16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 3987

Registration Code: S-Z1464180762

Revision of Guideline for Post-Earthquake Damage Evaluation of Reinforced Concrete Buildings in Japan

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Abstract

In Japan, the Guideline for Post-Earthquake Damage Evaluation and Rehabilitation, originally developed in 1991 and revised in 2001, was revised in 2015 based on the lessons from damaging earthquakes such as the 2011 East Japan Earthquake. The authors have developed a method to evaluate residual seismic capacity of reinforced concrete structures based on *R*-index, which was employed in the Damage Evaluation Guideline. The *R*-index is defined as the ratio of residual seismic capacity to the original capacity, and is calculated from residual seismic capacity in structural members. In this paper, firstly, the general concept of the Guideline for reinforced concrete buildings is presented. Secondly, the main points in the revision in 2015 are introduced.

In the guideline revision, the value of reduction factor for capacity of a structural member corresponding to its damage state was re-evaluated with recent experimental data of reinforced concrete beams, columns and shear walls. An evaluation method of residual seismic capacity, *R*-index, for a building with total collapse mechanism of beam yielding type was developed and introduced into the revised guideline in addition to story collapse mechanism.

R-index was originally developed for a building with story collapse mechanism, which is the most typical failure mechanism of reinforced concrete buildings observed in the past damaging earthquakes. However, total collapse mechanism, which is recommended in current design code and guidelines, is found in some middle or high rise buildings damaged by recent earthquakes and this type of failure is expected to increase in the future. Applicability of the proposed method for damage evaluation was investigated by a study of the database of RC buildings damaged by the recent major earthquakes and its accuracy and effectiveness was discussed.

Keywords: Reinforced concrete building, Post-earthquake damage evaluation, Residual seismic performance, Rehabilitation.

1. Introduction

To restore an earthquake-damaged community as quickly as possible, a well-prepared reconstruction strategy is essential. When an earthquake strikes a community and destructive damage to buildings occurs, immediate damage inspections are needed to identify which buildings are safe and which are not to aftershocks following the main event. However, since such quick inspections are performed within a restricted short period of time, the results may be inevitably coarse. Furthermore, it is not generally easy to identify the residual seismic capacities quantitatively from quick inspections. In the next stage following the quick inspections, a damage assessment should be more precisely and quantitatively performed, and then technically and economically sound solutions should be applied to damaged buildings, if rehabilitation is needed. To this end, a technical guide that may help engineers find appropriate actions required for a damaged building is needed.

In Japan, the Guideline for Post-Earthquake Damage Evaluation and Rehabilitation [1] (subsequently referred to as Damage Evaluation Guideline) was originally developed in 1991 and was revised in 2001 and 2015 considering damaging earthquake experiences in Japan. The main objective of the Damage Evaluation Guideline is to serve as a technical basis and to provide rational criteria when an engineer needs to identify and rate building damage quantitatively, determine necessary actions required for the building and provide technically sound solutions to restore the damaged building. It describes a damage evaluation basis and rehabilitation techniques for three typical structural systems in Japan, i.e., reinforced concrete, steel, and wooden buildings. This paper discusses the outline and the basic concept of the Guideline for reinforced concrete buildings, primarily focusing on (1) the damage rating procedure based on the residual seismic capacity index that is consistent with the Japanese Standard for Seismic Evaluation of Existing RC Buildings ([2], subsequently referred to as Seismic Evaluation Standard), (2) the main points in the Guideline revision in 2015, and (3) its validity through calibration with observed damage due to the recent major earthquake.

2. General Flow of Damage Evaluation and Rehabilitation

Damage evaluation of a building is performed on the foundation system and superstructure system, respectively, and the damage rating of each building is made in a combination form for each system such as "no damage in foundation and moderate damage in superstructure". Rehabilitation actions necessary for the building are then determined considering identified damage. Fig. 1 shows the general flow of damage evaluation and subsequent rehabilitation.

