The Use of Composites to Repair and Replace Damaged Metallic Ship Structures and Components

Composite Patch Repair of Cracked Aluminum Plates

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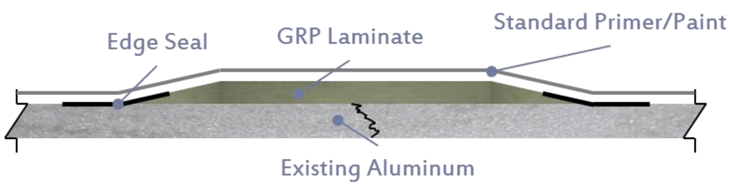
Naval Relevance

- Address cracking of aluminum deckhouses currently experiencing stress corrosion cracking as a result of inter-granular corrosion of sensitized plating
  - Generally not repairable by welding, often requiring large scale replacement of sensitized plating resulting in high maintenance costs to the fleet and potential impacts to operational availability
  - Composite patch repairs restore environmental and potentially structural integrity without further degrading adjacent structure thereby avoiding costly and time-consuming structural replacement

Composite Patches for Repair of Aluminum Ship Structure

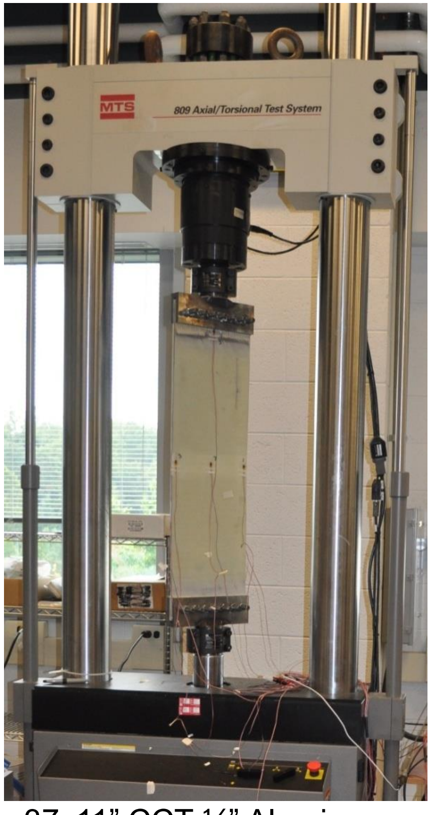
- Installed to repair aluminum superstructure cracks
- Designed for in-situ application
  - Conforms to local deck profile
  - Low modulus reduces stress concentrations
- Surface preparation and edge treatment details critical
  - Details specific to aluminum for enhanced bond strength and durability
  - Reinforced sealant protects patch edge from moisture ingress and mechanical wear
- Quasi-isotropic E-glass and toughened-epoxy laminate
  - Wet layup with vacuum consolidation and hand layup around deck details
- T&E on-going
  - Development of analytical, design, and decision tools and repair material
  - Formulation of resin or adhesives to meet FS&T and strength requirements
- 5+ years of fleet performance to-date
  - Prototypes aboard 11 ships totaling more than 1,600 sqft of laminate
  - Initial repairs performed FY11



Composite Patch Repairs (FY11-16)	
Total In-Service Repair Cost	$2.1M
Total Est Weld Repair Cost	$29.8M
Total Cost Avoidance	$27.7M
RDT&E Investment (FY'10-'16)	$6.1M

