MODULAR CONNECTION TECHNOLOGIES FOR SC WALLS OF SMRs

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Amit H. Varma, Jungil Seo, Tom Bradt
Purdue University
OUTLINE

- SC Wall-to-Wall T Connection
- SC Wall-to-Wall L Connection
- Benchmarking Analysis
- SC Slab-to-Wall Connection
- Findings
SC WALL-TO-WALL T CONNECTION

design philosophy

- Full-strength connection design philosophy
  - Develops the expected strength

- Implementation of full-strength design
  - Two parts in SC wall joints
    - SC wall and SC wall joints
  - Desired failure mode
    - Flexural yielding (ductile) – plastic hinges
SC WALL-TO-WALL T CONNECTION

DESIGN PHILOSOPHY

- SC wall-to-wall joints in the CIS
  - Common joint configurations (T and L)
- Implementation of full-strength design
  - The required joint shear strength
    - Based on the force transfer mechanism
  - Calculation of the available joint shear strength
    - ACI 349-06 equation
    - $\gamma = 12$ for SC wall T-joints
    - $\gamma = 8$ for SC wall L-joints
    - Verification is required

\[ V_n = \gamma \sqrt{f'_c A_j} \]
SC WALL-TO-WALL T CONNECTION

Experimental Program

- Four full-scale SC wall T-joint shear specimens
  - $T = 30$ in.
  - To evaluate the influence of (i) the shear reinforcement ratio and (ii) The steel headed stud layout
  - Designed to undergo joint shear failure

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Steel faceplate thickness, $t_p$ (in.)</th>
<th>Steel tie plate dimension</th>
<th>No. of tie plates in the Joint</th>
<th>Shear Stud Layout</th>
</tr>
</thead>
<tbody>
<tr>
<td>JS-T1-F</td>
<td>0.75</td>
<td>$3^{3/4} \times \frac{5}{16}$ in.</td>
<td>1</td>
<td>F</td>
</tr>
<tr>
<td>JS-T0-F</td>
<td>0.75</td>
<td>$3^{3/4} \times \frac{5}{16}$ in.</td>
<td>0</td>
<td>F</td>
</tr>
<tr>
<td>JS-T0-P</td>
<td>0.75</td>
<td>$3^{3/4} \times \frac{5}{16}$ in.</td>
<td>0</td>
<td>P</td>
</tr>
<tr>
<td>JS-T2-F</td>
<td>0.75</td>
<td>$3^{3/4} \times \frac{5}{16}$ in.</td>
<td>2</td>
<td>F</td>
</tr>
</tbody>
</table>
## SC WALL-TO-WALL T CONNECTION

### Experimental Program

![Diagram of SC WALL-TO-WALL T CONNECTION](image)

### Material properties

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Faceplates</th>
<th>Tie plates</th>
<th>Studs</th>
<th>Concrete, psi</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$F_y$, ksi</td>
<td>$F_u$, ksi</td>
<td>$F_y$, ksi</td>
<td>$F_u$, ksi</td>
</tr>
<tr>
<td>JS-T1-F</td>
<td>58.6</td>
<td>83.9</td>
<td>60.4</td>
<td>69.1</td>
</tr>
<tr>
<td>JS-T0-F</td>
<td>58.0</td>
<td>77.0</td>
<td>62.7</td>
<td>73.5</td>
</tr>
<tr>
<td>JS-T0-P</td>
<td>58.0</td>
<td>77.0</td>
<td>62.7</td>
<td>73.5</td>
</tr>
<tr>
<td>JS-T2-F</td>
<td>58.5</td>
<td>78.6</td>
<td>62.7</td>
<td>73.5</td>
</tr>
</tbody>
</table>

Avg = 6,502
Boundary conditions and joint shear force terms

\[ V_{jc} = H - \frac{R_y l}{jT} \]

\[ V_{jd} = -\left( \frac{H h}{jT} - \frac{R_y}{2} + \frac{H h}{T} \right) \]
SC WALL-TO-WALL T CONNECTION

Experimental Program

- Test-setup and loading protocol

$H_n = \text{Lateral load at the expected joint shear strength, } V_n$

$\Delta_y = \text{Projected displacement at } V_n$
### Summary of experimental results