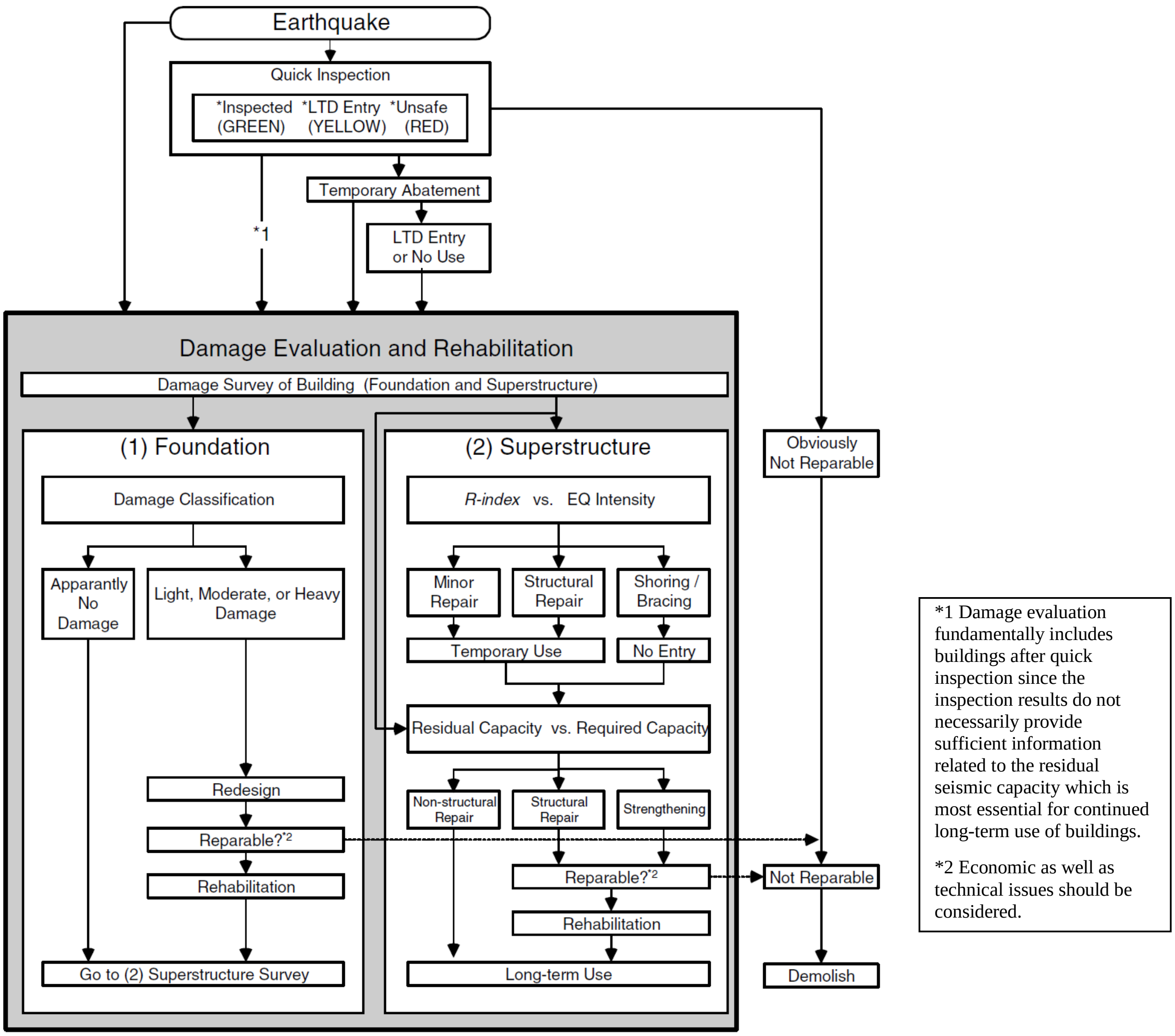


Fig.1 – General Flow of Damage Evaluation and Rehabilitation in the Guideline [3]

3. Damage Evaluation for Building Structure

3.1 General Procedure of Post-Earthquake Damage Evaluation

3.1.1 Basic Concept of Residual Seismic Capacity Ratio *R*-index

The structural damage state of RC buildings is identified using the residual seismic capacity ratio, R index, in the Damage Evaluation Guideline [1]. The R index is defined as the ratio of post-earthquake seismic capacity, $_{D}Is$ index, to original capacity, $_{D}Is$ index, and is given by Eq. (1) in the Guideline.

$$R = \frac{_{D}Is}{Is} \times 100 \ (\%) \tag{1}$$

where Is and $_{D}Is$ represent the seismic performance index of the structure before and after earthquake damage, respectively.

The Is index, which is defined in the Seismic Evaluation Standard [2], is widely applied to seismic evaluation of existing RC building structures in Japan. The Is index is evaluated based on the ultimate lateral strength index (C index) and ductility index (F index) of each lateral-load resisting member. The basic concept of the Is index is described in the Appendix.