Fatigue Testing

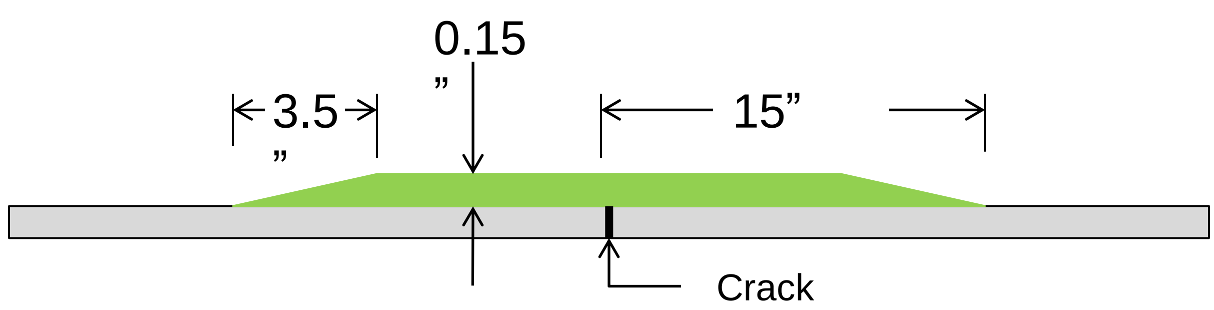
- Technical objective
  - Demonstrate performance of composite patch repair system
    - Delays initiation of crack progression
    - Limited laminate disbonding
    - Increased fatigue life
- Summary of Testing
  - Tension-tension cyclic loading
    - Far-Field Stress with a load rate of 1 Hz:
      - 5 ksi R=0.2 (Linear material behavior – Peak FEA deck stress)
      - 10.9 ksi R=0.1 (> 7.5ksi ABS Aluminum Fatigue Design Limit)
      - 14.5 ksi R=0.1 (Non-Linear material behavior)
  - Loading applied until failure
    - Failure = crack growth across entire width of aluminum plate
    - Stress levels of 5 & 10.9 ksi the composite patch continued to carry load
  - Data collected
    - Crack mouth opening displacement (CMOD) opposite of patch
    - Axial strain (far-field, in front of crack, across crack)
    - Load and actuator displacement
  - Aluminum
    - As-Delivered
    - Oven Sensitized



37x11" CCT ¼" Aluminum
0.15" Quasi-Isotropic Patch

Composite Patch Architecture

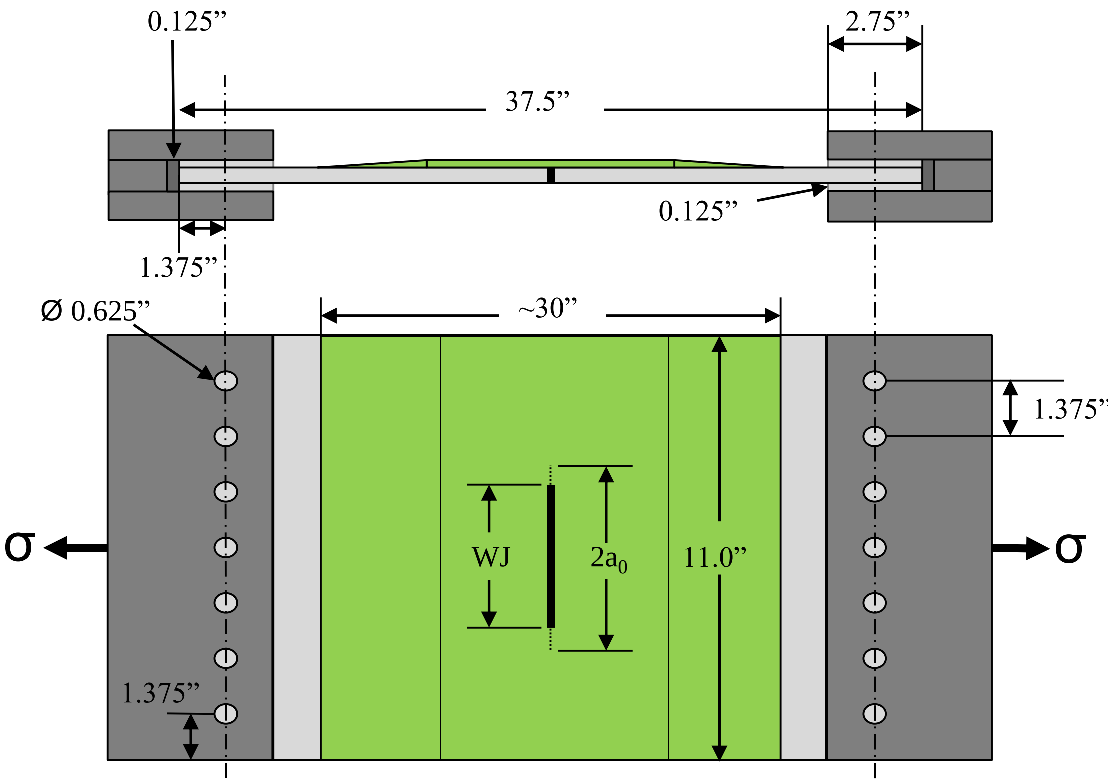
- Repair Patch Architecture and Procedure
  - Composite patches installed following standard procedure
    - Abrade surface, acid etch, apply silane bonding agent, hand laminate, vacuum consolidation, and post cure
  - Base plate: 0.25 inch 5456-H116 Aluminum plate
    - As-delivered
    - Oven sensitized (250^{0}F for 10 days to 47.3 mg/cm^2)
  - Layup:
    - 8 plies of E-Glass [7500/45/(0/90)/45/45/(0/90)/45/7781]
      - Hexcel 7500 E-Glass fabric (0.012 in/ply)
      - SAERTEX 12 oz Stitched ±45's (0.023 in/ply)
      - SARTEX 18 oz Stitched 0/90 (0.023 in/ply)
      - Hexcel 7781 8HS E-Glass fabric (0.011 in/ply)
    - Nominal thickness = 0.15"
    - ~3.5" Taper (0.5 in/ply drop)



