American Water Works Association | WATER INFRASTRUCTURE Conference

October 13–16, 2015
Bethesda, Maryland
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CFRP Repair of Pipelines – The Current State of the Art

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CFRP Repair of Pipe

+ Widely preferred method
+ No excavation
+ Standalone
+ Fast
+ Targeted or continuous repairs
+ Emergency repairs

- Specialty repair in confined space
- Environmental controls
- Cost

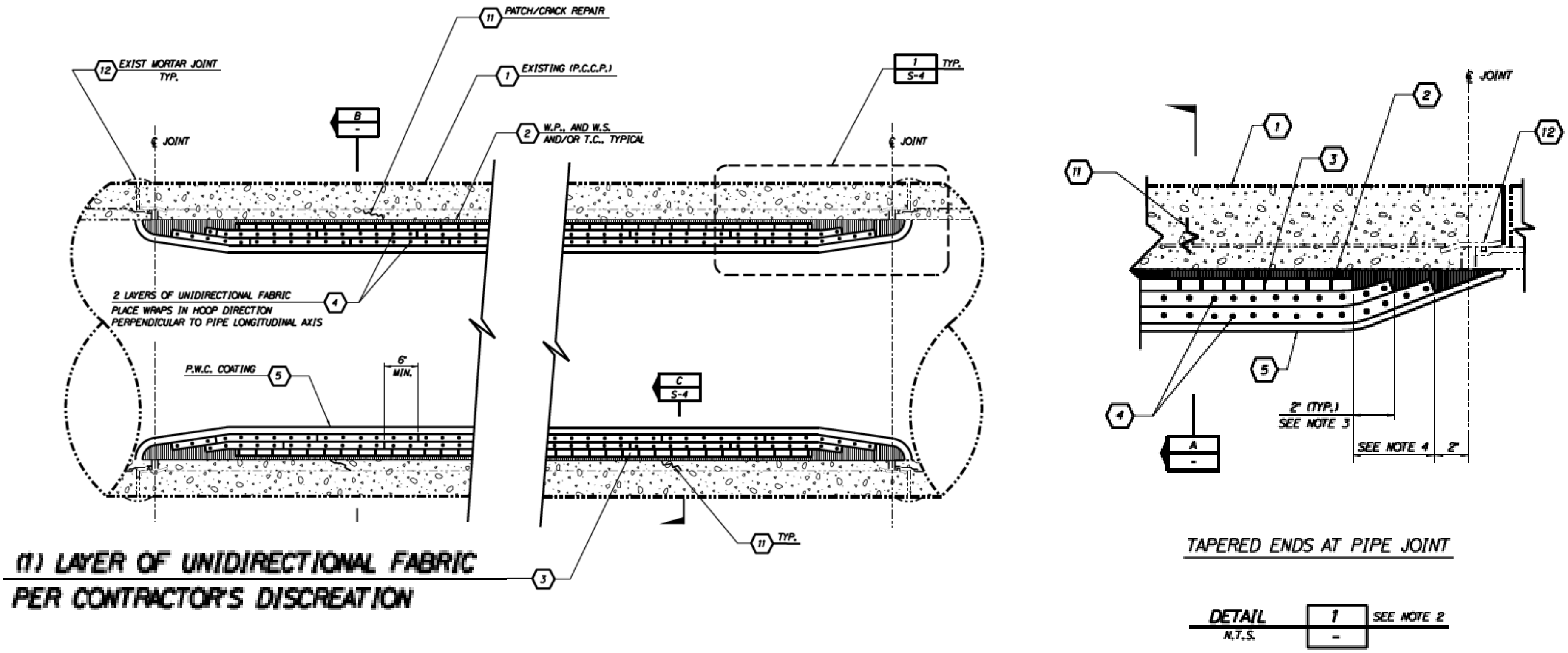
History

- 1980s: CFRP is used to repair civil infrastructure
- 1990s – early 2000s: Various utilities start using CFRP to repair pipe
- Mid-2000s: CFRP repair of pipe is widespread
- 2009: AWWA Concrete Pressure Pipe Committee appoints a subcommittee
- 2011: AWWA Standards Council approved the development of a standard
- 2011: Water Research Foundation awards the first research project to form the technical basis of the standard
- 2013 – 2015: Additional research on watertightness, degree of cure, etc.
- 2015: AWWA Draft Standard for CFRP Renewal and Strengthening of PCCP is complete (currently balloted)

Earlier Practice (1990s-2000s)

- "Factor of safety" design
- Few limit states (i.e., mostly pressure, Pr/t)
- Few CFRP layers, sometimes with no longitudinal
- CFRP terminated mostly on concrete
- No watertightness measures
- Limited QA inspections and testing
- Limited requirements to qualify material, contractor, designer, inspector

