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An overview of post-earthquake damage and residual capacity evaluation for reinforced concrete buildings in Japan

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ABSTRACT

Damage level classification is essential just after a damaging earthquake for decision of appropriate and necessary action in order to prevent from repeated damage due to after-shocks and future major earthquake, and to support well-organized recovery. Therefore, accurate and practical post-earthquake damage evaluation method has been studied and developed in Japan.

This paper overviews state-of-the-art of post-earthquake damage and residual seismic capacity for reinforced concrete buildings in Japan. Japanese Damage Evaluation Guideline was originally issued in 1991 and revised in 2001 and 2015. Evaluation of residual seismic capacity of whole building was introduced in the 2001 evaluated based on damage level considering residual crack width, crush of concrete and so on. Total collapse mechanism and damage in non-structural concrete wall were taken into the scope in the 2015 revision. Recently, residual seismic capacity evaluation based on response spectrum method is studied by authors. Basic concept of these method and application example are presented.

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 (JBDPA 2015) (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 (JBDPA 2001), 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 DAMAGE EVALUATION FOR BUILDING STRUCTURE

2.1 Basic concept of residual seismic capacity ratio R

The structural damage state of RC buildings is identified using the residual seismic capacity ratio, R index, in the Damage Evaluation Guideline (JBDPA 2015). The R index is defined as the ratio of post-earthquake seismic capacity, ${}_{D}Is$ index, to original capacity, Is index, and is given by Equation 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 I_s index, which is defined in the Seismic Evaluation Standard (JBDPA 2001), is widely applied to seismic evaluation of existing RC building structures in Japan. The I_s index is evaluated based on the ultimate lateral strength index (C index) and ductility index (F index) of each lateral-load resisting member.

2.2 Evaluation of post-earthquake seismic capacity

Similarly, the post-earthquake seismic capacity ${}_{D}I_s$ 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.

2.2.1 Damage class of structural elements

In the Damage Evaluation Guideline (JBDPA 2015), 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 Figure 1a, b. Examples of damage class for columns and walls are shown in Photo 1.

Table 1: Definition of Damage Classes of Structural Members (JBDPA 2015).

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.

