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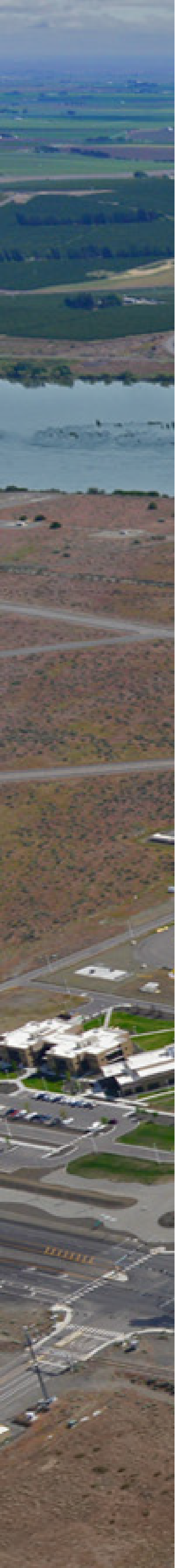

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U.S.NRC United States Nuclear Regulatory Commission

Protecting People and the Environment

NDE of Carbon Fiber Reinforced Polymer Composite (CFRP) Repairs

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PNNL

Work Sponsored by the U.S. NRC
Chinthaka Silva (COR)

NDE TIE Meeting, January 2026

U.S. DEPARTMENT of ENERGY BATTELLE

NDE of CFRP Materials

- The use of CFRP composites in nuclear applications under ASME Section XI has historically been limited and only recently applied to safety-related components
- In 2019, ASME approved Code Case (CC) N-871 for internal CFRP repairs of Class 2 and 3 piping for Service Levels A–D with a 50 year service life; CC N-871-1 was approved by ASME in October 2020 but was not included by NRC in Regulatory Guide 1.147 Rev. 21
- While NDE methods for ferritic and austenitic steels are well understood, the inspectability of CFRP repairs and the effects of manufacturing techniques remain poorly understood

Project Scope

Objective

- PNNL was tasked to perform confirmatory research to evaluate the capabilities and limitations of state-of-the-art NDE techniques for inspecting CFRP repairs and to identify the technical basis and best practices for CFRP qualification mockup fabrication to support reliable inspection

Scope

- Fabricate CFRP repair mockups per draft CC N-871-2 (record 24-2395), including representative flaws (e.g., substrate-to-composite disbands and interply delaminations) with varying substrate and laminate thicknesses and curvature
- Assess the impact of manufacturing parameters (e.g., fabric weight, epoxy content, layup practices) on NDE performance
- Evaluate multiple NDE methods, such as ultrasonic testing (UT), dynamic response spectroscopy (DRS), and tap testing, to:
  - Measure metal substrate thickness beneath CFRP repairs
  - Detect and characterize defects, including disbonds and delaminations
  - Determine the viability of tap testing as a screening tool

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Critical Areas for NDE

- The most critical examinations are:
  - the **substrate at the terminal end** under the composite
  - the **bond** between the substrate and composite at the terminal end
    - ✓ The integrity of the underlying substrate at the terminal end and the composite-to-metal bond is critical for load transfer
    - ✓ If the terminal end fails to retain structural integrity or the bond fails, it is reasonable to expect that the repair will fail to function as intended
- The second most critical examinations are for laminar flaws (voids or delaminations) within the composite laminate itself
- Tap testing is recommended for terminal ends as a screening tool to detect major defects in the composite laminate, including potential disbonds between the laminate and substrate.

