Seismic Evaluation and Retrofit of Beam-Column Joints of Mid-American Bridges
Part 1: Fiber Reinforced Polymer Retrofit

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New Madrid Seismic Zone Experience

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Participants

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Research Objectives

Develop a Comprehensive Research Program to Establish the Seismic Retrofit of a Beam/Column Joint According to Modern Seismic Design Principles Using CFRP Systems

♦ Plastic hinges to form at the ends of the columns
♦ Beams protected against any significant flexural or shear inelastic actions
♦ Beam/column joints retrofitted in order to minimize inelastic rotations in the beam/column joint regions

Current Design Deficiencies

Plastic Hinges Can Form Either in the Beams or Joints under Moderate Seismic Events

♦ Excessive - Column flexural reinforcement
♦ Inadequate - Column shear reinforcement
♦ Inadequate - Beam shear reinforcement
♦ Inadequate - Beam flexural reinforcement
♦ Inadequate - Joint shear reinforcement
### Performance Levels for a Typical Bent Cap/Column-bent Connection

<table>
<thead>
<tr>
<th>Bridge #</th>
<th>Year Built</th>
<th>Main Span Length</th>
<th>Girder Type</th>
<th>No. of Bents</th>
<th>No. of Columns/Bent</th>
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<tbody>
<tr>
<td>A-1466</td>
<td>1966</td>
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<td>3</td>
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<td>4</td>
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<td>1968</td>
<td>87</td>
<td>Steel Continuous</td>
<td>5</td>
<td>3</td>
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</table>
## Evaluation of Bridge Structures

<table>
<thead>
<tr>
<th>Bridge #</th>
<th>Bent Cap</th>
<th>Column</th>
<th>Flexural Failure</th>
<th>Joint Shear Failure</th>
<th>Column Shear</th>
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<tr>
<td>(#)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-1466</td>
<td>FAIL</td>
<td>PASS</td>
<td>(PASS/FAIL)</td>
<td>(PASS/FAIL)</td>
<td>PASS</td>
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<td>PASS</td>
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<td>MARGINAL</td>
<td>FAIL</td>
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<td></td>
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<tr>
<td>A-2332</td>
<td>PASS</td>
<td>FAIL</td>
<td>MARGINAL</td>
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<tr>
<td>A-2333</td>
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<td>MARGINAL</td>
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<tr>
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<td>MARGINAL</td>
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</tr>
<tr>
<td>A-2428</td>
<td>FAIL</td>
<td>FAIL</td>
<td>FAIL</td>
<td></td>
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</tr>
</tbody>
</table>

### Test Matrix

**Design of Two Test Units for Evaluation of Retrofit of Beam/Column Systems Using Carbon-FPP Composites**

- **Unit 1** – Incremental retrofit at different performance levels
- **Unit 2** – Complete retrofit before testing
Prototype Structure

FRP Retrofitting

Top & Bot. Bars Bent At Ends

Center of Bent Cap

Bolts

5 - D25 (#8) - Top Reinf.

610 D13 (#4) Hoops @ 120 o/c (0.40%)

D16 (#5) Stirrups @ 184 o/c

10 – D25 (#8) Bottom Reinf.

50 Cover

14 - D29 (#9) (ρt = 3.5%)

1 - D16 (#5) (Each Side)

Top & Bot. Bars Bent At Ends

Longitudinal Section
Beam & Column X-Sections

- 14 - D29 (#9) (ρl ≈ 3.5%)
- D13 (#4) Hoops @ 120 o/c (0.40%)
- D16 (#5) Stirrups @ 184 o/c
- 1 - D16 (#5) (Each Side)
- 10 – D25 #8) Bottom Reinf. Arranged in 2 Layers
- 5 - D25 (#8) Top Reinf.

FRP Retrofitting - 11
Demand Evaluation

\[
\begin{bmatrix}
M_C \\
H \\
\left( L - D \right) \\
P \left( L_1 - D \right) \\
\frac{M_C}{2} \\
\frac{H}{2} \\
\frac{L}{4} \\
\end{bmatrix}
\]

\[
V_B^{cr} = \frac{M_C}{2} \left( \frac{H}{2} \right) - \frac{P}{2}
\]

Support Blocks

Critical Section

Critical Section

Column

P/2

P/2

L

L_1

FRP Retrofitting - 14
**Material Properties**

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Concrete 28 Day Strength (psi)</th>
<th>Concrete Strength at Time of Testing (psi)</th>
<th>Steel Rebar Yield Strength (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam</td>
<td>5026</td>
<td>5342</td>
<td>8</td>
</tr>
<tr>
<td>Column</td>
<td>3525</td>
<td>3697</td>
<td>60</td>
</tr>
<tr>
<td>Beam</td>
<td>4216</td>
<td>4609</td>
<td>80</td>
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<tr>
<td>Column</td>
<td>4993</td>
<td>5419</td>
<td>75</td>
</tr>
</tbody>
</table>

**Column Shear Capacity Evaluation**

- Unit
- ACI 318-02
- UCSD
 Beam Shear Capacity Evaluation

Negative Moment

Positive Moment

FRP Retrofitting - 17

FRP Retrofitting - 18
Joint Principle Stresses Evaluation

Principal Tensile Stresses

Joint Shear Failure
Joint Shear Cracking

Unit

Predicted Seismic Response
Un-strengthened System

1. Column shear failure at $\mu_A < 3$ or onset of column cover concrete spalling
2. Onset joint shear failure at $\mu_A > 2$
**Column Retrofit**

Spliced Circular

14 - D29 (#9) ($\rho_l \cong 3.5\%$)