8	7781
7	+45
	-45
6	0
	90
5	+45
	-45
4	-45
	+45
3	90
	0
2	-45
	+45
1	7500

Specimen Geometry

- Manufacturing Process
  - Cut to size and waterjet cut center notch
  - Bond tabbing to specimen ends
  - Fatigue load to grow initial crack length ($2a_0$)
    - Constant K: 10 ksi-in$^{0.5}$
  - Selected plates oven sensitized
  - Apply composite patch and post-cure

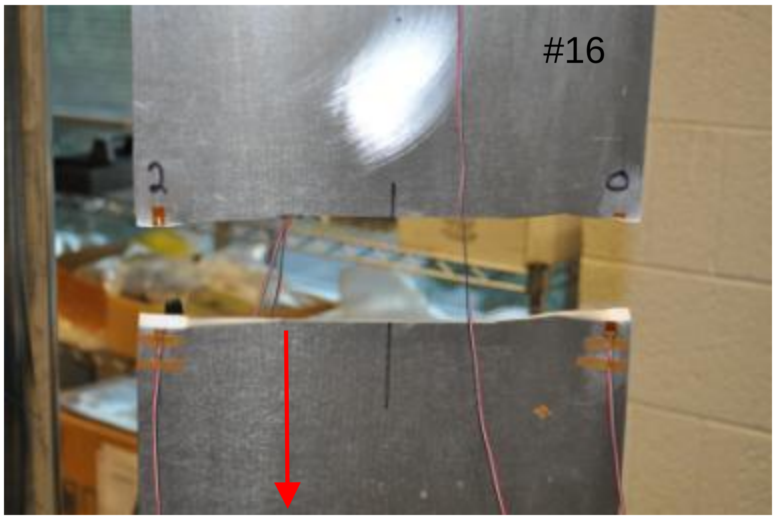


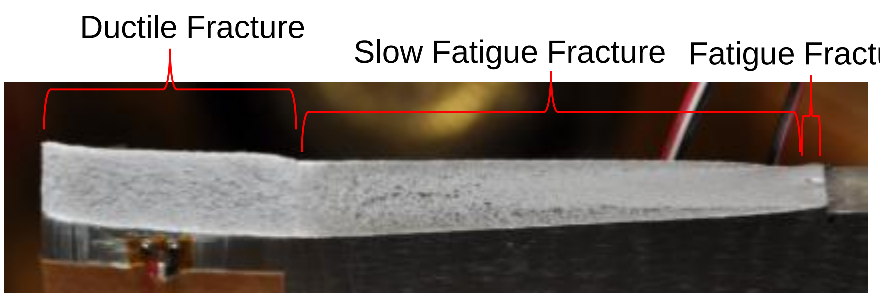
Specimen Dimensions

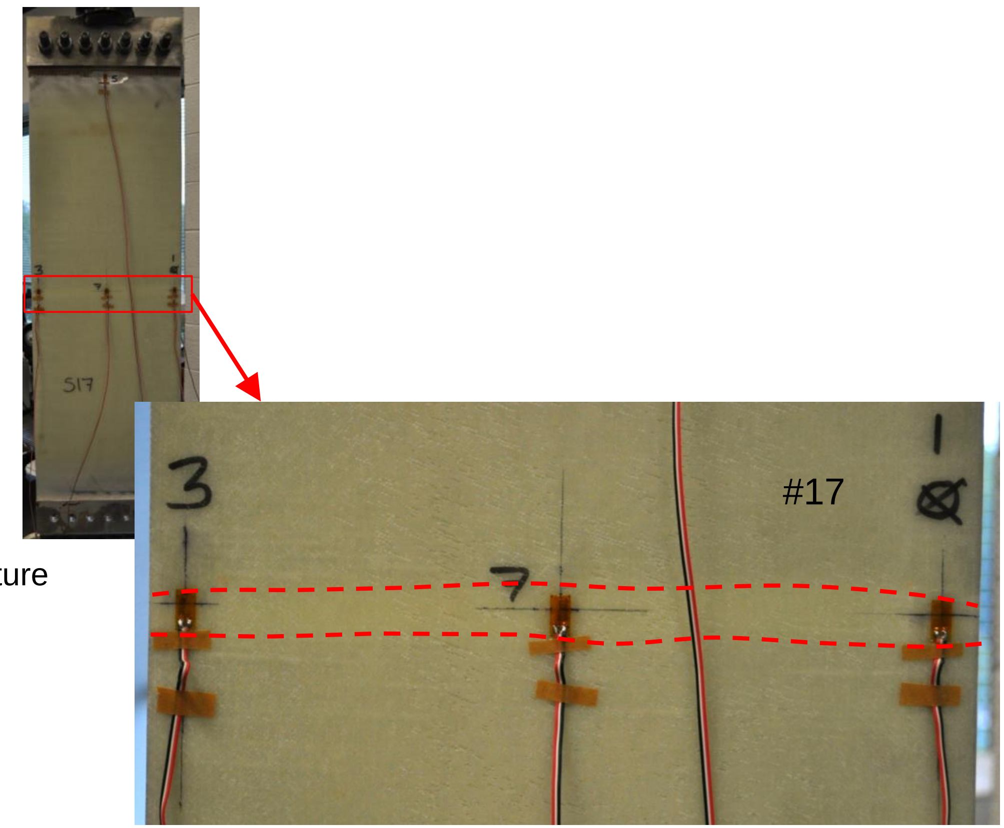
Specimen Width [in]	11
Specimen Length [in]	37.5
Patch Length [in]	~30
Number of Bolts	7
Bolt Diameter [in]	0.625
Pitch [in]	1.375
Bolt Edge Distance [in]	1.375
Bolt Side Distance [in]	1.375
WaterJet Notch (WJ) [in]	4.9
Tab Thickness [in]	0.125
Tab Length [in]	2.75
Initial Crack Length $2a_0$ [in]	5.0
Initial Aluminum Ligament [in]	3.0

Far-Field Stress 5 ksi

- Load cycled R=0.2 (3 – 14 kips)
  - #16 Failure at N=54,628 (Aluminum)
  - #11 Failure at N=284,300 (Aluminum w/Patch)
    - No disbond around crack, only loaded 3,000 cycles past aluminum failure
  - #17 Failure at N=234,800 (Sensitized w/Patch)
    - 0.5 in. Disbond across crack plane, additional 51,000 cycles past aluminum failure

