CFRP Repair of Pipelines – The Current State of the Art

Murat Engindeniz, Ph.D., P.E.

mengindeniz@sgh.com
(781) 907-9110
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)

(1) Layer of unidirectional fabric
Per contractor's discretion

Tapered ends at pipe joint

10/14/2015
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

Diagram showing a section of a pipe repair system with labels for components such as repaired pipe, adjacent non-repaired pipe, epoxy mortar, mortar coating, prestressing wires, outer core, steel cylinder, inner core, CFRP system, steel ring expanded against CFRP system and joint ring. The image also shows a person applying epoxy mortar to a pipe.
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
LRFD Approach

\[ R_u \leq \lambda \phi R_n = \lambda \phi (C R_o) \]

- \( R_u \) = required strength computed from factored load combinations
- \( \lambda \) = time effect factor
- \( \phi \) = resistance factor
- \( R_n \) = strength in the end-use condition
- \( C \) = material adjustment factor
- \( R_o \) = test strength of unexposed material
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
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

10/14/2015

54 in. ECP
Full-Scale Hydrostatic Pressure Tests

54 in. ECP

48 in. LCP

10/14/2015
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

10/14/2015
Degree of Cure

\[
\%\text{Cure} = \frac{H_t - H}{H_t}
\]
Degree of Cure vs Material Properties

Need minimum 85% cure before placing pipe back in service

<table>
<thead>
<tr>
<th>Cure Level</th>
<th>No. of Samples</th>
<th>Mean Strength (ksi)</th>
<th>Mean Modulus (ksi)</th>
<th>Mean Ultimate Strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>75% (24 hr at 70°F)</td>
<td>12</td>
<td>91.3</td>
<td>12</td>
<td>1.32%</td>
</tr>
<tr>
<td>88% (72 hr at 70°F)</td>
<td>12 (2)</td>
<td>163.1</td>
<td>12,100</td>
<td>1.32%</td>
</tr>
<tr>
<td>95% (24 hr at 70°F + 16 hr at 100°F)</td>
<td>12</td>
<td>145.4</td>
<td>11,800</td>
<td>1.23%</td>
</tr>
<tr>
<td>100% (69 hr at 70°F + 3 hr at 165°F)</td>
<td>12</td>
<td>144.9</td>
<td>12,300</td>
<td>1.18%</td>
</tr>
</tbody>
</table>
Progression of Cure

Varies by material
How to Verify Cure in Construction

- Take samples in field
- Send to laboratory
- Test (DSC)
- Determine degree of cure

- Data logger to monitor temperature and RH during shipment to laboratory
- Thickened epoxy samples chipped out from pipe surface

- 70°F/50% RH for 24 hrs, then 50°F/50% RH
- 70°F/50% RH for 24 hrs, then 50°F/100% RH
- 70°F/50% RH
- 70°F/50% RH for 24 hrs, then 70°F/Submerged
- 70°F/50% RH for 24 hrs, then 80°F/50% RH
- 70°F/50% RH for 24 hrs, then 80°F/100% RH
- 70°F/50% RH for 24 hrs, then 80°F/Submerged
- 90°F/50% RH
- 90°F/100% RH
- 110°F/50% RH
- 110°F/100% RH
- 70°F/50% RH for 24 hrs, then 50°F/50% RH for 96 hrs, then 90°F/100% RH
- 70°F/50% RH for 120 hrs, then 90°F/100% RH
+ 70°F/50% RH for 24 hrs, then 50°F/50% RH for 96 hrs, then 110°F/100% RH
- 70°F/50% RH for 120 hrs, then 110°F/100% RH

% Cure

Shore D Hardness
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
Watertightness Acceptance Criteria

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

Specimen with no leaks at 400 psi
Specimen with multiple leaks at 150 psi
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

10/14/2015
Questions?

Murat Engindeniz, Ph.D., P.E.
mengindeniz@sgh.com
(781) 907-9110