COMPREHENSIVE SERIES OF TESTS ON SEISMIC PERFORMANCE OF REINFORCED CONCRETE BEAM-COLUMN JOINTS

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Background

- RC beam-column joint safety in seismic design
- Joint shear strength design
- Potential of joint shear resistance were evaluated by lot of tests empirically
- Specimens with beams and columns heavily reinforced have been tested to assess the potential
- No comprehensive data set is available for actual strength and post-yielding behavior of joints with realistic range of reinforcement ratio in the beams and the columns
Test Program

- Planned such that a dependable data set of RC interior beam-column joint subassemblages should be obtained.
- Lateral capacity and post yielding behavior are discussed.
- Test parameters; including combinations of 3 factors:
  1. Amount of longitudinal reinforcement (3 levels)
  2. Ratio of the flexural strength of the beams to the flexural strength of the columns framing into a joint, (3 to 4 levels)
  3. Ratio of the depth of the beam to the depth of the column. (2 levels)
Conclusions

• Current seismic provisions for RC beam-column joints are deficient, because they can not secure the lateral strength of moment resisting frames predicted by the flexural theory of RC sections

• Hence a large number of existing moment resisting frame reinforced concrete structures may be more vulnerable than we expect.

• Serious consideration on this test results should be addressed by structural engineers, researchers and code writers.
Loading Setup

Specimens

Load cell

Oil Jack

PC rod

Pin joint
Loading Setup

Specimens

PC rod

Load Cell

Strong floor

Loading direction

Load Cycle

Story Drift Ratio

Load Cycle

Load Cell

Oil Jack

PC rod

Specimens

Load Cell

Pin joint

Strong floor
Loading Setup

- PC rod
- Specimens
- 0.5Qc
- 1/200
- 1/100
- 2
- 1/50
- 2
- 1/33
- 2

Load Cycle

Strong floor

Load Cell

Loading direction

Story Drift Ratio

Load Cycle

Load Cell

Oil Jack

PC rod

Specimens

pin joint
in total 31 specimens in FY2008
Three Major Test Parameters

(1) Amount of longitudinal reinforcement,

\[ p_t : 0.98\% - 3.98\% \]

(2) Ratio of the flexural strength of the beams to the flexural strength of the columns framing into a joint,

\[ \frac{\sum M_{uc}}{\sum M_{ub}} : 72\% - 268\% \]

(3) Ratio of the depth of the beam to the depth of the column.

\[ b_b / b_c : 1.0 \text{ and } 0.5 \]
Common Parameters

- Normal strength deformed steel bars
- Concrete strength = 30 MPa
- Beam width and column width = 240 mm
- Joint shear reinforcement = 2 sets of D6 rectangular hoop
- Column axial load = 0 kN
Typical Test Result

Yielding of longitudinal bars in beams and columns
Story shear-story drift relationships

Legend:
- Calcuatd story shear at flexural capacity of beam
- Yielding of joint hoop
- Yielding of longitudinal bar in beam (at diagonal crack)
- Yielding of longitudinal bar in beam (at face)
- Yielding of longitudinal bar in column (at diagonal crack)
- Maximum story shear

Series B
Story shear-story drift relationships

Legend:
- Calculated story shear at flexural capacity of beam
- Yielding of joint hoop
- Yielding of longitudinal bar in beam (at diagonal crack)
- Yielding of longitudinal bar in beam (at face)
- Yielding of longitudinal bar in column (at diaogonal crack)
- Maximum story shear

Series B
Story shear-story drift relationships

Legend:
- Dashed line: Calculated story shear at flexural capacity of beam
- Yielding of joint hoop
- Yielding of longitudinal bar in beam (at diagonal crack)
- Yielding of longitudinal bar in beam (at face)
- Yielding of longitudinal bar in column (at diatonic crack)
- Maximum story shear

Series B
Story shear-story drift relationships

Longitudinal bar horizontal and vertical, both of them yielded in joints.

Cracking and crushing of concrete concentrated in joints.

Maximum story shear observed were smaller than flexural capacity of beam or column in some specimens.

Legend:
- Calculated story shear at flexural capacity of beam
- Yielding of joint hoop
- Yielding of longitudinal bar in beam (at diagonal crack)
- Yielding of longitudinal bar in beam (at face)
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Hysteresis behavior showed slip shape commonly for all specimens

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- Yielding of longitudinal bar in beam (at face)
- Yielding of longitudinal bar in column (at diagonal crack)
- Maximum story shear

Series B
Evaluation of Current Design Equations

Joint shear capacity

Flexural Strength

Test (+)
Test (-)
Calculated (Flexural capacity of beam or column section)
Calculated (Nominal joint shear capacity : AJJ Guidelines)

Maximum attained story shear kN

Series B

B01, B04, B07, B08, B02, B05, B06, B03, B09, B10 Specimen

Tests
Evaluation of Current Design Equations

- Test (+)
- Test (-)
- Calculated (Flexural capacity of beam or column section)
- Calculated (Nominal joint shear capacity: AIJ Guidelines)

