Seismic Performance of PT High-Strength Concrete Beam-Column Connections in part of Special Moment Frames

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Contents

• Experimental Program
• Concrete Mixture Proportion
• Details of Specimens
• Reversed Cyclic Tests
• Test Results
• Conclusions
Experimental Program
Experimental Program - Joints of SMF

• Six Knee Joint Specimens / Four Exterior Joint Specimens

• Variables:
  1. Concrete compressive strength (35 ~ 120 MPa)
  2. Steel fiber volumetric ratio = 1%
  3. Ratio of joint shear strength (0.58 ~ 1.54)
  4. Presence of post-tensioning

<table>
<thead>
<tr>
<th></th>
<th>K-Joint</th>
<th>E-Joint</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>35 MPa (V_j/V_n=0.62)</td>
<td>100 MPa SFRC (V_j/V_n=1.28)</td>
</tr>
<tr>
<td>K-RC-N</td>
<td></td>
<td></td>
</tr>
<tr>
<td>K-PT-N-1</td>
<td>35 MPa PT (V_j/V_n=0.69)</td>
<td>80 MPa PT (V_j/V_n=0.98)</td>
</tr>
<tr>
<td>K-PT-N-2</td>
<td>35 MPa PT (V_j/V_n=0.98)</td>
<td>100 MPa PT (V_j/V_n=1.29)</td>
</tr>
<tr>
<td>K-PT-N-3</td>
<td>35 MPa PT (V_j/V_n=1.24)</td>
<td>120 MPa PT (V_j/V_n=1.54)</td>
</tr>
<tr>
<td></td>
<td>80 MPa RC (V_j/V_n=0.58)</td>
<td></td>
</tr>
<tr>
<td>K-SFRC-H</td>
<td>80 MPa SFRC (V_j/V_n=0.59)</td>
<td></td>
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</tbody>
</table>
Concrete Mixture Proportion
Concrete Trial Mixture (2014. 7. 29)

• Conducted trial mixture to find proper mixture proportion (HRWR = 10~12 kg/m$^3$)
• Target strength: 120 MPa, 120+@ MPa
• 120 MPa: Decreased 10 kg water from the original mixture proportion
• 120+@ MPa: Decreased 20 kg water from original mixture proportion
• Zirconium was used for low heat of hydration / long-term strength
## Concrete Trial Mixture Result

<table>
<thead>
<tr>
<th>Strength</th>
<th>Date</th>
<th>Test piece</th>
<th>$f_c'$ (3 day)</th>
<th>$f_c'$ (7 day)</th>
<th>$f_c'$ (28 day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>120 Mpa</td>
<td>2014.7.29</td>
<td>1</td>
<td>71.5</td>
<td>94.1</td>
<td>101.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>77.2</td>
<td>92.1</td>
<td>101.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>77.9</td>
<td></td>
<td>108.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average</td>
<td>75.5</td>
<td>93.1</td>
<td>104.1 MPa</td>
</tr>
<tr>
<td>120+@ Mpa</td>
<td>2014.7.29</td>
<td>1</td>
<td>82.3</td>
<td>96.8</td>
<td>110.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>81.7</td>
<td>93.8</td>
<td>106.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>79.6</td>
<td>92.1</td>
<td>105.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average</td>
<td>81.2</td>
<td>94.2</td>
<td>107.3 MPa</td>
</tr>
</tbody>
</table>
Mixture Proportion for Cast-In-Place

- Mixture proportion was finalized based on trial mixture proportion & facility.
- Concrete curing without heat treatment
- Used vinyl curtain to keep heat and prevent evaporation
- 7 day curing on the site for sufficient strength development
- One batch: 1.5 m$^3$ to prevent overload of silo

<table>
<thead>
<tr>
<th>Target Strength (MPa)</th>
<th>W/B (%)</th>
<th>S/a (%)</th>
<th>Unit weight (kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>W</td>
<td>C</td>
<td>Slag powder</td>
</tr>
<tr>
<td>80</td>
<td>18.8</td>
<td>40</td>
<td>150</td>
</tr>
<tr>
<td>100</td>
<td>14.9</td>
<td>36</td>
<td>140</td>
</tr>
<tr>
<td>120</td>
<td>13.5</td>
<td>35</td>
<td>130</td>
</tr>
</tbody>
</table>

W/B = water to binder ratio; S/a = fine aggregate percentage; Zr = zirconium; G = coarse aggregate; S = fine aggregate
Cast-In-Place
Final Strength

- 35, 80, 80 (SFRC), 100 (SFRC) MPa concretes
- 100, 120 MPa concretes did not exceed the target strength.