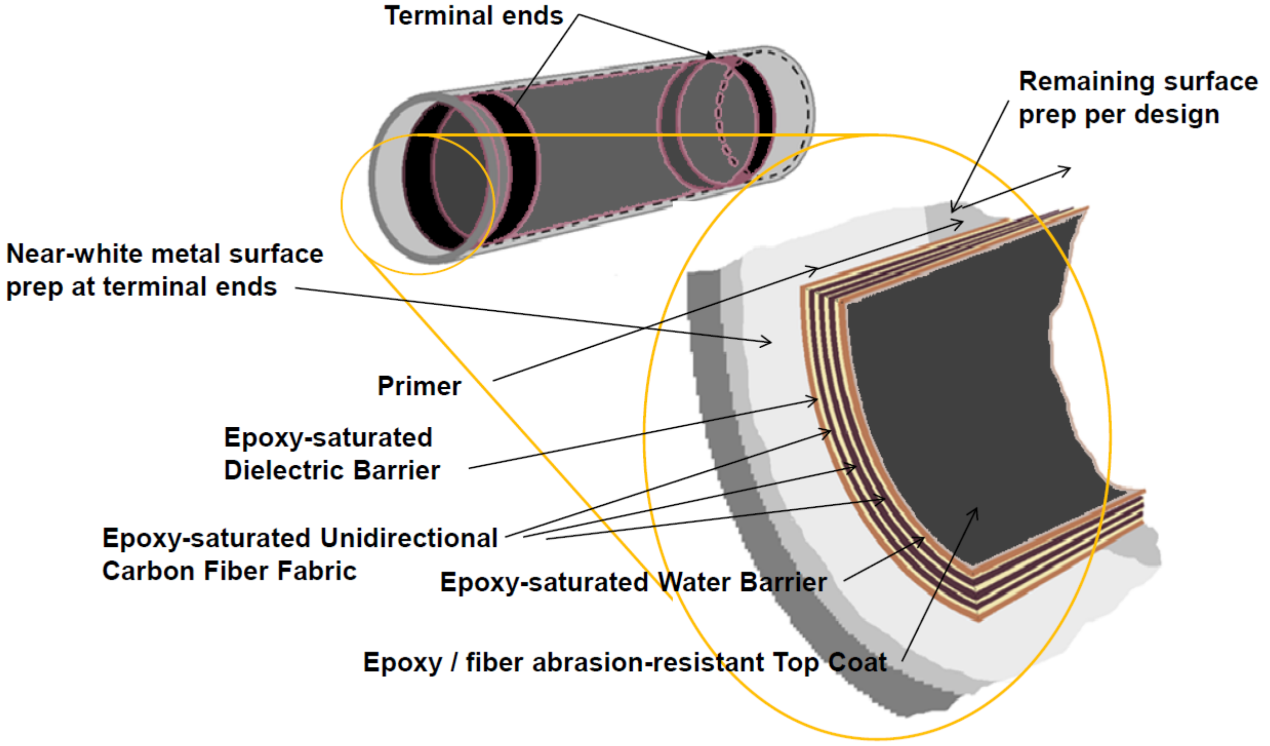
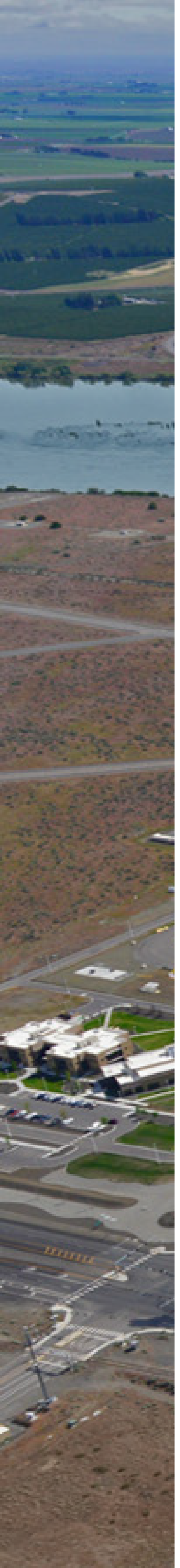
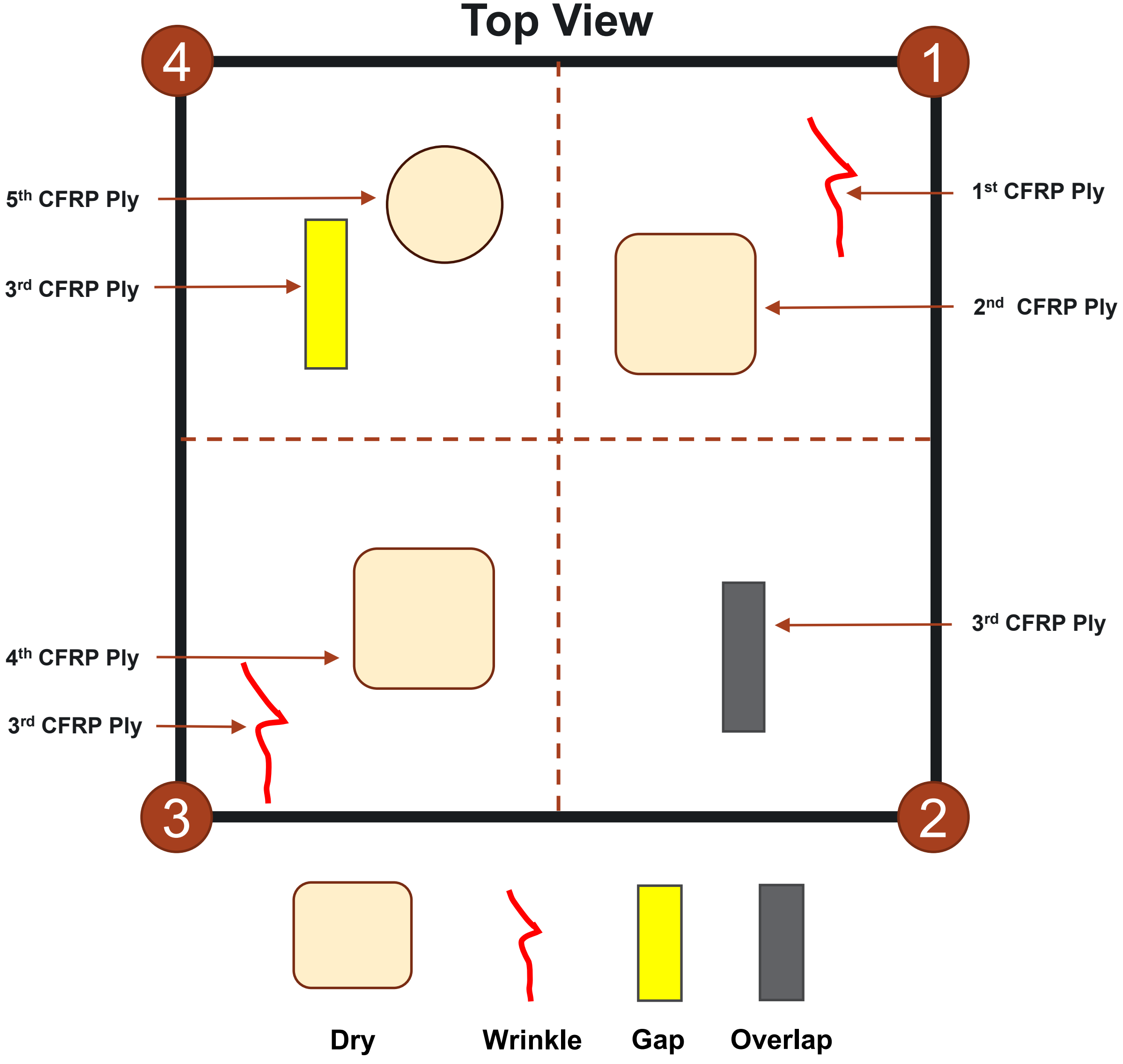


Figure on “CFRP Repair” from ML20014E606, Jim O Sullivan, “Code Case N-871-1 Status Update,” NRC Technical Exchange meeting, 2020

