Michigan DOT’s Use of Externally-Bonded FRP Systems for Bridge Element Strengthening

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A brief outline:

- I-75 over Rouge River case study
- I-75/M-8 Interchange Ramp case study
- Guide Specification for Bonded FRP Repair update
- The future of FRP in infrastructure
How is this relevant to ABC?

- Use of the Bonded FRP systems for substructure repairs resulted in no impacts to freeway traffic, and very little impact to local traffic

- These systems can be installed via prequalified contract, or direct-force maintenance staff

- Strengthening and/or confining concrete elements is a viable option to replacement, which has a larger impact
I-75 over Rouge River
Michigan’s largest bridge
<table>
<thead>
<tr>
<th>FACILITY</th>
<th>FEATURE CROSSED</th>
<th>LENGTH (ft)</th>
<th>WIDTH (ft)</th>
<th>DECK AREA (ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I-75</td>
<td>ROUGE RIVER, DEARBORN ST &amp; RR</td>
<td>8,627.00</td>
<td>132.40</td>
<td>1,142,215</td>
</tr>
<tr>
<td>I-75</td>
<td>STRAITS OF MACKINAC</td>
<td>19,247.70</td>
<td>53.80</td>
<td>1,035,526</td>
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<tr>
<td>I-75 SB</td>
<td>SAGINAW R, M-13, GTWRR (Zilwaukee)</td>
<td>8,084.97</td>
<td>74.50</td>
<td>602,331</td>
</tr>
<tr>
<td>I-75 NB</td>
<td>SAGINAW R, M13, GTWRR (Zilwaukee)</td>
<td>8,061.02</td>
<td>74.50</td>
<td>600,546</td>
</tr>
<tr>
<td>I-75, INTERNATIONAL BRIDGE</td>
<td>ST MARY RIV/PORTAGE AV W</td>
<td>9,280.18</td>
<td>34.50</td>
<td>320,166</td>
</tr>
<tr>
<td>I-94 EB</td>
<td>ST CLAIR RIVER, CN RR (Black River)</td>
<td>6,110.60</td>
<td>51.50</td>
<td>314,696</td>
</tr>
<tr>
<td>I-94</td>
<td>GTW, NS, CR RR &amp; RUSSEL</td>
<td>2,184.00</td>
<td>132.60</td>
<td>289,598</td>
</tr>
<tr>
<td>I-675</td>
<td>SAG RIV, H&amp;E SBS RR, M13 (Henry Marsh)</td>
<td>2,948.49</td>
<td>94.20</td>
<td>277,748</td>
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<tr>
<td>I-94 WB</td>
<td>ST CLAIR RIVER, CN RR (Black River)</td>
<td>6,178.51</td>
<td>37.40</td>
<td>231,076</td>
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<tr>
<td>BELLE ISLE TRAFFIC</td>
<td>DETROIT RIVER (McArthur)</td>
<td>2,291.31</td>
<td>87.90</td>
<td>201,406</td>
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<tr>
<td>M-231</td>
<td>GRAND RIVER</td>
<td>3,708.70</td>
<td>49.40</td>
<td>183,210</td>
</tr>
<tr>
<td>WOODSIDE AVE</td>
<td>SAGINAW RIVER AND MCRR</td>
<td>2,344.49</td>
<td>76.70</td>
<td>179,822</td>
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<tr>
<td>I-196 WB</td>
<td>GRAND R, I-296, SCRIB &amp; TURN</td>
<td>2,277.56</td>
<td>47.20</td>
<td>107,501</td>
</tr>
</tbody>
</table>
I-75 over Rouge River

- Prior to 2018, was in overall poor condition, with a Bridge Deck NBI rating of 4
- Steel girder superstructure, and piers in good/fair condition
- As part of a comprehensive asset management plan, options for rehabilitation were studied
- Ultimately the deck replacement option was selected, knowing we could maintain the substructure in good/fair condition during the life of the new bridge deck
Developed Bonded FRP repair program for confinement and strengthening of piers.
I-75 over Rouge River

- MDOT specification, with FRP sheet and adhesive composite system meeting CalTrans requirements

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**Table 1 Structural Adhesive Minimum Properties**