3.1.2 Evaluation of Post-Earthquake Seismic Capacity

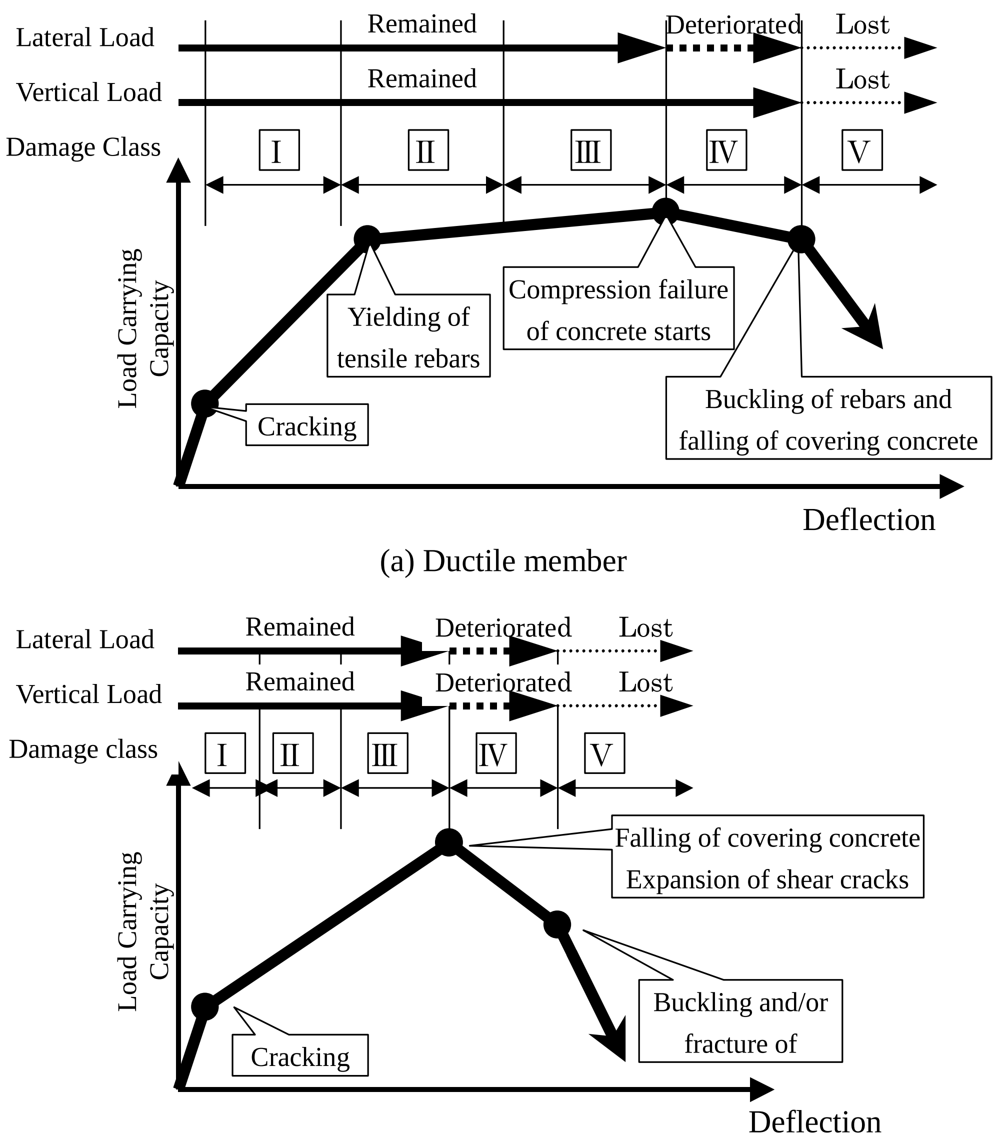
Similarly, the post-earthquake seismic capacity $_{D}Is$ index is evaluated based on the C and F indices. However, both indices are calculated using seismic capacity reduction factors (η-factors), which are described in detail later, to consider the deterioration of lateral strength and ductility corresponding to the damage state of each lateral-load resisting member.

In the Damage Evaluation Guideline [1], the state of damage of each structural member is first classified into one of the five classes listed in Table 1. The relationship between each damage class given in Table 1 and the lateral force-displacement curve is approximated as shown in Fig. 2. Examples of damage class for columns and walls are shown in Photo 1.

In Fig. 2(a), a ductile member deforms up to a maximum lateral strength level after yielding. Furthermore, after reaching the maximum strength, the reduction of strength is relatively small. If the maximum deformation during an earthquake does not reach deformation at yielding point, extensive damage would not occur. This state corresponds to damage class I, between the cracking and yield points. If the maximum deformation does not exceed the maximum strength, damage to cover concrete is limited and most of the lateral and vertical strengths remains in the flexural member. This state corresponds to damage class II and damage class III. If the maximum response exceeds the maximum lateral strength point, deterioration in lateral strengths with spalling of cover concrete would be observed. The vertical strength may remain if the buckling and/or fracture of reinforcing bars and crush of core concrete, etc., do not occur. This state corresponds to damage class IV. If buckling and/or fracture of reinforcing bars and crush of core concrete occur, both the lateral and vertical load carrying capacities will be lost (damage class V).