Earlier Practice (1990s-2000s)



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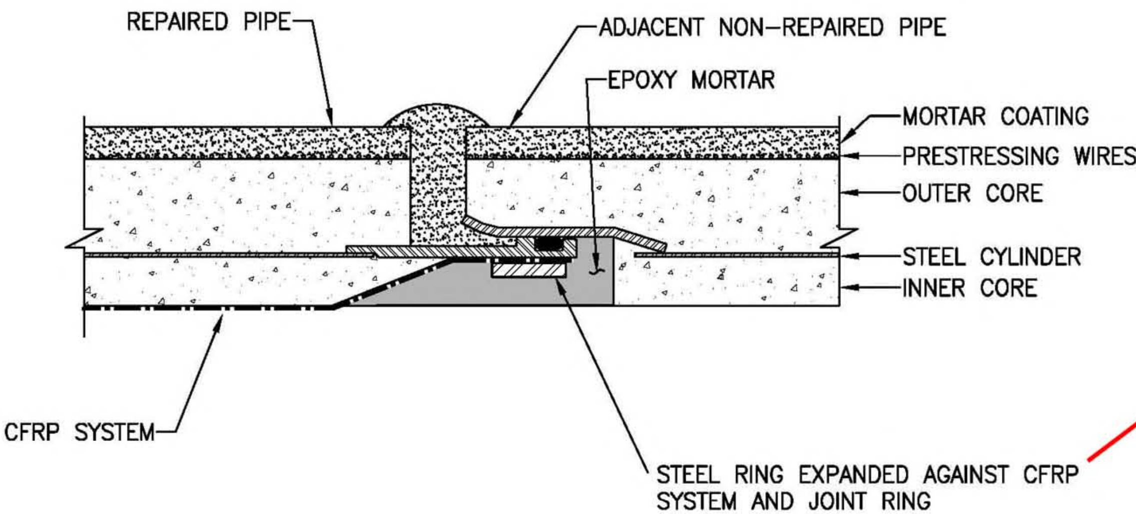
Practice in 2000s

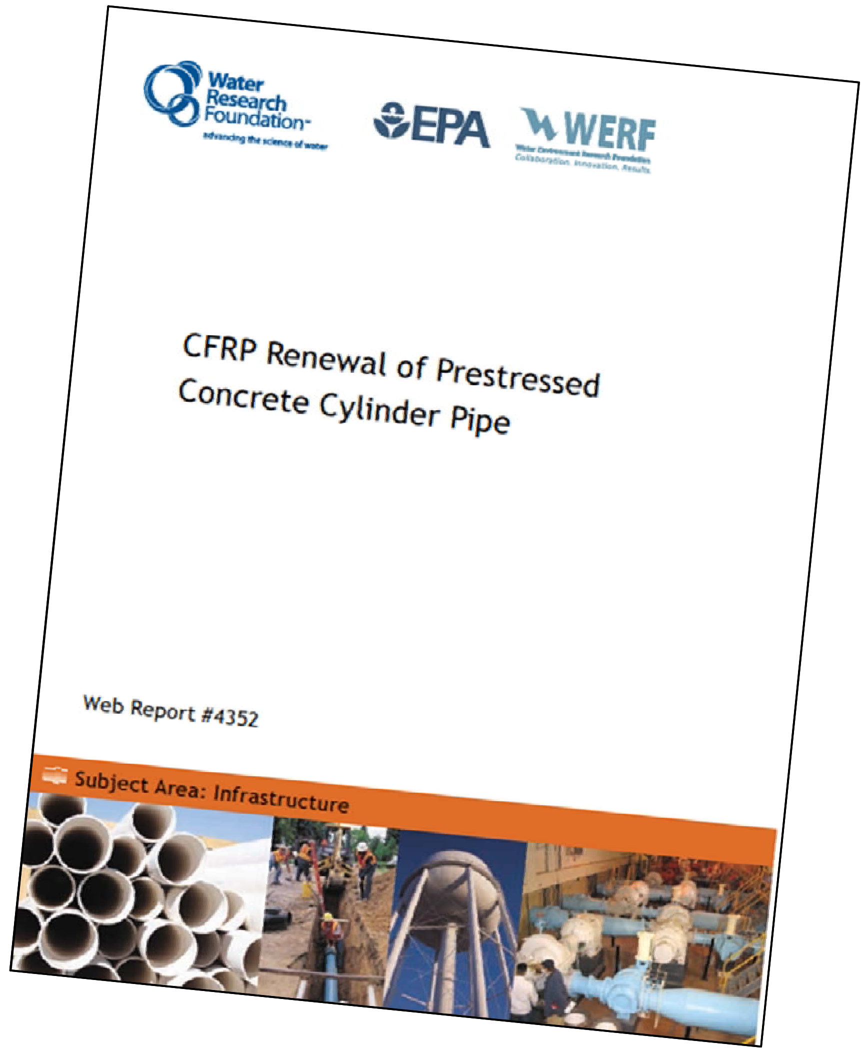
- Need for better termination is established
- Additional limit states are considered
- Standalone concept
- More CFRP layers
- Improved QA/QC requirements

