Presentation Overview

• Words of tribute for Fred D. Wilson
• Composite repair overview (State of the Art)
• Composite repair timeline
• Industry interest as reflected in PRCI studies
• Case study: Dent reinforcement design
• Looking forward
State of the Art

- Composite systems have been used to repair high pressure pipelines for more than 25 years
- The key to integrating composite technology is properly designing and installing systems possessing adequate service life
- Performance testing has been an essential element in demonstrating the capacity of composite repair technology
- Continued “pushing of the envelope”
Composite Repair Timeline (1/3)
(Based on work done by Stress Engineering)

1994  Started testing Clock Spring with GRI
      (primary interest reinforcing mechanical damage)

1997  Started testing Armor Plate® Pipe Wrap
      (wide range of studies including load transfer, dents, cyclic, etc.)

2000  Started testing for NRI and WrapMaster

2004  Started working with Pipe Wrap

2005  Started testing Aquawrap

2006  Stress Engineering ASME PCC-2 involvement
      Start of significant individual operator funding
      (e.g. El Paso, TransCanada, Panhandle, Williams, CenterPoint, & Chevron)
Composite Repair Timeline (2/3)
(Based on work done by Stress Engineering)

2008  PRCI long-term buried project (13 mfgs)  See below

- Armor Plate, Inc. (10 years)
- Air Logistics Corporation (3 years)
- Clock Spring Company, LLC (3 years)
- Citadel Technologies (10 years)
- EMS Group (10 years)
- Pipe Wrap, LLC (3 years)
- T.D. Williamson, Inc. (10 years)
- Walker Technical Resources Ltd. (3 years)
- Wrap Master (3 years)
- 3X Engineering (3 years)
- Furmanite (3 years)
- Neptune (3 years)
- Pipestream (10 years)

2009  First meeting of what would become CRUG

2010  Started testing for Pipestream (re-rate / cracks)

2012  Started testing for Fyfe Company

Composite Repair Timeline (3/3)
(Based on work done by Stress Engineering)

2014 Elevated temperature testing
Reinforcement of fittings with combined loads
Optimizing composite repair designs using FEA
Validation testing for ASME PCC-2
Dent Validation Collaborative Industry Program
(DV-CIP participants: ROSEN, 5 operators, and 6 repair companies)

2015 Six (6) Joint Industry Programs (JIPs, next slide)
BSEE / PHMSA study sponsorship
2015-2016 JIPs

• Studies being conducted
  ▪ Offshore Study (10,000-hr test in simulated seawater)
  ▪ Onshore Study
  ▪ Load Transfer Study
  ▪ Wrinklebend Study
  ▪ Crack Reinforcement Study
  ▪ Crack Arrestor Study

• Participation composite manufacturers
  ▪ Air Logistics
  ▪ Citadel
  ▪ Furmanite
  ▪ Milliken
  ▪ NRI
  ▪ Western Specialties
PRCI Research Programs

- MATR-3-4  Long-term performance (10-year study)
- MATR-3-5  Repair of dents
- MATR-3-6  Repair of subsea pipelines/risers
- MATR-3-7  Girth weld reinforcement
- MATV-1-2  Wrinkle bend reinforcement
- MATR-3-9  Re-rating to establish MAOP
- NDE 2-3   NDE & Inspection Techniques
- MATR-3-10 Composite Repair Guideline Document
- MATR-3-11 Load transfer / pressure during installation
- MATR-3-12 Effects of delamination on performance
- Composite Roadmap (being updated)
Case Study
Development of design basis for reinforcing dents
Modern Dent Assessment

- ILI geometry tool produces R-θ-Z data
- The geometry data used as input into the finite element (FEA) model
- The FEA model used to calculate dent SCFs
- Literally hundred of dents can be in one pass
Design Basis

• Formulation must take into account stiffness of the composite, relative to the pipe
• Relative stiffness of the pipe (D/t) is an important consideration when evaluating dents
• The starting point is to look for trends in body of existing research, especially strains and composite thicknesses
• If appropriate, consider variations in performance of different fibers
Proposed Design Equation

\[ t_{\text{comp}} = \frac{1}{M} \left( \frac{E_{\text{pipe}}}{E_{\text{comp}}} \right) \left( \frac{\Delta P \cdot D}{2 \cdot f \cdot S_{\text{yield}}} \right) \]

- **E-glass systems**: \( M = 3.5 \)
- **Carbon systems**: \( M = 2.0 \)

- \( t_{\text{comp}} \): Thickness of composite (inch)
- \( M \): Empirically-based parameter
- \( E_{\text{pipe}} \): Elastic modulus of pipe (psi)
- \( E_{\text{comp}} \): Elastic modulus of composite (psi)
- \( \Delta P \): Applied pressure range (psi)
- \( f \): Pipeline design factor (0.72 rec.)
- \( S_{\text{yield}} \): SMYS of pipe (psi)
### Goal Seeking Value(s) for “M”

