Prestressed Concrete Pipe Fitness for Service and Repair

Rasko Ojdrovic
rpojdrovic@sgh.com
781-907-9231

IAEA - EPRI

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SGH Pipeline Experience

• More than 25 years of research, analysis, design, condition assessment, failure investigation and repair of pipelines
• Developed AWWA C304 standard for design of PCCP
• Developed AWWA M9 thrust restraint design procedure
• Developed procedure for risk assessment (fitness for service) of PCCP
• Developing standards for CFRP repair design of pipe
PCCP Distress Signs

- Coating cracks and delaminations
- Corrosion of prestressing wires
- Broken prestressing wires
- Longitudinal cracks in inner core
- Hollow sounding inner core
- Corrosion of steel cylinder
- Leak (through joints or steel cylinder)
Prestressing Wire Breakage

- Corrosion
- Embrittlement
Mortar Coating – Petrographic Analysis

- Determine quality and condition after years of service
- Petrographic analysis and testing of polished and thin sections
Steel Pipe Mortar Lining
PCCP Condition Assessment – What Works, What Doesn’t, What’s Next
Water Research Foundation Project 04233

- Provides utilities with a Best Practices Manual based on the available state-of-the-art condition assessment and service life estimation approaches for PCCP lines
  - Most appropriate condition assessment technologies
  - Best practice in condition assessment
  - Limits of applicability of available technologies

- Wrote sections on inspection prioritization for Concrete pipe in EPRI report 1016456, “Recommendations for an Effective Program to Control the Degradation of Buried and Underground Piping and Tanks,” 2010, used by nuclear power plants
Pipeline Condition Assessment

**Likelihood of Failure (Desktop)**

Review Pipeline Data:
- Age, Design, Manufacturing, Installation
- Environment, corrosivity
- Performance history
- Operation (working and trans. pressure)

Analysis:
- Structural evaluation
- Failure margin analysis

Optional Lower Cost Condition Assessment:
- Internal visual and sounding inspection
- External inspection/ material properties
- Over the line surveys
- Pipe stiffness testing

**Consider System Constraints**
- Time the line can be out of service
- Dewatering time and cost
- Access cost for excavation
- Other

**Consequences of Failure**
- Life safety and property damage
- Service interruption downstream
- Political costs
- Loss of public trust

**Determine Pipe Risk of Failure and Pipeline Criticality**

<table>
<thead>
<tr>
<th>Risk of Failure</th>
<th>None</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Risk</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
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<tr>
<td>Medium</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>High Risk</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

**1 – Low Risk/Criticality**

Perform economic analysis to select one of the following options:
- Do nothing / Run to failure
- Leak detection

**2 – Medium Risk/Criticality**

Perform economic analysis to select one or more of the following options to identify lower and higher risk portions of the pipeline:
- Internal visual and sounding inspection
- External inspection/ material testing
- Leak detection
- Pipe stiffness testing

**3 – High Risk/Criticality**

Perform economic analysis to select one or more of the following options to identify distressed pipe pieces and higher risk portions of the pipeline:
- Internal visual and sounding inspection
- External inspection/ material testing
- Leak detection
- Electromagnetic inspection
- Failure Margin Analysis/ Repair Prioritization

**Rehabilitation**
- None
- Repair individual pipe pieces
- Rehabilitate pipeline section

**Update Pipeline Likelihood of Failure**

SIMPSON GUMPERTZ & HEGER
Engineering of Structures and Building Enclosures
Fitness for Service - Failure Margin Analysis of Distressed Pipe with Broken Wires

- Evaluate the effects of broken prestressing wires on the pipe failure margin using risk curves
- Establish pipe repair priorities (immediate, mid term, no repair)
- Identify high risk pipes for repair to maintain pipeline reliability

- **Risk Curves**
- **Serviceability Limit State** – onset of visible cracking of core
- **Damage Limit State** – core structural cracking and increase in wire stress adjacent to BWZ
- **Strength Limit State** – pipe failure
Risk Curves - Repair Priority 2

Repair Priority 2:
- Exceeds the damage limit state
- Does not exceed strength limit state
- Failure occurs with time
- Pipe should be repaired typically between now and five years

