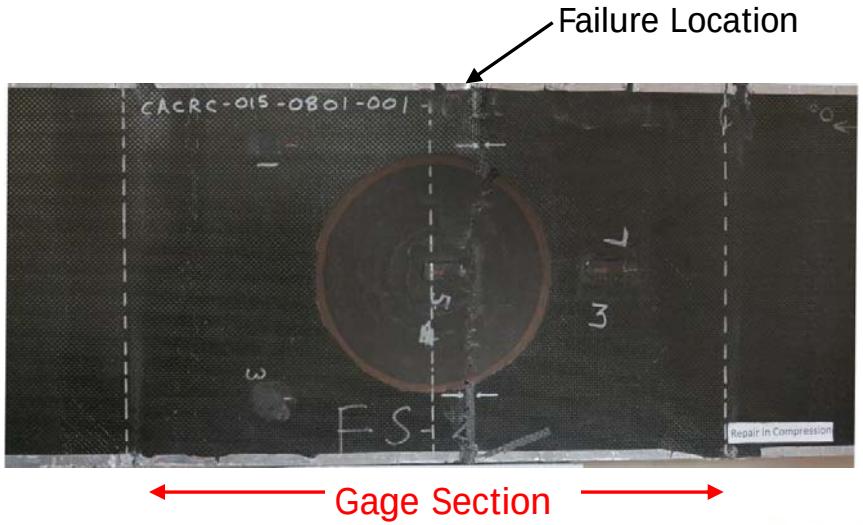

Gage Section

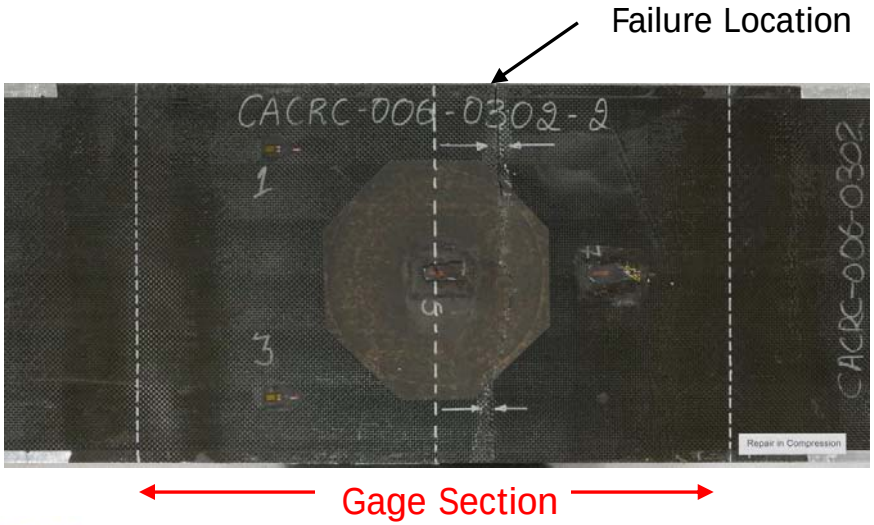
# Results – CACRC Prepreg Repairs – Representative Failure Modes

All elements repaired with CACRC prepreg yielded laminate compression failures in the gage section (48% failed outside the repair, 52% failed within the repair)