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Ultimate joint shear, kips</th>
<th>Shear strain at the ultimate joint shear</th>
<th>Governing failure mode</th>
<th>Event order in the Joint region</th>
</tr>
</thead>
<tbody>
<tr>
<td>JS-T1-F</td>
<td>438.4</td>
<td>0.0049</td>
<td>Joint shear</td>
<td>Concrete crack ↓ Yielding of steel tie plate ↓ Extensive concrete cracking</td>
</tr>
<tr>
<td>JS-T0-F</td>
<td>455.5</td>
<td>0.0070</td>
<td>Joint shear</td>
<td>Concrete crack ↓ Extensive concrete cracking</td>
</tr>
<tr>
<td>JS-T0-P</td>
<td>427.8</td>
<td>0.0069</td>
<td>Joint shear</td>
<td>Concrete crack ↓ Extensive concrete cracking</td>
</tr>
<tr>
<td>JS-T2-F</td>
<td>431.6</td>
<td>0.0060</td>
<td>Joint shear</td>
<td>Concrete crack ↓ Yielding of steel tie plates ↓ Extensive concrete cracking</td>
</tr>
</tbody>
</table>
SC WALL-TO-WALL T CONNECTION
Experimental Program

- Joint shear – displacement response

\[
V_{js} - \Delta'
\]

- \( V_{njs}^{TEST} \) within the range of 426.7 - 454 kips
- Greater than \( V_{njs}^{ACI-exp} \) (413 kips) by 3.1 - 10.3%.
SC WALL-TO-WALL T CONNECTION

Experimental Program

- Joint shear – shear strain response

- JS-T1-F

- JS-T0-F

- JS-T0-P

- JS-T2-F
SC WALL-TO-WALL T CONNECTION
Experimental Program

- Crack pattern at the ultimate joint shear: all specimens
SC WALL-TO-WALL T CONNECTION

Benchmarking Analysis

- 3-D FE analysis for additional insights
- Comparison with experimental results
- ABAQUS explicit
  - The quasi static analysis
  - Shell (S4R) elements for steel, solid (C3D8R) elements for concrete, and Timoshenko beam elements (B32) for stud
  - Connector elements (CONN3D2)
- CEF concrete model
  - Elastic in compression, Uniaxial tension strength and post-peak behavior defined in CEB-FIP mc 90 (1993)
  - Element deletion to prevent excessive deformation
- Steel material model
  - Multi-axial plasticity theory
  - Idealized uniaxial stress-strain curve
SC WALL-TO-WALL T CONNECTION

Analysis Results

- Joint shear – displacement response

![Graphs showing joint shear vs. displacement with different lines for Experiment, FEM, and ACI349-06.](image)
### SC WALL-TO-WALL T CONNECTION

#### Benchmarking Analysis

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Ultimate joint shear, kips</th>
<th>Shear strain at the ultimate joint shear</th>
<th>Governing failure mode</th>
<th>Event Order in the Joint region</th>
</tr>
</thead>
<tbody>
<tr>
<td>JS-T1-F</td>
<td>450.0</td>
<td>0.0157</td>
<td>Joint shear</td>
<td>Concrete crack ↓</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Yielding of steel tie plate ↓</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Extensive concrete cracking</td>
</tr>
<tr>
<td>JS-T0-F</td>
<td>418</td>
<td>0.0142</td>
<td>Joint shear</td>
<td>Concrete crack ↓</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Extensive concrete cracking</td>
</tr>
<tr>
<td>JS-T0-P</td>
<td>455.4</td>
<td>0.0164</td>
<td>Joint shear</td>
<td>Concrete crack ↓</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Extensive concrete cracking</td>
</tr>
<tr>
<td>JS-T2-F</td>
<td>465.6</td>
<td>0.0147</td>
<td>Joint shear</td>
<td>Concrete crack ↓</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Yielding of steel tie plates ↓</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Extensive concrete cracking</td>
</tr>
</tbody>
</table>
SC WALL-TO-WALL L CONNECTION
Experimental Program

- One full-scale SC wall L-joint shear specimens
  - \( T = 30 \) in.
  - To experimentally investigate the joint shear behavior of SC wall-to-wall L joint
  - The same specimen design approach and test procedure from SC wall-to-wall T joint specimens

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Steel faceplate thickness, ( t_p ) (in.)</th>
<th>Steel tie plate dimension</th>
<th>No. of tie plates in the Joint</th>
<th>Shear Stud Layout</th>
</tr>
</thead>
<tbody>
<tr>
<td>JS-L-T0-F</td>
<td>0.75</td>
<td>( 3\frac{3}{4} \times \frac{5}{16} ) in.</td>
<td>0</td>
<td>F</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( 3\frac{3}{4} \times \frac{1}{2} ) in.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
SC WALL-TO-WALL L CONNECTION
Experimental Program