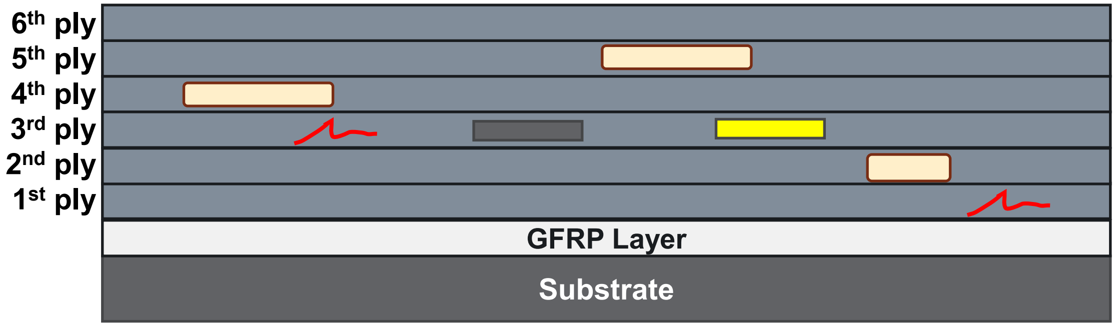


PNNL CFRP Mockups: Generic Design

Top View

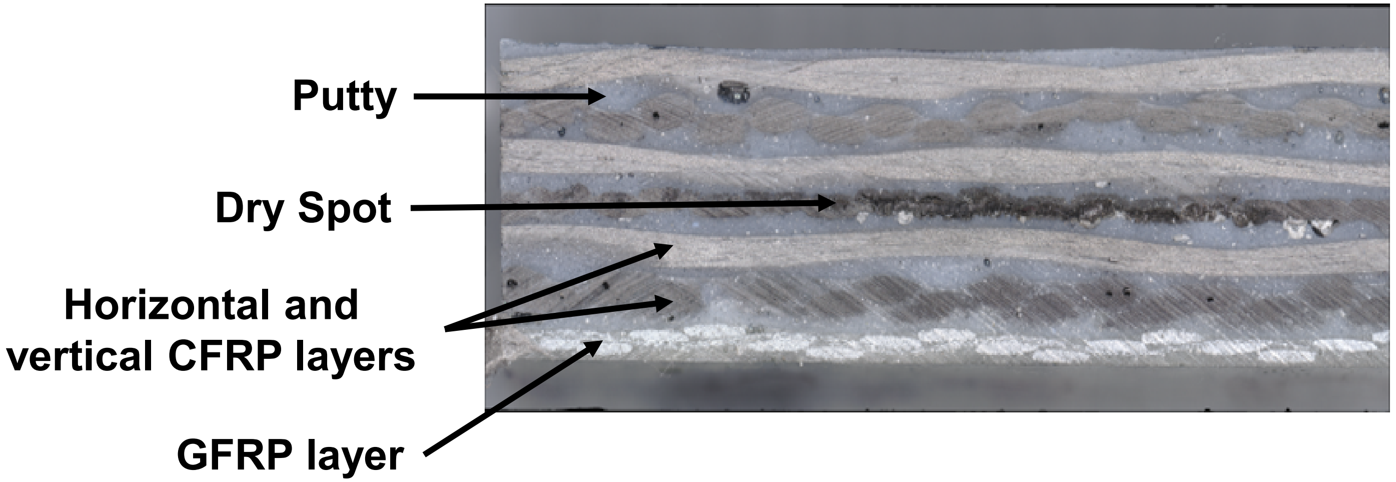


Side View



Putty and topcoat are not shown

Example cross-section, no substrate



PNNL CFRP Mockups: Test Matrix

- Eight CFRP plate mockups, each with six plies of CFRP and one ply of glass fiber reinforced polymer (GFRP)
  - Varying percent of fumed silica in putty: 6.3%, 8.3%, 10.3%
  - Putty layer thickness 0.031 in., 0.125 in.
  - Carbon fabric 19.5 oz/yd^2, 0.036 in. thick
- Two Mockups (7 and 8) had varying surface preparation and defects in the GFRP layer

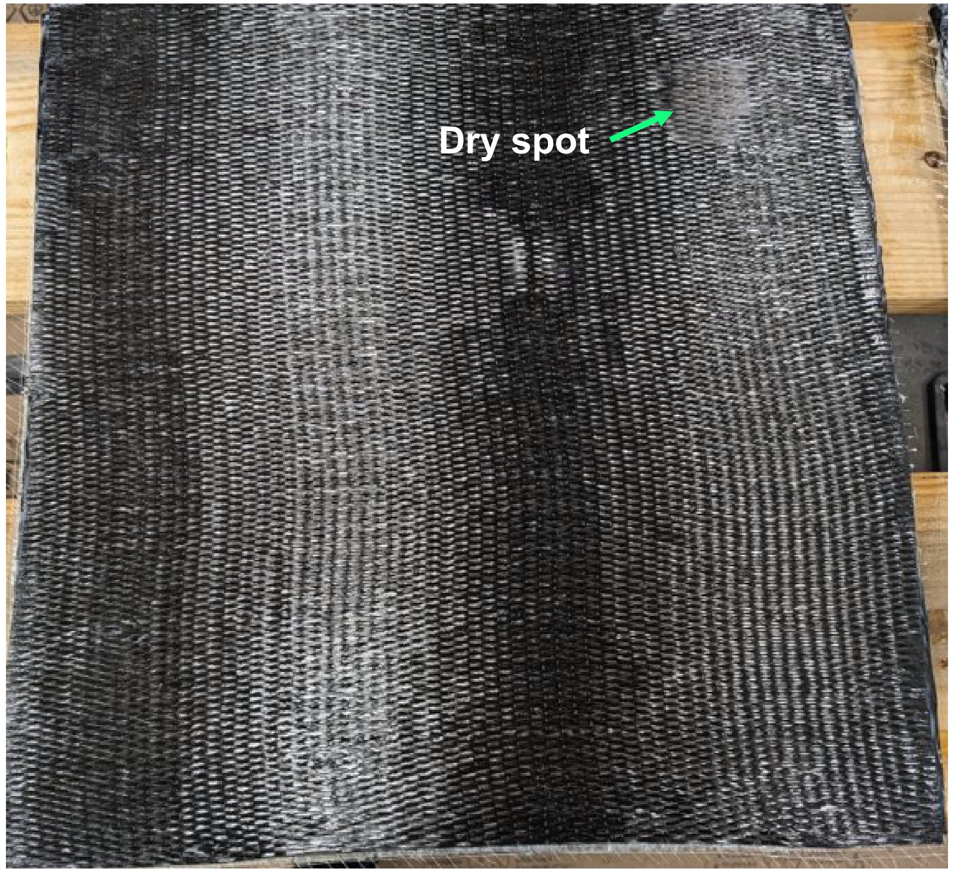
Mockup	1	2	3	4	5	6	7	8
% of Fumed Silica	6.3	8.3	10.3	6.3	8.3	10.3	8.3	8.3
Thickness of Putty Between Each Layer (in.)	0.031	0.031	0.031	0.125	0.125	0.125	0.031	0.125
Dry Spot (9 in.^{2} square)	*P2-Q1 P4-Q3	P2-Q1 P4-Q3	P2-Q1 P4-Q3	P2-Q1 P4-Q3	P2-Q1 P4-Q3	P2-Q1 P4-Q3	P0-Q1	P0-Q1
Dry Spot (3 in.^{2} circle)	P5-Q4	P5-Q4	P5-Q4	P5-Q4	P5-Q4	P5-Q4	P0-Q1	P0-Q1
Wrinkles (2–3 in.)	P1-Q1 P3-Q3	P1-Q1 P3-Q3	P1-Q1 P3-Q3	P1-Q1 P3-Q3	P1-Q1 P3-Q3	P1-Q1 P3-Q3		
Gap (3 in. long × 1 in. wide)	P3-Q4	P3-Q4	P3-Q4	P3-Q4	P3-Q4	P3-Q4		
Overlap (3 in. long × 1 in. wide)	P3-Q2	P3-Q2	P3-Q2	P3-Q2	P3-Q2	P3-Q2		
Primer Partial Cure Before Ply							P0-Q2	P0-Q2
Lack of Adhesion (Improper Surface Prep)							P0-Q3	P0-Q3

