Evaluation of Grouted Splice Sleeve Connections for Reinforced Precast Concrete Bridge Piers

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INTRODUCTION

Accelerated Bridge Construction (ABC)

- Innovative techniques, methodologies, and materials
- Reduced construction time and traffic disruption
- Higher level of work-zone safety
- Environmental-friendly procedures
- PBES

PBES:
Courtesy of DTOP

INTRODUCTION
Common Emulative ABC Connections

- Under Study (Especially for high-seismic zones)
- Already Implemented
- Experimental Research:

**INTRODUCTION**

Common Emulative ABC Connections

- Grouted Duct Connections

**INTRODUCTION**
Common Emulative ABC Connections

• Pocket Connections

Column-to-cap beam connection (NCHRP 698)

INTRODUCTION

Common Emulative ABC Connections

• Socket Connections (Khaleghi et al., 2012)

Column-to-footing connection
Grouted Duct connection used for cap beam

INTRODUCTION
Common Emulative ABC Connections

- Hybrid Connections (Pre-tensioning)


INTRODUCTION

Common Emulative ABC Connections

- Advanced Materials, SMA (Tazarv et al., 2014)

INTRODUCTION
Grouted Splice Sleeve (GSS) Connections

- Alternatively called:
  - Mechanical rebar splices
  - Grout-filled steel sleeves
- Components:
  - Rebar
  - Sleeve
  - Grout
- GSS in Design Codes
  - ACI 550 (Type 1, Type 2)
  - AASHTO (Full mechanical connection)
  - Caltrans (Service and ultimate couplers)

INTRODUCTION

- Used as replacement for welded and lapped splices
- Considerably reduced dowel length
- Grouted splice sleeves are suitable for precasting (good construction tolerance)
- Not permitted in plastic hinge zone of bridge piers in seismic regions

Haber et al. (2015)
Previous Research

Large scale tests conducted in Japan:

- Limited to strength properties
- Typical of buildings

ISR method (Yoshino et al., 1996)

Previous Research

- Two half-scale specimens @ UNR (Haber et al. 2013)

1. Footing dowels/No pedestal
2. Footing dowels/12-in. pedestal

GGSS in column end
Research Objective

- To evaluate seismic performance of precast bridge piers with GSS inside and outside column plastic hinge

**INTRODUCTION**

**Research Objective**

**Category I:**
- Column-to-cap beam connection
- Fastened/Grouted Splice Sleeve Connector (FGSS)

**Category II:**
- Column-to-footing connection
- Grouted/Grouted Splice Sleeve Connector (GGSS)
Connector Tests

- Monotonic tensile load
- Pullout failure
- 1.44\(fy\) average strength (nominal)
- Type 1 splice (building)
- FMC (bridge)
## Connector Tests

<table>
<thead>
<tr>
<th>Air test identification</th>
<th>Maximum load (kip)</th>
<th>Maximum bar stress (ksi)</th>
<th>Maximum bar stress normalized to $f_y$</th>
<th>Observed failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air test-1</td>
<td>69.7</td>
<td>88.2</td>
<td>1.47</td>
<td>Reinforcing bar pullout</td>
</tr>
<tr>
<td>Air test-2</td>
<td>71.5</td>
<td>90.5</td>
<td>1.51</td>
<td>Reinforcing bar pullout</td>
</tr>
<tr>
<td>Air test-3</td>
<td>66.4</td>
<td>84.1</td>
<td>1.40</td>
<td>Reinforcing bar pullout</td>
</tr>
<tr>
<td>Air test-4</td>
<td>68.0</td>
<td>86.1</td>
<td>1.43</td>
<td>Reinforcing bar pullout</td>
</tr>
<tr>
<td>Air test-5</td>
<td>64.6</td>
<td>81.8</td>
<td>1.36</td>
<td>Reinforcing bar pullout</td>
</tr>
<tr>
<td>Air test-6</td>
<td>69.1</td>
<td>87.5</td>
<td>1.46</td>
<td>Reinforcing bar pullout</td>
</tr>
</tbody>
</table>