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Material</th>
<th>( E_{\text{comp}} ) (cycles)</th>
<th>Nominal Pipe Diameter (inches)</th>
<th>Dent Strain (( \mu \varepsilon ))</th>
<th>SCF</th>
<th>( t_{\text{repair}} ) (inches)</th>
<th>( t_{\text{repair}}_{\text{CALC}} ) (inches)</th>
<th>% diff</th>
<th>( t_{\text{repair}}_{\text{CALC}} ) (inches)</th>
<th>% diff</th>
<th>Notes and Comments</th>
</tr>
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<tbody>
<tr>
<td>Unrepaired</td>
<td>N/A</td>
<td>N/A</td>
<td>23,512</td>
<td>835</td>
<td>3,510</td>
<td>4.20</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>Unrepaired: No repair installed</td>
</tr>
<tr>
<td>A-PD-24-1</td>
<td>E-glass / urethane 2.28</td>
<td>100,623</td>
<td>836</td>
<td>1,235</td>
<td>1.48</td>
<td>0.928</td>
<td>0.940</td>
<td>-1.3%</td>
<td>1.645</td>
<td>-43.6%</td>
<td>Good performance (E-glass)</td>
</tr>
<tr>
<td>AE-PD-24-1</td>
<td>Steel Sleeve</td>
<td>N/A</td>
<td>40,877</td>
<td>831</td>
<td>870</td>
<td>1.05</td>
<td>0.283</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>AE-PD-24-2</td>
<td>Steel Sleeve</td>
<td>N/A</td>
<td>101,999</td>
<td>819</td>
<td>3,720</td>
<td>4.54</td>
<td>0.276</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
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<tr>
<td>B-SW-24-1</td>
<td>Carbon / epoxy</td>
<td>102,950</td>
<td>834</td>
<td>1,144</td>
<td>1.37</td>
<td>0.494</td>
<td>0.180</td>
<td>174.3%</td>
<td>0.315</td>
<td>56.8%</td>
<td>Seams material interaction</td>
</tr>
<tr>
<td>B-DC-24-1</td>
<td>Carbon / epoxy</td>
<td>100,623</td>
<td>830</td>
<td>1,812</td>
<td>2.18</td>
<td>0.484</td>
<td>0.180</td>
<td>168.8%</td>
<td>0.315</td>
<td>53.6%</td>
<td>Corrosion interaction (40% deep)</td>
</tr>
<tr>
<td>B-PD-24-1</td>
<td>Carbon / epoxy</td>
<td>102,950</td>
<td>848</td>
<td>1,198</td>
<td>1.41</td>
<td>0.497</td>
<td>0.180</td>
<td>176.0%</td>
<td>0.315</td>
<td>57.7%</td>
<td>Seams material interaction</td>
</tr>
<tr>
<td>C-PD-24-1</td>
<td>E-glass / epoxy</td>
<td>106,252</td>
<td>813</td>
<td>1,178</td>
<td>1.45</td>
<td>0.477</td>
<td>0.487</td>
<td>-2.1%</td>
<td>0.852</td>
<td>-44.0%</td>
<td>Good performance / optimized</td>
</tr>
<tr>
<td>C-SW-24-1</td>
<td>E-glass / epoxy</td>
<td>106,252</td>
<td>813</td>
<td>1,152</td>
<td>1.42</td>
<td>0.503</td>
<td>0.487</td>
<td>3.3%</td>
<td>0.852</td>
<td>-41.0%</td>
<td>Seams material interaction</td>
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<tr>
<td>C-DC-24-1</td>
<td>E-glass / epoxy</td>
<td>56,726</td>
<td>835</td>
<td>3,194</td>
<td>3.83</td>
<td>0.474</td>
<td>0.487</td>
<td>-2.7%</td>
<td>0.852</td>
<td>-44.4%</td>
<td>Corrosion interaction (40% deep)</td>
</tr>
<tr>
<td>C-GW-24-1</td>
<td>E-glass / epoxy</td>
<td>104,206</td>
<td>843</td>
<td>1,221</td>
<td>1.45</td>
<td>0.477</td>
<td>0.487</td>
<td>-2.1%</td>
<td>0.852</td>
<td>-44.0%</td>
<td>Girth weld interaction</td>
</tr>
<tr>
<td>D-PD-24-1</td>
<td>Carbon / epoxy</td>
<td>101,151</td>
<td>833</td>
<td>722</td>
<td>0.87</td>
<td>0.361</td>
<td>0.221</td>
<td>63.4%</td>
<td>0.387</td>
<td>-6.6%</td>
<td>Seams material interaction</td>
</tr>
<tr>
<td>D-DC-24-1</td>
<td>Carbon / epoxy</td>
<td>101,151</td>
<td>834</td>
<td>768</td>
<td>0.92</td>
<td>0.552</td>
<td>0.221</td>
<td>149.9%</td>
<td>0.387</td>
<td>42.8%</td>
<td>Seams material interaction</td>
</tr>
<tr>
<td>E-PD-24-1</td>
<td>Carbon / epoxy</td>
<td>101,151</td>
<td>834</td>
<td>453</td>
<td>0.54</td>
<td>0.341</td>
<td>0.208</td>
<td>63.9%</td>
<td>0.364</td>
<td>-6.3%</td>
<td>Seams material interaction</td>
</tr>
<tr>
<td>E2-PD-24-1</td>
<td>Carbon / epoxy</td>
<td>102,000</td>
<td>877</td>
<td>1,033</td>
<td>1.18</td>
<td>0.333</td>
<td>0.208</td>
<td>60.1%</td>
<td>0.364</td>
<td>-8.5%</td>
<td>Seams material interaction</td>
</tr>
<tr>
<td>E2-PD-24-2</td>
<td>Carbon / epoxy</td>
<td>102,000</td>
<td>877</td>
<td>1,128</td>
<td>1.29</td>
<td>0.303</td>
<td>0.170</td>
<td>78.2%</td>
<td>0.298</td>
<td>1.8%</td>
<td>Good performance / optimized</td>
</tr>
</tbody>
</table>