Strength with contribution of soil
Strength without contribution of soil
Serviceability
Damage

RP1
RP2
RP3
RP4

Pressure (psi)
Number of Broken Wires

- Serviceability: onset of coating cracking
- Structural cracking of concrete core and high wire stress
- Ultimate strength of pipe without soil resistance
- Ultimate strength of pipe with soil resistance
- Steel cylinder ultimate strength
- Steel cylinder yield strength
Basis of Failure Margin Analysis - Risk Curves

- Hydrostatic pressure tests of pipe with broken wires
- Non-linear and linear finite-element models of the failure of PCCP with broken wires subjected to combined internal pressure and external loads
- Field inspection of distressed pipe to characterize pipe condition near broken wire zones
- Risk curves technology (US Patent 7043373)
Hydrostatic Pressure Testing
Nonlinear Finite Element Analysis
Verification of Risk Curves

- Serviceability limit state
- Damage limit state
- Strength limit state without soil resistance
- Strength limit state with soil resistance
- Cylinder ultimate strength
- Cylinder yield strength
- Pipe No. 5BH9
- 1996 Failed Pipe
Verification of Risk Curves

48 in. LCP, Canada
Repair and Rehabilitation Options

- Repair distressed pipe so that the repair pipe would have the desired strength, durability, reliability, and hydraulic performance
- Evaluate repair options including
  - External
    - Post-tensioning
    - Pipe replacement with closure piece
    - Replacement of a portion of the pipeline
    - Concrete encasement
    - External FRP repair
  - Internal
    - CFRP hand lay-up repair
    - Steel or FRP liner
    - HDPE slip-lining repair
CFRP Liners

- No need for external access
- >15 year track record
- Draft AWWA Standard and ASME Code Case in progress
• Research basis for CFRP repair design

CFRP Renewal of Prestressed Concrete Cylinder Pipe

Web Report #4352

Subject Area: Infrastructure
CFRP Design Approach

- Consider degradation level of host pipe
- Stand-alone versus composite design (with remaining host pipe)
- Use LRFD

Circumferential Design

<table>
<thead>
<tr>
<th>Limit State</th>
<th>Loads</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFRP Rupture</td>
<td>Internal pressure + External gravity loads</td>
</tr>
<tr>
<td>Buckling</td>
<td>External loads including Groundwater + Vacuum</td>
</tr>
<tr>
<td>Debonding</td>
<td>Empty pipe under external loads</td>
</tr>
</tbody>
</table>

Longitudinal Design

<table>
<thead>
<tr>
<th>Limit State</th>
<th>Loads</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFRP Rupture</td>
<td>Internal pressure (Thrust, Poisson) + Temperature</td>
</tr>
<tr>
<td>Debonding</td>
<td>Internal pressure (Thrust, Poisson) + Temperature</td>
</tr>
<tr>
<td>Buckling</td>
<td>Temperature</td>
</tr>
</tbody>
</table>
The WaterRF Project

Objective: Develop all necessary technical background for an LRFD-based AWWA Standard.

$$R_u \leq \lambda \phi R_n = \lambda \phi C R_0$$

- $R_u$ = required strength computed from factored load combinations
- $\lambda$ = time effect factor that accounts for creep rupture of material under sustained loads,
- $\phi$ = resistance factor that accounts for the variability of material properties and uncertainty in predictive formulas,
- $R_n$ = strength in the end-use condition,
- $C$ = material adjustment factor that accounts for durability of material (i.e., retained strength) exposed to environment for the duration of its service life, and
- $R_o$ = Characteristic value of the test strength of material prior to exposure to the environment.
Load Combinations

- **Circumferential Load Combinations**
  - $1.4 \left( P_w + P_t \right)$
  - $1.4 \left( W_e + W_p \right)$
  - $1.2 \left( W_e + W_p \right) + 1.6 W_t$
  - $1.4 \left( P_w + W_e + W_p \right) + W_f$
  - $1.2 \left( P_w + W_e + W_p \right) + W_f + 1.6 W_t$
  - $1.2 \left( W_e + W_p \right) + W_f + 1.2 P_w + 1.2 P_t$

