Revised Guideline for Post-Earthquake Damage Evaluation of RC Buildings in Japan

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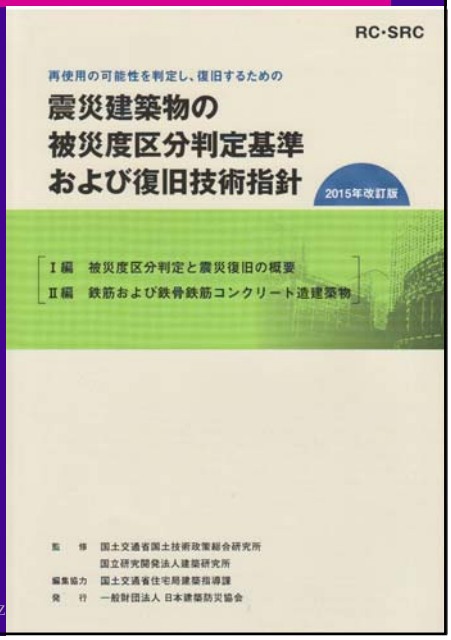
Post-EQ Inspections and Rehabilitation in Japan

- Rapid Inspection (1st Level)
  - Identify Which buildings are safe and Which are not to ***Aftershocks*** (Potential Risk Evaluation)
- Damage Evaluation (2nd Level)
  - Damage level classification and decision of necessary actions to the building against ***Future Major EQs*** (Repair / Strengthening / Reconstruction)

Guideline for Post-EQ Damage Evaluation and Rehabilitation

- Japan Building Disaster Prevention Association
  - issued in 1990,
  - revised in 2001 and 2015
- ✓ Committee (2011-2015) for revision of Guideline of RC buildings chaired by the author.



Procedure of Damage Evaluation and Rehabilitation

- Inspection of structural members and damage classification
  → Damage Class : I, II, III, IV, V
- Calculation of *R*-index

$$R = \frac{\text{Post-EQ Seismic Capacity}}{\text{Original Seismic Capacity}} \quad (\%)$$

- Damage rating based on *R*
  → Slight, Minor, Moderate, Severe, Collapse
- Decision making of post-EQ action
  - Experienced EQ Intensity vs. Damage (or Residual Cap.)
  - Repair Acceptable? Strengthening Needed?

Basic Concept of Post-EQ Damage Evaluation

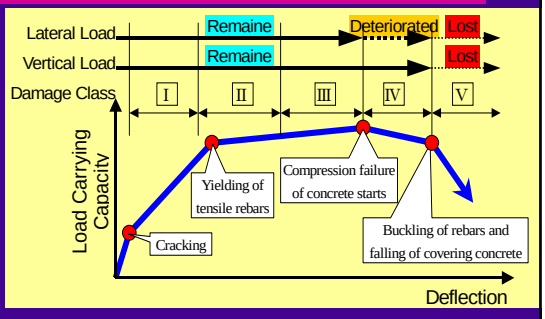
- Damage is rated by Residual seismic capacity ratio, *R*-index
  - *R*-index is evaluated by damage class (I, II, III, IV, V) of structural members

	R - *index* (%)	*Limit state*
[Slight]	95 - 100	Serviceability
[Minor]	80 - 95	
[Moderate]	60 - 80	Reparability
[Severe]	- 60	Safety
[Collapse]	≒0	

Load Carrying Cap. vs. Damage Class

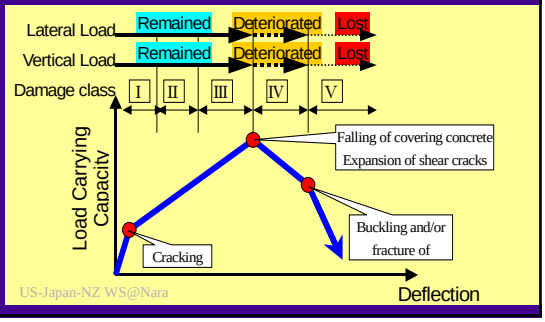
Ductile members

(Flexural columns)



Brittle members

(Shear columns)