**No adhesion failures, all facesheet failures**



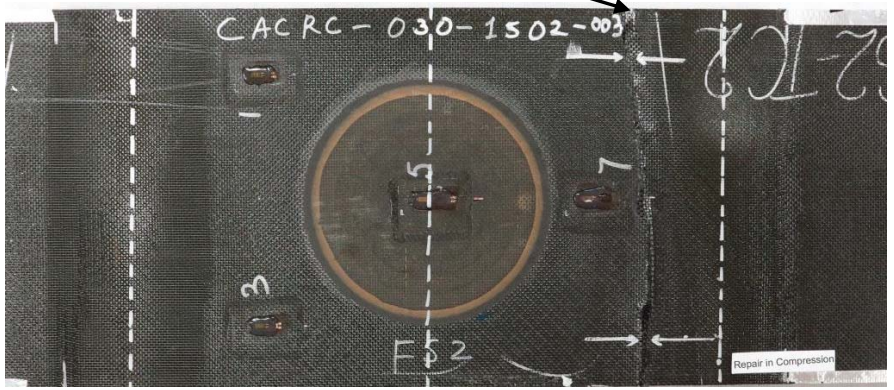



# Results – CACRC Prepreg Repairs – Representative Failure Modes

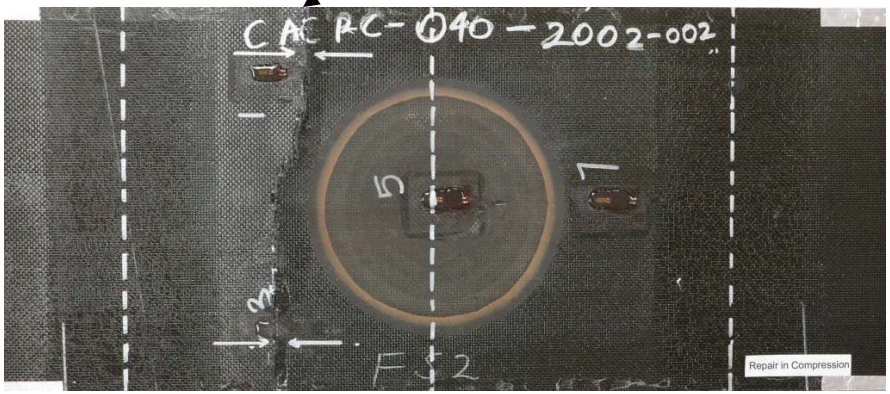
All elements repaired with CACRC prepreg yielded laminate compression failures in the gage section (48% failed outside the repair, 52% failed within the repair)

Failure Location



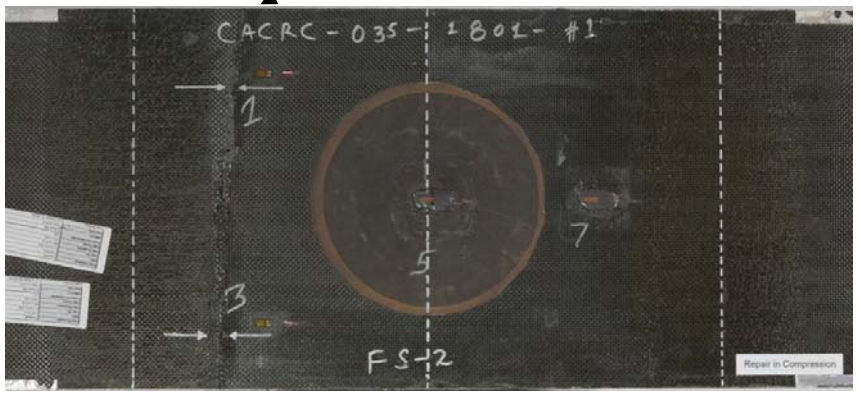

Gage Section

Failure Location




Gage Section

Failure Location

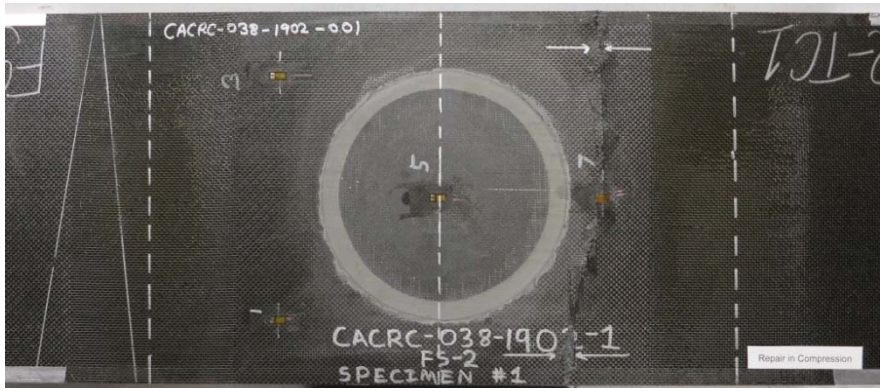



Gage Section

# Results – OEM Prepreg Repairs – Representative Failure Modes

All elements repaired with OEM prepreg yielded laminate compression failures in the gage section outside the repair