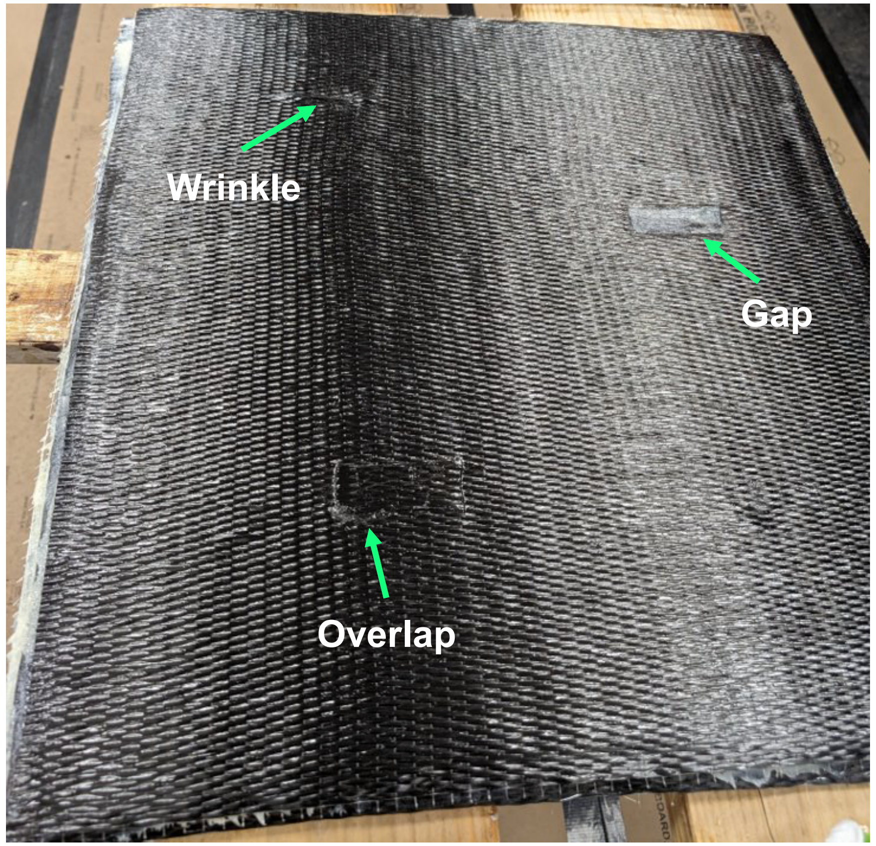
*P=Ply, Q=Quadrant

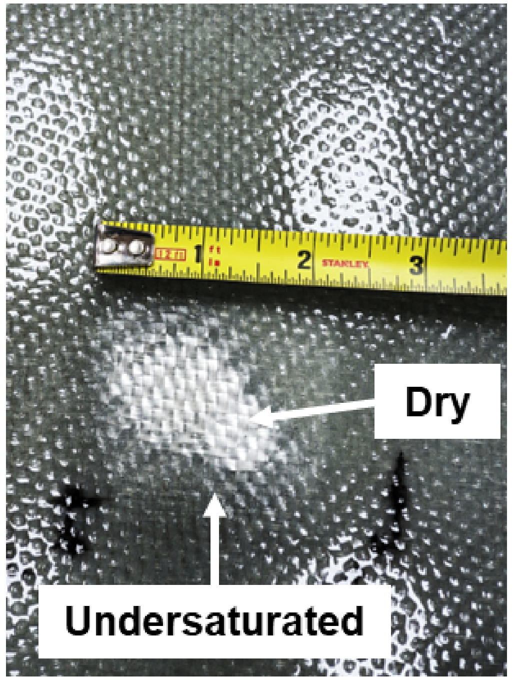
Elen M., N.A Conway (2025) "NDE of Novel Materials (CFRP)" PNNL-36392, NRC ADAMS ML25111A059

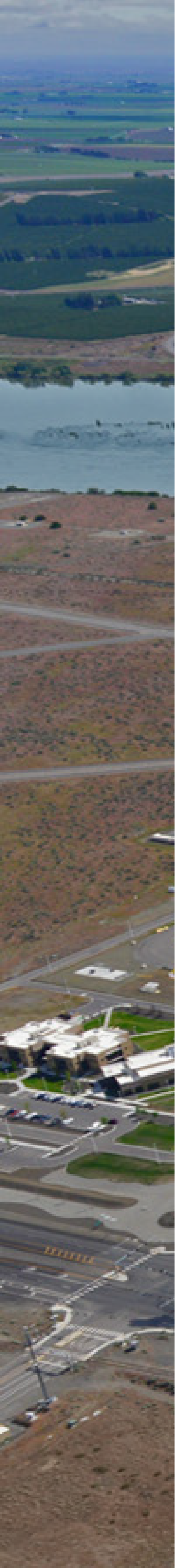
CFRP Mockup Defects

- Fabrication of the dry spots was difficult, as the planned dry spots were 9 in.^{2} and 3 in.^{2}, but due to fabric saturation, the area was reduced, resulting in a combination of undersaturated and dry spots
- Note that CC N-871-1 requires defects in terminal ends larger than 2 in.^{2} to be repaired; essentially all the dry spots in the mockups exceed this and must therefore be detectable with NDE