Damage Class III

Crack with about 2mm on structural concrete

Spalling of covering concrete and rebar slightly exposed

Damage Class IV

Rebars exposed but their buckling / fracture not observed

Key points in 2015 revision

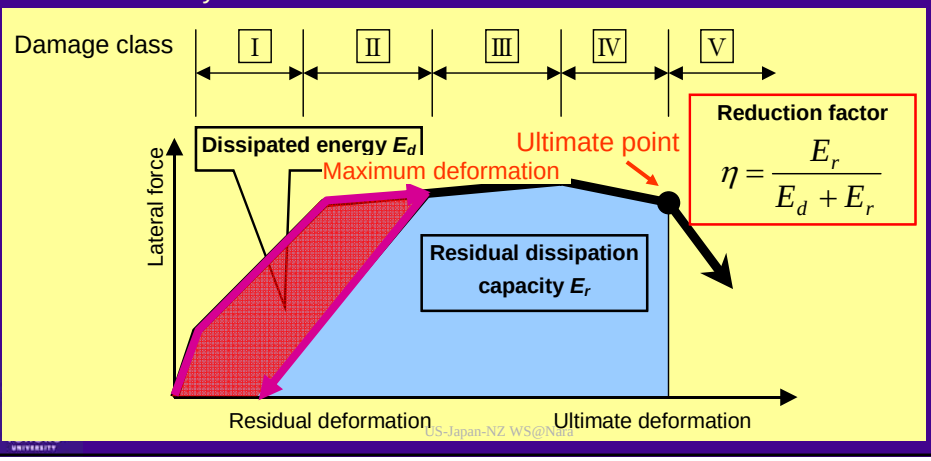
- Re-evaluation of Reduction Factor η
  - New categories: beams, …
  - Re-evaluation of η values based on recent test data
- Introduction of calculation of *R*-index for a building with total collapse mechanism
- Damage level of non-structural walls
- Damage level due to tsunami

Seismic Capacity Reduction Factor η

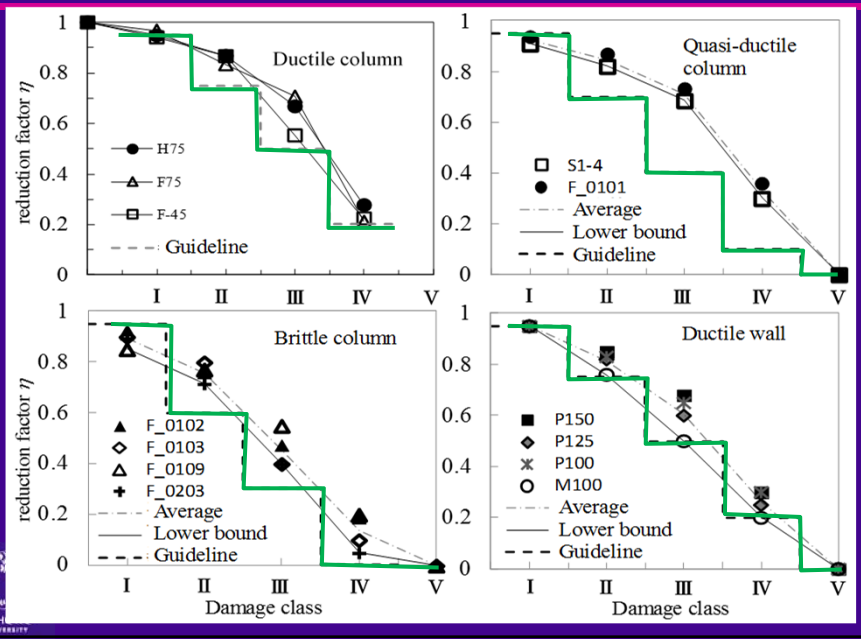
Reduce energy dissipation capacity (C X F)
for damaged structural members

C : Strength index (base shear coefficient)

F : Ductility index



Experimental data of reduction factor η



Reduction Factor η in 2015 revision

Damage class	column			beam		shear wall	
	ductile	quasi-ductile	brittle	ductile	brittle	ductile	brittle
I	0.95	0.95	0.95	0.95	0.95	0.95	0.95
II	0.75	0.7	0.6	0.75	0.7	0.7	0.6
III	0.5	0.4	0.3	0.5	0.4	0.4	0.3
IV	0.2	0.1	0	0.2	0.1	0.1	0
V	0	0	0	0	0	0	0

