RESILIENCE EVALUATION OF REINFORCED CONCRETE BUILDINGS

Sam Kono, Ryo Kuwabara, Fuhito Kitamura, Eko Yuniarsya, Hidekazu Watanabe, Tomohisa Mukai, and David J. Mukai

Tokyo Institute of Technology, Yokohama, Japan
Building Research Institute, Tsukuba, Japan
University of Wyoming, Laramie, USA
Ben Lomond
Lessons from 2016 Kumamoto EQ

• Safety is still the most critical issue.

• People want to use their buildings continuously after EQ’s without losing any building functions.
  – Intermediate or severe damage to structural and non-structural elements cannot be accepted anymore.
Current design issues
(Evolution of PBEE methodology)
Evaluation of minor/intermediate damages of RC buildings
Continual functionality 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.

From Tokyo tech
Mr. Eko Yuniarsyah
Mr. F. Kitamura
Prof. H. Watanabe
Prof. S. Kono
Objectives
set up by Tokyo Tech

• Simulate the behavior of a 5-story building specimen with FE analysis.

• Simulate damages
  – numbers/width/length of cracks
  – area of cover spalling
  – extent of concrete crushing
  – extent of rebar yielding/bucking/fracturing
Specimen

The experiment was conducted by NILIM and BRI. Tokyo Tech was one of three universities who collaborated with them. (Papers in WCEE 2017)
Specimen

Beam section

Corner column section

Typical story elevation in the longitudinal direction
Crack distributions

R=0.25%  R=0.5%  R=1%
Crack measurement

- Crack width
- Crack length
- Concrete spalling
Summary of recorded cracks

\[
\text{Crack length ratio (\%)} = \frac{\text{Total Crack length (mm)}}{\sqrt{\text{Surface area (\sqrt{mm^2})}}}
\]

Roof drift

- 0.2 to 1.0 mm
- Less than 0.2 mm

(0.063\%) (0.125\%) (0.25\%) (0.5\%) (1.0\%)
Numerical model using FEM Program “FINAL”

Concrete (Comp.)
Modified Ahmad Model

Concrete (Tens.)
Izumo Model

Stress-Strain relations

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

- Roof drift (%)
- Base shear force, Q (kN)

FEM

Experiment
FEM Results
Member level

実験
解析
柱主筋降伏（実験）
柱主筋降伏（解析）
部材回転角θ（%）
1F層せん断力Q（kN）

北柱

実験
解析
梁主筋降伏（実験）
梁主筋降伏（解析）
部材回転角θ（%）
1F層せん断力Q（kN）

中柱北側袖壁

実験
解析
開口補強筋降伏（実験）
開口補強筋降伏（解析）
部材回転角θ（%）
1F層せん断力Q（kN）
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

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
- \( d_{by} \) = longitudinal bar diameter
- \( p_y \) = ratio of the area of reinforcement effectively bonded to the concrete to the cross-sectional area

Graph showing crack spacing and roof drift for various crack spacings.

<table>
<thead>
<tr>
<th>Roof drift</th>
<th>Crack spacing (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/1600</td>
<td>1000</td>
</tr>
<tr>
<td>1/800</td>
<td>800</td>
</tr>
<tr>
<td>1/400</td>
<td>600</td>
</tr>
<tr>
<td>1/200</td>
<td>400</td>
</tr>
<tr>
<td>1/100</td>
<td>200</td>
</tr>
</tbody>
</table>

Experimental (Average) values:

- 0.063% for 189 mm
- 0.125% for 189 mm
- 0.25% for 189 mm
- 0.5% for 189 mm
- 1.0% for 189 mm
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

2. Width

Axial strain distribution $\varepsilon$

Corner Column

Crack spacing

Accumulation crack width

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

$L(mm)$

$\sum w_{cr}(mm)$
Flexural crack simulation

2. Width

Accumulation crack width (mm)

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

Total crack width

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

Accumulation crack width (mm)
**Flexural crack simulation**

3. Length

\[ W_{cr-visible} : \text{minimum visible crack width} (=0.01\text{mm}) \]

- \( W_{cr} \): crack width
- \( X_n \): neutral axis depth (mm)
- \( L_{min} \): invisible crack length (mm)
- \( L_{cr} \): visible crack length (mm)
Flexural crack simulation

3. Length

\[ \alpha_1 = \frac{L_v}{L_a} \quad \text{(detouring & meandering)} \]

\[ \alpha_2 = \frac{L_v}{L_h} \quad \text{(horizontal to diagonal)} \]

\( L_h \): Horizontal projection
\( L_a \): Real crack length
\( L_v \): Distance between two points
Flexural crack simulation

Procedure flow

1. Crack spacing $S_{rm}$
2. Crack width (Peak)
3. Horizontal crack length

Conversion factor $\alpha$(exp.)