<table>
<thead>
<tr>
<th>PROPERTIES</th>
<th>MINIMUM VALUES</th>
<th>ASTM TEST METHOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength</td>
<td>9,000 psi</td>
<td>D 836</td>
</tr>
<tr>
<td>Elongation at break</td>
<td>4.4%</td>
<td>D 638</td>
</tr>
<tr>
<td>Modulus of elasticity 7 days</td>
<td>390,000 psi</td>
<td>D 836</td>
</tr>
<tr>
<td>Flexural strength</td>
<td>6,700 psi</td>
<td>D 790</td>
</tr>
<tr>
<td>Shear strength 14 days</td>
<td>3,600 psi</td>
<td>D 732</td>
</tr>
<tr>
<td>Deflection temperature</td>
<td>47 C</td>
<td>D 548</td>
</tr>
<tr>
<td>Water absorption</td>
<td>0.03%</td>
<td></td>
</tr>
</tbody>
</table>
I-75 over Rouge River

This spreadsheet is intended to calculate the net axial confinement strengthening of FRP wraps applied to bridge columns. Reference document ACI 440.2R-08. Use of FRP wraps for axial confinement strengthening is not recommended for members featuring side aspect ratios A/h greater than 2.5 or face dimensions b or h exceeding 36 in., unless testing demonstrates their effectiveness (ACI 12.1.2).

Details section - Information from manufacturer's data sheets and bridge plans

Column Dimensions (Figure 12-3 from ACI 440.2R-08)

![Diagram](image)

ColumnType :=

- Circular
- Rectangular

Inputs

FRP

- $c_y = 0.0167$ (Fiber ultimate strain (in/in.), provided by manufacturer)
- $E_y = 330000000$ psi (Fiber tensile modulus (psi), provided by manufacturer)
- $n = 1$ (number of FRP wraps, typically 2 but modified as needed)
- $t_y = 0.0085$ in. (FRP thickness (in.), provided by manufacturer)
I-75 over Rouge River

Concrete

- $f_c = 3500$ psi: concrete compressive strength (psi), substructure concrete
- $f_y = 0.02$: longitudinal steel reinforcement ratio assumed at 0.02

- $e_c := 0.002$: maximum strain of unconfined concrete corresponding to $f_c$, in./in., may be taken as 0.002

Column

- $h := 60$ in
- $b := 48$ in

- $r_c := 3$ in: corner radius typically 3 in, but manufacturer recommended value
- $D_c := 42$ in: input the circular column dimension, leave as default if rectangular column.

D := \begin{cases} \sqrt{\frac{a^2 + h^2}{D_c}} & \text{ColumnType} = \text{"Rectangular"} \\ \frac{D_c}{a} & \text{otherwise} \end{cases}

ACI equation 12-8 for equivalent circular cross section

D = 76.637 in

$A_g := b \cdot h$ if ColumnType = "Rectangular" otherwise

Gross cross section area

$A_g := \frac{D^2}{d}$ otherwise

$A_g := 2880$ in$^2$

Effective confinement cross sectional area ratio ($A_g/A_c$) for non-circular shapes

This ratio is used for non circular cross sections to calculate the appropriate shape factors, $e_c$, and $k_a$, which depend on the area of effectively confined concrete and the side aspect ratio h/b.

See ACI section 12.1.2.

Effective Confinement Ratio := \begin{cases} \frac{\frac{h}{b} (b - 2c)^2 + \frac{b}{h} (b - 2c)^2}{3A_g} & \text{ACI equation 12-81} \\ \frac{1}{1 - \frac{f_y}{f_c}} & \text{otherwise} \end{cases}
Effective Confinement Ratio = 0.464

Shape Factors (non circular shapes). For circular shapes, ACI 12.1.2 specifies \( \kappa_c \) and \( \kappa_b \) set to

\[
\begin{align*}
\kappa_b &= \frac{\text{Effective Confinement Ratio \( \left( \frac{b}{h} \right)^2 \)}}{1.0} \quad \text{if \ ColumnType = "Rectangular"} \\
&= 0.297 \\
\kappa_b &= \frac{\text{Effective Confinement Ratio \( \left( \frac{h}{b} \right)^{0.5} \)}}{1.0} \quad \text{if \ ColumnType = "Rectangular"} \\
&= 0.519
\end{align*}
\]

FRP Strain efficiency factor, \( \eta_y \)

\( \eta_y = 0.55 \) Per ACI section

FRP effective strain at failure, \( \varepsilon_{fu} \)

\( \varepsilon_{fu} = 0.85 \times \varepsilon_f \) FRP ultimate strain reduced by environmental factor of 0.85 per ACI table 9-1

\( \varepsilon_{fu} = \begin{cases} 
\varepsilon_f \times \varepsilon_{fu} & \text{if \ } \varepsilon_f \times \varepsilon_{fu} < 0.004 \\
0.004 & \text{otherwise}
\end{cases} \quad \text{ACI Equation 12-12. Limited to ensure the integrity of the confined concrete.}

