Damage due to Earthquakes and Improvement of Seismic Performance of Reinforced Concrete Buildings in Japan

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Tohoku University
Summary

- History of Damaging EQ and Revision of Seismic Codes in Japan
- Damage to RC Buildings and Lessons from 1995 Kobe EQ
- Basic Concept of Seismic Capacity Evaluation
- Damage to RC Buildings due to recent EQs
  - 2011 East Japan EQ
  - 2016 Kumamoto EQ
Damaging EQ and Code Revision (1)

1891  Nohbi EQ  M8.0
1923  Great Kantoh EQ  M7.9  death:140000

◆ 1924  *Introduction of Seismic design to building code*

  Allowable stress design

  1944  Nankai EQ  M8？
  1945  Toh-Nankai EQ  M8？
  1948  Fukui EQ  M7.3  death:3895

◆ 1950  *Building Standard Law*

  1964  Niigata EQ  M7.5  death:26
  1968  Tokachi-oki EQ  M7.9  death:52

  Damage to RC buildings (shear failure)

◆ 1971  *Revision (requirement for mimimum hoop spacing changed from 30cm to 10cm)*
Damage to RC Buildings

(1968 Tokachi –oki EQ)
Damage to RC Buildings
(1978 Miyagiken-oki EQ)

Obisan building
Damage to RC Buildings
(1978 Miyagike-oki EQ)
Collapse of RC Building with soft
(1978 Miyagike-oki EQ)
Damaging EQ and Code Revision (2)

1977  Guideline of Seismic Evaluation and Retrofit of Existing Buildings

1978  Miyagi-ken-oki EQ          M7.4  Death: 28

1981  Revision (Ultimate State Design)

\[ C_B = C_o \times D_s \text{ (not less than } 0.3 \text{ for RC) } \]

\[ C_B : \text{Design Base Shear Coefficient} \]
\[ C_o : \text{Design Spectrum} \]
\[ \text{(not less than } 1.0 \text{ g for peak acc.)} \]
\[ D_s : \text{Reduction Factor by Ductility} \]
\[ \text{(not less than } 0.3 \text{ for RC)} \]
### Damaging EQ and Code Revision (3)

<table>
<thead>
<tr>
<th>Year</th>
<th>Region</th>
<th>EQ</th>
<th>Magnitude</th>
<th>Death</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1983</td>
<td>Nihonkai-chubu EQ</td>
<td>M7.7</td>
<td>death:104</td>
<td>(Tsunami)</td>
<td></td>
</tr>
<tr>
<td>1993</td>
<td>Kushiro-oki EQ</td>
<td>M7.8</td>
<td>death:2</td>
<td></td>
<td></td>
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<tr>
<td>1993</td>
<td>Hokkaido-nansei-oki EQ</td>
<td>M7.8</td>
<td>death:230</td>
<td>(Tsunami)</td>
<td></td>
</tr>
<tr>
<td>1994</td>
<td>Hokkaido-tohou-oki EQ</td>
<td>M8.1</td>
<td>no death</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1994</td>
<td>Sanriku-harukaoki EQ</td>
<td>M7.5</td>
<td>death:3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1995</td>
<td>Hyogoken-Nambu(Kobe) EQ</td>
<td>M7.2</td>
<td>death:6430</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Severer damage to existing buildings**

- **1995** Law for Promotion of Seismic Evaluation and Retrofit
Damage to RC buildings and lessons from 1995 Kobe Earthquake
Nojima Fault Caused 1995 Hyogo-ken Nanbu Earthquake.
Collapse of RC Building with soft first story

(1995 Kobe EQ)
Total collapse of RC Buildings

Total collapse
(1995 Kobe EQ)
Damage in old and new Buildings

Few hoops (pre-1971)

Hoop spacing is 10cm (Post-1971)
Damage Statistics for RC school buildings

631 RC school buildings

- Total
- Post-1982
- 1972-1981
- Pre-1971

Legend:
- Collapse
- Severe
- Moderate
- Minor
- Slight/None

0% 20% 40% 60% 80% 100%
New Law to Promote Seismic Retrofit


New Law to promote Seismic Evaluation and Retrofit of Pre-code Revision

- School, Hospital, Theater, Department Store, Hotel, Market etc.
  