Table 1 – Definition of Damage Classes of Structural Members [2]

Damage Class	Observed Damage on Structural Members
I	Some cracks are found. Crack width is smaller than 0.2 mm.
II	Cracks of 0.2 - 1 mm wide are found.
III	Heavy cracks of 1 - 2 mm wide are found. Some spalling of concrete is observed.
IV	Many heavy cracks are found. Crack width is larger than 2 mm. Reinforcing bars are exposed due to spalling of the covering concrete.
V	Buckling of reinforcement, crushing of concrete and vertical deformation of columns and/or shear walls are found. Side-sway, subsidence of upper floors, and/or fracture of reinforcing bars are observed in some cases.



(a) Ductile member

(b) Brittle member

Fig. 2 – Idealized lateral force-displacement relationships and damage class [2]

Damage class III: (left) Cracks with a width of about 2mm on structural concrete
(right) Spalling concrete cover and slightly exposed rebars

Damage class IV: Exposed rebars without buckling or fracture

Damage class V:

Photo 1 – Damage class examples

The degree of damage in a brittle member, as shown in Fig. 2(b), is similar to that of a ductile member up to the maximum strength, although diagonal or X-shape cracks may also be visible (damage classes I, II and III). After the maximum strength is reached, a significant reduction in both lateral and vertical strength may occur (damage class IV). Finally, X-shape shear cracks widen and both lateral and vertical load carrying capacity will be lost suddenly (damage class V).

In the Seismic Evaluation Standard [2], the most fundamental component for the *Is* index is the E_0 index, which is calculated from the product of the strength index (*C* index) and the ductility index (*F* index) (see Appendix). Accordingly, the E_0 index corresponds to the energy dissipation capacity in a structural member. Fig. 3 shows a conceptual diagram illustrating the lateral force-displacement curve and a definition of the η factors. When the maximum response reaches point A during an earthquake and residual displacement (point B) occurs, the area of E_d and E_r is assumed to be the dissipated energy during the earthquake and the residual energy dissipation capacity after the earthquake, respectively. The η factor is defined as the ratio of residual energy dissipation capacity, E_r, to original energy dissipation capacity, E_t (= E_d+ E_r), and can be calculated by Eq. (2).

$$\eta = \frac{E_r}{E_t} \qquad (2)$$

where, E_d : dissipated energy, E_r : residual energy dissipation capacity, E_t : original energy dissipation capacity ($E_t = E_d + E_r$).

The seismic capacity reduction factors, *i.e.*, η factors for structural members corresponding to the damage classes, are listed in Table 2. The values for η factors are determined from the residual crack width and the overall damage state of RC columns observed in the first author's laboratory experiments [4] and analytical studies [5], [6]. The post-earthquake seismic capacity, $_{D}Is$ index, of the overall building after earthquake damage can be calculated based on the E_0 index reduced by the η factor corresponding to the observed damage class of each structural member.