\( \varepsilon_{fu} = 0.004 \)

Maximum compressive strain in the confined concrete, \( \varepsilon_{ccu} \)

\[
\varepsilon_c = \frac{2 \varepsilon_f \times \eta_y \times \varepsilon_{fe}}{D} \quad \text{ACI equation 12-4}
\]

\( f_c = 22,333 \) psi

\( f'_{cc} = f_c + 0.05 \times 3.5 \times \eta_y \times f'_l \) ACI equation 12-3

\( f'_{cc} = 3621 \) psi

\[
\varepsilon_{ccu} = \varepsilon_c \left[ 1.50 + 12 \alpha_b \frac{f'_{cc}}{f'_{ce} \times 0.45} \right]
\]

\( \varepsilon_{ccu} = 0.003 \) Note that \( \varepsilon_{ccu} \) must be \( \leq 0.01 \) per ACI equation 12-7.
I-75 over Rouge River

Confinement Ratio = $\frac{h}{r_c}$

Confinement Ratio = 0.055

Additional strength contribution of the FRP wrap

$\phi = 0.85$

$P_{rel} = 0.8 \times \left[ 0.85 \left( f_{ck} - f_y \right) A_y \left( 1 - \frac{r_o}{r_i} \right) \right]$

$P_{rel} = 25.9$ kip

ACI recommends the confinement ratio to be ≥ 0.08

Axial compression strength reduction factor, $\phi$, per ACI 318

Modified from ACI equation 12.1b, to determine the net axial strength contribution of FRP.
Piers contain slag aggregate as opposed to crushed limestone, and have had cracking and spalling issues.

Air Cooled Blast Furnace Slag (magnification 15x)
- Highly porous, glassy material
- Minimal fracture toughness, cracks propagate through the aggregate
- Little to no aggregate interlock after crack formation
I-75 over Rouge River
I-75 over Rouge River
I-75 over Rouge River

- $6.5 million rehabilitation project
- 23 pier bents rehabilitated, a total of 71 columns
- 489 cyd of patching concrete
- 49,000 sft of externally bonded FRP reinforcement
- Prime Contractor Posen Construction – now called Z-Contractors
- FRP specialist subcontractor Structural Group
- April to November 2010
I-75/M-8 Interchange Ramp
I-75/M-8 Interchange Ramp
I-75/M-8 Interchange Ramp

- Intermediate single column pier with fixed bearing and steel pier bent
- 950 foot radius curve
- Non Uniform Span Length (86 feet and 137.5 feet)
- Longitudinal and transverse forces caused cracking and spalling
I-75/M-8 Interchange Ramp
I-75/M-8 Interchange Ramp
I-75/M-8 Interchange Ramp
I-75/M-8 Interchange Ramp
I-75/M-8 Interchange Ramp