Practice in 2000s



WRF Projects (2011-2015)

- LRFD procedure
- FEA of CFRP-lined pipe
- Full-scale tests
  - Hydrostatic pressure
  - Three-edge bearing
- Laboratory tests
  - Shear bond strength
  - Degree of cure
  - Watertightness



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LRFD Approach

$$R_u \leq \lambda\phi R_n = \lambda\phi(CR_o)$$

- R_u = required strength computed from factored load combinations
- λ = time effect factor
- ϕ = resistance factor
- R_n = strength in the end-use condition
- C = material adjustment factor
- R_o = test strength of unexposed material

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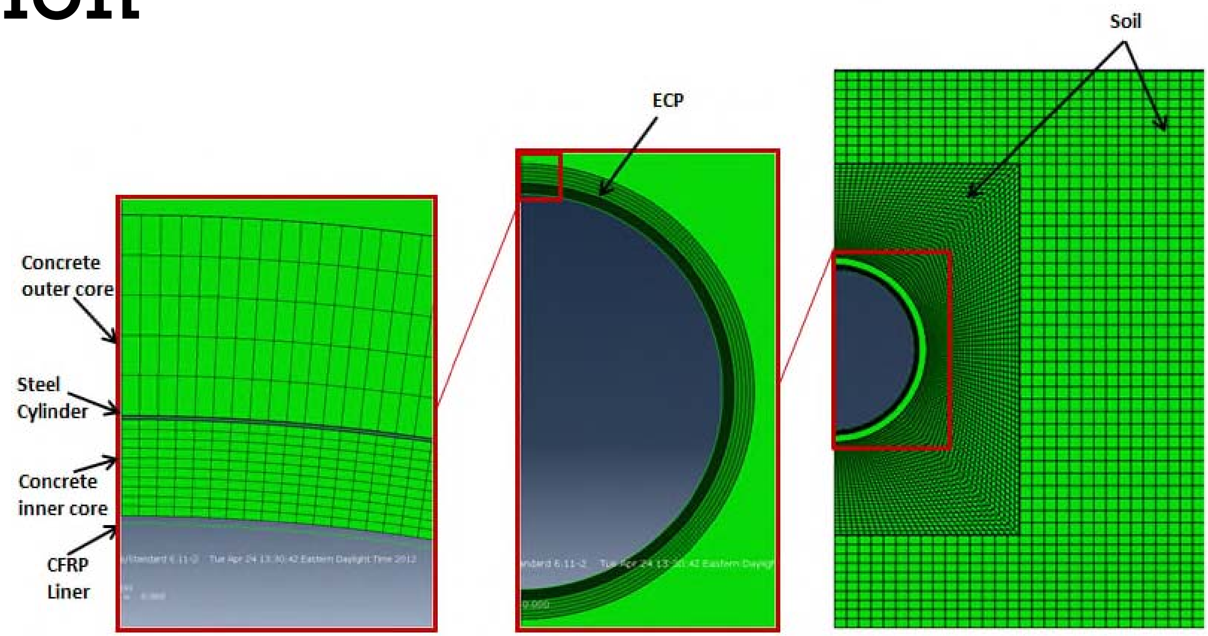
Limit States

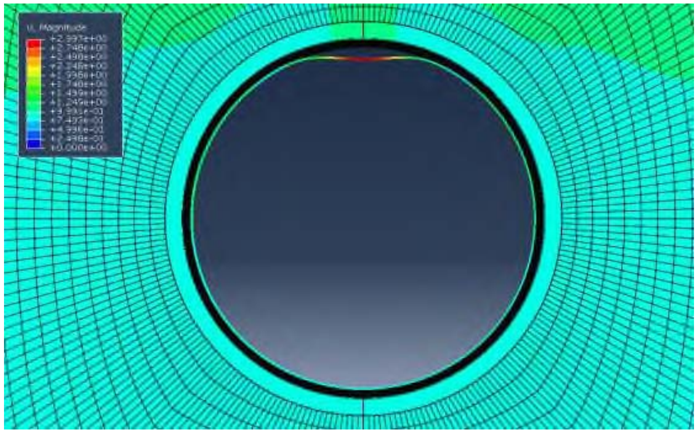
- Hoop rupture under pressure
- Hoop rupture in bending
- Hoop rupture under combined pressure and bending
- Hoop buckling
- Longitudinal rupture in tension
- Longitudinal rupture at BWZ edge
- Longitudinal buckling
- Shear debonding at pipe ends