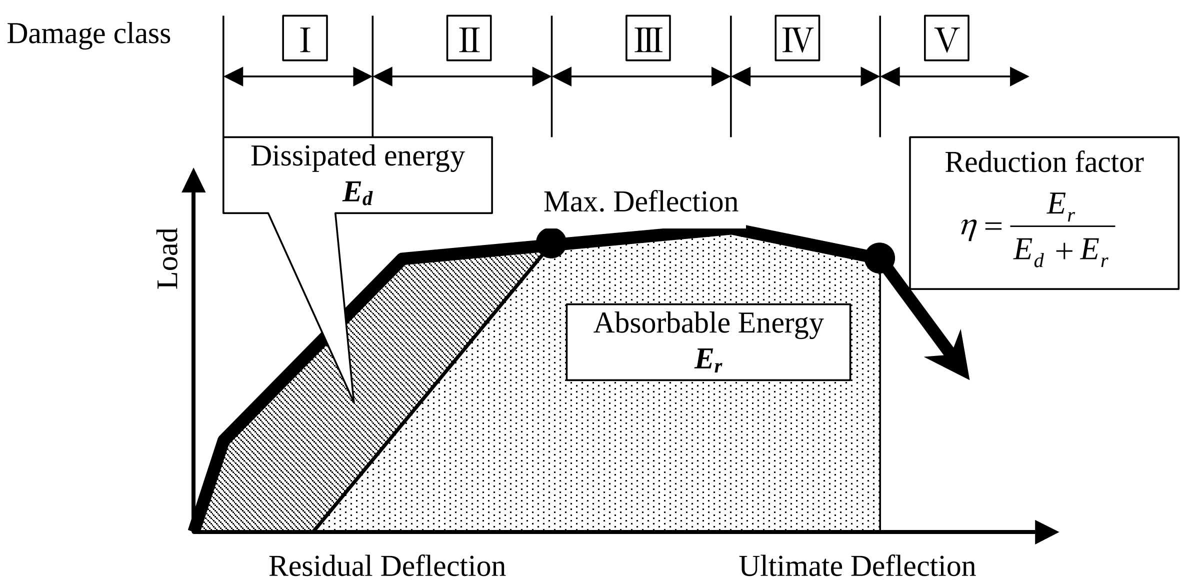


Fig. 3 – Seismic capacity reduction factor η

Table – 2 Seismic capacity reduction factor η in 2001 version [1]

<table>
<tr><th>Damage class</th><th>Ductile column</th><th>Brittle column</th><th>Shear wall</th></tr>
<tr><td>I</td><td>0.95</td><td colspan="2">0.95</td></tr>
<tr><td>II</td><td>0.75</td><td colspan="2">0.6</td></tr>
<tr><td>III</td><td>0.5</td><td colspan="2">0.3</td></tr>
<tr><td>IV</td><td>0.1</td><td colspan="2">0</td></tr>
<tr><td>V</td><td>0</td><td colspan="2">0</td></tr>
</table>

3.2 Revision of Damage Evaluation Guideline in 2015

Over ten years have passed and several damaging earthquakes have occurred in Japan since the revision of Damage Evaluation Guideline in 2001. JBDPA (Japan Building Disaster Prevention Association) established a committee for revision of the Guideline just after the 2011 East Japan Earthquake. The main topics in the revision by RC working group, which is chaired by the first author, are as follows;

1) The values for η factors are re-evaluated by recent experiments and analysis.

2) An evaluation method of residual seismic capacity, *R*-index, for a total collapse mechanism is introduced into scope of application.

The values of η factors for brittle columns were applied to shear walls in the previous Guideline [1], and no recommendation for beams as shown in Table 2, because experimental data focused on residual seismic capacity was quite limited at the 2001 revision. In the 2015 revision, the values of η factors were enhanced through examination of experimental data [7,8]. A new category of "Quasi-ductile columns" was introduced in addition to ductile and brittle columns in the previous Guideline. The values of η factors were re-evaluated based on conservative estimation of experimental data are shown in Fig. 4. Moreover, η factors for beams and walls were given independently as shown in Table 3.