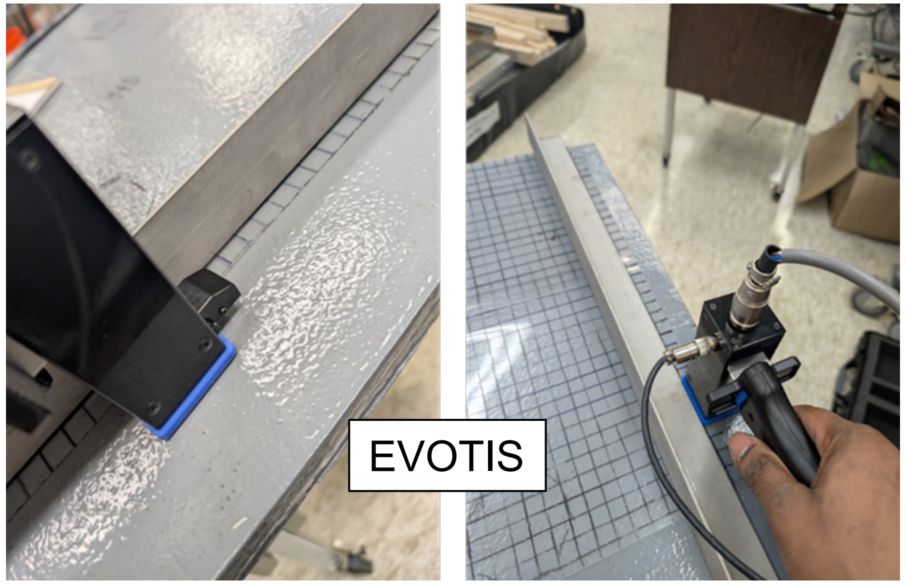




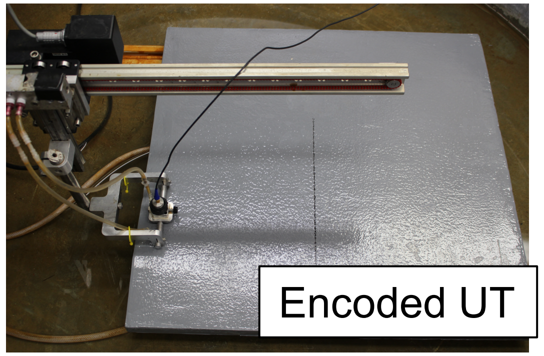
NDE Data Collection at PNNL

- Manual tap testing (MTT)
  - Aerospace tap hammer
  - Low-cost
  - Easily deployable
  - Requires trained inspector to interpret audible responses for flaw identification
- Automated tap testing (ATT)
  - EVOTIS Automated Tap Tester
  - Measures both piezoelectric and acoustic response
  - Records measurements digitally and processed through data analysis
- Encoded/Automated pulse-echo ultrasonic testing (PE-UT) method
  - Zetec DYNARAY w/ ZMC^2 (UV3, 2.5 mm scan/step increment)
  - Olympus V101 (0.5 MHz, 1.0 in. diameter) and Krautkramer 389-057-070 BMC (1 MHz, 0.5 in. diameter with 1 in. Rexolite delay line)
    - Frequencies were chosen based on preliminary testing
    - Normal beam (i.e., 0 degree incident angle)
    - Contact probe
    - Pulse-echo

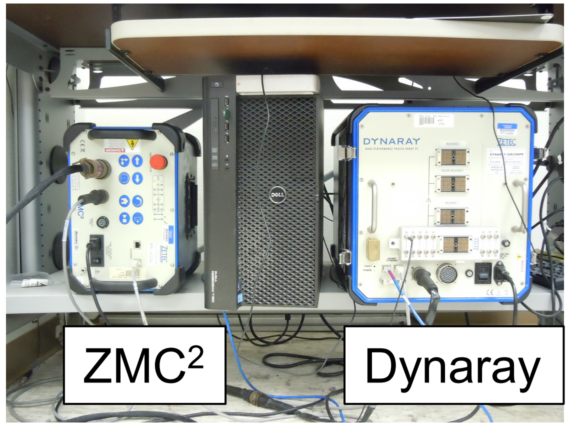
Manual Tap Hammer



EVOTIS



Encoded UT



ZMC^2

Dynaray

UT Transducers

Dynamic Response Spectroscopy (DRS)

- Dynamic response spectroscopy (DRS) is a UT method of measuring the substrate thickness. It also provides information about the location and extent of disbond and delamination defects.
- DRS uses low-frequency UT to penetrate the CFRP layers and interrogate the substrate using a frequency resonance technique.
- DRS was performed on all eight PNNL mockups by Sonomatic, Inc.

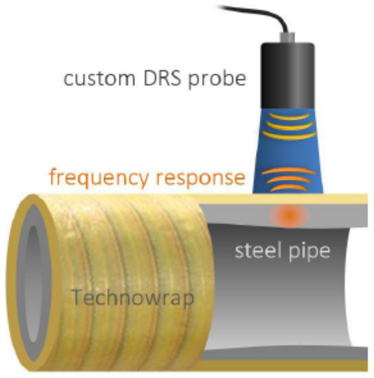


Figure A2: DRS inspection through coating.