FEA Validation

Sequential analysis of buried CFRP-lined pipe that continues to degrade



Buckling analysis



Full-Scale 3-Edge Bearing Tests

48 in. LCP - Control

48 in. LCP

54 in. ECP

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Full-Scale Hydrostatic Pressure Tests

54 in. ECP

48 in. LCP

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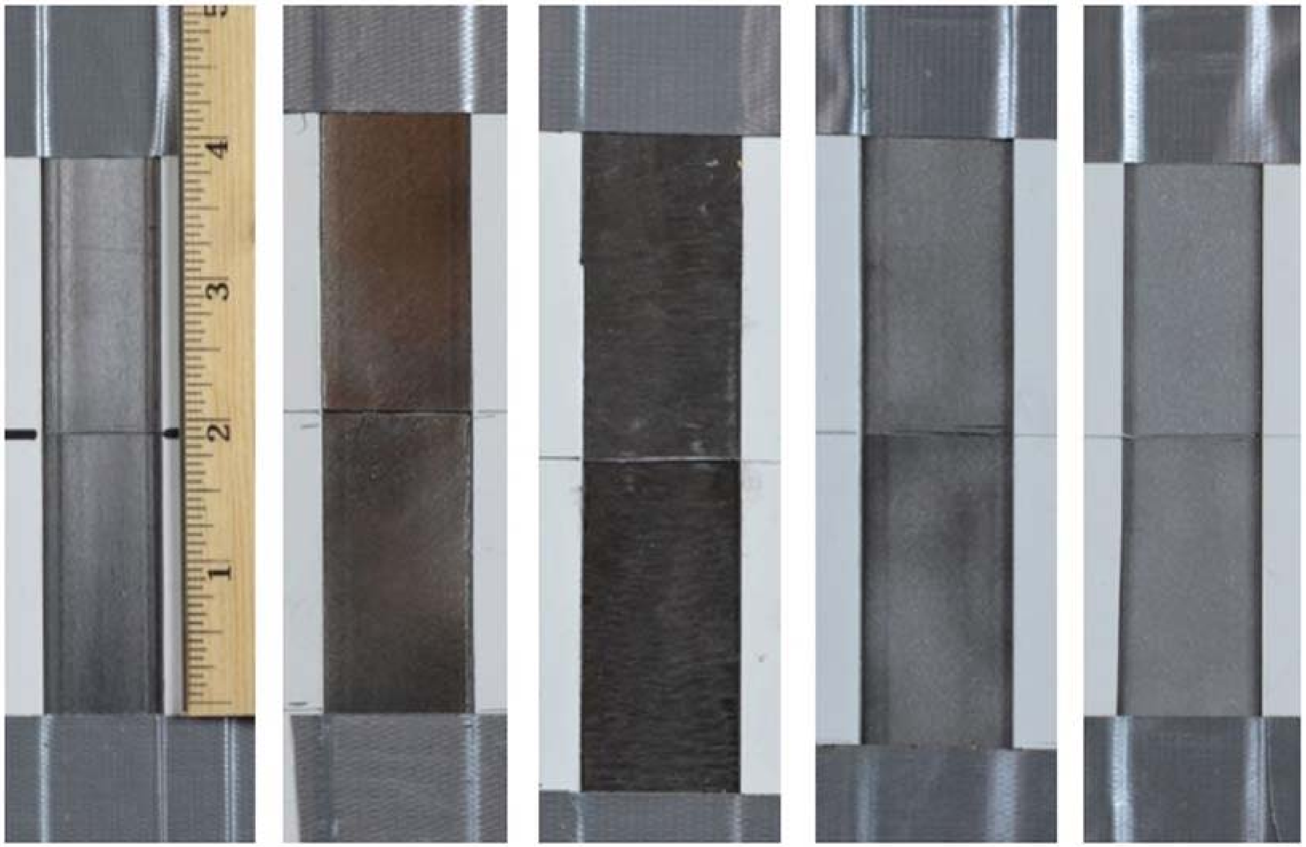
Shear Bond Strength on Steel Substrate



Cleaning with acetone | Cleaning with wirewheel | Grinding | Sandblasting to SSPC SP-10 near-white finish | Sandblasting to SSPC SP-5 white finish