- Member type
  - ✓ Column: ductile, quasi-ductile, brittle
  - ✓ Beam, shear wall: ductile, brittle
- η values are evaluated by recent test data

Key points in 2015 revision

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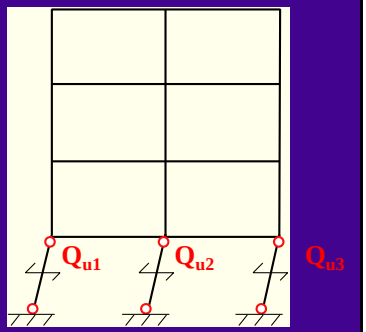
Story collapse of RC buildings in past EQs

(a) 1978 Miyagi-ken-oki Earthquake

(b) 1995 Kobe Earthquake

R-index for soft story collapse mechanism

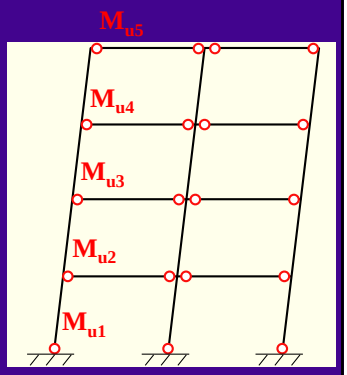
- Previous guideline
  - Soft story collapse mechanism is assumed because it is most popular for old and vulnerable buildings.
  - (Residual) Capacity is evaluated by shear strength *Qu* and reduction factor η of vertical members.
  - R-index and damage level is estimated for each story.



$$R = \sum \left(\frac{Q_{ui}}{\sum Q_{ui}} \times \eta_i \right)$$

R-index for total collapse mechanism

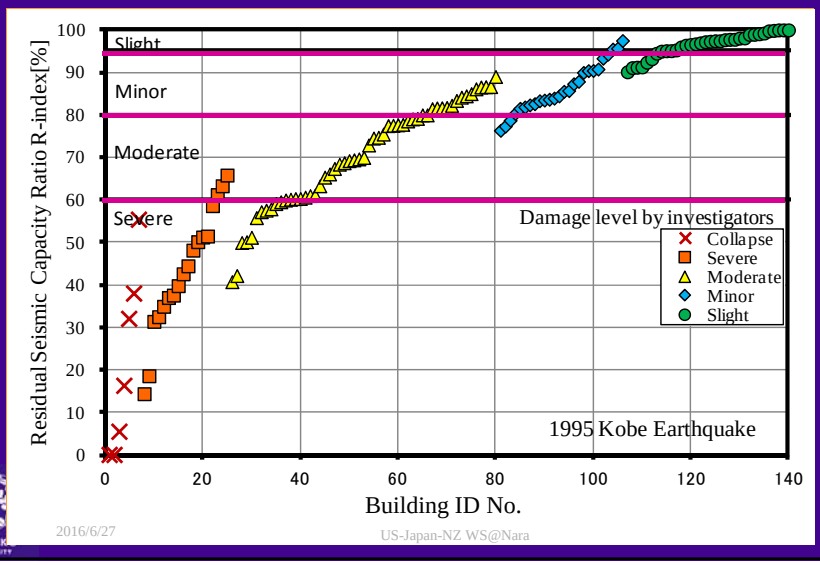
- 2015 guideline revision
  - Evaluation method for total collapse mechanism is introduced.
  - (Residual) Capacity is evaluated by flexural moment *Mu* and reduction factor η at plastic hinges.
  - Evaluation method can be applied to recent analysis-based procedure such as push-over.
  - R-index and damage level is estimated for a whole structure.