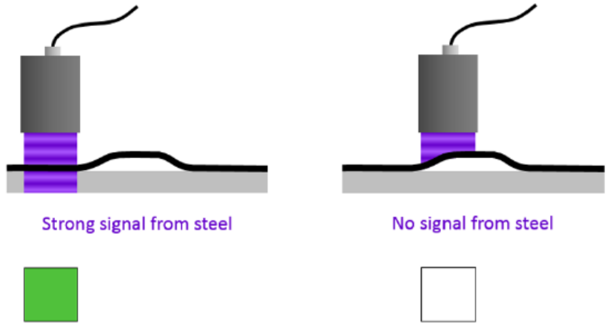


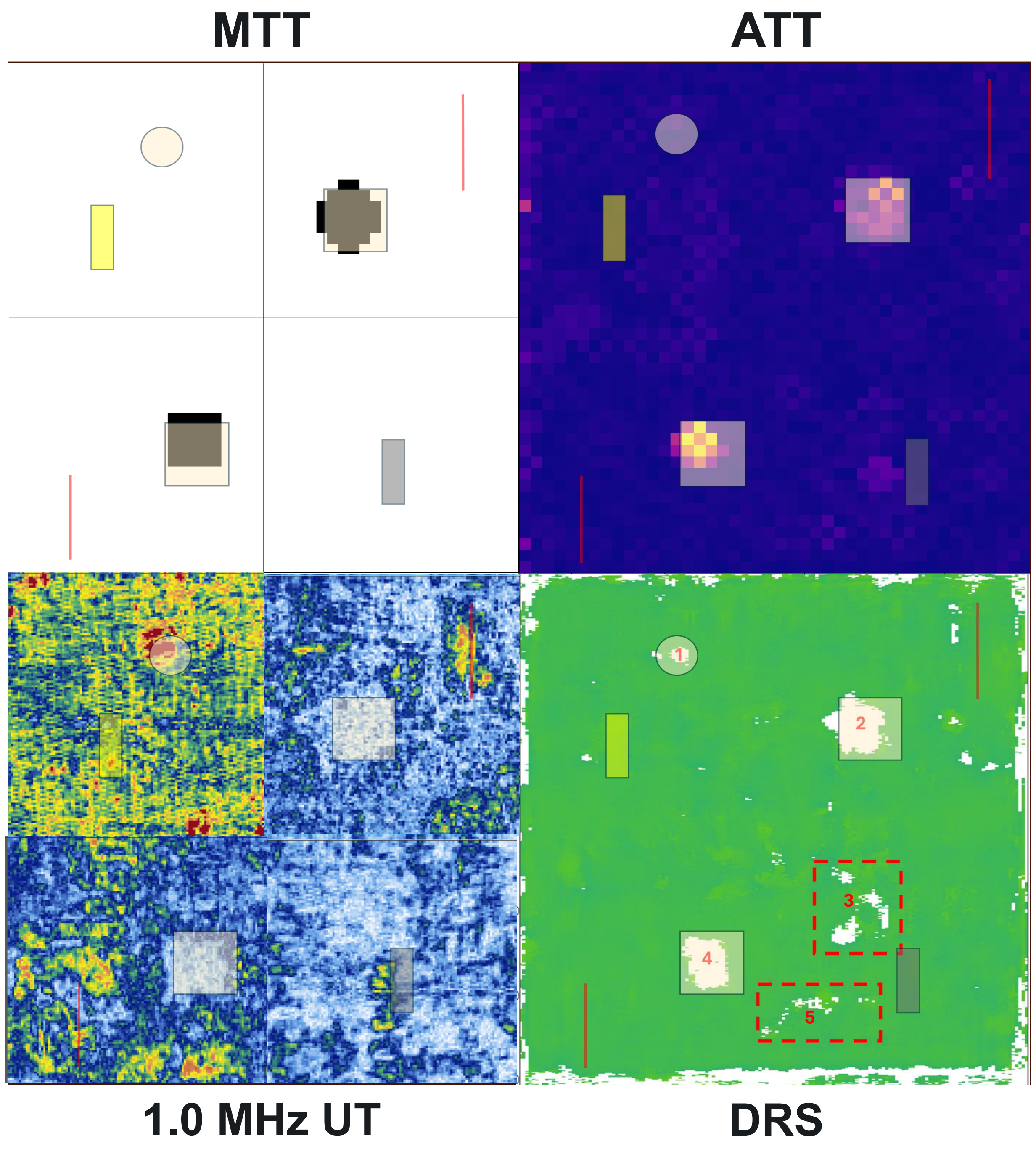
Figure A5: DRS signals do not travel through air, so bubbles and delaminations in the coating are evident where the signals from the steel are lost.

Figure A6: Example of a DRS map showing coating anomalies in white where the steel response is lost.

Images courtesy of Sonomatic, Inc.

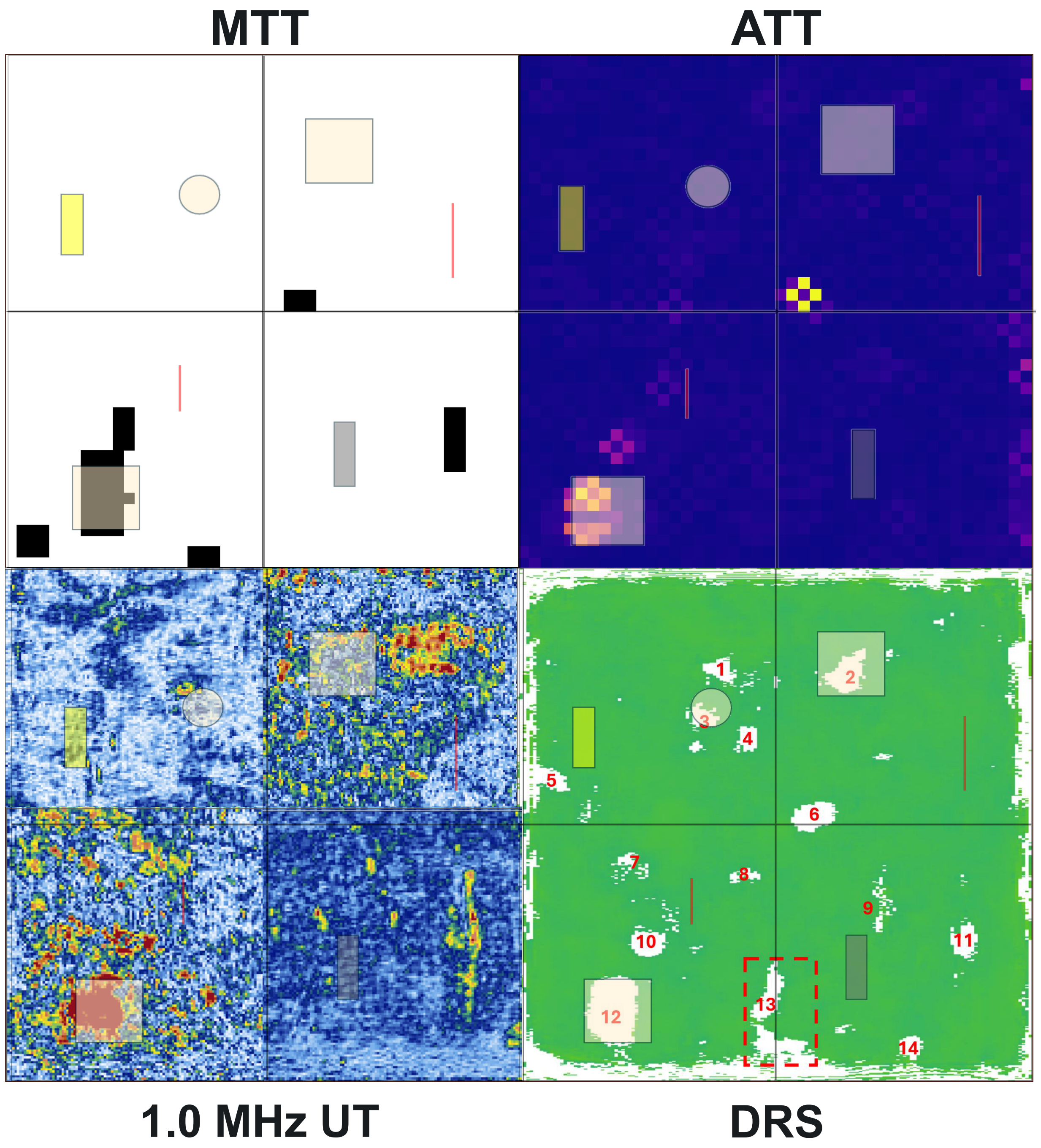
Results – Mockup #1

- Mockup 1 is the best-case scenario, with 6.3% of fumed silica, and 0.031 in. putty thickness between each layer (i.e., thinnest putty and thinnest layers)
- All techniques was able to identify the two 9 in.^{2} dry spots
- DRS and UT identified the smaller 3 in.^{2} dry spot
- Detection of gaps were not detected by any method, as they may have been filled with epoxy
- Overlaps and wrinkles were detected by 1.0 MHz UT