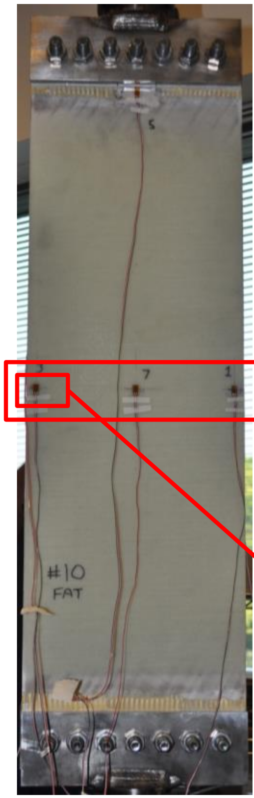


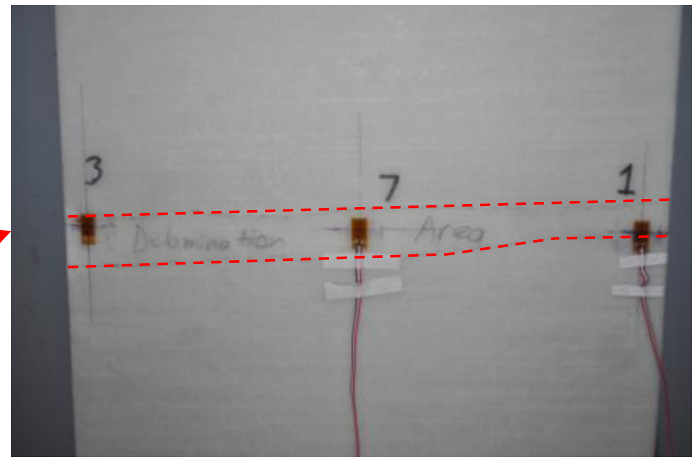


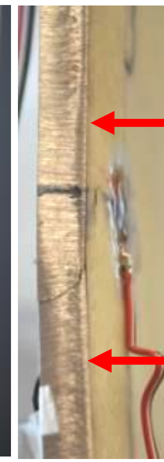


Far-Field Stress 10.9 ksi

- Load cycled R=0.1 (3 – 30 kips)
  - #15 Failure at N=5,305 (Aluminum)
  - #10 Failure at N=39,890 (Aluminum w/Patch)
    - 1 in. disbond across crack, only loaded 563 cycles past aluminum failure
  - #19 Failure at N=34,323 (Sensitized w/Patch)
    - Disbond initiates after aluminum failure near 36,000 cycles
    - Disbond grew until ultimate failure at 50,871 cycle





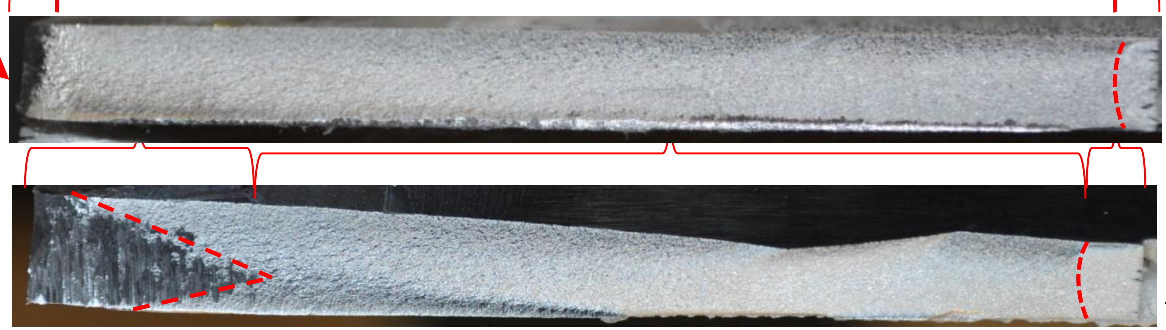


Bridging Under Load

Unstable Fracture

Slow Speed Fatigue Fracture

Fatigue Fracture



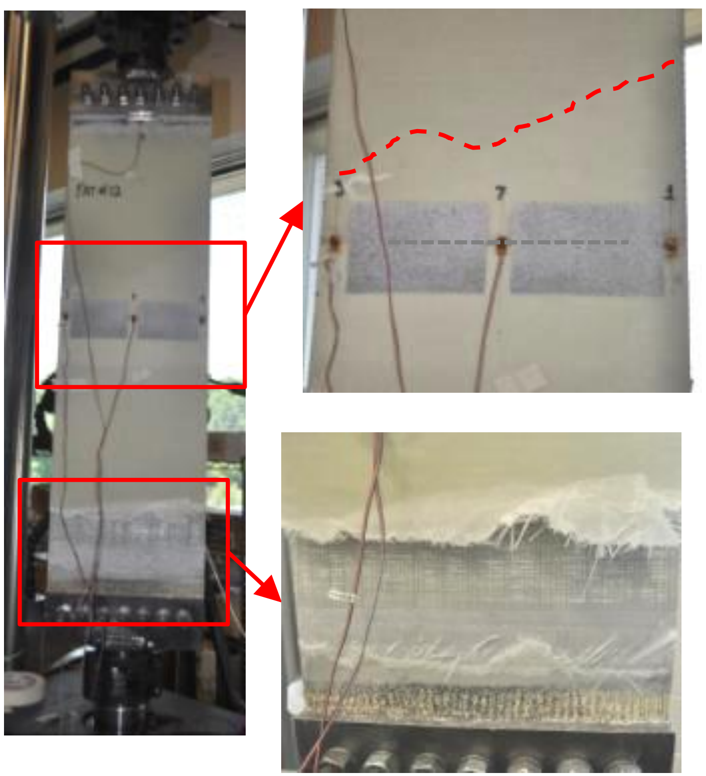
#10

#19

Note: Difference in unstable fracture surface for oven sensitized (typical)