Failure Location




Gage Section

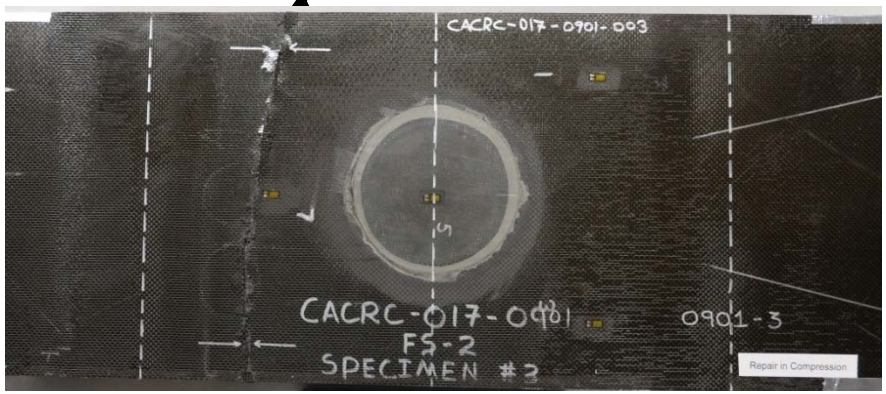
0.5” scarf overlap repair

Failure Location


Gage Section

0.25” scarf overlap repair

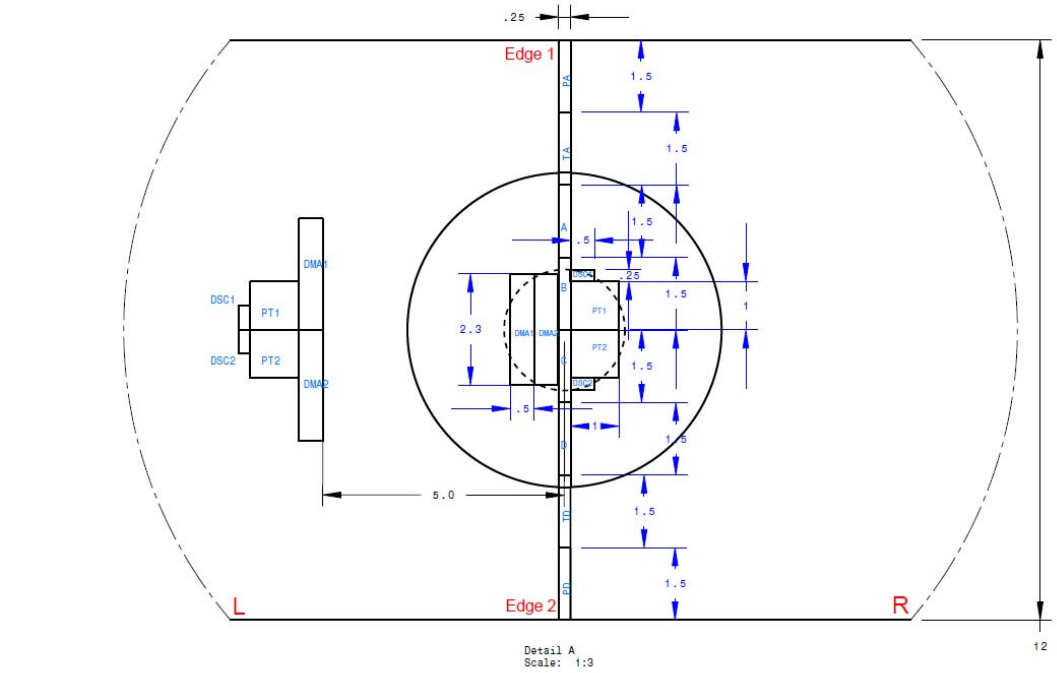
Failure Location

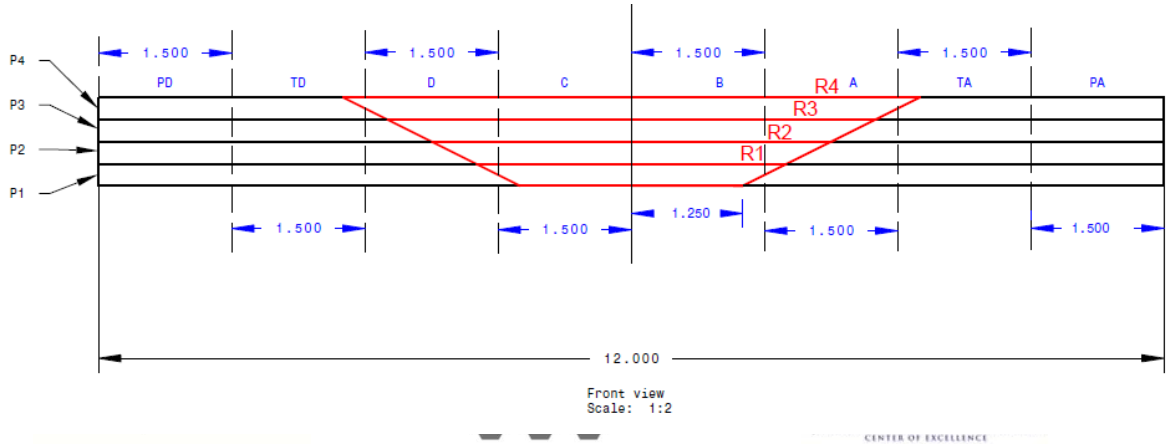



Gage Section

0.25” scarf overlap repair

# Post Test Analysis, Prepreg Repairs

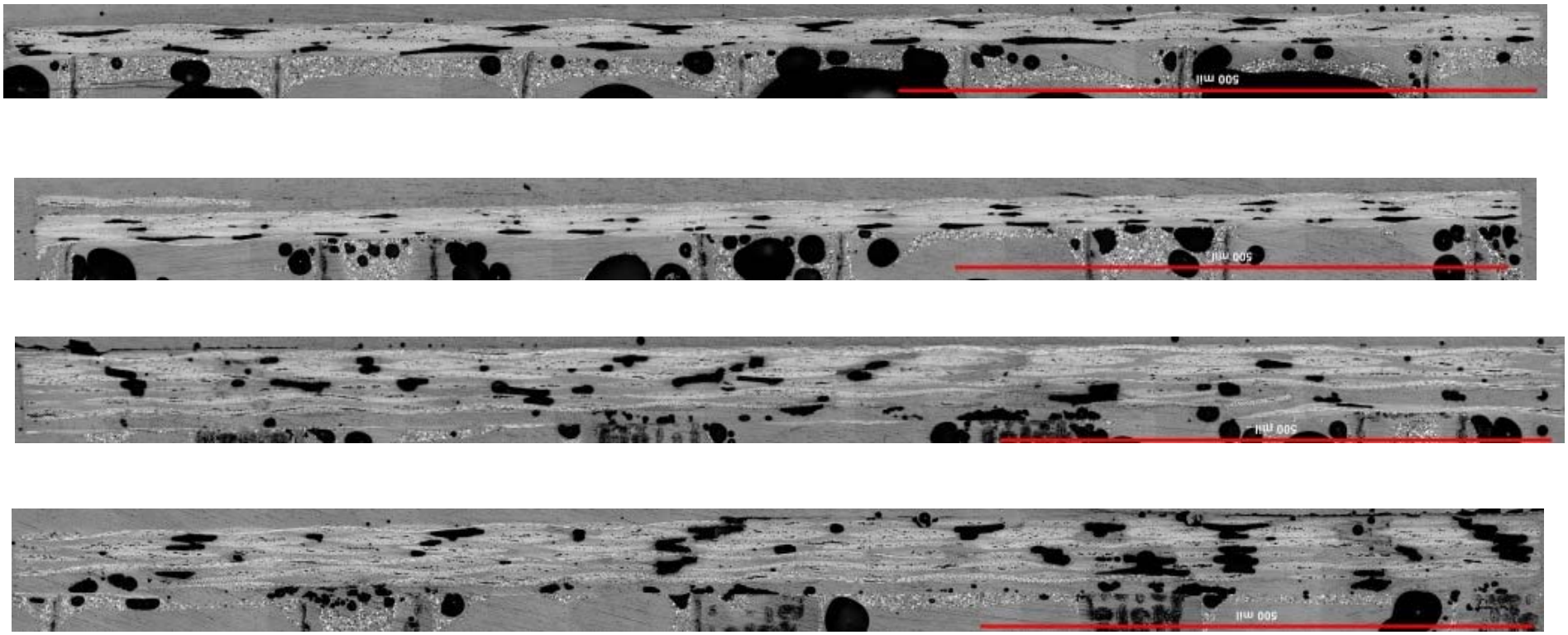


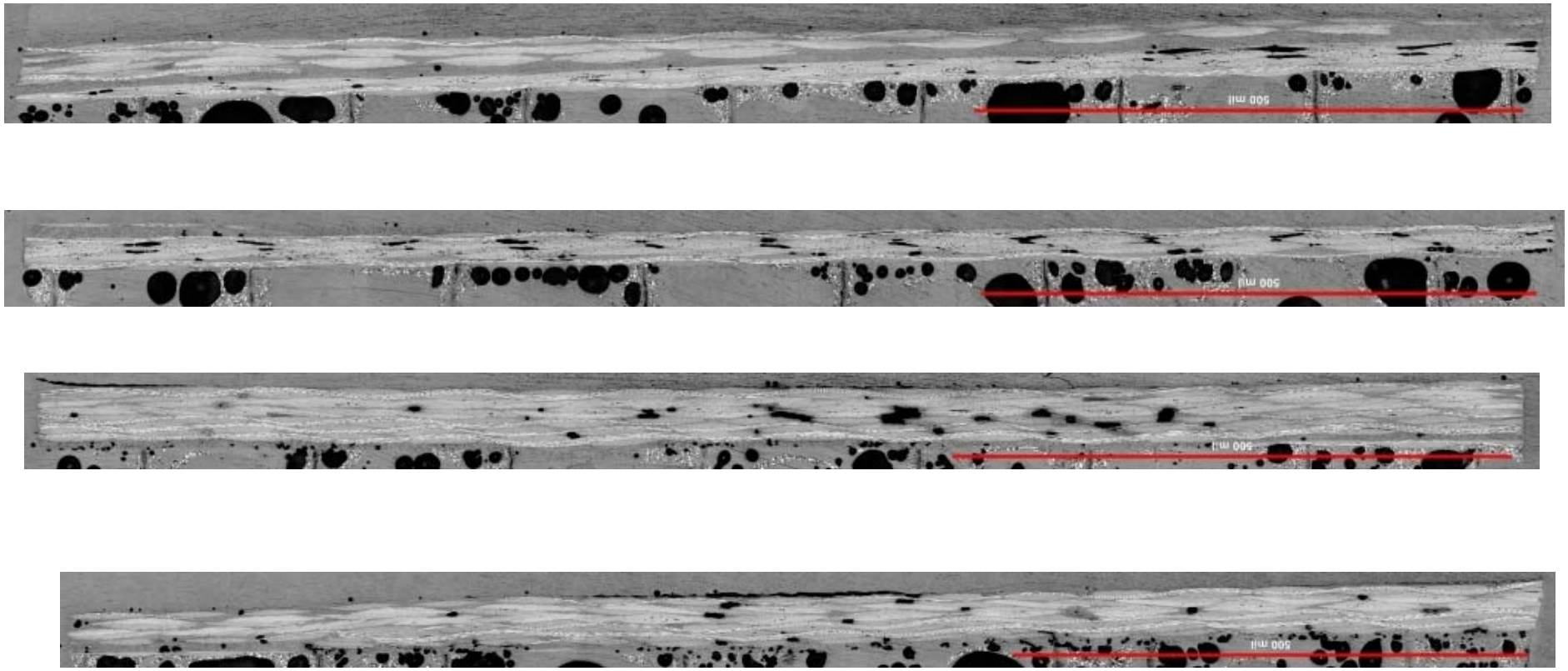

- Post-Test Analysis conducted on 29 elements repaired with M20
- Thermal Analysis
- Physical Tests
- Photomicrographs

- Optimal repairs
  - Porosity levels less than 4.2% (failure outside the repair)
- Low Performance/ Understrength repairs
  - High porosity (Up to 11%)

# Post Test Analysis, Porous Repair



# Post Test Analysis, Low-Porosity Repair



# Some Key Lessons

- **Infrastructure for maintenance and supportability** – robust repair design and execution will yield strong durable bonded repairs

- **CACRC standards** cannot be used as a sole document without a detailed repair document, can be used along with an SRM
  - Best practices/ techniques for repair (repair designer's responsibility to select which ones to use)
  - Part specific document required (Ideally a part specific SRM)

- **Workforce Education and Training**
  - Composite repair personnel education, training, certification and periodic training re-validation
  - Part specific training, taking into account learning curve (practice/ iterations with actual parts yielding consistent repairs)

# Some Key Lessons

- **Repair process development and substantiation**
  - Knowledge transfer (training, robust validated repair instructions, repair records and documentation)

    Detailed repair instructions specific to repair system

    Workforce proficient in all materials and processes used for repair