## Half-scale Experiment: Test Matrix

<table>
<thead>
<tr>
<th>No.</th>
<th>Specimen</th>
<th>Connector Location</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>FGSS-1</td>
<td>Column</td>
<td>Precast</td>
</tr>
<tr>
<td>(b)</td>
<td>FGSS-2</td>
<td>Cap Beam</td>
<td>Precast</td>
</tr>
<tr>
<td>(c)</td>
<td>FGSS-CIP</td>
<td>--</td>
<td>Cast in Place</td>
</tr>
</tbody>
</table>

![Connector Diagrams]

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**CATEGORY I**
Half-scale Experiment: Design and Construction

• Design according to AASHTO Guide Specifications
Half-scale Experiment: Design and Construction
• FGSS-2

Half-scale Experiment: Design and Construction
• FGSS-CIP
Half-scale Experiment: Design and Construction

- Grouting Operation

Half-scale Experiment: Test Procedure and Instrumentation

- Test Setup
Half-scale Experiment: Test Procedure and Instrumentation

• Strain Gauges

Half-scale Experiment: Test Procedure and Instrumentation

• LVDTs
Half-scale Experiment: Test Procedure and Instrumentation

- String Potentiometers

ACI 374 instructions followed
- Displacement-controlled history
- Two cycles per drift ratio
- First cycle $\Delta y/2$ (predicted)
- Multiples of $\Delta y$ for higher excursions
- 1.2 & 4.0 in/min displacement rate
Test Results: Hysteretic Response/FGSS-1

@ 3% drift - Peak

@ 6% drift - Peak

Test Results: Damage Progression/FGSS-1

@ 3% drift

@ 6% drift
Test Results: Hysteretic Response/FGSS-2

Test Results: Damage Progression/FGSS-2
Test Results: Hysteretic Response/FGSS-CIP

@ 3% drift

@ 6% drift

@ 10% drift

Test Results: Damage Progression/FGSS-CIP
Test Results: Displacement Capacity

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Last Drift</th>
<th>$F_Y$ (kip)</th>
<th>$\Delta_y$ (in.)</th>
<th>$\Delta_u$ (in.)</th>
<th>$K_{eff}$ (kip/in)</th>
<th>$\mu_\Delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FGSS-1</td>
<td>6</td>
<td>35.35</td>
<td>1.08</td>
<td>5.32</td>
<td>32.70</td>
<td>4.9</td>
</tr>
<tr>
<td>FGSS-2</td>
<td>7</td>
<td>33.29</td>
<td>1.11</td>
<td>6.50</td>
<td>29.92</td>
<td>5.8</td>
</tr>
<tr>
<td>FGSS-CIP</td>
<td>10</td>
<td>32.33</td>
<td>0.90</td>
<td>8.95</td>
<td>35.84</td>
<td>9.9</td>
</tr>
</tbody>
</table>

Test Results: Energy Dissipation Capacity

- Cumulative Energy
- Equivalent Viscous Damping
Test Results: Residual Drift

- Desirable performance (ductile), rebar fracture, $\mu_\Delta$ equal to 9.9 for FGSS-CIP.
- FGSS-CIP had very good hysteretic performance, energy dissipation capacity, and well-distributed flexural cracks.
- Localized damage for FGSS-1. Smaller spalled region with respect to FGSS-CIP.
- Similar damage states for FGSS-2 and FGSS-CIP, with no FGSS in the column base.
- Rebar fracture for FGSS-CIP and premature rebar fracture for one FGSS-2 bar due to higher values of concentrated strains at interface. Excessive bond-slip led to pull-out failure of FGSS-1 and FGSS-2’s east rebar.
Test Results: Conclusions, cont’d

- A more ductile response achieved by incorporating FGSS inside cap beam. One bar fractured and $\mu$ increased from 4.9 to 5.8.

- Different distribution of inelasticity for FGSS-1, as FGSS connectors were in the column base. Similar inelasticity distribution for FGSS-2 and FGSS-CIP.

- Strain gauge data showed both field and factory dowel yielded for FGSS-1. The factory dowel of FGSS-2 did not yield at all.

