Concrete-Filled FRP Arch System

- Lightweight inflatable composite arch tubes
- Formed to any geometry in lab or on construction site
- Placed by hand labor or light equipment
- Stay-in-place formwork and structural reinforcement for concrete
- Spans up to 60’, tube thickness up to ½”, manufactured at AEWC
Concrete-Filled FRP Arch System

Lifting and Installation by Hand Labor

Arch Filling Technique

22’ Span Arches Weigh ~70 lb Each

60’ Span Arch Manufactured at AEWC
Three Components of Reinforcement

- Confinement of concrete
  - Increased compressive strength
  - Increased ductility
Nonlinear Flexural Response

- Two sources of nonlinearity:
  - Nonlinear stress-strain relationship of confined concrete in compression
  - Progressive cracking of concrete in tension
Beam Structural Testing

- Flexure only response
- 4-point bending
- 12” diameter tubes
- 12’ span
- 0.10” wall thickness
- Load applied at L/3
- 3 specimens subjected to quasistatic loading
# Beam Test Setup & Instrumentation

<table>
<thead>
<tr>
<th>Location</th>
<th>Distance</th>
<th>Instrumentation – Data Collected</th>
</tr>
</thead>
</table>
| North End           | 0 in     | 1 – Stringpot – Horizontal core slip  
  1 – 1” LVDT – Vertical support deflections                                                    |
| North Load Point    | 48 in    | 2 – 3” LVDT – Vertical deflection & rotation                                                  |
| Section A           | 60 in    | 2/3 – 1” Strain Gages – Strain, curvature                                                   |
| Midspan             | 72 in    | 2 – 5” LVDT – Vertical deflection & rotation                                                  |
| Section B           | 84 in    | 2/3 – 1” Strain Gages – Strain, curvature                                                   |
| South Load Point    | 96 in    | 2 – 3” LVDT – Vertical deflection & rotation                                                  |
| South End           | 144 in   | 1 – Stringpot – Horizontal core slip  
  1 – 1” LVDT – Vertical support deflections                                                    |

[Beam Test Fixtures Diagram]
Moment vs. Curvature for Concrete-Filled FRP Tubular Beams

Specimen 2, data clipped due to strain gage failure
Deflection at Midspan

Load vs. Midspan Deflection for Concrete Filled FRP Tubular Beams

Applied Load, P (kip)

Beam 01-Midspan
Beam 02-Midspan
Beam 03-Midspan
Model

L = 144 in

P/2

48 in
Deflection at Load Points

Load vs. Load-Point Deflection for Concrete Filled FRP Tubular Beams

Applied Load, P (kip)

Load Point Deflection (in)

Beam_01-North
Beam_01-South
Beam_02-North
Beam_03-North
Beam_03-South
Model

L = 144 in
P/2
48 in
## Failure Load & Moment

### Beam Failure Moment – Experimental & Predicted

<table>
<thead>
<tr>
<th>Experimental Values</th>
<th>Failure Moment (in*kip)</th>
<th>Percent Difference From Experimental</th>
<th>Failure Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam 01</td>
<td>1426</td>
<td>----</td>
<td>Tensile Rupture</td>
</tr>
<tr>
<td>Beam 02</td>
<td>1365</td>
<td>----</td>
<td>Tensile Rupture</td>
</tr>
<tr>
<td>Beam 03</td>
<td>1243</td>
<td>----</td>
<td>Tensile Rupture</td>
</tr>
<tr>
<td>Mean Experimental</td>
<td>1345</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>Predicted</td>
<td>1380</td>
<td>2.60%</td>
<td>Tensile Rupture</td>
</tr>
</tbody>
</table>

Typical Failed Beam Specimen

Constant Moment Region
Arch Structural Testing

- Static testing carried out on 4 arch specimens
  - 22’ Span
  - 13’ Radius of curvature
  - 12” Diameter
  - 0.10” Wall thickness
- Two-pinned arches
- Patch load applied vertically at crown
# Arch Specimen Instrumentation