- **Shear (2 Plies)**
  \[ t_j = \frac{V^o}{\Phi_s - (V_c + V_s + V_p)} \]
  \[ 0.5 \pi f_y D \cot \theta \]

- **Confinement (9 Plies)**
  \[ t_j = 0.10 (\varepsilon_{Cu} - 0.004) D f'_{cc} \]

- **Retrofit Design**
  - Target $\mu_\Delta$ = 12.0

**Column Retrofit Evaluation**

**Displacement Ductility**

- **Unit Original**
- **Unit Retrofit**
- **ACI 318-02**
- **UCSD**

FRP Retrofitting - 21

FRP Retrofitting - 22
Material Properties

Carbon Fiber Reinforced Polymer (CFRP)

<table>
<thead>
<tr>
<th>Property</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate Tensile Strength</td>
<td>550 ksi</td>
</tr>
<tr>
<td>Ultimate Rupture Strain</td>
<td>1.67%</td>
</tr>
<tr>
<td>Tensile Modulus</td>
<td>33,000 ksi</td>
</tr>
<tr>
<td>Fabric Width</td>
<td>24 in.</td>
</tr>
<tr>
<td>Nominal Thickness</td>
<td>0.0065 in/ply</td>
</tr>
</tbody>
</table>

Specimen # 1 and 2

Column

Retrofit
Joint Retrofit

\[ F_{H} = T_{C} \left( \frac{0.7D - 0.5c_{u}}{0.5h_{b}} \right) \]

\[ F_{V} = T_{B} \left( \frac{D - 0.5c_{u}}{0.5D} \right) \]

\[ n_{t_{j}} = \frac{F_{\text{CFRP}}}{1 - w_{j}f_{w}} \]

\[ F_{\text{CFRP}} = \sqrt{(F_{H})^2 + (F_{V})^2} \]
Unit 2 – Retrofit Specimen

GFRP Anchors Layout

CFRP Sheets Layout

Experimental Results

- Loading Levels
- Locations where dynamic testing was performed
- Locations where retrofit was added to the structure (Specimen #1 Only)

Single Cycles to First Yield
(Load Control)

3 Cycles at Each
Displacement Level
Above Yield
(Displacement Control)

Number of Cycles (#)

Displacement Ductility ($m_D$)

V=19.43 k
V=38.85 k
V=58.28 k

Single Cycles to First Yield
(Displacement Control)

3 Cycles at Each
Displacement Level
Above Yield
(Displacement Control)

$\alpha_1 = 0.75^\circ$
$\alpha_2 = 1.17^\circ$
$\alpha_3 = 1.56^\circ$
$\alpha_4 = 2.34^\circ$
$\alpha_5 = 3.32^\circ$
$\alpha_6 = 4.08^\circ$
$\alpha_7 = 5.00^\circ$
$\alpha_8 = 6.24^\circ$
$\alpha_9 = 9.36^\circ$
Unit 2: Experimental Results

Life Safety
MCE Reliable:
\[ \mu_d = 6 \]
\[ F_U = 400kN \]

Occupational
MCE Reliable:
\[ \mu_d = 2 \]
\[ F_U = 530kN \]
Unit 2 - Conclusions

- Column shear capacity was enhanced by applying CFRP sheets in the hoop direction.
- Strengthening of the joint region was adequate in preventing joint shear failure.
- Some level of strength degradation was observed in the joint region.
- Main failure mode was characterized by fracture of the column long. reinforcement.

Elastic Shear Forces

<table>
<thead>
<tr>
<th>Distance From NMSZ (km)</th>
<th>SA (%g)</th>
<th>VE (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.60</td>
<td>2.99</td>
<td>2130</td>
</tr>
<tr>
<td>16.0</td>
<td>1.39</td>
<td>1000</td>
</tr>
<tr>
<td>160</td>
<td>0.91</td>
<td>650</td>
</tr>
</tbody>
</table>

\[ W = 710 \text{kN} \]
\[ F_V = 320 \text{kN} \]
\[ \Delta_Y = 10.2 \text{mm} \]
\[ T_N = 0.31 \text{sec.} \]
# New Madrid Seismic Zone

FRP Retrofitting

## Seismic Demand

<table>
<thead>
<tr>
<th>Distance From NMSZ (km)</th>
<th>Performance Objective</th>
<th>R</th>
<th>Demand (kips)</th>
<th>System Capacity (kips)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.6</td>
<td>Life Safety</td>
<td>2.55</td>
<td>832</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>Operational</td>
<td>1.31</td>
<td>1623</td>
<td>535</td>
</tr>
<tr>
<td>16</td>
<td>Life Safety</td>
<td>2.61</td>
<td>378</td>
<td>400</td>
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<td>Operational</td>
<td>1.32</td>
<td>752</td>
<td>535</td>
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<td>160</td>
<td>Life Safety</td>
<td>2.66</td>
<td>240</td>
<td>400</td>
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<tr>
<td></td>
<td>Operational</td>
<td>1.33</td>
<td>485</td>
<td>535</td>
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</tbody>
</table>

Life Safety
MCE Reliable:
\[ \mu_s = 6 \]
\[ F_{U} = 400kN \]

Occupational
MCE Reliable:
\[ \mu_s = 2 \]
\[ F_{U} = 530kN \]

\[ R = 1 + (\mu_s - 1) \frac{T}{1.25T_s} \]
Seismic Evaluation Conclusions

♦ Column shear capacity was enhanced by applying CFRP sheets in the hoop direction

   Adequate for any Seismic Level Hazard

♦ Strengthening of the joint region was adequate in preventing joint shear failure

Life Safety: 16km from the NMSZ fault
Operational: 160km from the NMSZ fault