Current Testing Results and Validation of the Tyfo® Fibrwrap® Systems for Pipeline Rehabilitation

Scott F. Arnold, PE
Testing Programs Recently Completed

- Watertightness Testing at SGH Pressure Chamber for Improved Detailing
- Defect Criticality Testing at SGH Pressure Chamber to Understand the Structural Significance of Typical Cosmetic Anomalies
- Aerospace Durability Testing on the Tyfo Systems to Understand the Properties after 50-to-100 Years of Exposure
- Aerospace Durability Report on Specimens Exposed to 15-years at the Yolo Causeway
- Tensile Testing from In-Service Materials Taken after 18-years of Environmental Exposure
Saturation and Application
Impregnate Carbon Fiber fabric with Epoxy

Longitudinal layer

Circumferential layer

Watertightness layer
Tyfo® SEH Systems – Glass Systems

- Glass Fibers
  - Tyfo® SEH-51A
  - Tyfo® WEB
- Epoxies
  - Tyfo® S Epoxy
  - Tyfo® SW1S Epoxy
  - Tyfo® S-T Epoxy
  - Thickened Tyfo® S and Tyfo® S-T Epoxies
Tyfo SCH Systems – Carbon Systems

- Carbon Fibers
  - Tyfo® SCH-41
  - Tyfo® SCH-41-2X
  - Tyfo® SCH-Mark V
  - Tyfo® SCH-11UP
- Epoxies
  - Tyfo® S Epoxy
  - Tyfo® SW1S Epoxy
  - Tyfo® S-T Epoxy
  - Thickened Tyfo® S and Tyfo® S-T Epoxies
Watertightness Test Apparatus at SGH

- Introduce a watertight layer in the layup
- Test the laminate
  - Pressurize laminate over approximate 1 ft opening with 96 in. diameter curvature
  - Test laminate to 400 psi min
Tyfo® Fibrwrap® Systems retain watertightness characteristics to pressures beyond 400 psi and up to rupture strain.

Figure 3 — Strains in the fiber direction of the inner layer of CFRP at 500 psi pressure. Note maximum strain of 0.55 percent.
## Watertightness (Round 2) Testing

### Table 1 – Summary of Test Results

<table>
<thead>
<tr>
<th>Specimen #</th>
<th>Description</th>
<th>Materials</th>
<th>Pressure at Leak (psi)</th>
<th>Max. Strain Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1L+1G 1H L and H = 0.08 in. CFRP G = thin layer of woven glass fabric</td>
<td>CFRP system with 0.08 in. lamina and Proprietary woven glass fabric</td>
<td>Visible cracking of thickened epoxy between fiber bundles at 275 psi. 0.025 in. wide crack at 500 psi. No weepage at 500 psi.</td>
<td>0.96</td>
</tr>
<tr>
<td>2</td>
<td>Same as Specimen 1</td>
<td>Same as Specimen 1</td>
<td>Visible cracking of thickened epoxy between fiber bundles at 175 psi. 0.013 in. wide crack at 400 psi. Minor weepage through crack in thickened epoxy at 450 psi. Weepage unchanged at 500 psi.</td>
<td>0.97 and 1.20</td>
</tr>
<tr>
<td>3</td>
<td>1L+1G 1H L and H = 0.04 in. CFRP G = thin layer of woven glass fabric</td>
<td>CFRP System with 0.04 in. Lamina and Proprietary Glass Fabric</td>
<td>Visible cracking of thickened epoxy between fiber bundles at 175 psi. 0.022 in. wide crack at 225 psi. No weepage prior to rupture. Laminate ruptured at 300 psi.</td>
<td>1.19</td>
</tr>
</tbody>
</table>
## Watertightness (Round 1) Testing

<table>
<thead>
<tr>
<th>Sample Tested</th>
<th>Date Tested In 2014</th>
<th>Max Pressure (psi)</th>
<th>Percent Cure at Testing</th>
<th>Max Strain at Center of CFRP(%)</th>
<th>Failure Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>2L+1H+2L</td>
<td>21-Jul-</td>
<td>375</td>
<td>95.1</td>
<td>0.70 Sample cured beyond 95% leaked and ruptured at 375 psi.</td>
</tr>
<tr>
<td>4</td>
<td>2L+1H+1G+2L</td>
<td>22-Jul-</td>
<td>426</td>
<td>95.1</td>
<td>0.84 No failure, unloaded after reaching 426 psi.</td>
</tr>
<tr>
<td>3</td>
<td>2L+1H+2L</td>
<td>30-Jul-</td>
<td>276</td>
<td>90.9</td>
<td>0.69 Small leak developed through crack in CFRP</td>
</tr>
<tr>
<td>4</td>
<td>2L+1H+1G+2L</td>
<td>30-Jul-</td>
<td>450</td>
<td>90.9</td>
<td>0.78 No failure, unloaded after reaching 450 psi, small amount of delamination.</td>
</tr>
<tr>
<td>1</td>
<td>1L+1H</td>
<td>26-Aug</td>
<td>251</td>
<td>86.7</td>
<td>0.54 Sample leaked and burst at above 250 psi.</td>
</tr>
<tr>
<td>2</td>
<td>1L+1G+1H</td>
<td>26-Aug</td>
<td>400</td>
<td>86.7</td>
<td>0.78 No failure, unloaded after reaching 400 psi.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Specimen #</th>
<th>Layup</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1L + 1 H</td>
<td>2X</td>
</tr>
<tr>
<td>2</td>
<td>1L + 1G + 1H</td>
<td>2X and Glass</td>
</tr>
<tr>
<td>3</td>
<td>2L + 1H + 2L</td>
<td>1X</td>
</tr>
<tr>
<td>4</td>
<td>2L + 1H + 1G + 2L</td>
<td>1X and Glass</td>
</tr>
</tbody>
</table>
Hand Layup Anomalies