$$R = \sum \left(\frac{M_{ui}}{\sum M_{ui}} \times \eta_i \right)$$

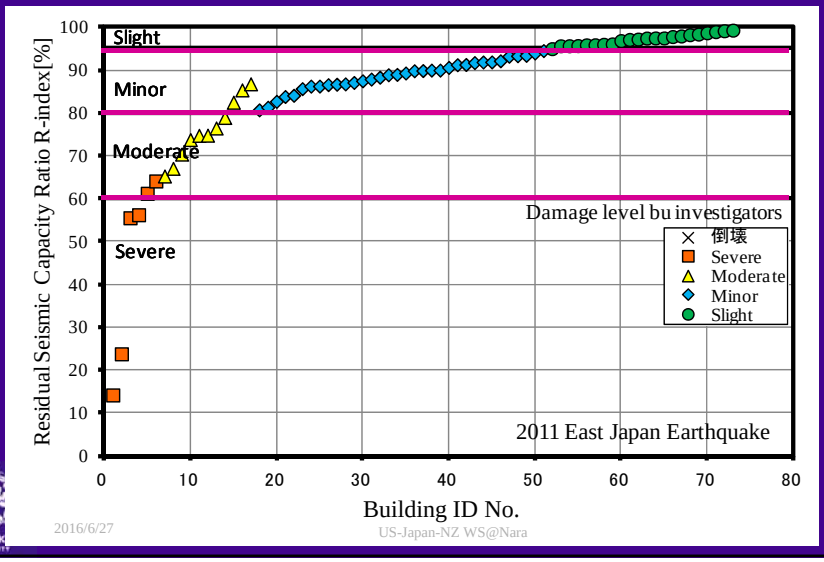
Residual Capacity *R*-index vs. Observed Damage

- 140 RC school bldgs. suffered 1995 Kobe EQ



Residual Capacity *R*-index vs. Observed Damage

- 70 RC school bldgs. suffered 2011 East Japan EQ



Application to RC buildings damage by recent EQs

Revised R-index are applied to damage rating RC school buildings suffered

- 1995 Kobe EQ
- 2011 East Japan EQ

	R – index (%)	*Limit state*
[Slight]	95 - 100	Serviceability
[Minor]	80 - 95	
[Moderate]	60 - 80	Reparability
[Severe]	- 60	Safety
[Collapse]	Building which is deemed to have $R \fallingdotseq 0$ due to overall/partial collapse	

Example of a building with total collapse mechanism and damage to non-structural elements

- Suffered from 2011 East Japan EQ
- 11 storied apartment
- SRC frame structure
- Const. in 1979

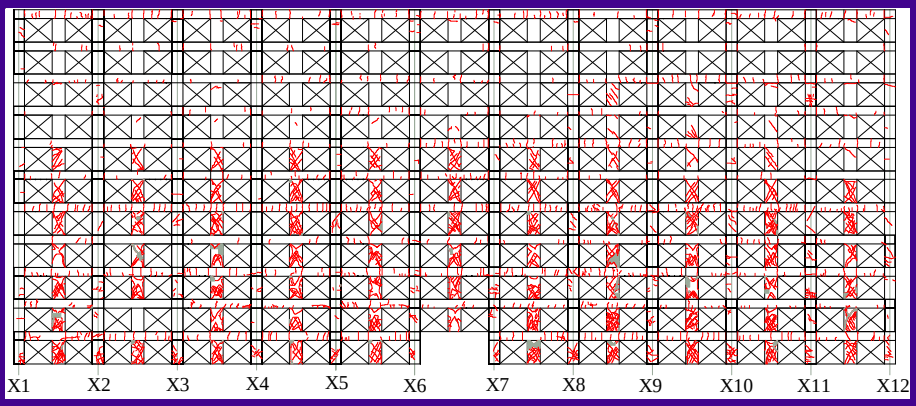
- Total collapse mechanism with beam plastic hinges

Damage to non-structural concrete walls

Shear failure in non-structural walls

- No severe damage to structural elements such as beams and columns
- However, demolished and rebuilt

Crack map



Damage level

Structure: [Minor] R=87% (total collapse)

