Seismic performance of RC beams focusing on failure mode and crack evaluation

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Background and Objectives

Using 685MPa shear rebars, the following behavior was studied.

- Validation of capacity using code equation (AIJ 1999 guidelines)
  - $Q_f$ (Flexural capacity)
  - $Q_{su}$ (Shear capacity)
  - $Q_{bu}$ (Bond capacity)

- Study on residual cracks
  - Shear cracks and shear deformation (AIJ 2004 guidelines)
Current design issues (Evolution of PBEE methodology)
Specimen configuration

Long. rebar SD590
Shear rebar SD685
Section of beams

#1, #2, #4, #5

#3

#6

#7, #8
## Test Variables

<table>
<thead>
<tr>
<th>Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>B x D (mm)</td>
<td>340 X 450</td>
<td>340 X 450</td>
<td>420 X 560</td>
<td>340 X 450</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>f'c (MPa)</td>
<td>24.0</td>
<td>24.0</td>
<td>48</td>
<td>24</td>
<td>33</td>
<td>48</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Span L (mm)</td>
<td>1350</td>
<td>1350</td>
<td>2250</td>
<td>1350</td>
<td>1680</td>
<td>1800</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M/QD</td>
<td>1.50</td>
<td>1.50</td>
<td>2.50</td>
<td>1.50</td>
<td>2.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Long. Rebar</td>
<td>3+3-D25 SD590</td>
<td>3+3-D25 SD590</td>
<td>3+3-D25 SD590</td>
<td>3+3-D25 SD590</td>
<td>5+3-D25 SD590</td>
<td>3-D25 SD345</td>
<td>3-D25 SD345</td>
<td></td>
</tr>
<tr>
<td>Trans. Rebar</td>
<td>D10 @210</td>
<td>D10 @70</td>
<td>D10 @52.5</td>
<td>D10 @210</td>
<td>D10 @210</td>
<td>D10 @170</td>
<td>D10 @105</td>
<td>D10 @105</td>
</tr>
<tr>
<td>pw (%)</td>
<td>0.200</td>
<td>0.600</td>
<td>1.20</td>
<td>0.200</td>
<td>0.400</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Role</td>
<td>(Shear) Standard</td>
<td>(Shear) Higher pw</td>
<td>(Shear) Highest pw</td>
<td>(Shear) Larger L/2D</td>
<td>(Shear) Higher f'c</td>
<td>(Shear) Larger BxD</td>
<td>(Bond) Standard</td>
<td>(Flexure) Higher f'c</td>
</tr>
</tbody>
</table>
Loading system

EAST ↔ + WEST

3000kN hydraulic jack

2200

Out-of-Plane Restrainer

4000kN hydraulic jack

Disp. Gauges

Moment Distribution

Specimen
Loading system
Shear force – drift relations

- **F’c=24MPa**
  - M/QD=1.5
  - Pw=0.2%
  - Qex/Qcal=1.24 Shear tens.

- **F’c=48MPa**
  - M/QD=2.5
  - Larger section
  - Pw=1.2%
  - Qex/Qcal=1.16 Shear tens.

- **Qmax**
- **Qsu**
- **Qfu**
- **Qcr**
- **Qecr**
- **fwy**

- **#1**
- **#2**
- **#3**
- **#4**
- **#5**
- **#6**
## Capacity equations

<table>
<thead>
<tr>
<th>Failure mode</th>
<th>Capacity Equation</th>
<th>No.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Maximum capacity</strong></td>
<td>:[ Q_u = \min(Q_{fu}, \max(Q_{cr}, \min(Q_{bu}, Q_{su}))) ]</td>
<td>(1)</td>
</tr>
<tr>
<td><strong>Shear cracking</strong></td>
<td>:[ Q_{cr} = \phi \left( \sqrt{\sigma_T^2 + \sigma_0 \cdot \sigma_T} \right) b \cdot \frac{D}{K} \quad \sigma_T = 0.33 \sqrt{\sigma_B} \quad \text{(MPa)} ]</td>
<td>(2)</td>
</tr>
<tr>
<td><strong>Bond failure</strong></td>
<td>:[ Q_{bu} = j_e \sum (\tau_{bu}) + \left( v \sigma_B - \frac{2.5 \sum (\tau_{bu})}{\lambda b_e} \right) \frac{bD}{2} \tan \theta ]</td>
<td>(3)</td>
</tr>
<tr>
<td><strong>Shear capacity</strong></td>
<td>:[ Q_{su} = \min(Q_{su1}, Q_{su2}, Q_{su3}) ]</td>
<td>(4)</td>
</tr>
<tr>
<td></td>
<td>:[ Q_{su1} = \mu \cdot p_{we} \cdot \sigma_{wy} \cdot b_e \cdot j_e + \left( v \cdot \sigma_B - \frac{5 \cdot p_{we} \cdot \sigma_{wy}}{\lambda} \right) \frac{b \cdot D}{2} \tan \theta ]</td>
<td>(5)</td>
</tr>
<tr>
<td></td>
<td>:[ Q_{su2} = \frac{\lambda \cdot v \cdot \sigma_B + p_{we} \cdot \sigma_{wy}}{3} \cdot b_e \cdot j_e ]</td>
<td>(6)</td>
</tr>
<tr>
<td></td>
<td>:[ Q_{su3} = \frac{\lambda \cdot v \cdot \sigma_B}{2} \cdot b_e \cdot j_e ]</td>
<td>(7)</td>
</tr>
<tr>
<td><strong>Flexure capacity</strong></td>
<td>:[ Q_{fu} ]: computed with an in-house fiber model</td>
<td>(8)</td>
</tr>
</tbody>
</table>
Crack patterns