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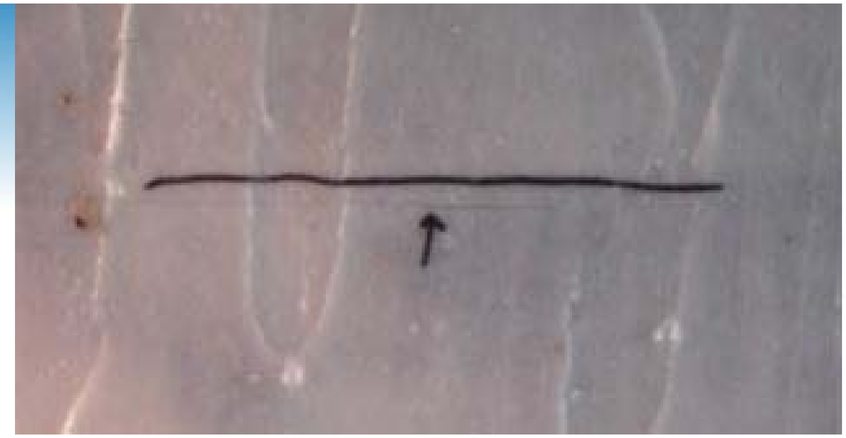
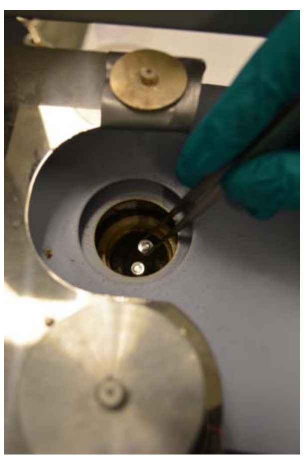
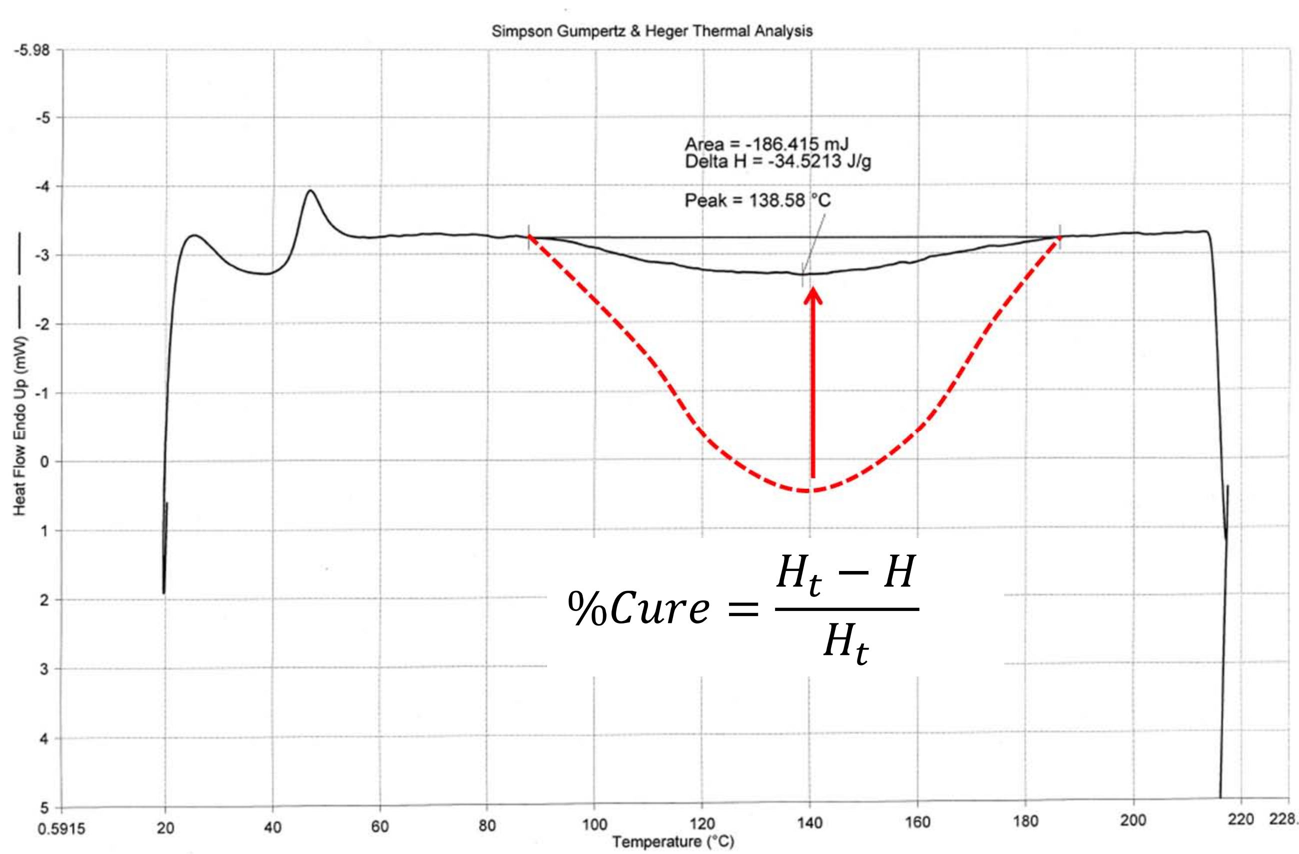
Degree of Cure