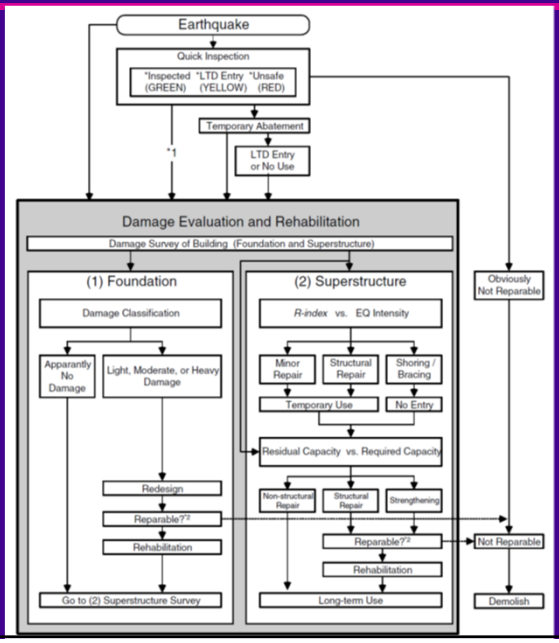
Non-structural walls: [moderate]

Concluding Remarks

- Basic concept of the Japanese Guideline post-EQ damage evaluation of RC buildings was described.
- Definition and supporting data for residual seismic capacity ratio, *R*-index, was presented.
- Major items in the guideline revision were;
  - Introduction of evaluation method for total collapse mechanism.
  - Re-evaluation of reduction factor η.
- Good agreement between the residual seismic capacity ratio, *R*-index, and the observed damage levels in recent severe earthquakes was found.

Thank you for your attention

General Flow of Damage Evaluation & Rehabilitation



Reduction Factor η in 2001 guideline

Damage class	Ductile column	Brittle column	Shear wall
I	0.95	0.95	
II	0.75	0.6	
III	0.5	0.3	
IV	0.1	0	
V	0	0	

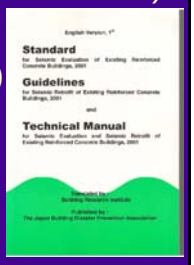
Definition of Damage Class

Damage Class	Description of Damage
I	- Visible narrow cracks on concrete surface (Crack width is less than 0.2 mm)
II	- Visible clear cracks on concrete surface (Crack width is about 0.2 -1.0 mm)
III	- Local crush of covering concrete - Remarkable wide cracks (Crack width is about 1.0 - 2.0 mm)
IV	- Remarkable crush of concrete with exposed reinforcing bars - Spalling off of covering concrete (Crack width is more than 2.0 mm)
V	- Buckling of reinforcing bars - Cracks in core concrete - Visible vertical deformation in columns and/or walls - Visible settlement and/or inclination of the building