Results – Mockup #6

- Mockup #6 is the worst-case scenario, with 10.3% of fume silica in putty, and 0.125 in. thickness of putty between each layer (i.e., thickest putty and thickest layers)
- DRS and UT were able to identify the two 9 in.^{2} dry spots
- MTT and ATT identified the two 9 in.^{2} dry spots (in Q3)
- DRS and UT identified the smaller 3 in.^{2} dry spot
- Gaps, Overlaps and Wrinkles were not identified



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Results – Dry Spots

- The dry spots were readily detected by all methods in Mockups 1 through 3, except for the spot in Q4 of Mockup 1, which was missed by ATT and MTT
- In Mockups 4 through 6, with the thick putty, both tap methods struggled, and detection with UT was more challenging
- The 9 in.^{2} dry spot from Mockup 7 was detected only by DRS. All other techniques failed to detect any dry spots in the GFRP Layer

Mockup	Location (Ply-Quadrant-Size)	0.5 MHz UT	1.0 MHz UT	DRS	MTT	ATT
1	P2-Q1-9 in.^{2}	x	x	x	x	x
1	P4-Q3-9 in.^{2}	x	x	x	x	x
1	P5-Q4-3 in.^{2}	?	x	x		
2	P2-Q1-9 in.^{2}	x	x	x	x	x
2	P4-Q3-9 in.^{2}	x	x	x	x	x
2	P5-Q4-3 in.^{2}	x	x	x	x	x
3	P2-Q1-9 in.^{2}	x	x	x	x	x
3	P4-Q3-9 in.^{2}	x	x	x	x	x
3	P5-Q4-3 in.^{2}	x	x	x	x	
4	P2-Q1-9 in.^{2}		x	x	x	x
4	P4-Q3-9 in.^{2}	x	x	x		
4	P5-Q4-3 in.^{2}	x	x			
5	P2-Q1-9 in.^{2}	x	x	x		
5	P4-Q3-9 in.^{2}		x	x	x	
5	P5-Q4-3 in.^{2}	x	x	x		
6	P2-Q1-9 in.^{2}	x	?	x		
6	P4-Q3-9 in.^{2}	x	x	x		
6	P5-Q4-3 in.^{2}	x	x	x	x	x
7	P0-Q1-9 in.^{2}			x		
7	P0-Q1-3 in.^{2}					
8	P0-Q1-9 in.^{2}	-	-	-	-	-
8	P0-Q1-3 in.^{2}					

The square dry spot in Mockup 8 was saturated completely, so data were not recorded for it (marked with a "-" in the table).

Results – Other Defects

- Detection of the gaps was very difficult with any method, but overlaps were detected with 1.0 MHz UT
- The gaps may have been filled with resin during the mockup fabrication process, and were not detectable by any NDE method
- Several wrinkles were detected or possibly detected with 1.0 MHz UT, but all other methods struggled or missed the wrinkles entirely. Visual inspection after each layer is recommended to identify these defects.

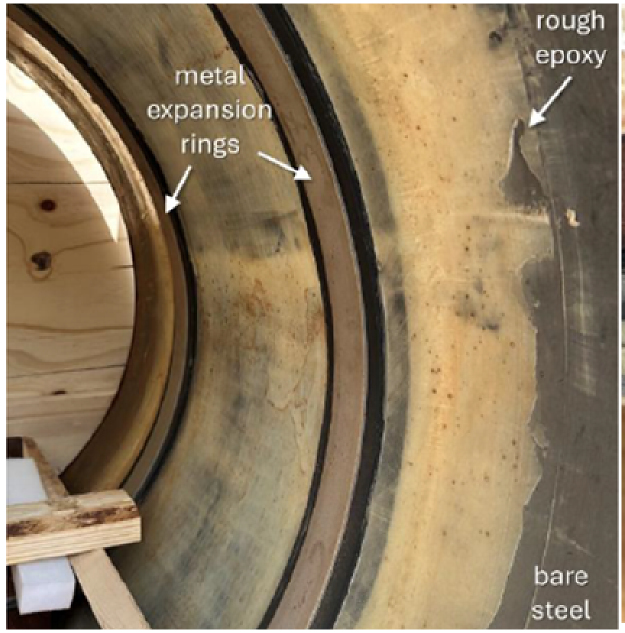
Defect	0.5 MHz UT	1.0 MHz UT	DRS	MTT	ATT
Overlaps (6)*		5			
Gaps (6)			1		
Wrinkles (12)	2	7	1		

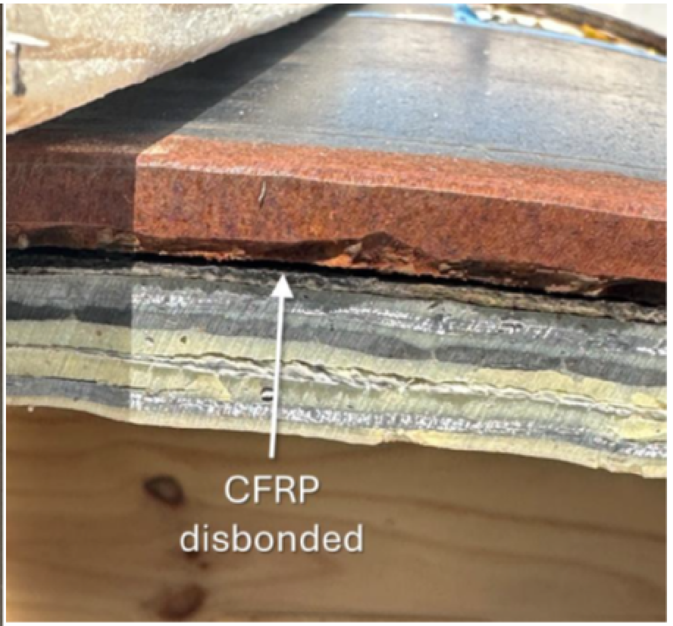
* The number in () indicates the total defects in the test matrix. Blank(s) indicates that no defect was detected