$$\%Cure = \frac{H_t - H}{H_t}$$

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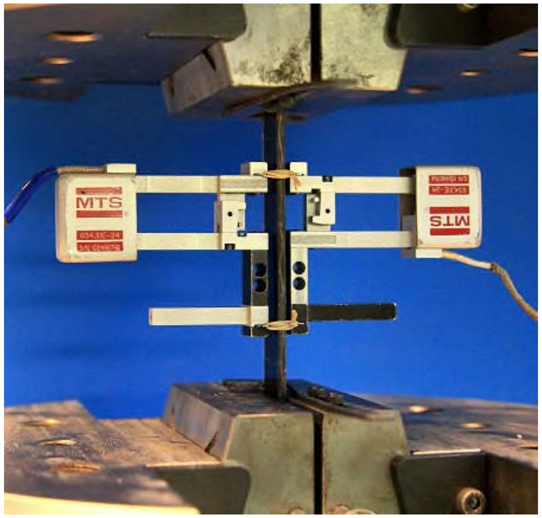
Degree of Cure vs Material Properties

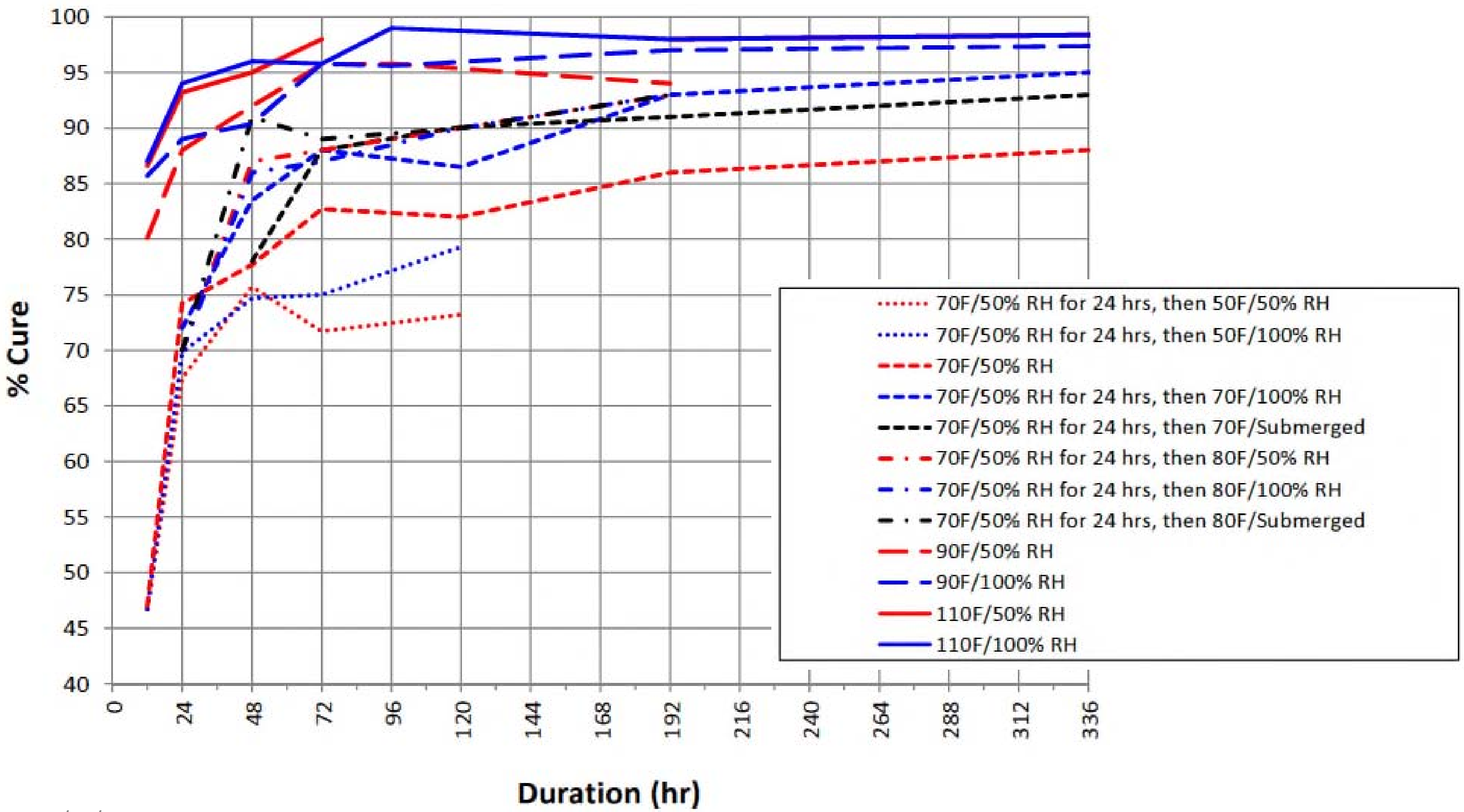


Need minimum 85% cure before placing pipe back in service

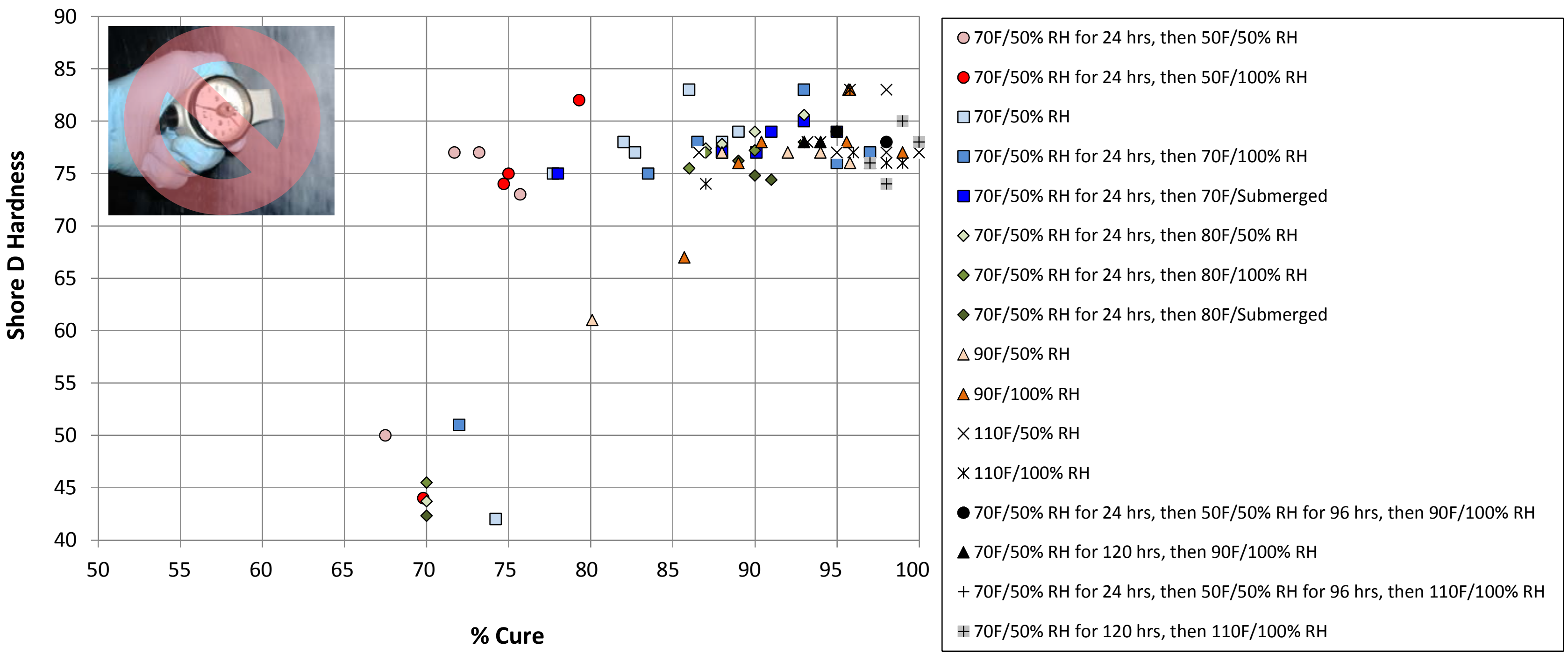
Cure Level	No. of Samples	Mean Strength (ksi)	Mean Modulus (ksi)	Mean Ultimate Strain (%)
75% (24 hr at 70°F)	12	91.3	-(1)	-(1)
88% (72 hr at 70°F)	12(2)	163.1	12,100	1.32%
95% (24 hr at 70°F + 16 hr at 100°F)	12	145.4	11,800	1.23%
100% (69 hr at 70°F + 3 hr at 165°F)	12	144.9	12,300	1.18%