Flexural Strength
Joint shear capacity
Tests

Series B

Maximum attained story shear kN

Specimen

B01, B04, B07, B08, B02, B05, B06, B03, B09, B10
Evaluation of Current Design Equations

1.0 1.5 1.3 1.2 1.0 1.4 1.8 1.0 1.0 1.0

$\frac{\sum M_{uc}}{\sum M_{ub}}$

Series B

Tests

Flexural Strength

Joint shear capacity

Test (+)
Test (-)
Calculated (Flexural capacity of beam or column section)
Calculated (Nominal joint shear capacity: AIJ Guidelines)
Story shear-story drift relationships

Legend:
- Calculated story shear at flexural capacity of beam
- Yielding of joint hoop
- Yielding of longitudinal bar in beam (at diagonal crack)
- Yielding of longitudinal bar in beam (at column face)
- Yielding of longitudinal bar in column (at diagonal crack)
- Yielding of longitudinal bar in column (at beam face)
- Maximum story shear
Story shear-story drift relationships

Longitudinal bar horizontal and vertical, both of them yielded in joints

Legend:
- Calculated story shear at flexural capacity of beam
- Yielding of joint hoop
- Yielding of longitudinal bar in beam (at diagonal crack)
- Yielding of longitudinal bar in beam (at column face)
- Yielding of longitudinal bar in column (at diagonal crack)
- Yielding of longitudinal bar in column (at beam face)
- Maximum story shear

Series D
Story shear-story drift relationships

Longitudinal bar horizontal and vertical, both of them yielded in joints

Cracking and crushing of concrete concentrated in joints

Legend:
- Calculated story shear at flexural capacity of beam
- Yielding of joint hoop
- Yielding of longitudinal bar in beam (at diagonal crack)
- Yielding of longitudinal bar in beam (at column face)
- Yielding of longitudinal bar in column (at diagonal crack)
- Yielding of longitudinal bar in column (at beam face)
- Maximum story shear

Series D
Story shear-story drift relationships

Longitudinal bar horizontal and vertical, both of them yielded in joints

Cracking and crushing of concrete concentrated in joints

Maximum story shear observed were smaller than flexural capacity of beam or column in more specimens

Legend:
- Calculated story shear at flexural capacity of beam
- Yielding of joint hoop
- Yielding of longitudinal bar in beam (at diagonal crack)
- Yielding of longitudinal bar in beam (at column face)
- Yielding of longitudinal bar in column (at diagonal crack)
- Yielding of longitudinal bar in column (at beam face)
- Maximum story shear

Series D
Longitudinal bar horizontal and vertical, both of them yielded in joints

Cracking and crushing of concrete concentrated in joints

Maximum story shear observed were smaller than flexural capacity of beam or column in more specimens

Hysteresis behavior showed slip shape commonly for all specimens

Series D
Evaluation of Current Design Equations

Maximum attained story shear kN

Test (+)
Test (-)
Calculated (F) (Flexural capacity of beam or column section)
Calculated (S) (Joint shear capacity: AIJ Guidelines)

Series D

Specimen (D-series and E-series)

High Strength Concrete Specimens

Tests
Evaluation of Current Design Equations

Maximum attained story shear kN

Series D

Tests

Joint shear capacity

Flexural Strength

Calculated (F) (Flexural capacity of beam or column section)

Calculated (S) (Joint shear capacity: AIJ Guidelines)

High Strength Concrete Specimens

Specimen (D-series and E-series)
Evaluation of Current Design Equations

Maximum attained story shear kN

Test (+)
Test (-)
Calculated (F) (Flexural capacity of beam or column section)
Calculated (S) (Joint shear capacity: AIJ Guidelines)

Series D

Tests

High Strength Concrete Specimens

Flexural Strength

Joint shear capacity

<table>
<thead>
<tr>
<th>Specimen (D-series and E-series)</th>
<th>D01</th>
<th>D02</th>
<th>D03</th>
<th>D04</th>
<th>D05</th>
<th>D06</th>
<th>D07</th>
<th>D08</th>
<th>D09</th>
<th>D10</th>
<th>D11</th>
<th>E01</th>
<th>E02</th>
<th>E03</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sum M_{uc}/\sum M_{ub})</td>
<td>1.0</td>
<td>1.4</td>
<td>2.2</td>
<td>0.7</td>
<td>1.0</td>
<td>1.3</td>
<td>1.7</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.4</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Mechanical Reinforcement Ratio and Strength

\[ \sum M_{uc} / \sum M_{ub} = 1.0 \]

\[ \frac{M_j}{b_b D_b^2 f'_c} \]

- **Series B**
  - Calculated (F)
  - B01
  - B02
  - B03

- **Series D**
  - Calculated (F)
  - D01
  - D05
  - D08

- **Nominal joint shear strength**
- **Flexural strength of section**

\[ \frac{\sum a_t f_y}{b_b D_b f'_c} \]
Flexural Strengths Ratio
(Beam vs. Column)

Normalized moment
\[
\frac{M_j}{bD^2f_c}
\]

Flexural strength ratio
\[
\frac{\Sigma M_{uc}}{\Sigma M_{ub}}
\]

Series B

Calculated (S)
Calculated (F)
beam

Series D

Calculated (S)
Calculated (F)
beam
Summary of Test Results
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- Maximum story shear of some specimens are smaller 5% to 30% than the story shear calculated by the flexural strength of the beam or the column
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- Those joints are conformed to current seismic provision, i.e. they have safety margin of the nominal joint shear strength by 0% to 50%.
Summary of Test Results

• Maximum story shear of some specimens are smaller 5% to 30% than the story shear calculated by the flexural strength of the beam or the column.