  (≥ 3 stories and ≥ 1,000m² total floor area)

- Equivalent capacity required in the current code

- Japanese *Guideline for Seismic Evaluation and Retrofit* are applied.
Basic Concept of
Japanese Seismic Evaluation Guideline
Seismic Capacity Evaluation

 Isa-Index  defined in the Japanese Seismic Evaluation Guideline (1977, revisied in 2001)

\[ I_s = E_0 \times S_D \times T \]

- \( E_0 \): Basic structural seismic capacity index
- \( S_D \): Shape index \((0.4 - 1.0)\)
- \( T \): Age index \((0.5 - 1.0)\)
$E_0 = \phi \times C \times F$

$\phi$: Mode Shape Factor (1.0 for 1\textsuperscript{st} story)

$C$: Strength Index (Story Shear Coefficient)

= lateral strength / building weight

$F$: Ductility Index (0.8, 1.0-3.2)
Basic Structural Index $E_0$ - (2)

Extremely brittle column

Shear column & Shear wall

Flexural column ($F=1.27\sim3.2$)

Flexural wall ($F=1.0\sim2.0$)

Shear column & Shear wall

Extremely brittle column

C-Index vs. F-Index

0.8 1.0 1.27 3.2

(1/500) (1/250) (1/150) (1/30)

Story drift angle
Shape Index $S_D$

A factor to modify $E_0\text{-index}$ due to structural irregularity

- Irregular shaped plan

- Unbalanced distribution of stiffness (strength)
  - Torsion
  - Soft story mechanism
Age Index T

A factor to allow for the deterioration of original performance

◆ Structural Cracking and deflection
  - Crack by uneven settlement, shear crack
  - Deflection of a slab and/or beam

◆ Deterioration and aging
  - Rust of reinforcing bar
  - Crack by concrete expansion
  - Crack by a fire disaster
Is-Index defined in the Japanese Seismic Evaluation Guideline (1977, revisited in 2001)

\[ Is = E_0 \times S_D \times T \]

- \( E_0 \) : Basic structural seismic capacity index
- \( S_D \) : Shape index (0.4 - 1.0)
- \( T \) : Age index (0.5 - 1.0)
Seismic Capacity $I_s$ index vs. Construction Age

No severe damage when $I_s > 0.6$

*Seismic retrofit of buildings before 1981*

Classification by Investigators
- Collapse
- Severe
- Moderate
- Minor
- Slight or None

Judging criteria $I_s = 0.6$
Damage Level vs. Seismic Capacity Is

Seismic Performance Indices, Is₂

Damage Indices, D

Classification by Investigators
- × Collapse
- ▲ Severe
- ◊ Moderate
- △ Minor
- ○ Slight or None

Ductile structure
2000 **Performance-based Design**

- **2000** Geiyo EQ  
  - M6.7  
  - death: 2

- **2004** Niigata-ken-chuetsu  
  - M6.8  
  - death: 68

- **2007** Miyagi-ken-oki EQ  
  - M6.8  
  - death: 15

- **2011** Great East Japan EQ  
  - M9.0  
  - death: 15894, missing: 2561 (Tsunami)

- **2016** Kumamoto EQ  
  - M7.3  
  - death: 88
Damage to RC buildings due to 2011 East Japan Earthquake
Summary of 2011 East Japan EQ

- Date: March 11, 2011 at 14:46 pm
- Location: 38.06° N 142.51° E
- Depth: 24km
- Magnitude: 9.0
2011 East Japan Earthquake

2011/03/11 14:46 (JST)

Some old RC building was Damaged
### Seismic record in Miyagi pref.

<table>
<thead>
<tr>
<th>Station</th>
<th>PGA (gal)</th>
<th>PGV (kine)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MYG004 (Tsukidate) NS</td>
<td>2699</td>
<td>118</td>
</tr>
<tr>
<td>EW</td>
<td>1269</td>
<td>51</td>
</tr>
<tr>
<td>MYG013 (Sendai) NS</td>
<td>1517</td>
<td>84</td>
</tr>
<tr>
<td>EW</td>
<td>982</td>
<td>43</td>
</tr>
<tr>
<td>THU (Sendai) NS</td>
<td>332</td>
<td>49</td>
</tr>
<tr>
<td>EW</td>
<td>330</td>
<td>61</td>
</tr>
<tr>
<td>JMA 4B9 (Furukawa) NS</td>
<td>550</td>
<td>78</td>
</tr>
<tr>
<td>EW</td>
<td>456</td>
<td>87</td>
</tr>
</tbody>
</table>
Acceleration spectrum

Period T (sec)

5% damped Response Spectrum

Accelleration (cm/sec^2)

- 2011 East Japan MYG004
- 1994 Northridge
- 2011 East Japan MYG013
- 2011 4B9
- 1995 Kobe
- 2011 Christchurch
- 2011 East Japan THU
- 2011 East Japan MYG013
- 1978 Miyagi-Oki

2011 East Japan MYG004
1994 Northridge
2011 East Japan MYG013
2011 4B9
1995 Kobe
2011 Christchurch
2011 East Japan THU
1978 Miyagi-Oki
Damage ratio of RC school buildings due to 1995 Kobe Earthquake