- Repair Design completed in August of 2013 by Lawrence Technological University

Notes and assumptions:
- The average existing concrete strength is taken as 5000 psi.
- The calculations were performed according to ACI-440.2R-08, Chapter 12.
- The calculations show only the increase in the axial load carrying capacity due to confinement of the pier. Calculations for the moment-axial force interaction are not provided.
- The increase in the axial load carrying capacity of the pier is achieved by increasing the average compressive strength of the concrete through confinement.
- Two cases of confinement are provided; the first case considers the confinement of the pier with FRP materials applied directly to the surface without any shape modification while the second case considers the confinement of the pier with FRP wraps after modifying the shape to a near circular using steel plates and pipes.
- The analysis was performed based on the material properties of a uni-axial carbon fiber fabric (Replark). However, the analysis can be adjusted for other types of FRP fabric as well.
**Notations:**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A_{bc}</td>
<td>Ratio between confined and total concrete cross-sectional areas*</td>
</tr>
<tr>
<td>A_b</td>
<td>Gross area of concrete section*</td>
</tr>
<tr>
<td>A_{nc}</td>
<td>Total area of longitudinal reinforcement*</td>
</tr>
<tr>
<td>b</td>
<td>Width of compression face of pier*</td>
</tr>
<tr>
<td>D</td>
<td>Diameter of compression member*</td>
</tr>
<tr>
<td>E_2</td>
<td>Slope of linear portion of stress-strain model for confined concrete*</td>
</tr>
<tr>
<td>f_c</td>
<td>Modulus of elasticity of concrete*</td>
</tr>
<tr>
<td>E_f</td>
<td>Tensile modulus of elasticity of FRP*</td>
</tr>
<tr>
<td>f_c</td>
<td>Concrete compressive strength*</td>
</tr>
<tr>
<td>f_{c0}</td>
<td>Theoretical compressive strength of confined concrete*</td>
</tr>
<tr>
<td>f_{c0,mod}</td>
<td>Actual compressive strength of confined concrete*</td>
</tr>
<tr>
<td>f_y</td>
<td>Maximum confining pressure due to FRP jacket*</td>
</tr>
<tr>
<td>f_y</td>
<td>Yield strength of longitudinal reinforcement*</td>
</tr>
<tr>
<td>h</td>
<td>Depth of the compression face of the pier*</td>
</tr>
<tr>
<td>k_s</td>
<td>Efficiency factor for FRP reinforcement in determining f_a*</td>
</tr>
<tr>
<td>k_p</td>
<td>Efficiency factor for FRP in determining f_r*</td>
</tr>
<tr>
<td>n</td>
<td>Efficiency factor taken as 0.58*</td>
</tr>
<tr>
<td>n</td>
<td>Number of plies of FRP*</td>
</tr>
<tr>
<td>P_{nc}</td>
<td>Nominal axial compressive strength of unconfined concrete section*</td>
</tr>
<tr>
<td>P_{nc,mod}</td>
<td>Nominal Axial compressive strength of confined concrete section*</td>
</tr>
<tr>
<td>\Delta P</td>
<td>% Increase in the axial compressive strength due to confinement*</td>
</tr>
<tr>
<td>r_c</td>
<td>Radius of edges of the cross section*</td>
</tr>
<tr>
<td>r</td>
<td>Nominal thickness of one ply of FRP*</td>
</tr>
<tr>
<td>\varepsilon_{ccu}</td>
<td>Theoretical ultimate axial compressive strain of confined concrete*</td>
</tr>
<tr>
<td>\varepsilon_{c,mod}</td>
<td>Actual ultimate axial compressive strain of confined concrete*</td>
</tr>
<tr>
<td>e_{frp}</td>
<td>Effective strain level in FRP*</td>
</tr>
<tr>
<td>\varepsilon_{frp}</td>
<td>Design rupture strain of FRP reinforcement*</td>
</tr>
<tr>
<td>\varepsilon_{l}</td>
<td>Ratio of area of longitudinal reinforcement to gross sectional area*</td>
</tr>
<tr>
<td>\varepsilon_{r}</td>
<td>Design ultimate strength of FRP*</td>
</tr>
</tbody>
</table>
### Properties of FRP materials

- $f_f = 23,000 \text{ psi}$
- $f_{c,0} = 4000 \text{ psi}$
- $f_{c,0} = 0.04 \text{ in}$
- $f_{c,0} = 0.94 \text{ in}$

#### Calculate the axial load carrying capacity of the pier:

- $h = 42 \text{ in}$
- $l = 94 \text{ in}$
- $A_{w} = 34.16 \text{ in}^2$
- $A_{g} = h \cdot b = 3.528 \times 10^3 \text{ in}^2$
- $f_p = 6000 \text{ psi}$

#### Calculate the axial load carrying capacity of the unstrengthened pier:

- $f_p = 5000 \text{ psi}$
- $P_{n} = 0.8 \left( f_{n} \cdot \left( A_{w} - A_{u} \right) + f_{y} \cdot A_{u} \right)$
- $P_{n} = 1.55 \times 10^3 \text{ lb}$

#### Calculate the axial load carrying capacity of the pier when strengthened with layers of FRP materials directly applied to the sides of the pier with no shape modification:

- $D = (b^2 + h^2)^{0.5} = 93.915 \text{ in}$
- $P_{y} = \frac{A_{w}}{A_{g}} = 9.739 \times 10^{-3}$
- $f_c = 0 \text{ psi}$
- $n = 5$
I-75/M-8 Interchange Ramp

\[
\frac{b(h\pm2k_b)^2}{h} - \frac{k_Y}{k_Y}\left(\frac{b(h\pm2k_b)^2}{h}\right)
\]

\[
\lambda_{ec} = \frac{V}{P_d} = 0.327
\]

\[
k_Y = \lambda_{ec}\left(\frac{b(h\pm2k_b)^2}{h}\right) = 0.072
\]

\[
k_Y = \lambda_{ec}\left(\frac{b(h\pm2k_b)^2}{h}\right) = 0.462
\]

\[
k_Y = 0.58
\]

\[
\varepsilon_p = \frac{b(h\pm2k_b)^2}{h} = 8.526 \times 10^{-3}
\]

\[
f_{ij} = \frac{2(k_i + k_y)cp}{D} = 835.216 \text{ psi}
\]

\[
\frac{f}{f_{ij}} = 0.167
\]