- **Buckling Load Combinations**
  - $1.4 \left( P_{gw} + W_e^* + W_p^* \right)$
  - $1.2 \left( P_{gw} + W_e^* + W_p^* \right) + 1.2 P_v$
  - $1.2 \left( P_{gw} + W_e^* + W_p^* \right) + 1.6 W_t$

- **Longitudinal Load Combinations**
  - $1.4 P_w + 1.2 T + 1.4 S + 1.4 F$
  - $1.2 P_w + 1.2 P_t + 1.2 T + 1.2 S + 1.2 F$

F = thrust-related axial force
$P_w$ = working Pressure
$P_t$ = Transient Pressure
$P_v$ = vacuum Pressure
$P_{gw}$ = ground water pressure
$S$ = differential settlement
$T$ = temperature load
$W_e$ = earth load
$W_p$ = pipe weight
$W_f$ = fluid weight
$W_t$ = live load
Strength

Depends on the number of layers
Durability - Retained Strength

Data Courtsey of Fyfe Company

Water immersion at 73°F

Salt/Alkali Solution immersion at 73°F
# Material Adjustment Factor, C

<table>
<thead>
<tr>
<th></th>
<th>50-yr. Exposure</th>
<th>Tension</th>
<th>Flexure</th>
<th>Short-Beam Shear</th>
<th>Pull-Off Strength</th>
<th>In-Plane Shear</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Strength</td>
<td>Modulus</td>
<td>Strength</td>
<td>Modulus</td>
<td>Strength</td>
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<tr>
<td><strong>Water</strong></td>
<td>73°F</td>
<td>0.85</td>
<td>0.95</td>
<td>0.7</td>
<td>0.9</td>
<td>0.7</td>
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<tr>
<td></td>
<td>100°F</td>
<td>0.85</td>
<td>0.95</td>
<td>0.6</td>
<td>0.85</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>140°F</td>
<td>0.7</td>
<td>0.95</td>
<td>0.45</td>
<td>0.85</td>
<td>0.5</td>
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<tr>
<td><strong>Salt Solution</strong></td>
<td>73°F</td>
<td>0.75</td>
<td>0.95</td>
<td>0.7</td>
<td>0.85</td>
<td>0.7</td>
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<tr>
<td><strong>Alkali Solution</strong></td>
<td>73°F</td>
<td>0.75</td>
<td>0.95</td>
<td>0.65</td>
<td>0.80</td>
<td>0.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>5-yr. Exposure</th>
<th>Tension</th>
<th>Flexure</th>
<th>Short-Beam Shear</th>
<th>Pull-Off Strength</th>
<th>In-Plane Shear</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Strength</td>
<td>Modulus</td>
<td>Strength</td>
<td>Modulus</td>
<td>Strength</td>
</tr>
<tr>
<td><strong>Water</strong></td>
<td>73°F</td>
<td>0.90</td>
<td>1.0</td>
<td>0.85</td>
<td>0.95</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td>100°F</td>
<td>0.90</td>
<td>1.0</td>
<td>0.75</td>
<td>0.90</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>140°F</td>
<td>0.80</td>
<td>1.0</td>
<td>0.60</td>
<td>0.90</td>
<td>0.65</td>
</tr>
<tr>
<td><strong>Salt Solution</strong></td>
<td>73°F</td>
<td>0.85</td>
<td>0.95</td>
<td>0.85</td>
<td>0.90</td>
<td>0.85</td>
</tr>
<tr>
<td><strong>Alkali Solution</strong></td>
<td>73°F</td>
<td>0.90</td>
<td>0.95</td>
<td>0.80</td>
<td>0.85</td>
<td>0.85</td>
</tr>
</tbody>
</table>
### Summary of target reliability indices ($\beta$) and resistance factors ($\phi$)