1st generation 2nd generation 3rd generation
Seismic code revision Code revision Kobe EQ East Japan EQ

1st generation: 73
2nd generation: 34
3rd generation: 50

40% 50% 60% 70% 80% 90% 100%

Less damage for new buildings owing to seismic code revision
Damage ratio of RC school buildings due to 2011 East Japan Earthquake

- 1st generation (w/o retrofit): 9
  - Slight: 50%, Minor: 40%, Moderate: 10%

- 1st generation (retrofitted): 57
  - Slight: 60%, Minor: 30%, Moderate: 10%

- 2nd generation (w/o retrofit): 16
  - Slight: 70%, Minor: 30%

- 2nd generation (retrofitted): 224
  - Slight: 40%, Minor: 50%, Moderate: 10%

- 3rd generation: 240
  - Slight: 95%, Minor: 5%

Less damage to new buildings
Damage ratio of RC school buildings due to 2011 East Japan Earthquake

1st generation (w/o retrofit): 9
1st generation (retrofitted): 57
2nd generation (w/o retrofit): 16
2nd generation (retrofitted): 224
3rd generation: 240

Less damage for retrofitted buildings
Seismic Capacity Is index vs. Construction Age
2011 East Japan

Criteria for school bldgs.
Residual seismic capacity ratio, $R\[%\]$

- Slight
- Minor
- Moderate
- Severe

Criteria for school bldgs.
Summary of damage

◆ Seismic capacity of existing RC school buildings in Miyagi prefecture were much improved owing to "seismic evaluation & retrofit".

◆ Good correlation between Is-index and damage level is observed.

However,

◆ Some of "retrofitted" and "evaluated-safe" buildings suffered from damage, even though they escaped collapse. Those buildings were un-functional and some were demolished.
Building of civil eng. and architecture, Tohoku Univ.

- **1968年** Constructed
- **1978年** Miyagi Oki earthquake
  - Moderate damage
- **2001年** Seismically Retrofitted
- **2011年** Great East Japan earthquake
  - Severe damage

Strong motion was observed over 40 years, leading to severe damage after the building experienced large earthquakes. The building was retrofitted, but it still suffered severe damage.
Damage (crack) pattern

1978 EQ

2011 EQ
Damage to Building of civil eng.

- 3<sup>rd</sup> story was most severely damaged.
- Large displacement occurred in shear wall.
- Spalling and crush of concrete, fracture and buckling of rebars are observed in corner columns.
3rd floor plan and seismic retrofit

- Damage levels are classified by residual seismic capacity ratio R.
- Correlation between damage level and Is-index are observed.

Axis 3 shown in crack figure

Seismic retrofitted symbols:
- Reinforcement of floor slab
- Replace of concrete side wall
- Install of steel brace
- Reinforcement of beam by steel plate wrap
Damage to columns in 3rd story

Severe damage to corner columns

Shear wall
Damage to shear wall and columns in 3rd story

Cracks at the bottom of shear wall due to pull-out reinforcement with poor anchorage

High axial load in column due to overturning moment
Damage to corner columns in 3rd story

- Fracture of steel
- Crush of concrete
- Buckling
Primary School Buildings

3 stories RC building, Const. in 1974
- West side structure
  \( I_s = 0.8 > I_{so} \text{(required)} \)
  No Retrofit was needed
  moderate damage
- East side structure
  Seismically retrofitted
  slight damage

2017/06/16
Seismic Capacity

<table>
<thead>
<tr>
<th>Building</th>
<th>C</th>
<th>F</th>
<th>SD</th>
<th>T</th>
<th>Is</th>
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<tbody>
<tr>
<td>East Building</td>
<td>0.66</td>
<td>1</td>
<td>0.88</td>
<td>0.98</td>
<td>0.57</td>
</tr>
<tr>
<td>before retrofit</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>East Building</td>
<td>0.88</td>
<td>1</td>
<td>0.88</td>
<td>0.98</td>
<td>0.75</td>
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<tr>
<td>after retrofit</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>West Building</td>
<td>0.5</td>
<td>1.75</td>
<td>0.93</td>
<td>0.98</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Ductility = Damage

Slight damage

Moderate
Shear failure of column and wall observed in un-retrofitted west building

Short column failed in shear
Damage classification of “Post-earthquake Damage Evaluation Standard” used in Japan
Damage distribution in west building

Building (B) 1st floor
Damage distribution

- Damage was concentrated to short columns in North side corridor.
- Is= strength index X ductility=C X F = 0.5 × 1.75 =0.8 by ignoring brittle short column.
- The damage pattern agree with seismic evaluation results.
Less damage to retrofitted building