Correction factor $\alpha_1, \alpha_2$(exp.)

Visible crack width $W_{cr-visible}$

Residual Crack Summary

$\sum L_{fi}$ for $0mm < W < 0.2mm$
$\sum L_{fi}$ for $0.2mm < W < 1mm$
$\sum L_{fi}$ for $1mm < W < 2mm$
3. Length

\[ \text{crack length ratio (\%)} = \frac{\text{Total Crack length (mm)}}{\sqrt{\text{Surface area (\text{mm}^2)}}} \]

Crack width:
- Under 0.2 mm (Exp.)
- 0.2 to 1.0 mm (Exp.)

Total crack length ratio:
- Under 0.2 mm (FEM)
- 0.2 to 1.0 mm (FEM)

Roof drift:
- (0.063%)
- (0.125%)
- (0.25%)
- (0.5%)
- (1.0%)
**Flexural crack simulation**

**Final results**

\[
\text{Residual crack length ratio} = \frac{\Sigma(\text{Residual crack length})}{\sqrt{\text{Surface area}}} \times 100
\]
Coordinate conversion
Summary of Experiment and Simulation

Flexural crack

Shear crack

合計曲げひび割れ幅 (ピーク, 2014年度試験体)

合計せん断ひび割れ幅 (ピーク, 2014年度試験体)

Flexural crack width $\Sigma(W_f)$

Shear crack width $\Sigma(W_s)$
Summary of crack evaluation

• In order to assess damage states of reparability limit state, cracks were numerically simulated and compared to the test results for the five story RC building.
  – Crack width and spacing were well simulated for peak points but not so for unloaded points.
  – Crack length was simulated from FEM results by considering limit visible width.
  – Finally, computed crack length ratio agreed with experimental results.
Design concept for safety limit state
(1981 Design Standard)

Building response
× Collapse
● Target

Lateral load

Drift

Low seismic performance

Safe

Required performance

Strength dependent resistance

Ductility dependent resistance
ひび割れ幅の比較

合計ひび割れ幅および最大ひび割れ幅の実験値と解析値の比較
（2014年度試験体北柱）
Shear Crack Width and Shear Drift Component in RC Beams with High Strength Transverse Rebars

Ricky Rinaldi, Advisor: Prof. Susumu Kono, Tokyo Institute of Technology

Introduction

Crack width and slip were measured using crack gauges as shown on Fig. 1. Crack gauges were attached perpendicular to cracks on the center line as shown on Fig. 2. Shear drift component was measured using diagonal displacement gauges. The following equations were used to compare the horizontal crack component (\(W_{hl}\)) with shear drift component (\(\delta_s\)).

\[ \delta_s = \sum_{i=1}^{n} W_{hl} \]

According to AIJ Guidelines (a) Specimen #1 (b) Specimen #2

Experimental Result

Displacement Gauge

Kumamoto Earthquake (BRI, 2016)

\(\delta_s\) should be same

Displacement Gauge

Figure 3 Displacement Gauges

Figure 4 Relation between Crack Width and Shear Deformation

Conclusion

The summation of horizontal component of cracks has good agreement with shear drift component. Compared to higher residual drift, the crack gauges picked up shear drift component better at lower residual drifts.

Contribution to Society

This study provides a better understanding of earthquake damage on RC structures, and contributes to the development of low damage structural system and resilient structures.
Rocking system (Ductility with resiliency)

RC walls

Rocking wall (No damper)

Rocking wall (With damper)

No.33
Kamo River, Kyoto
Damage to RC Structures at Kumamoto Earthquake, 2015
Kumamoto
Uto municipal office
Kumamoto
Kumamoto
Kumamoto
New call from the society

• How to make a quick recovery after EQ’s with losing no/minor loss of building functions.
FEM Results
Member level (Q-\(\theta\) relation)

Base shear force, \(Q\) (kN)

Member rotation (%)
FEM Results

Member level (deformation decomposition)
Flexural crack simulation

2. Width

Relation between residual crack width ($W_r$) and peak crack width ($W_p$)

$$W_r = \alpha W_p$$

$\alpha = 0.23$ (Column), 0.43 (Wall), 0.60 (Beam)
Flexural crack simulation

2. Width

- Residual crack width (mm) vs. peak crack width (mm) for different structures with linear regression equations:
  - y = 0.23x, \( R^2 = 0.57 \)
  - y = 0.43x, \( R^2 = 0.71 \)
  - y = 0.60x, \( R^2 = 0.92 \)
Flexural crack simulation

2. Width

Peak crack width multiplied $\alpha$ is residual crack width.

Accumulation crack width (mm)

Height of column (mm)

Peak

Residual
Flexural crack simulation

3. Length

Crack length = \( L_h \times \alpha_1 \times \alpha_2 \)