**Notes and Comments**

- **DV-CIP Data** (24-inch x 0.25-inch, Grade X42 pipe | cycled from 100 to 630 psi, \( \Delta P = 60\% \) SMYS | Average residual dent depth of 4.8% | 100,000 cycle runout)
- **MATR-3-5 Data** (12.75-inch x 0.188-inch, Grade X42 pipe | cycled from 100 to 890 psi, \( \Delta P = 64\% \) SMYS | Average residual dent depth of 4.7% | 250,000 cycle runout)

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**DV-CIP Data**

- **Unrepaired**: No repair installed
- **A-PD-24-1**: Good performance (E-glass)
- **AE-PD-24-1**: Seams material interaction
- **AE-PD-24-2**: Seams material interaction
- **B-SW-24-1**: Seams material interaction
- **B-DC-24-1**: Corrosion interaction (40% deep)
- **B-PD-24-1**: Seams material interaction
- **C-PD-24-1**: Good performance / optimized
- **C-SW-24-1**: Seams material interaction
- **C-DC-24-1**: Corrosion interaction (40% deep)
- **C-GW-24-1**: Girth weld interaction
- **D-PD-24-1**: Seams material interaction
- **D-DC-24-1**: Corrosion interaction (40% deep)
- **E-PD-24-1**: Seams material interaction
- **E2-PD-24-1**: Seams material interaction
- **E2-PD-24-2**: Good performance / optimized

**MATR-3-5 Data**

- **A-PD**: System under-designed
- **B-PD**: System under-designed
- **C-PD**: This always system has same thickness
- **D-PD**: System under-designed
- **E-PD**: System did not test well (disregard data)
- **F-PD**: System did not test well (disregard data)
- **G-PD**: System under-designed
- **H-PD**: System under-designed
- **I-PD**: System under-designed
- **J-PD**: System under-designed
- **Unrepaired**: No repair installed
Composite Qualification Design Flowchart

STEP #1
Design composite repair geometry based on PCC-2 methods.

STEP #2
Validate design using “Standard” 12-inch NPS pipe dent test.

STEP #3
Establish dent “SCF” using strain gage measurements.

STEP #4
With pipeline pressure data use Miner’s Rule to establish equivalent pressure range.

Estimate remaining life.

STEP #5A
Estimate life using experimental data from Step #2 (apply fatigue safety factor of 10 or more).

STEP #5B
Estimate life using dent SCF from Step #3 and appropriate S-N curve.

NOTE: A Simulated Integration Test (SIT) can be used on a case-by-case basis to validate a specific composite repair design for reinforcing a specific dent geometry using the methods outlined in this flow chart.
Equation Validation Process

• Two studies: MATR-3-5 and DV-CIP
• Pipe D/t ratios ranging from 34 to 96
• Number of dents
  ▪ 25 repaired
  ▪ 2 unrepaired
• No effective means to numerically account for filler material (at the present time)
• Data showed that performance of carbon-reinforced systems cannot be determined by modulus alone
Prescriptive Testing Methods

12-ft test sample
4-ft (typ)
Plain Dents (2)

ERW pipe seam

Profile after 10 GPa cycle

UR-GW-2

Close-up View of Dented Region

2-in

(this length might change based on profile of first dent)
Looking Forward

• Reinforcement of cracks using composite materials
• Finite element modeling to optimize repairs for critical applications
• Moving beyond corrosion and dents; providing reinforcement for bends, tees, and other features
• Need to better understand elevated temperature performance (i.e. loss of strength)
• Joint industry studies a huge plus for the industry
• Continued work with PRCI (NEW: BSEE & PHMSA)

All of the above items were listed last year; we are now doing them!
Thank You!