Check confinement: "Okay" if \( \frac{f}{f_{ij}} > 0.8 \\
"Redesign" otherwise

Check confinement = "Okay".

\[
\varepsilon_p = 0.002
\]

\[
\varepsilon_p = \varepsilon_p + 0.053.3k_f = 5.214 \times 10^{-3}
\]

\[
\varepsilon_{cu} = \frac{\varepsilon_p}{0.45}
\]

\[
\varepsilon_{cu} = 6.558 \times 10^{-3}
\]

\[
\varepsilon_{cu, mod} = \varepsilon_{cu} \text{ if } \varepsilon_{cu} < 0.01
\]

\[
\varepsilon_{cu, mod} = 6.558 \times 10^{-1}
\]
I-75/M-8 Interchange Ramp

\[ E_s = 35 \times 10^6 \text{ lb/in}^2 \]

\[ f_{y,s} = \frac{f_{y,s}}{f_{y,0}} = 0.262 \times 10^6 \text{ lb/in}^2 \]

\[ f_{c,b} = f_{c,b} = 5.214 \times 10^3 \text{ lb/in}^2 \]

\[ P_{c,b,mod} = f_{c,b} f_{c,b,mod} = 5.214 \times 10^3 \text{ lb/in}^2 \]

\[ P_{n,c,b} = 0.85 f_{c,b} f_{c,b,mod} \left( \lambda_n - \lambda_{n,mod} \right) \xi_{c,b} = 1.404 \times 10^7 \text{ lb} \]

\[ \Delta P_n = \frac{P_{n,c,b} - P_n}{P_n} = 3.19 \% \]

Calculate the axial load carrying capacity of the pier when strengthened with 5 layers of FRP materials applied to the modified shape (as shown in the attached drawing in the PDF file) of the pier:

\[ D = \left( \alpha_p \right)^{0.5} = 93.015 \text{ ft} \]

\[ \frac{\lambda_{n,mod}}{\lambda_{n}} = 9.739 \times 10^{-1} \]

\[ \xi_{c,b} = 1.0 \]

\[ \xi_{c,b} = 1.0 \]

\[ \xi_{c,b} = 1.0 \]

\[ \xi_{c,b} = 0.58 \]

\[ c_{f,0} - k_c c_n = 8.526 \times 10^{-5} \]
I-75/M-8 Interchange Ramp

- Before FRP Installation
  - Close Local Road Adjacent to Repair
  - Temp support all beam ends
  - Patch Concrete
I-75/M-8 Interchange Ramp

- Rough Patch Edges
I-75/M-8 Interchange Ramp

- Grind Surface Irregularities
I-75/M-8 Interchange Ramp

- Grind Corners
I-75/M-8 Interchange Ramp

- Clean and Prepare Surface
- Apply Surface Primer
I-75/M-8 Interchange Ramp

- Apply Surface Leveler
I-75/M-8 Interchange Ramp

- Apply Saturant
I-75/M-8 Interchange Ramp

- Lay up and roll in Carbon Fiber
I-75/M-8 Interchange Ramp

- Apply Second Coat of Saturant
I-75/M-8 Interchange Ramp

- Surface Coat areas accessible to the public, for aesthetics
I-75/M-8 Interchange Ramp - Project Summary

- Carbon Fiber Design Completion in August of 2013
- Design and Construction of Detour and Temporary Beam End Supports Completed August 2014 by State Forces
- Concrete Patched by State Forces August of 2014
- FRP Installed September of 2014 (After 28 day concrete cure)
- Cost of Carbon Fiber Materials - $2,470
- FRP Installation time – 1 Day
Complex Engineering yet Simplistic Installation

State Maintenance Crews are very capable of repair

Be ready to sign an end use agreement when purchasing carbon fiber
I-75/M-8 Interchange Ramp
AASHTO Update
The Future of FRP in Infrastructure:

- Now that there are FRP design and construction specifications, what about:
  - Life cycle maintenance
  - Inspection
  - Performance if damaged
  - Load Rating, over loads, and permit loads
  - Better understanding failure modes

- The AASHTO T-6 committee, and TRB AFF80 committee should be thinking about this jointly, and considering future research projects geared towards better understanding these items.

- AASHTO T-6, TRB AFF80, and industry also need to work together on this
Questions?