<table>
<thead>
<tr>
<th>Location</th>
<th>Location</th>
<th>Instrumentation</th>
<th>Data Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>North support</td>
<td>A</td>
<td>1 – 10” SP</td>
<td>Support Rotation</td>
</tr>
<tr>
<td>North section, 96 in from crown</td>
<td>B</td>
<td>2 – 10” SP</td>
<td>Horizontal &amp; vertical deflection</td>
</tr>
<tr>
<td>North section, 18 in from crown</td>
<td>C</td>
<td>3 – 1” SG</td>
<td>Cross-section strain distribution</td>
</tr>
<tr>
<td>Crown</td>
<td>D</td>
<td>1 – 10” SP</td>
<td>Vertical deflection</td>
</tr>
<tr>
<td>South section, 18 in from crown</td>
<td>E</td>
<td>3 – 1” SG</td>
<td>Cross-section strain distribution</td>
</tr>
<tr>
<td>South section, 96 in from crown</td>
<td>F</td>
<td>2 – 10” SP</td>
<td>Horizontal &amp; vertical deflection</td>
</tr>
<tr>
<td>South support</td>
<td>G</td>
<td>1 – 10” SP</td>
<td>Support rotation</td>
</tr>
<tr>
<td>South support</td>
<td>H</td>
<td>4 – 0.5” SG</td>
<td>Horizontal thrust force</td>
</tr>
<tr>
<td>South half of specimen</td>
<td>----</td>
<td>PONTOS (DIC)</td>
<td>XYZ Deflections</td>
</tr>
</tbody>
</table>

*Notation:*
- SP – String Potentiometer
- SG – Strain Gage
Initial Loading

- Initial failure due to tensile rupture of FRP at crown
- Corresponds to location of maximum positive bending moment
- Result is a plastic hinge at crown
Secondary Loading

Three-Hinged Arch Behavior

Secondary Failure

- Post-failure arch specimen exhibits three-hinged behavior
- Secondary failure due to tensile rupture at shoulder
- Corresponds to location of maximum neg. bending moment
Load vs. Deflection at Crown

Load-Deflection at Crown

- Load vs. Deflection at Crown

- Arch 1, Arch 2, Arch 3, Arch 4, Model
Full Field Deflected Shape

Arch Deflected Shape, Experimental and Predicted
(Deflections Magnified 15X)
## Capacity & Failure Mode

### Experimental & Predicted Capacity

<table>
<thead>
<tr>
<th></th>
<th>Failure Load (kip)</th>
<th>COV</th>
<th>Number of specimens</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Initial</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experimental</td>
<td>72.0</td>
<td>2.55%</td>
<td>3</td>
<td>4.14%</td>
</tr>
<tr>
<td>Predicted</td>
<td>69.0</td>
<td>--------</td>
<td>--------</td>
<td></td>
</tr>
<tr>
<td><strong>Secondary</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experimental</td>
<td>57.6</td>
<td>7.75%</td>
<td>3</td>
<td>1.10%</td>
</tr>
<tr>
<td>Predicted</td>
<td>57.0</td>
<td>--------</td>
<td>--------</td>
<td></td>
</tr>
</tbody>
</table>

**Load-Deflection Response of Concrete-Filled FRP Tubular Arch**

- **Initial hinge forms at crown**
- **Subsequent hinges form at shoulders resulting in instability and structural collapse**

![Graph showing load-deflection response](image-url)
Neal Bridge Project: Background

- MDOT #2600
- Route 100/11
- Pittsfield, ME
- Spans Neal Brook
- Existing structure:
  - Reinforced concrete
  - Built in 1917
  - Expanded in 1932
Neal Bridge Deterioration

- Concrete Spalling
- Exposed Steel Rebar
- Concrete Spalling
Construction Process

- 23 FRP arch tubes spaced at 2’ O.C.
- Arches covered with corrugated FRP decking to retain backfill
Construction Process

- Arches filled with concrete through a small hole at crown
- FRP headwalls & precast concrete wingwalls installed
- Soil backfill placed and compacted
Completed Structure
Field Instrumentation

- Strain gages at 3 locations per arch, 4 arches instrumented
- Soil pressure gages at 5 locations, 1 arch instrumented
- Displacement gages at 6 locations, 1 arch instrumented
- PONTOS – deflections of 2 arches and decking between
Field Instrumentation & Load Testing

- Roadway
- Concrete Filled FRP Arches
- Footing
- Instrumented Arches
- Bedrock
- Bedrock
Field Load Testing, April 14, 2009

Data Collection Station

Setup of PONTOS digital image correlation system: Uses two high resolution digital cameras to track movement of arches in three-dimensions
Field Load Testing, April 14, 2009

Truck Positions Along Span of Bridge

Awaiting Truck Placement
Field Load Testing, April 14, 2009

Recording Strain, Displacement & Soil Pressure Data

Recording Displacement Data From PONTOS
Field Load Testing, April 14, 2009

- Two loaded dump trucks, axle weight and spacing as shown
- Trucks positioned on bridge in parallel and series to produce maximum load effects
- Static & dynamic load tests
- Results of test will provide:
  - Load rating
  - Information into longitudinal & transverse load distribution
  - Information into in-service soil-structure interaction