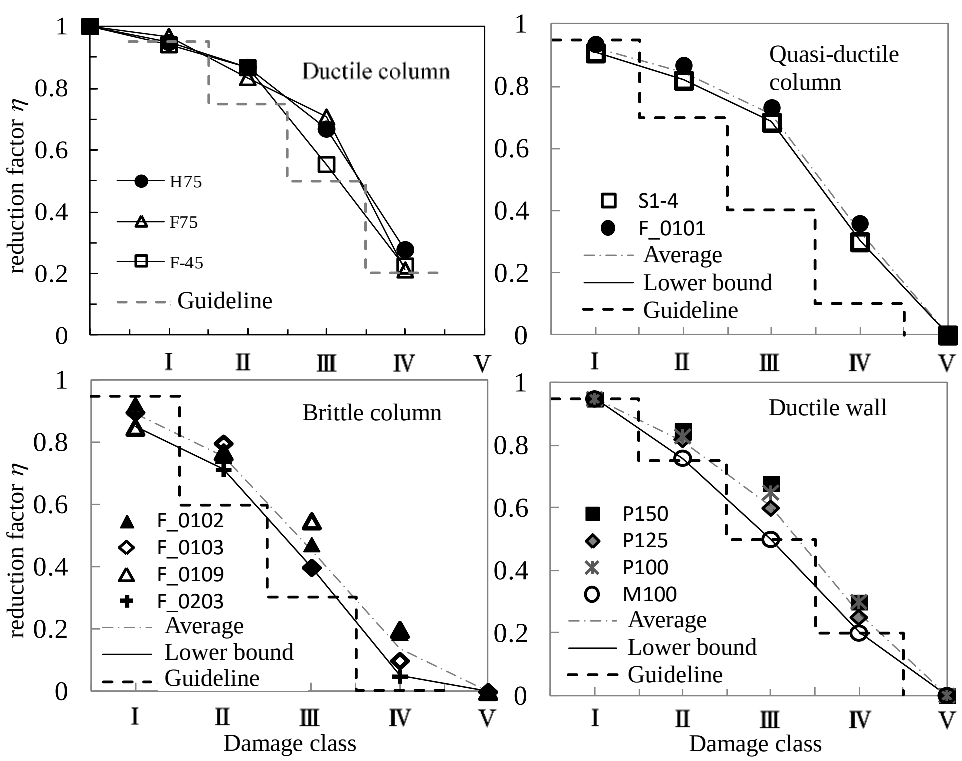


Fig. 4 – Experimental data of Seismic capacity reduction factor η

Table 3 – Seismic capacity 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

Fig. 5 shows typical collapse mechanism of frame structures. As was revealed in past damaging earthquakes in Japan, typical life-threatening damage is generally found in vertical members, and story collapse mechanism, as shown in Fig. 5(a) and Photo 2, is formed. Therefore, the current Guideline is essentially designed to identify and classify damage in columns and walls rather than in beams, and residual seismic capacity, *R*-index, can be evaluated based on story shear by Eq. (3) assuming ductility index (*F* index) is uniform in all the vertical elements in the story. When damage is found in beams, the damage classification needs to be performed considering their deficiency in vertical load carrying capacity as well as lateral resisting of columns adjacent to damaged beams.

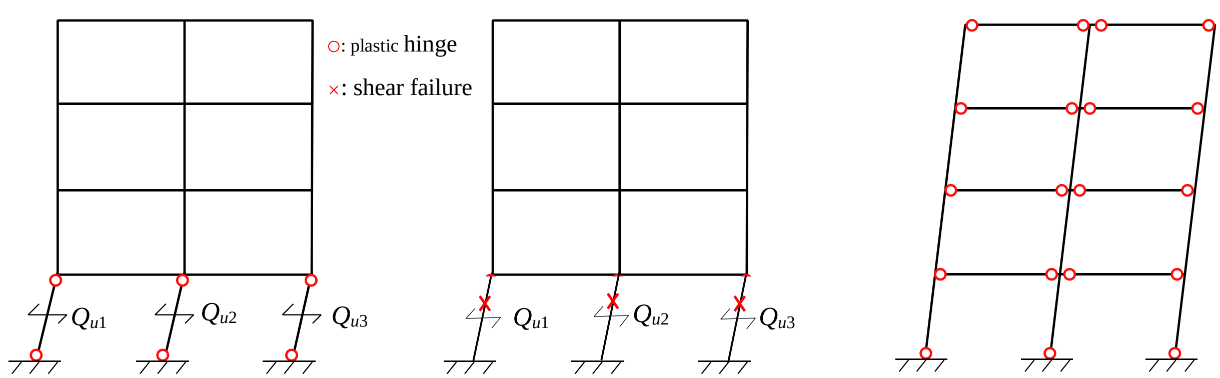
$$R = \sum\left(\frac{Q_{ui}}{\sum Q_{ui}} \times \eta_i\right) \tag{3}$$

Where, Q_{ui}: lateral strength of vertical structural member, *i.e.*, columns and walls, η_i: seismic capacity reduction factor of each member.

Although story collapse is the most popular failure mechanism, other relatively ductile failure patterns, total collapse mechanism, were observed in reinforced concrete buildings damage by recent earthquakes such as the 2011 East Japan Earthquake. Beam yielding total collapse mechanism (Fig. 5(b)), which is recommended in the current seismic code and guidelines, was found in some relatively new middle or high rise buildings designed according to current seismic codes. Therefore, the evaluation method for total collapse mechanism, proposed by the first author et al. [9], is introduced into the Guideline and the scope of application was widened. *R*-index for total collapse mechanism is evaluated by Eq. (4). Eq. (4) gives a ratio of internal work at all the plastic hinges in virtual work method before and after an earthquake.

$$R = \sum\left(\frac{M_{ui}}{\sum M_{ui}} \times \eta_i\right) \tag{4}$$

Where, M_{ui}: ultimate flexural moment at yielding hinge in mechanism.



(a) Story collapse mechanism (b) Total collapse mechanism

Fig. 5 – typical collapse mechanism of frame structures

(a) 1978 Miyagi-ken-oki Earthquake

(b) 1995 Kobe Earthquake

Photo 2 – Story collapse of reinforced concrete buildings due to past earthquakes

4. Application to Buildings Damaged due to Recent earthquakes in Japan

The proposed damage evaluation method was applied to reinforced concrete buildings damaged due to the 1995 Hyogo-Ken-Nambu (Kobe) Earthquake and the 2011 East Japan Earthquake. The residual seismic capacity ratio, *R* index, of about 140 reinforced concrete buildings damaged due to the Kobe Earthquake and about 70 buildings due to the East Japan Earthquake are shown in Fig. 6 together with the observed damage levels from field surveys by experts such as professors. The horizontal lines in Fig. 6 are the boundaries between damage levels employed in the Damage Evaluation Guideline in 2001.