- Test-setup and loading protocol
Boundary conditions and joint shear force terms

\[ V_j = H \left( \frac{1}{2} - \frac{l}{jT} \right) \]
SC WALL-TO-WALL CONNECTION
Experimental Program

Joint shear – displacement response

![Graphs showing joint shear vs. displacement and shear strain vs. shear strain](image)

<table>
<thead>
<tr>
<th>Ultimate joint shear, kips</th>
<th>Shear strain at the ultimate joint shear</th>
<th>Governing failure mode</th>
<th>Event order in the Joint region</th>
</tr>
</thead>
<tbody>
<tr>
<td>261.7 (-)</td>
<td>-0.0071 (-)</td>
<td>Joint Shear Failure</td>
<td>Concrete crack</td>
</tr>
<tr>
<td>290.3 (+)</td>
<td>0.0089 (+)</td>
<td></td>
<td>Extensive concrete cracking</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Yielding of diaphragm plates</td>
</tr>
</tbody>
</table>

$V_{njs}^{TEST} = 276$ kips  $V_{njs}^{ACI-exp} (262.7$ kips)
SC WALL-TO-WALL L CONNECTION

Experimental Program

- Crack pattern at the ultimate joint shear
BENCHMARKING ANALYSIS

- Analysis results – Specimen JS-T1-F
  - Joint shear – displacement response
BENCHMARKING ANALYSIS

- Analysis results – Specimen JS-T1-F
  - Stress and strain distribution
BENCHMARKING ANALYSIS

- Analysis results – Specimen JS-T1-F
  - Crack pattern
BENCHMARKING ANALYSIS

- Analysis results – Specimen JS-L-T0-F
  - Joint shear – displacement response
  - Joint shear – shear strain response

- $V_{js}^{ACI349-06} = 262.7$ Kips (1.17 MN)
- $V_{js}^{FEM} = 292.3$ Kips (1.3 MN) (+ 29.6 kips)
- $V_{js}^{Exp} = 276$ Kips (1.22 MN) (+ 13.3 kips)
- Joint shear failure
**BENCHMARKING ANALYSIS**

- Analysis results – Specimen JS-L-T0-F
  - Stress and strain distribution

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**LE max**

- LE, Max. Principal (Avg. 75%)
  - +3.006e-02
  - +3.000e-03
  - +2.402e-03
  - +1.204e-03
  - +1.206e-03
  - +6.074e-04
  - +9.309e-06

**S min**

- S, Min. Principal (Avg. 75%)
  - +4.492e-02
  - +0.000e+00
  - -1.180e+00
  - -2.360e+00
  - -3.540e+00
  - -4.720e+00
  - -5.900e+00
  - -1.301e+01

**PEEQ**

- PEEQ Multiple section points (Avg. 75%)
  - +4.120e-03
  - +1.000e-03
  - +8.000e-04
  - +6.000e-04
  - +4.000e-04
  - +2.000e-04
  - +0.000e+00
SC SLAB-TO-WALL CONNECTION
Experimental Program

- **Background**
  - Existing design recommendations and aids for RC slab (column) to slab connections
  - No existing design recommendation for SC slab-to-wall connection
  - The applicability of existing code provisions for RC slab (column) to slab connection on SC slab-to-wall connection

- **Design philosophy**
  - The full strength connection design philosophy
  - The connection region should not be the weakest point
  - Capability of transferring both shear and flexural demand
SC SLAB-TO-WALL CONNECTION

Experimental Program

- Test parameters
  - Slab type: RC or half SC (HSC)
  - Rebar: rebar type (Hooked bar or T headed rebar), Reinforcement ratio, Embedded length, and Rebar location in the SC wall portion
SC SLAB-TO-WALL CONNECTION

Experimental Program

- Test setup
FINDINGS

○ SC wall-to-wall T connection test
  • The joint shear failure mode for all test specimens
  • No significant effects of the shear reinforcement ratio and the steel headed stud layout
  • $V_{nj_s}^{TEST}$ within the range of 426.7 kips - 454 kips Greater than $V_{nj_s}^{ACI-exp}$ (413 kips) by 3.1% - 10.6%
  • The ACI 349-06 (2006) code equation is applicable and conservative for estimating the joint shear strength of SC wall-to-wall T joints with $\gamma$ of 12

○ SC wall-to-wall L connection test
  • The joint shear failure mode
  • $V_{nj_s}^{TEST}$ of 261.7 kips close to $V_{nj_s}^{ACI-exp}$ (262.7 kips)
  • The ACI 349-06 (2006) code equation is applicable for estimating the joint shear strength of SC wall-to-wall L joints with $\gamma$ of 8
Publications