<table>
<thead>
<tr>
<th>Design strength</th>
<th>Date</th>
<th>$f_{c}'$ (28 day)</th>
<th>$f_{c}'$ (90 day)</th>
<th>$f_{c}'$ (120 day)</th>
<th>$f_t$ (120 day)</th>
<th>$f_{c}' / f_t$ (120 day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>07.31</td>
<td>37.0</td>
<td>38.3</td>
<td>41.3</td>
<td>5.4</td>
<td>0.13</td>
</tr>
<tr>
<td>80</td>
<td>09.20</td>
<td>87.3</td>
<td>85.0</td>
<td>103.4</td>
<td>9.2</td>
<td>0.09</td>
</tr>
<tr>
<td>80</td>
<td>09.23</td>
<td>67.3</td>
<td>94.7</td>
<td>100.3</td>
<td>10.6</td>
<td>0.11</td>
</tr>
<tr>
<td>100</td>
<td>10.14</td>
<td>71.7</td>
<td>75.5</td>
<td>80.6</td>
<td>9.4</td>
<td>0.12</td>
</tr>
<tr>
<td>100 (SFRC)</td>
<td>09.29</td>
<td>92.3</td>
<td>101.3</td>
<td>102.8</td>
<td>12.4</td>
<td>0.12</td>
</tr>
<tr>
<td>120</td>
<td>10.02</td>
<td>69.7</td>
<td>97.0</td>
<td>96.0</td>
<td>7.6</td>
<td>0.08</td>
</tr>
</tbody>
</table>
Concrete Stress-Strain Curves

- The ultimate strain $\varepsilon_{cu}$ for 35 MPa, 80 MPa, 80 MPa (SFRC) $\sim 0.003$. 

![Stress-Strain Curves Diagram]

Stress (MPa) vs. Strain
Very High-Strength Concrete

- 35 MPa (without Zr): gray
- High-strength concrete (with Zr): gray (7~15 mm depth), blue-green (inside)
- After splitting tensile tests, it was found that aggregates were destructed. (Typical feature of high-strength concrete)
Deformed Steel Bars

Stress (MPa)

Strain

SD400 D19  SD400 D22  SD400 D29

$f_y = 524$ MPa  $f_y = 474$ MPa  $f_y = 503$ MPa

$fu = 648$ MPa  $fu = 667$ MPa  $fu = 612$ MPa
Deformed Steel Bars

\[ f_y = 675 \text{ MPa} \]
\[ f_y = 627 \text{ MPa} \]
\[ f_u = 800 \text{ MPa} \]
\[ f_u = 758 \text{ MPa} \]

SD600 D22
SD600 D29
Strand Stress-Strain Curves

- 15.2 mm diameter unbonded tendons (1860 MPa)
- Measured 1776 < 1860 MPa (270 ksi) was likely due to grease-induced wedge slip.
Steel for Heads of Headed Bars

Stress (MPa)

752 MPa

Strain
Details of Specimens
K-Joint (High-strength Concrete)

- Head-restraining bars are placed just before the head. (2/3 of required amount)
- K-SFRC-H specimen w/ $V_f = 1\%$ had 150\% of the spacing of hoops.
K-Joint (High-strength Concrete)

K-SFRC-H (Unit: mm)
K-PT-Joints (Normal-strength Concrete)

- Four Grade 270, 0.6 in. diameter unbonded tendons were provided.
- Three joint shear to joint shear strength ratios \( \frac{V_j}{V_n} = 0.76, 1.01, 1.36 \)

K-PT-N-1 (Unit: mm)
K-PT-Joints (Normal-strength Concrete)

Beam Section
- D22-3ea (Top)
- Grade 270 15.2 mm unbonded tendons
- D22-3ea (Bottom)

Column Section
- D22-4ea
- D29-12ea

K-PT-N-1 (Unit: mm)
E-PT-Joints (High-strength Concrete)

- Six Grade 270, 0.6 in. diameter unbonded tendons were provided.
- Three joint shear to joint shear strength ratios ($V_j / V_n = 1.22, 1.3, 1.52$)

E-PT-H-1 (Unit: mm)
E-PT-Joints (High-strength Concrete)

E-PT-H-1 (Unit: mm)
E-PT-Joints (High-strength Concrete)