- Displacement ductility for all specimens exceeded minimum component ductility of 3 per Caltrans SDC. $\mu_\Delta$ of 5.8 (FGSS-2) was greater than maximum ductility demand of 5.0 per AASHTO Guide Specifications for single-column bents.
Connector Tests

- Monotonic tensile load
- Bar Fracture
- 1.69fy average strength (nominal)
- Type 2 splice (building)
- FMC (bridge)

**CATEGORY II**

<table>
<thead>
<tr>
<th>Connector test identifier</th>
<th>Maximum load (kip)</th>
<th>Maximum bar stress (ksi)</th>
<th>Maximum bar stress normalized to $f_y$</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Connector test-1</td>
<td>81.2</td>
<td>102.8</td>
<td>1.71</td>
<td>Bar fracture</td>
</tr>
<tr>
<td>Connector test-2</td>
<td>80.7</td>
<td>102.2</td>
<td>1.70</td>
<td>Bar fracture</td>
</tr>
<tr>
<td>Connector test-3</td>
<td>80.1</td>
<td>101.4</td>
<td>1.69</td>
<td>Bar fracture</td>
</tr>
<tr>
<td>Connector test-4</td>
<td>79.9</td>
<td>101.1</td>
<td>1.69</td>
<td>Bar fracture</td>
</tr>
<tr>
<td>Connector test-5</td>
<td>80.0</td>
<td>101.3</td>
<td>1.69</td>
<td>Bar fracture</td>
</tr>
<tr>
<td>Connector test-6</td>
<td>77.3</td>
<td>97.8</td>
<td>1.63</td>
<td>Bar fracture</td>
</tr>
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## Half-scale Experiment: Test Matrix

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<td>Column</td>
<td>Precast</td>
</tr>
<tr>
<td>(b)</td>
<td>GGSS-2</td>
<td>Footing</td>
<td>Precast</td>
</tr>
<tr>
<td>(c)</td>
<td>GGSS-3</td>
<td>Column</td>
<td>Precast with debonded bars in footing</td>
</tr>
<tr>
<td>(d)</td>
<td>GGSS-CIP</td>
<td>--</td>
<td>Cast in Place</td>
</tr>
</tbody>
</table>

### CATEGORY II

![Diagram]

**Debonded**

### Half-scale Experiment: Design and Construction

- Design according to AASHTO Guide Specifications
Half-scale Experiment: Design and Construction

• **GGSS-1**

  ![](image1.png)

  **CATEGORY II**

Half-scale Experiment: Design and Construction

• **GGSS-2**

  ![](image2.png)

  **CATEGORY II**
Half-scale Experiment: Design and Construction

- **GGSS-3**

CATEGORII

Half-scale Experiment: Design and Construction

- **GGSS-CIP**

CATEGORII
Half-scale Experiment: Design and Construction

- Grouting Operation

Half-scale Experiment: Test Procedure and Instrumentation

- Test configuration and instrumentation similar to CATEGORY I

Drift (%)

8 ft

Cycles
Test Results: Hysteretic Response/GGSS-1

@ 3% drift

@ 6% drift

@ 8% drift

@ 8% drift - rebar fracture
Test Results: Hysteretic Response/GGSS-2

Test Results: Damage Progression/GGSS-2

@ 3% drift

@ 7% drift

@ 7% drift - rebar fracture
Test Results: Hysteretic Response/GGSS-3

Test Results: Damage Progression/GGSS-3

@ 3% drift

@ 8% drift

@ 8% drift - rebar fracture
Test Results: Hysteretic Response/GGSS-CIP

@ 3% drift
@ 6% drift
@ 9% drift

Test Results: Damage Progression/GGSS-CIP
### Test Results: Displacement Capacity