[slight damage]	$R \geq 95$ %
[minor damage]	$80 \leq R < 95$ %
[moderate damage]	$60 \leq R < 80$ %
[severe damage]	$R < 60$ %
[collapse]	$R \approx 0$

The boundary lines between damage levels were examined in the 2001 Guideline revision for the buildings in Fig. 6(a), of which failure mechanism is story collapse. The boundary line between slight and minor damage was set to R = 95% to harmonize "slight damage" to the serviceability limit state in which the building is functional without repair. Almost all severely damaged buildings and approximately 1/3 of moderately damaged buildings were demolished and rebuilt after the earthquake according to a report of the Hyogo Prefectural Government (1998). If the boundary between moderate and severe damage was set to R = 60%, "moderate damage" may correspond to the repairability limit state.

As shown in Fig. 6(b), the damage levels based on the *R* index generally agree with those classified by investigators for the buildings suffered from the 2011 East Japan Earthquake, which include buildings with total collapse mechanism. Photo 3 shows overall view and damages to a residential buildings suffered from the 2011 East Japan Earthquake. The building was a 11-storied steel reinforced concrete structure constructed in 1979. Structural drawing of an outside frame was shown in Fig.7 together with crack maps. Damage to non-structural walls are severe, in particular, in lower stories and shear failure was found as shown in photo 4(b) and (c). On the other hand, damage to structural frame was limited. The frame formed total collapse mechanism with plastic hinges at beam ends by flexural yielding (Photo 4 (d)). Major damage class of beams were III for lower stories and I or II for middle and higher stories. Assuming story collapse mechanism, R-index is evaluated story by story ranging from 69% in the 2nd story to 95% in 8th story and as a result damage level is classified as "moderate". However, calculation method for total collapse mechanism gives one R-index of 87% in the sense of an average of whole structure. As a result, damage level is rated as “minor damage”, which seems to be relatively reasonable estimation considering

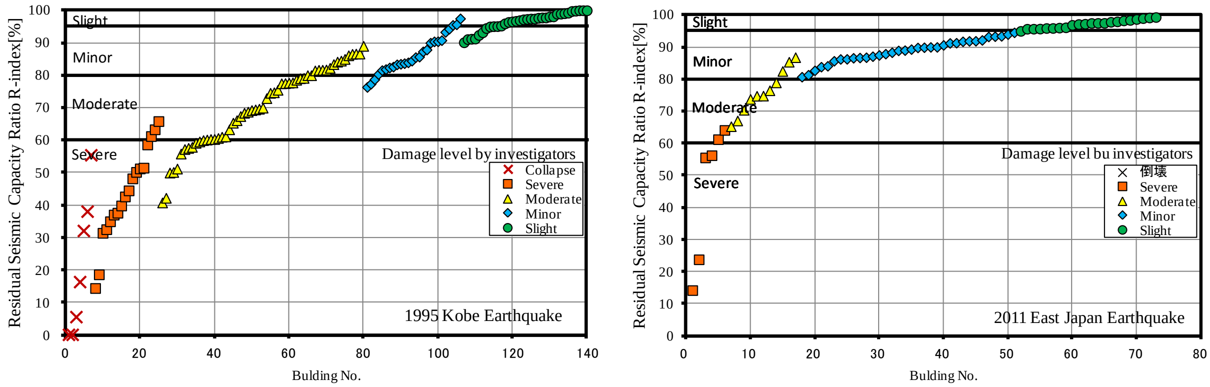


Fig. 6 – Residual seismic capacity index *R* and observed damage levels due to the 1995 Kobe Earthquake and 2011 East Japan Earthquake

(a) Overall view

(b) Shear failure of non-structural wall

(c) Shear failure of non-structural wall

(d) Crush of concrete at plastic hinge region of a beam end

Photo 3 – Damage to a residential building with total collapse mechanism of beam yielding type