Seismically retrofitted by steel bracing

Effect of seismic retrofit was observed
Damage to non-structural concrete walls in apartment

- Const. in 1979
- 11 story, SRC
- Enough is-index, but...
Damage to non-structural elements

RC non-structural walls failed in shear

- RC moment frame structure escaped from major damage.
- However,... Demolished.
Gym

constructed about 10 years ago

- Rehabilitated after Iwate-Miyagi EQ in 2008

- Again damaged by 2011 earthquake
Non structural element damage
(Junior high school gym in Kurihara city)

Large parts of the ceiling fell down (3/11, and also in 4/7)

The fixed parts after 2008 EQ escaped damage
Damage by tsunami

Onagawa town

Minami Sanriku town
Damage by tsunami

Most of students and teachers were killed by tsunami.
Damage by tsunami

Passage collapsed due to tsunami.  Bottom of column of passage.
Damage to buildings
due to 2016 Kumamoto Earthquake
Affected area & Epicenter

- Main shock (4/16, Mj=7.3)
- Fore-shock (4/14, Mj=6.5)

From Google Map

Minamiaso
Kumamoto Airport
Mashikimachi
Nishihara
Uto City
Kumamoto
Uto City
Damage in Mashiki town

- Local destructive damage
- Some of current code timber houses suffered collapse or severe damage
Madage in Mashiki town

◆ Damage to steel and RC structures
Damage in Minami Aso village

Land slides around Aso Mt.
## Results of Quick Inspection in Kumamoto

<table>
<thead>
<tr>
<th></th>
<th>inspected number</th>
<th>Green</th>
<th>yellow</th>
<th>Red</th>
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<tbody>
<tr>
<td><strong>Kumamoto city</strong></td>
<td>30,487</td>
<td>14,126</td>
<td>10,514</td>
<td>5,847</td>
</tr>
<tr>
<td><strong>Ratio[%%]</strong></td>
<td>100</td>
<td>46</td>
<td>35</td>
<td>19</td>
</tr>
<tr>
<td><strong>Mashiki town</strong></td>
<td>9,769</td>
<td>3,006</td>
<td>2,957</td>
<td>3,806</td>
</tr>
<tr>
<td><strong>Ratio[%%]</strong></td>
<td>100</td>
<td>31</td>
<td>30</td>
<td>39</td>
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<tr>
<td><strong>Uto city</strong></td>
<td>1,265</td>
<td>506</td>
<td>531</td>
<td>228</td>
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<tr>
<td><strong>Ratio[%%]</strong></td>
<td>100</td>
<td>40</td>
<td>42</td>
<td>18</td>
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</tbody>
</table>
Damage to RC buildings

- Un-retrofitted buildings designed by old seismic code.
- Soft first story collapse.
- Non-structural elements (nonstructural wall, ceiling etc.).

Most of the damage was similar to those observed in the past earthquakes.

Important point is to speed up retrofit schemes to existing vulnerable buildings.
Building designed by old seismic code without retrofitting

◆ Buildings of high school C

4-story RC building constructed in 1960
Shear failure of columns

4-story RC building constructed in 1964
Shear failure of wall
Building designed by old seismic code without retrofitting

◆ City hall (5-story, RC)

Story collapse occurred at the 4th story
There was future plans to rebuild because of its low seismic capacity index, $I_s$. 
Building with soft first story

◆ Apartment K
  ▪ 7-story, RC, designed by old seismic code, without retrofitting
  ▪ L shape plan, core wall for EV and staircase located on one side.
Collapse in soft first story
Apartment G

- Damage to structure elements is slight, nonstructural wall failed in shear.
Damage to non-structural elements

♦ School gym

- Falling of ceiling, exterior wall (window sash and glass)
- Damage of the steel frame-RC column joint
Damage Statistics of Public School Buildings in Kumamoto City

◆ Public school buildings for damage assessment

RC buildings + corridors connecting buildings (121 in total) were assessed.

Note 1: Total number of buildings and passages is 911.

Note 2: Ratio of buildings satisfying the current design code is 100%.
Concluding remarks
- preparedness for coming earthquakes -

◆ Seismic upgrading
  ■ Progressive for Public buildings. Almost completed for school bldgs. Private buildings are the problem.
  ■ Damage to disaster management facilities may be a big obstacle to recovery of damaged community.
  ■ Soft first story collapse was repeated.
  ■ Collapse of old timber housed induced casualty.

◆ Non-structural elements
  ■ Non-structural damage does not affect safety but function.
  ■ Fall of ceiling boards may cause casualty.
  ■ Structural engineer should be responsible seismic design of whole building structure including non-structural elements.