- The imperfections below are the most typical of those seen during inspections of previously applied CFRP
  - Blisters / Voids
  - Wrinkles (misaligned fiber strands)
  - Fiber Separation (gaps at butt splice)
  - Insufficient Epoxy Top Coat
Typical projects have an affected surface area <0.5% of the total installed surface area

Question: Are these anomalies affecting the long term lifespan of the installed Tyfo Systems?

Department of Defense’s Composite Materials Handbook allows for defects of <1% of the surface area in fracture critical aircraft

No current guidelines in AWWA Standard for CFRP or third party testing*

*New AWWA CFRP Standard Pending
Test Specimen Preparation
Gap (Insufficient Butt-Splice Tolerance) Imperfection
Void Imperfection
Improper Fabric Saturation Imperfection
## Defect Criticality Testing (Phase 1)

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Pressure and Observations</th>
<th>Max. Recorded Hoop Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control specimen</td>
<td>First weep through laminate at 200 psi, leak with continuous water stream at 225 psi, test terminated at 250 psi</td>
<td>0.43% at 250 psi</td>
</tr>
<tr>
<td>Specimen with “gap” imperfection</td>
<td>First weep through laminate at 100 psi, multiple weep locations at 200 psi, test terminated at 225 psi</td>
<td>0.43% at 171 psi*</td>
</tr>
<tr>
<td>Specimen with “void” imperfection</td>
<td>First weep through laminate at 425 psi, test terminated at 450 psi</td>
<td>0.39% at 172 psi*</td>
</tr>
<tr>
<td>Specimen with “improper fabric saturation” imperfection</td>
<td>First weep within the improperly saturated zone at 350 psi, increased weep with continuous water stream at 400 psi, test terminated at 450 psi</td>
<td>0.44% at 201 psi*</td>
</tr>
<tr>
<td>Specimen with “waviness” defect imperfection</td>
<td>Weep at multiple locations at 425 psi, test terminated at 425 psi</td>
<td>0.44% at 177 psi*</td>
</tr>
</tbody>
</table>

* The strain gage measuring the maximum hoop strain was damaged because of epoxy cracking at the pressure shown and did not yield reliable data at higher pressures.
Void Imperfection Inspection After Testing
Long-Term Tensile Property Predictions for Fyfe Company
SCH-41/Tyfo® S Carbon/Epoxy Composites from Arrhenius
Analyses of Accelerated Durability Data

October 5, 2015

Gary L. Stadel
Space Materials Laboratory
Physical Sciences Laboratories

Prepared for:
Fyfe Company
3940 Raffin Road, Suite C
San Diego, CA 92123

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Expected 50 year Retention of CFRP* at various service Temperatures

- Young's Modulus Retention, E
- Ultimate Tensile Strength Retention, $\sigma_u$

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Young's Modulus</th>
<th>Ultimate Tensile Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>22°C (72°F)</td>
<td>96% 98% 97% 98% 96%</td>
<td>93% 95% 95% 87% 79%</td>
</tr>
<tr>
<td>38°C (100°F)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>49°C (120°F)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>58°C (136°F)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>66°C (151°F)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Tyfo SCH-41 System Panels on the Yolo Causeway

October 1998

September 1999
Tyfo SEH-51 System Panels on the Yolo Causeway

October 1998  September 1999
15-Year Exposure Testing of the Tyfo Systems

Typical stress-strain curves for Tyfo Fibrwrap composite control samples and 15-yr Yolo Causeway exposure samples.

SCH-41/Tyfo S Sample No. HF-3K2A — Control No. HF-4G2
Advantex/Tyfo S Sample No. FG2I2A — Control No. FG2H1
SEH-51/Tyfo S Sample No. HF-2M1B — Control No. HF-1G4
In 1996, Wellington’s Aotea Quay Overbridge became the first bridge in New Zealand to be seismically strengthened with FRP composite materials.

In 2013, a panel was carefully abstracted and tested at a certified laboratory.
18-Year Exposure Testing of the Tyfo SEH-51 System

**Strength: 79% retained**

- Tyfo® SEH-51 Controls: 80 ksi
- 18-yr-old Tyfo® SEH-51: 68 ksi

**Modulus: 6% increase**

- Tyfo® SEH-51 Controls: 4 Msi
- 18-yr-old Tyfo® SEH-51: 4.2 Msi

12 ksi = Design Stress

3 Msi = Design Modulus
The Four Cornerstones of our Products and Services

- Product Qualifications
- Installer Qualifications
- Design Qualifications
- Field Quality Control