Progression of Cure

Varies by material



How to Verify Cure in Construction



Take samples in field

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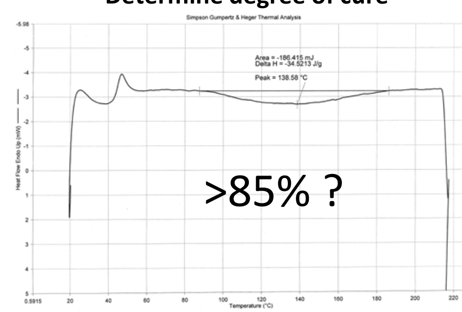
Send to laboratory

Test (DSC)

Determine degree of cure

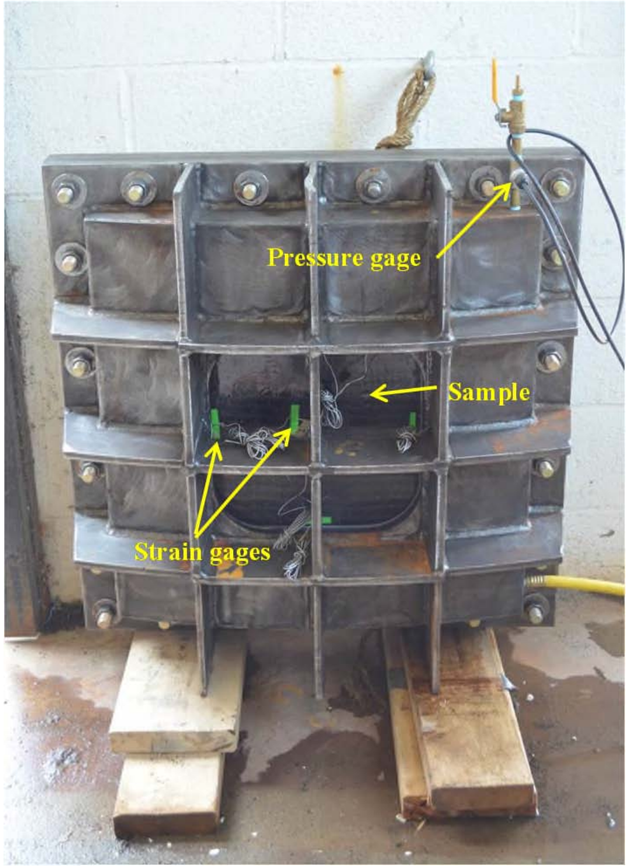


The Latest Development: Watertightness Test

- Will standalone CFRP remain watertight at design pressure?
- Watertightness is affected by:
  - Saturation
  - Laminate architecture
  - Brittleness of resin
  - Degree of cure
  - Top coat

The Latest Development: Watertightness Test

- Allows testing of laminates on a project-by-project basis
- Allows proof-of-concept tests at reasonable cost
    - New fabrics, resins, top coats
- 500 psi capacity



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Watertightness Acceptance Criteria

- $P_{WLT} = \min(P_{test1}, P_{test2}, P_{test3}, \ldots)$
- $P_{WLT} > 2P_{design}$

Specimen with no leaks at 400 psi

Specimen with multiple leaks at 150 psi

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Summary of Current Practice

- Qualification of designers, materials, contractors, inspectors
- LRFD design per AWWA Standard
  - Consistent design with solid experimental and analytical basis
- Varying laminate architectures
- Watertightness measures
- More layers now? – yes and no
- Improved QA procedures (e.g., cure)

Closure

- CFRP repair of pipe is a well-established technology.
- As with other technologies, it has evolved over the years.
- A standard has been developed, which will result in more consistent design and installation.
- Moving forward, methodologies are not expected to change significantly.
- Focus may be shifted to new CFRP lining methods, materials, reducing cost, etc.

Acknowledgement

- Water Research Foundation
- American Concrete Pressure Pipe Association
- Hanson Pipe and Products
- Tarrant Regional Water District
- Metropolitan Water District of Southern California
- Howard County Department of Public Works
- Washington Suburban Sanitary Commission
- Structural Technologies
- Fyfe Company
- Fibrwrap Construction

Questions?

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