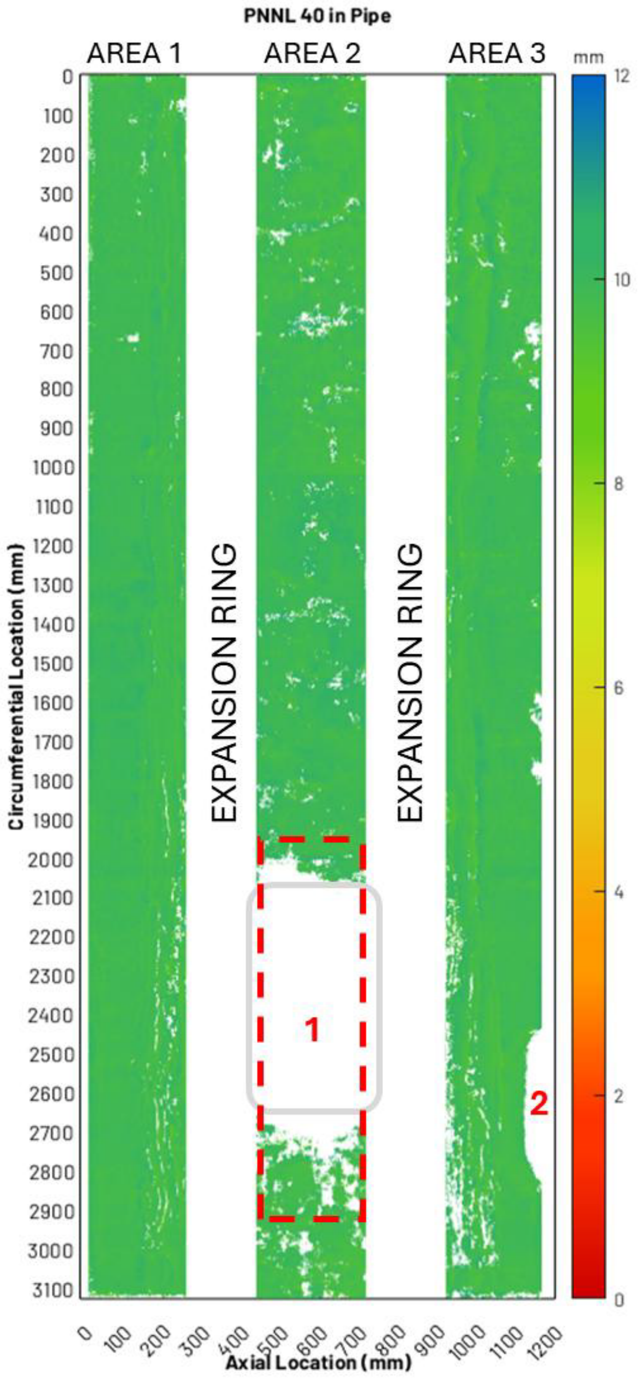
CFRP Pipe Mockup

- DRS inspection was also performed on a CFRP repair on an NRC-owned pipe with a cutout
- The pipe was subjected to hydrostatic blast testing, and stored outdoors for ~2 years exposed to environmental conditions
- The hydrostatic blast testing produced a river-like matrix crack in the missing steel region
- The DRS results showed that the CFRP is well bonded to the steel pipe
- Some areas of the epoxy surface were rough enough to prevent good contact with the DRS scanning head, which resulted in some white pixels in the map that were not flagged as indications
- Two large indications, labeled 1 and 2, were identified as defects, 1 corresponding to the cutout and 2 to a disbond

Photo showing cutout region

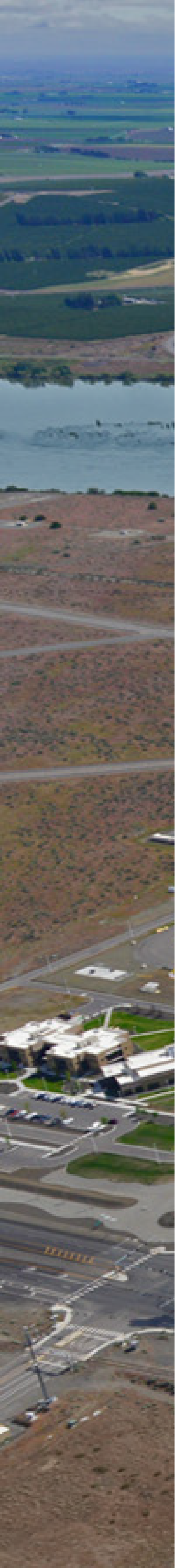






Results Summary

- This study evaluated the fabrication of CFRP repair mockups and the performance of several NDE methods to provide a technical basis for NRC review of requests for alternative using CFRP repairs, including those in CC N-871-1
- MTT and ATT were effective for detecting shallow dry spots in repairs with thin putty layers but performed poorly on thicker repairs and deeper defects. Neither MTT nor ATT reliably detected gaps, overlaps, or wrinkles. MTT generally showed higher sensitivity than ATT but required significant inspector experience and was adversely affected by industrial noise, which reduced detection reliability
- DRS demonstrated higher sensitivity to dry spots than tap testing but produced numerous additional indications that could not be confirmed without destructive testing
- DRS inspection of the pipe mockup identified the disbond regions where the steel substrate was absent but did not detect internal CFRP damage, such as matrix cracking, highlighting a fundamental limitation of the technique
- Conventional UT, particularly at 1.0 MHz, demonstrated the strongest overall performance on, detecting dry spots, overlaps, and some wrinkles
- Putty thickness was the dominant parameter affecting defect detectability across all NDE methods; thicker epoxy layers significantly reduced inspection sensitivity
- Overall, UT performance degraded with increasing putty thickness, defect depth, and laminate complexity, and data interpretation required significant expertise. UT and DRS were the only methods sensitive to deep defects
- A Technical Report Letter is expected to be publicly available in 2026



Remaining Questions and Gaps

- Although layer-by-layer inspections were not performed, the observed limitations of post-installation NDE suggest that inspection only after the repair is fully complete may be insufficient. Combining in-process and post-installation inspections may improve confidence in repair quality
- The current work did not evaluate whether nominally identical mockups could be fabricated to specification repeatedly and reliably, determine if equivalent mockups could be fabricated by different vendors, or perform destructive testing to confirm defect location and size
- Additional studies focused on identifying critical defect sizes that affect structural performance, as well as on verifying whether available NDE methods can reliably detect those defects under worst-case repair configurations, may provide a stronger technical basis for NRC to review requests for alternative and for industry to implement CFRP repair code cases

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Questions?

Thank you

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