• Those joints are conformed to current seismic provision, i.e. they have safety margin of the nominal joint shear strength by 0% to 50%.

• The extent of insufficiency in the story shear is larger
  
a. if the flexural strength of the column is equal or nearer to the flexural strength of the beam, and

b. if the depth of the column is larger than that of the beam.
Modeling of yielding of longitudinal bars in a beam-column joint

To understand the reason why the flexural theory overestimates strengths
Modeling of yielding of longitudinal bars in a beam-column joint
diagonal cracking

diagonal cracking

story shear

story drift
load reversals
before yielding

crack closing

story shear
story drift
unloading

story shear

story drift
load reversals after yielding

crack remain due to residual stain after tensile yielding

crack remain

residual crack remain

story shear

story drift
load reversals after yielding

story shear

story drift
Definition of Ultimate Moment Capacity of Joint

T

C

yield

yield

yield

j

j

T

C
Proposed Equations for Ultimate Moment Capacity of Joint (by Shiohara et al.: Nine Parameter Model)

\[
C = T_y
\]

\[
\dot{j}_1 = \frac{1}{2} D \left( g - \frac{T_y}{bD\beta_3 f'_c} \right)
\]

\[
M_{ju} = 2\dot{j}_1 T_y = 2\dot{j}_1 C
\]

\[
C_1 = T_y, \quad C_2 = \alpha T_y
\]

\[
\dot{j}_1 = \frac{1}{2} D \left( g - \frac{C_1}{bD\beta_3 f'_c} \right), \quad \dot{j}_2 = \frac{1}{2} D \left( (1 - g) - \frac{C_2}{bD\beta_3 f'_c} \right)
\]

\[
M_{ju} = 2 \left( \dot{j}_1 T_y + \dot{j}_2 \alpha T_y \right) = 2 \left( \dot{j}_1 C_1 + \dot{j}_2 C_2 \right)
\]
Prediction of Maximum Story Shear
(by New Model)

- Test (+)
- Test (-)
- Calculated (Flexural capacity of beam or column section)
- Calculated (Nominal joint shear capacity: AIJ Guidelines)
- Calculated (Ultimate moment capacity of joint)
- Calculated (Moment at balanced failure of joint)

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Maximum attained story shear kN</th>
<th>Current</th>
<th>New Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>B01</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>B04</td>
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<td>B07</td>
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<td>B08</td>
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<td>B05</td>
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<td>B02</td>
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<td>B06</td>
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<td>B03</td>
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<td>B09</td>
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<tr>
<td>B10</td>
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<td></td>
</tr>
</tbody>
</table>

Maximum attained total moment kN

- B01
- B04
- B07
- B08
- B05
- B02
- B06
- B03
- B09
- B10

- Moment capacity of joint
Prediction of Maximum Story Shear
(by New Model)

- Test (+)
- Test (-)
- Calculated (Ultimate moment capacity of joint)
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- Calculated (Moment at balanced failure of joint)

**Current**

**New Model**
Conclusions

- Current seismic provisions for RC beam-column joints are deficient and cannot secure the lateral strength of moment resisting frames predicted by the flexural theory of RC sections.
- The design parameters considered is not a rare feature but is rather seen frequently in existing reinforced concrete buildings.
- Hence a large number of existing RC moment resisting frame structures may be more vulnerable than we expected.
Recommendation

• Serious consideration on the impacts of this test dataset on huge stock of RC building in the world should be addressed by structural engineers, researchers and code writers.
Let's challenge!
Fig. 1. Dimensions and details of Specimens AL1, AS1, AL2, and AS2 (in mm)

(a) Specimens AL1 and AS1

(b) Specimen AS1

Acknowledgment

- The authors acknowledge the supports by the Grant-in-aid for researches on the building codes improvement by Ministry of Land, Infrastructure, Transport and Tourism, Japan, awarded to a research proposal entitled “Research on design parameters of RC reinforced concrete beam-column joint necessary for ductile behavior of building structures (PI: Hitoshi Shiohara),” FY2008.
Yielding of longitudinal bars in beams and columns
Observed Crack at 3% Story Drift
Observed Crack at 3% Story Drift

![Image of a cracked wall with labels A, B, C, and D, indicating a story drift of 3%](image)

Story drift = 3%
Observed Crack at 3% Story Drift
loading
corner cracking

story shear

story drift
corner cracking

story shear

story drift
diagonal cracking

\[
\text{story shear}
\]

\[
\text{story drift}
\]
load reversals
crack opening

story shear

story drift
yielding

story shear

story drift
yielding

story shear

story drift

story shear

story drift
ultimate

story shear

story drift