<table>
<thead>
<tr>
<th>Limit State</th>
<th>$\beta$</th>
<th>$\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFRP laminate rupture in axial tension/compression in either direction</td>
<td>3.5</td>
<td>0.75</td>
</tr>
<tr>
<td>CFRP laminate rupture in bending in circumferential direction</td>
<td>3.5</td>
<td>0.70</td>
</tr>
<tr>
<td>CFRP laminate rupture in bending in longitudinal direction, at BWZ edge</td>
<td>3.5</td>
<td>0.75</td>
</tr>
<tr>
<td>CFRP laminate buckling in circumferential direction</td>
<td>3.0</td>
<td>0.55</td>
</tr>
<tr>
<td>CFRP laminate buckling in longitudinal direction</td>
<td>3.0</td>
<td>0.75</td>
</tr>
<tr>
<td>CFRP debonding from steel substrate at pipe ends due to shear</td>
<td>3.0</td>
<td>0.75</td>
</tr>
<tr>
<td>CFRP debonding from steel substrate at pipe ends governed by CFRP strain</td>
<td>3.0</td>
<td>0.90</td>
</tr>
<tr>
<td>CFRP debonding from concrete inner core due to radial tension</td>
<td>3.0</td>
<td>0.50</td>
</tr>
<tr>
<td>CFRP debonding from concrete inner core due to shear</td>
<td>3.0</td>
<td>0.60</td>
</tr>
</tbody>
</table>
FEA Validation

Analyzed 10 Different PCCPs, ranging in type, diameter, concrete strength, cylinder thickness, wire diameter, earth load, and pressure. Prestress was based on design, CFRP by AWWA Standard for CFRP Renewal and Strengthening of PCCP.
### Comparison of FEA and Design Equations

**60 in. ECP, H = 6 ft, \( P_w = 100 \) psi, \( P_t = 40 \) psi, and \( M_s = 3,000 \) psi**

<table>
<thead>
<tr>
<th>Item</th>
<th>Load</th>
<th>FEA</th>
<th>AWWA Draft Standard</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Thrust at springline (lb./in.)</strong></td>
<td>Earth load and pipe weight</td>
<td>-242</td>
<td>-247</td>
<td>AWWA is in agreement</td>
</tr>
<tr>
<td><strong>Horizontal deflection (in.)</strong></td>
<td>Earth load and pipe weight</td>
<td>0.10</td>
<td>0.17</td>
<td>AWWA is conservative</td>
</tr>
<tr>
<td><strong>Maximum Strain in CFRP at invert (( \mu e ))</strong></td>
<td>Earth load and pipe weight</td>
<td>27</td>
<td>331</td>
<td>AWWA is conservative</td>
</tr>
<tr>
<td></td>
<td>Earth load, pipe weight and working pressure</td>
<td>910</td>
<td>1,278</td>
<td>AWWA is conservative</td>
</tr>
<tr>
<td></td>
<td>1,350</td>
<td>1,660</td>
<td></td>
<td>AWWA is conservative</td>
</tr>
</tbody>
</table>
Constrained Buckling of CFRP Liner

Glock Equation for Liner Buckling inside a Rigid Pipe: \( P_{cr,\text{Gluck}} = \frac{E}{1-\nu^2} \left( \frac{t}{D} \right)^{2.2} \)

Runs made for a range of different pipes and soils show \( P_{cr,\text{FEM}} / P_{cr,\text{Gluck}} = 0.70 \) to 0.82
Experimental Study

- Hydrostatic pressure Tests on 6 pipes (3 ECP and 3 LCP)
- Three-edge bearing tests on 8 pieces (1 control with no liner, four pieces of 48 in. LCP and three pieces of 54 in. ECP).
- The results of experimental study was introduction of new failure modes/limit states:
  - Longitudinal bending of CFRP laminate at the edge of BWZ.
  - Loss of CFRP laminate/steel bond failure
  - Loss of watertightness of the CFRP laminate.
- Delamination is very sensitive to CFRP laminate/concrete bond strength
Hydrostatic Pressure Testing and Three-Edge Bearing Test
Loss of Watertightness
How to Ensure Watertightness?

- By testing of the laminate
- By introducing a watertight layer
- By curing to close to 100%
- By replacing introducing an alternate for thickened epoxy used for surface preparation and final coating.

Watertightness Test apparatus
Summary

• Presented basis of fitness for service of distressed PCCP and verification of results
  – FEA alone is not sufficient to evaluate PCCP failure

• Presented basis of CFRP repair design
  – Not the same as steel
Thank you

Questions?

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