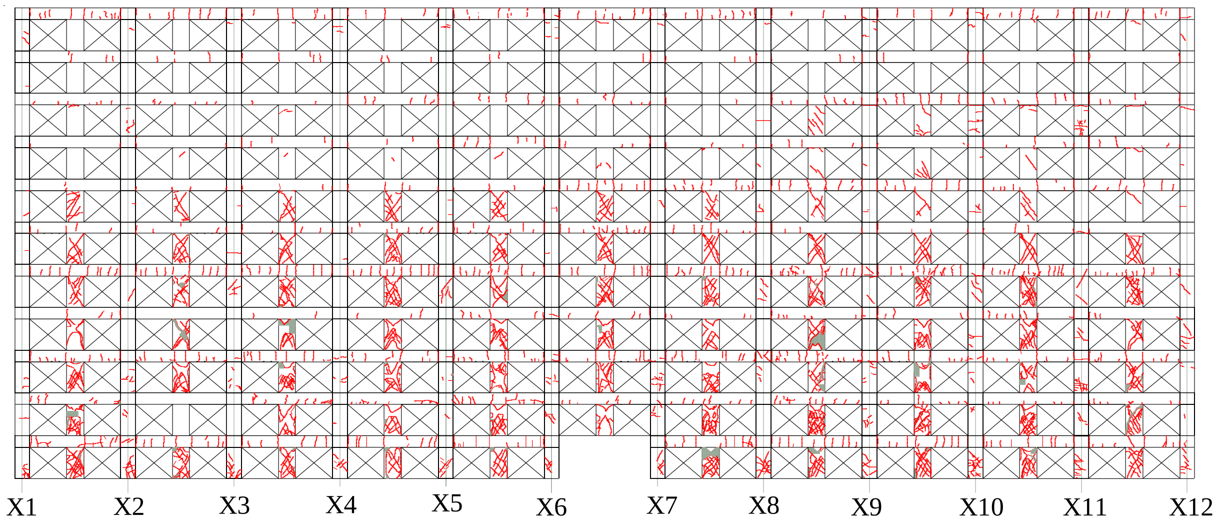


Fig. 7 – Elevation of a frame with crack map of a residential building damaged due to the 2011 East Japan Earthquake

5. Concluding Remarks

In this paper, the basic concept of the Guideline for Post-Earthquake Damage Evaluation of RC buildings in Japan was presented. The concept and supporting data of the residual seismic capacity ratio, *R* index, which is assumed to represent post-earthquake damage of a building structure, were discussed.

Major items in the guideline revision were;

(1) introduction of evaluation method for total collapse mechanism, and

(2) Re-evaluation of reduction factor η

Good agreement between the residual seismic capacity ratio, *R* index, and the observed damage levels of RC buildings in recent severe earthquakes was found.

6. Acknowledgements

The authors express sincere gratitude to the members in the working group for Revision of Post-Earthquake Damage Evaluation Guideline of Reinforced Concrete Buildings chaired by the first author.

7. Appendix - Basic Concept of Japanese Standard for Seismic Evaluation of Existing RC Buildings-

The Standard consists of three procedures of different levels, i.e., first, second and third level procedures. The first level procedure is the simplest but most conservative since only the sectional areas of columns and walls and concrete strength are considered to calculate the strength, and the inelastic deformability is neglected. In the second and third level procedures, the ultimate lateral load carrying capacity of vertical members or frames is evaluated using material and sectional properties together with reinforcing details based on field inspections and structural drawings.
In the Standard, the seismic performance index of a building is expressed by the *Is* index for each story and each direction, as

shown in Eq. (A1)

$$Is = E_0 \times S_D \times T \tag{A1}$$

where, E_0 : basic structural seismic capacity index calculated from the product of strength index (C), ductility index (F), and story index (ϕ) at each story and each direction when a story or building reaches the ultimate limit state due to lateral force, *i.e.*, $E_0 = \phi \times C \times F$.

Strength index C: index of story lateral strength, calculated from the ultimate story shear in terms of story shear coefficient.

Ductility index F: index of ductility, calculated from the ultimate deformation capacity normalized by the story drift of 1/250 when a standard size column is assumed to fail in shear. F is dependent on the failure mode of the structural members and their sectional properties such as bar arrangement, shear-span-to-depth ratio, shear-to-flexural-strength ratio, etc. In the standard, F is assumed to vary from 1.27 to 3.2 for ductile columns, 1.0 for brittle columns and 0.8 for extremely brittle short columns (shear-span-to-depth ratio less than 2).

ϕ : index of story shear distribution during earthquake, estimated by the inverse of design story shear coefficient distribution normalized by base shear coefficient. A simple formula of $\phi = \frac{n+1}{n+i}$ is basically employed for the i-th story level of an n-storied building by assuming inverted triangular shaped deformation distribution and uniform mass distribution.

S_D: factor to modify E_0-Index due to stiffness discontinuity along stories, eccentric distribution of stiffness in plan, irregularity and/or complexity of structural configuration, basically ranging from 0.4 to1.0

T: reduction factor to allow for the deterioration of strength and ductility due to age after construction, fire and/or uneven settlement of foundation, ranging from 0.5 to 1.0.

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