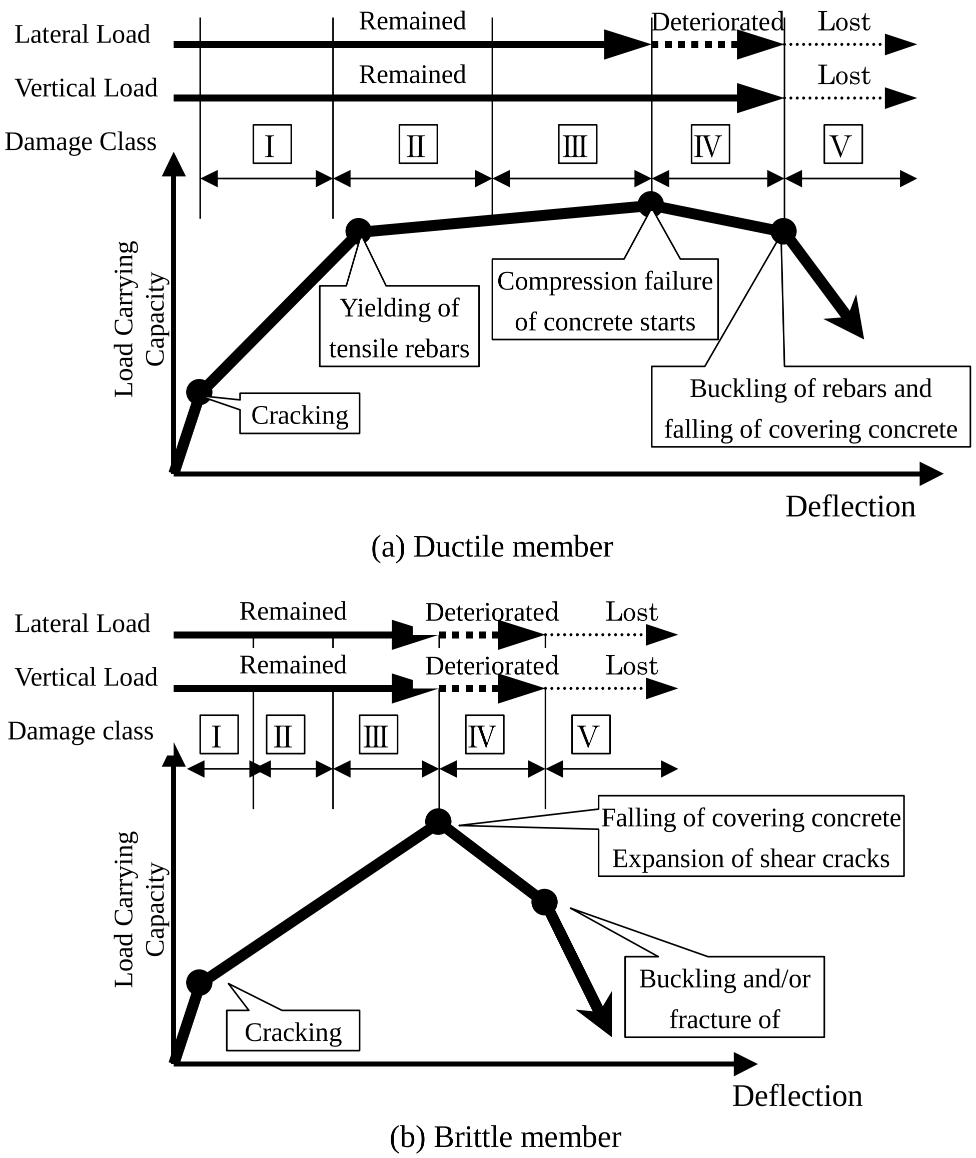


Figure 1: Idealized lateral force-displacement relationships and damage class (JBDPA 2015)

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

In Figure 1a, 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).

The degree of damage in a brittle member, as shown in Figure 1b, 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)

2.2.2 Reduction factor

In the Seismic Evaluation Standard (JBDPA 2001), the most fundamental component for the I_s 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. Figure 2 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 Equation 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 experiments (Maeda 2004) and analytical studies (Maeda 2001 and Maeda 2009). The post-earthquake seismic capacity, $_DIs$ 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.

The values of η factors for brittle columns were applied to shear walls in the previous Guideline (JBDPA 2015), 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 (Maeda2014 and Itoh 2015). 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 Figure 3. Moreover, η factors for beams and walls were given independently as shown in Table 2.