<table>
<thead>
<tr>
<th>Specimens</th>
<th>$V_j$</th>
<th>$V_n$</th>
<th>$V_j / V_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-PT-H-1</td>
<td>2443</td>
<td>2004</td>
<td>0.98</td>
</tr>
<tr>
<td>E-PT-H-2</td>
<td>2914</td>
<td>2241</td>
<td>1.29</td>
</tr>
<tr>
<td>E-PT-H-3</td>
<td>3737</td>
<td>2455</td>
<td>1.54</td>
</tr>
</tbody>
</table>

$V_j$ : joint shear force demand at $M_{pr}$ (assuming internal level arm $\sim 0.9d$);
$V_n$ : joint shear strength
Jacking
Reversed Cyclic Tests
Test Set-up (K-Joints)

- Hinge
- Ball jig
- Actuator
- Pin-support
- 4500 mm
- 2255 mm
Test Set-up (K-Joints)
Test Set-up (E-Joints)

Actuator

Ball jig

Hinge

Hinge

4050 mm

3500 mm
Loading Histories (K-Joints)

Drift Ratio (%)

Cycle
Loading Histories (E-Joints)
K-PT-N-1 Test Video Clip

Drift Ratio 0.35% 8 mm
K-PT-N-3 Test Video Clip
E-PT-H-1 Test Video Clip

Drift Ratio 0.5% 20 mm
E-PT-H-2 Test Video Clip

Drift Ratio 0.5% 20 mm
E-PT-H-3 Test Video Clip

Drift Ratio 0.5% 20 mm
Test Results
Test Results (Moments of RC K-Joints)

- For knee joints’ tests, axial forces should be considered because the actuator applies lateral loading by pushing or pulling the beam longitudinally.
- Measured peak moments exceeded the calculated nominal moments ($M_n$).

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$M_n$ (kN-m)</th>
<th>$M_{peak}$ (kN-m)</th>
<th>$M_{peak} / M_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>K-RC-N (closing)</td>
<td>387</td>
<td>425</td>
<td>1.10</td>
</tr>
<tr>
<td>K-RC-N (opening)</td>
<td>318</td>
<td>328</td>
<td>1.03</td>
</tr>
<tr>
<td>K-RC-H (closing)</td>
<td>460</td>
<td>623</td>
<td>1.35</td>
</tr>
<tr>
<td>K-RC-H (opening)</td>
<td>381</td>
<td>486</td>
<td>1.27</td>
</tr>
<tr>
<td>K-SFRC-H (closing)</td>
<td>463</td>
<td>667</td>
<td>1.44</td>
</tr>
<tr>
<td>K-SFRC-H (opening)</td>
<td>381</td>
<td>487</td>
<td>1.28</td>
</tr>
</tbody>
</table>

$M_n$ : Calculated nominal moment (based on actual material properties, measured axial force); $M_{peak}$ : Peak moment (measured)
Test Results (Moments of PT K-Joints)

- For knee joints’ tests, axial forces should be considered because the actuator applies lateral loading by pushing or pulling the beam longitudinally.
- Measured peak moments exceeded the calculated nominal moments ($M_n$).

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$M_n$ (kN-m)</th>
<th>$M_{peak}$ (kN-m)</th>
<th>$M_{peak} / M_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>K-PT-N-1 (closing)</td>
<td>352</td>
<td>469</td>
<td>1.33</td>
</tr>
<tr>
<td>K-PT-N-1 (opening)</td>
<td>275</td>
<td>338</td>
<td>1.23</td>
</tr>
<tr>
<td>K-PT-N-2 (closing)</td>
<td>504</td>
<td>613</td>
<td>1.22</td>
</tr>
<tr>
<td>K-PT-N-2 (opening)</td>
<td>405</td>
<td>532</td>
<td>1.31</td>
</tr>
<tr>
<td>K-PT-N-3 (closing)</td>
<td>652</td>
<td>715</td>
<td>1.10</td>
</tr>
<tr>
<td>K-PT-N-3 (opening)</td>
<td>541</td>
<td>612</td>
<td>1.13</td>
</tr>
</tbody>
</table>

$M_n$ : Calculated nominal moment (based on actual material properties, measured axial force, ACI 318-11 Equation for $f_{ps}$);
$M_{peak}$ : Peak moment (measured)
Test Results (Moments of E-Joints)

- No axial forces (lateral loading was applied perpendicular to the beam axis)
- Measured peak moments exceeded the calculated nominal moments ($M_n$).