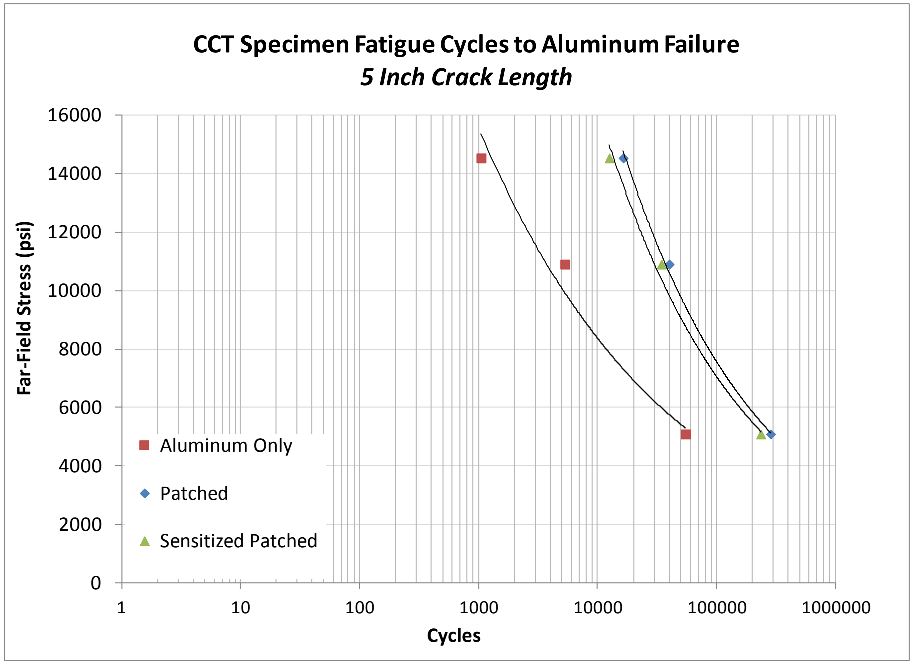
Far-Field Stress 14.5 ksi

- Load cycled R=0.1 (4 – 40 kips)
  - #14 Failure at N=1,047 (Aluminum)
  - #12 Failure at N=16,390 (Aluminum w/Patch)
    - Delamination and material failure 268 cycles after aluminum failure
  - #18 Failure at N=12,517 (Sensitized w/Patch)
    - Delamination started at aluminum failure and progressed for 364 cycles



Lower Laminate Plies Adhered to Lower Plate

Fatigue Test Results



- Single specimen per case
- Composite patch repair increased fatigue life more than 4x
- Increased benefit of composite patch with increased stress level (4x, 6x, and 10x)
  - σ = 5 ksi, R=0.2, Patch increased fatigue life by more than 4x
    - Composite patch continued to carry load, testing was stopped
  - σ = 10.9 ksi, R=0.1, Patch increased fatigue life by more than 6x
    - Composite patch continued to carry load, testing was stopped
  - σ = 14.5 ksi, R=0.1, Patch increased fatigue life by more than 10x
    - Composite patch material failure and delamination immediately following aluminum failure

Future Efforts

- Test composite patched shipboard sensitized aluminum plate
  - Complete data set with as-delivered, oven-sensitized, and shipboard sensitized plate
    - Clean, Heat Damage, Heat and Corrosion
- Development of data for additional applications of composite patches
  - Currently applied to low stress areas though higher capacity possible
  - Test applications with out of plane loading (pressure, bending, structural details)

- Proposing FY18 Future Naval Capability (FNC) Project “Non-Welded Repair of Naval Structures”
  - Goals
    - Fast and efficient options to meet operational availability (Ao) needs
      - Demonstrated >$25M in cost savings on CG-47 class (FY11-15)
    - Currently limited to non-structural repairs with fire performance (FS&T) limits
    - Applicable to reinforcement, plate wastage, corrosion, and cracking
  - Aluminum and Steel Products
    - Develop methods and materials to extend current composite patch repair from low stress applications to structural repairs and class wide alterations
    - Research and develop bonded repair for use on steel
      - Corroded/compromised tanks
      - Deck/hull plate wastage

Composite Material Repair

Review & Wrap-Up

15 December 2015

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