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Last Drift</th>
<th>$F_y$ (kip)</th>
<th>$\Delta_y$ (in.)</th>
<th>$\Delta_u$ (in.)</th>
<th>$K_{eff}$ (kip/in)</th>
<th>$\mu_\Delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GGSS-1</td>
<td>8</td>
<td>41.8</td>
<td>1.34</td>
<td>7.32</td>
<td>31.2</td>
<td>5.4</td>
</tr>
<tr>
<td>GGSS-2</td>
<td>7</td>
<td>32.6</td>
<td>1.05</td>
<td>6.42</td>
<td>31.0</td>
<td>6.1</td>
</tr>
<tr>
<td>GGSS-3</td>
<td>8</td>
<td>38.2</td>
<td>1.11</td>
<td>7.58</td>
<td>34.4</td>
<td>6.8</td>
</tr>
<tr>
<td>GGSS-CIP</td>
<td>9</td>
<td>33.6</td>
<td>0.95</td>
<td>8.45</td>
<td>35.4</td>
<td>8.9</td>
</tr>
</tbody>
</table>

### Test Results: Energy Dissipation Capacity

- **Cumulative Energy**
- **Equivalent Viscous Damping**
Test Results: Bond-Slip Rotation

![Graph showing bond-slip rotation versus drift ratio for different specimens.]

Test Results: Conclusions

- Desirable performance (ductile), rebar fracture, $\mu_A$ equal to 8.9 for GGSS-CIP.

- GGSS-CIP had very good hysteretic performance, energy dissipation capacity, and well-distributed flexural cracks.

- Localized damage for GGSS-1 and GGSS-3. Smaller spalled region with respect to GGSS-CIP.

- Similar damage states for GGSS-2 and GGSS-CIP, with no GGSS in the column base.

- Rebar fracture for GGSS-CIP and premature rebar fracture for all precast specimens due to higher values of concentrated strains at interface.
Test Results: Conclusions, cont’d

- A more ductile response achieved by incorporating GGSS inside footing. Displacement ductility capacity increased from 5.4 to 6.1.

- The most ductile response was achieved for GGSS-3 with connectors in column base + debonding in footing. Compare displacement ductility of 6.8 vs. 6.1.

- Different distribution of inelasticity for GGSS-1 and GGSS-3, as GGSS connectors were in the column base. Similar inelasticity distribution for GGSS-2 and GGSS-CIP.

- Strain gauge data showed both field and factory dowel yielded for GGSS-1 and GGSS-3. The factory dowel of GGSS-2 did not yield at all.

- Displacement ductility for all specimens exceeded minimum component ductility of 3 per Caltrans SDC and maximum ductility demand of 5 per AASHTO-Seismic for single-column bents.

CATEGORY II

- For flexural-dominant precast components connected by Grouted Splice Sleeve connectors:
  - Well-confined connector zone is advantageous. Transverse reinforcement shall be used to secure the GSS connectors.
  - Spiral splice length equal to two extra turns was found satisfactory.
  - FGSS was found promising for moderate-seismic zones, if the limitation on displacement ductility is accounted for.
  - Enhanced ductility capacity may be achieved when FGSS is inside the cap beam. This alternative is more cumbersome.
  - GGSS was found promising for high-seismic zones, if the limitation on displacement ductility is accounted for.
  - More ductile performance is achievable when GGSS is in the column base and a debonded rebar zone in top of the footing is implemented.

RECOMMENDATIONS
Recommended design approach for precast flexural columns:

- Design procedure based on AASHTO Guide Specifications and Caltrans SDC using a predefined length of plastic hinge.

\[ \mu_c = \frac{\Delta_c}{\Delta_{ycol}} \quad \Delta_c = \Delta_{ycol} + \Delta_p \]

\[ \Delta_{ycol} = \frac{L^3}{3} \varphi_y \quad \Delta_p = (\varphi_u - \varphi_y) L_p (L - \frac{L_p}{2}) \]

- Reduced displacement capacity of bridge columns with Grouted Splice Sleeves, as observed in the experiments, can be represented by a reduced length of plastic hinge.

- Research is ongoing to determine reduced plastic hinge length for precast bridge columns.

**RECOMMENDATIONS**
**RECOMMENDATIONS**

Curvature Distribution Schematic for Precast with GSS

\[ \phi = \frac{M}{EI} \]

Actual

Idealized

\[ \phi_y \]

\[ \phi_u \]

\[ L_{P,GSS} < L_{P,CIP} \]

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- NMB Splice Sleeve
- Erico