F'c=24MPa
M/QD=1.5
Pw=0.2%

Pw=0.2%

Pw=1.2%

M/QD=2.5
F'c=48MPa
Larger section
Shear crack width measurement
Coordinate conversion
Shear drift = \sum (W_h) \quad ??? \quad (No. 1)

\[ W_h: \text{horizontal component of crack width} \]
Crack opening – drift relations (No.1)
Shear drift \( = \sum(W_h) \) (No. 1)

\[ W_h: \text{horizontal component of crack width} \]
Shear drift = \( \sum(W_h) \) (No. 5)
Conclusions

Eight beam specimens were tested to see their seismic performance. The following conclusions were drawn.

✓ Mode of peak load deterioration and peak load were simulated with good accuracy using the 1999 AIJ design guidelines,

✓ Shear component of drift, $\delta_s^+$, comprises of horizontal component of positive cracks under positive loading, $\sum_{i=1}^{n} W_{hi\,(blue)}^+$, and horizontal component of negative cracks under positive loading, $\sum_{j=1}^{m} W_{hj\,(red)}^+$. 
Continuity of building functions using real scale five-story RC buildings

The experiment was conducted by NILIM and BRI. Tokyo Tech was one of three universities who collaborated with them.
Crack measurement

- Crack width
- Crack length
- Concrete spalling
Crack distributions

R=0.25%

R=0.5%

R=1%
Numerical model using FEM Program “FINAL”

Stress-Strain relations

Concrete (Comp.)
Modified Ahmad Model

Concrete (Tens.)
(Izumo Model)

Reinforcement
(Modified Menegotto–Pinto model)
FEM Results Base shear force – Roof drift relation

- Real base shear capacity: 0.45xWeight
- Design base shear capacity: 0.3xWeight
Flexural crack simulation

1. Spacing (Number of cracks)
   ◦ CEB–FIP Model Code

2. Width
   ◦ Use axial strain of FEM

3. Length
   ◦ Flexural analysis based on FEM
Flexural crack simulation

2. Width

Crack pattern at 1/400 (0.25%)
Corner column (Exp.)

Accumulation crack width (mm)

Peak
Residual

- 1/100 (FEM)
- 1/200 (FEM)
- 1/400 (FEM)

Total crack width

Crack width

$w_{cr1}$ (mm)

$w_{cr1} + w_{cr2}$

$w_{cr1} + w_{cr2} + w_{cr3}$

$w_{cr1} + w_{cr2} + \ldots + w_{crn}$
Summary of Experiment and Simulation

**Flexural crack**

- 合計曲げひび割れ幅 (ピーク, 2014年度試験体)
  - 北柱 (FEM)
  - 北柱 (EXP)
  - 中柱北側袖壁 (FEM)
  - 中柱北側袖壁 (EXP)
  - 北梁下端 (FEM)
  - 北梁下端 (EXP)

**Shear crack**

- 合計せん断ひび割れ幅 (ピーク, 2014年度試験体)
  - 北柱 (FEM)
  - 北柱 (EXP)
  - 中柱北側袖壁 (FEM)
  - 中柱北側袖壁 (EXP)
  - 北梁下端 (FEM)
  - 北梁下端 (EXP)
Flexural crack simulation

1. Spacing

Crack spacing formula (CEB-FIP 1978)

\[ s_{rm} = 2 \left( c_s + \frac{s_y}{10} \right) + k_1 k_2 \frac{d_{by}}{p_y} \]

- \( s_{rm} \) = mean crack spacing
- \( c_s \) = clear concrete cover
- \( s_y \) = maximum spacing between longitudinal bars
- \( k_1 \) = factor that takes into account bond properties of reinforcing bar (0.4 for deformed bars)
- \( k_2 \) = factor that takes into account strain gradient
- \( k_2 = 0.25(\varepsilon_1 + \varepsilon_2)/\varepsilon_1 \)
- \( \varepsilon_1 \) and \( \varepsilon_2 \) correspond to the largest and smallest concrete tensile strain
- \( d_{by} \) = longitudinal bar diameter
- \( p_y \) = ratio of the area of reinforcement effectively bonded to the concrete to the cross-sectional area

<table>
<thead>
<tr>
<th>Roof drift (%)</th>
<th>Cal. (189mm)</th>
<th>Exp. (Average)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.063%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.125%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.25%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0%</td>
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</tbody>
</table>

Corner column at 1/400

Crack spacing

Cal. (189mm)

Exp. (Average)
Flexural crack simulation

2. Width

The crack width of the $i$-the crack, $w_i$, in a region from $h_i$ to $S_{rm}+h_i$ is expressed as:

$$w_i = \int_{h_i}^{S_{rm}+h_i} \varepsilon_{zz} \, dz$$

Assumption: axial strain is caused by cracks but not concrete (concrete does not deform).
Flexural crack simulation

Axial strain distribution $\varepsilon$

Corner Column

Crack spacing

Accumulation crack width

$w_{cr} = \int_{0}^{s_{rm}} \varepsilon \, dy$

$L(mm)$

$\Sigma w_{cr}(mm)$

Accumulation

$w_{cr1} + w_{cr2}$

$w_{cr1} + w_{cr2} + w_{cr3}$

$w_{cr1} + w_{cr2} + \ldots + w_{crn}$