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$M_n$ (kN-m)</th>
<th>$M_{peak}$ (kN-m)</th>
<th>$M_{peak} / M_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-SFRC-H (P)</td>
<td>1141</td>
<td>1431</td>
<td>1.25</td>
</tr>
<tr>
<td>E-SFRC-H (N)</td>
<td>1141</td>
<td>1478</td>
<td>1.30</td>
</tr>
<tr>
<td>E-PT-H-1 (P)</td>
<td>1360</td>
<td>1686</td>
<td>1.24</td>
</tr>
<tr>
<td>E-PT-H-1 (N)</td>
<td>1360</td>
<td>1775</td>
<td>1.31</td>
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<td>E-PT-H-2 (P)</td>
<td>1485</td>
<td>1800</td>
<td>1.21</td>
</tr>
<tr>
<td>E-PT-H-2 (N)</td>
<td>1485</td>
<td>1855</td>
<td>1.25</td>
</tr>
<tr>
<td>E-PT-H-3 (P)</td>
<td>1846</td>
<td>2069</td>
<td>1.12</td>
</tr>
<tr>
<td>E-PT-H-3 (N)</td>
<td>1846</td>
<td>2197</td>
<td>1.19</td>
</tr>
</tbody>
</table>

$M_n$: Calculated nominal moment (based on actual material properties, ACI 318-11 Eq. for $f_{ps}$);
$M_{peak}$: Peak moment (measured)
Test Results (Moment-Drift Ratio)

Drift Ratio (%)

(kN-m)

(kips-in)

Moment

Opening

Closing

K-RC-N

K-RC-H

College of Engineering, Seoul National University, Korea
Test Results (Moment-Drift Ratio)

![Graphs showing test results for K-SFRC-H and K-PT-N-1.](image)
Test Results (Moment-Drift Ratio)

(kN-m)

(kips-in)

Drift Ratio (%)

K-PT-N-2

K-PT-N-3
Test Results (Moment-Drift Ratio)

- E-SFRC-H
- E-PT-H-1

Drift Ratio (%)

Moment

(kN-m)

(kips-in)
Test Results (Moment-Drift Ratio)

Drift Ratio (%)

E-PT-H-2

E-PT-H-3
Test Results (Joint Shear Distortion)

Joint Shear Distortion (rad.)

Opening

Closing

K-RC-N (Front)

K-RC-N (Back)
Test Results (Joint Shear Distortion)

- **Joint Shear Distortion (rad.)**
  - $V_j / V_n$
  - Opening
  - Closing

- **Graphs**:
  - K-RC-H (Front)
  - K-SFRC-H (Front)
Test Results (Joint Shear Distortion)

K-PT-N-1 (Front)

K-PT-N-1 (Back)
Test Results (Joint Shear Distortion)

Joint Shear Distortion (rad.)

K-PT-N-2 (Front)

K-PT-N-2 (Back)
Test Results (Joint Shear Distortion)

Joint Shear Distortion (rad.)

K-PT-N-3 (Front)

K-PT-N-3 (Back)
Test Result (Joint Shear Distortion)

<p>| | | |</p>
<table>
<thead>
<tr>
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<tbody>
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</tr>
</tbody>
</table>

- **E-SFRC-H (Front)**
  - Joint Shear Distortion (rad.)
  - Pushing
  - Pulling

- **E-SFRC-H (Back)**
  - Joint Shear Distortion (rad.)
  - Pushing
  - Pulling
Test Result (Joint Shear Distortion)

$\frac{V_j}{V_n}$ vs. Joint Shear Distortion (rad.)

- **E-PT-H-1 (Front)**
- **E-PT-H-1 (Back)**
Test Result (Joint Shear Distortion)

Joint Shear Distortion (rad.)

\[ V_j / V_n \]

Pushing
Pulling

E-PT-H-2 (Front)
E-PT-H-2 (Back)
Test Result (Joint Shear Distortion)

E-PT-H-3 (Front)

E-PT-H-3 (Back)
Test Results (Beam Moment-Curvature)

Beam Curvature @ Plastic Hinge
(1/mm)

K-PT-N-2

K-PT-N-3
Conclusions
PT Beam-Column Joints of Special Moment Frames

• All PT specimens showed excellent seismic performance for every performance indicators (essentially did not completely fail until the end of testing, except for E-PT-H3 which failed at a drift ratio of 4%).

• Very high-strength concrete and SD 600 (Grade 90) steel bars can be promoted for tall buildings (joints, coupling beams, boundary elements of core walls, transfer slabs/girders) and mega infrastructures.

• Joint shear strengths of PT beam-column joints were turned out to be much larger than those for conventional RC beam-column joints.

• Applications of post-tensioning, high-strength materials, steel fibers (1% volume fraction ratio) are promising.

• Test program & data are of great value for PT / seismic / materials societies.
Thank you

Further development of the data will be made and shared with the PT industry.

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