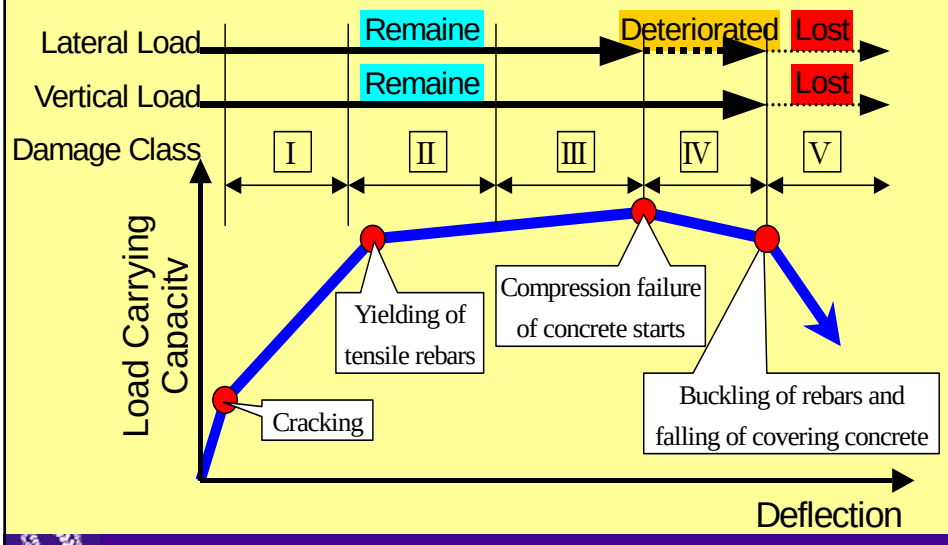
Residual Seismic Capacity Ratio *R*

$$R = \frac{{}_D Is}{Is} \times 100 \quad (\%)$$

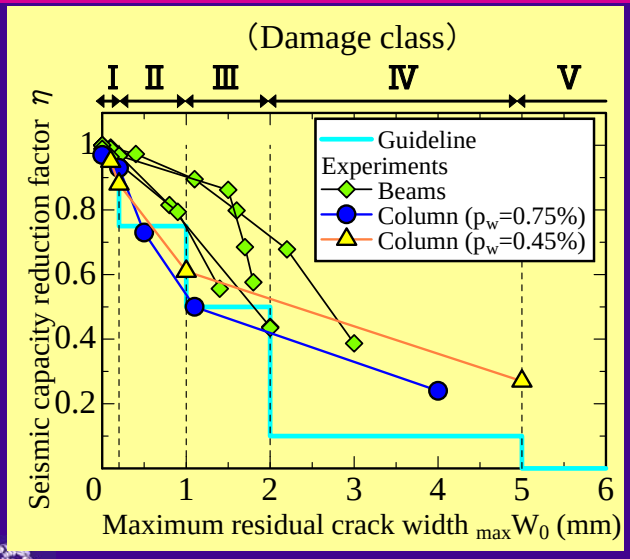
- Original Cap. *Is*-index (Standard for Seismic Evaluation)
  - $Is = \Sigma (C \times F) \times S_D \times T$
  - *C* : lateral strength index (story shear/weight)
  - *F* : ductility index
  - S_D : shape factor
  - *T* : age factor
- Residual Cap. ${}_D Is$
  - ${}_D Is = \Sigma (\eta \times C \times F) \times S_D \times T$
  - Reduction factor η : Depending on damage class



Load Carrying Cap. vs. Damage Class

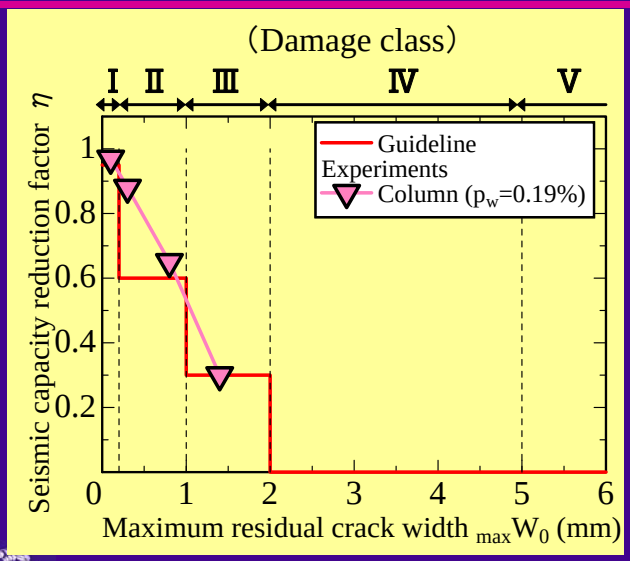


Reduction Factor η for Ductile Members



Damage Class	η
I	0.95
II	0.75
III	0.5
IV	0.1
V	0

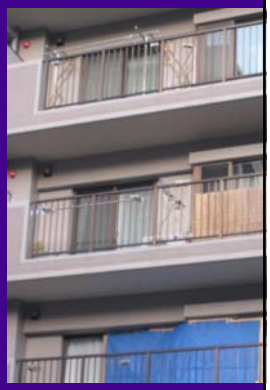
Reduction Factor η for Brittle Members



Damage Class	η
I	0.95
II	0.6
III	0.3
IV	0
V	0

Damage level of non-structural walls

- Damage to non-structural walls was found in high-rise RC residential buildings in recent EQs.
- Damage to non-structural walls is negligible in R-index but influence functionality and repairability.
- Damage level is estimated independently.



Ratio of non-structural wall with damage class IV or V	partial	Approx. 50%	almost
Damage level	Minor	Moderate	Severe

Damage level due to tsunami

- General damage due to tsunami
  - Slight damage to RC structural elements
  - Severe non-structural elements (washed away of partition, ceiling, window, equipment…)
- Damage level is estimated independently.

Flood depth/height of building	< 50%	> 50%	> 100%
Damage level	Minor	Moderate	Severe