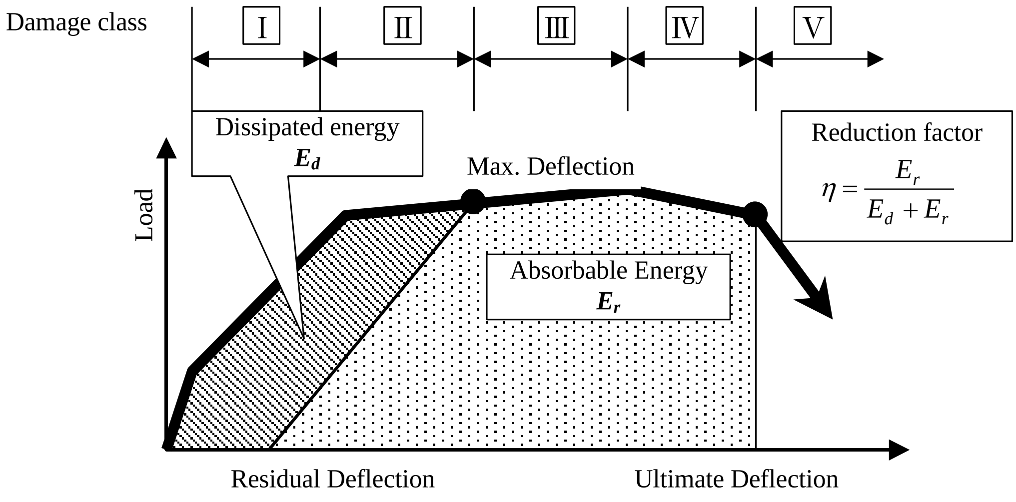


Figure 2: Seismic capacity reduction factor η

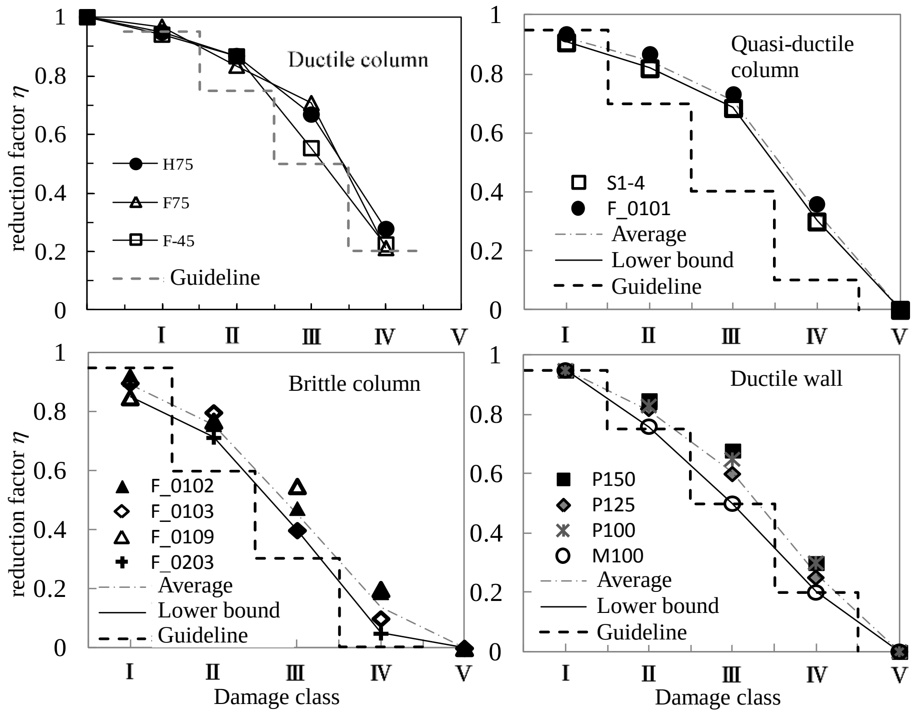


Figure 3: Experimental data of Seismic capacity reduction factor η

Table 2: Seismic capacity reduction factor η.

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

2.3 Practical approximation of *R*-index

Figure 4a ,b 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 Figure 4a 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 Equation 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.

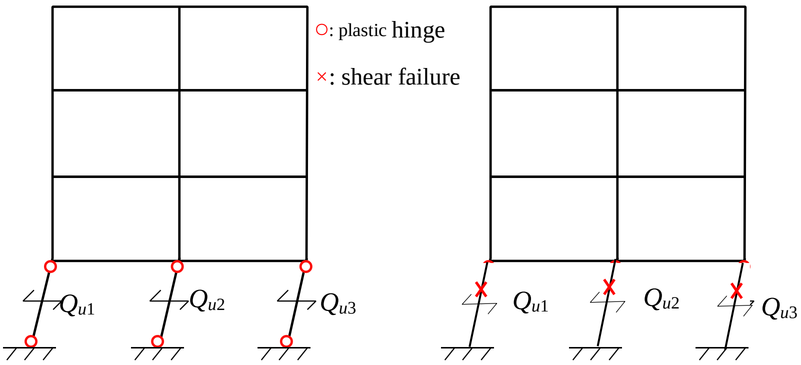
$$R = \sum \left(\frac{Q_{ui}}{\sum Q_{ui}} \times \eta_i \right) \tag{3}$$

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

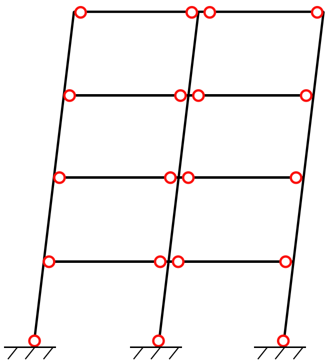
Although story collapse is the most popular failure mechanism, other relatively ductile failure patterns, total collapse mechanism, were observed in reinforced concrete buildings damage by recent earthquakes such as the 2011 East Japan Earthquake. Beam yielding total collapse mechanism (Fig. 4b), which 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 (Bao 2010) is introduced into the Guideline and the scope of application was widened. *R*-index for total collapse mechanism is evaluated by Equation 4. Equation 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

Figure 4: 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

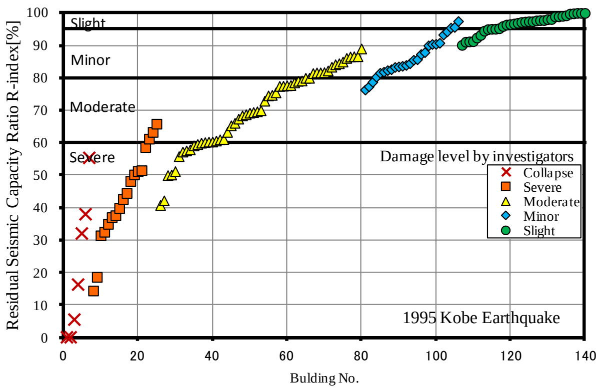
3 APPLICATION TO BUILDINGS DAMAGED DUE TO RECENT EARTHQUAKES IN JAPAN

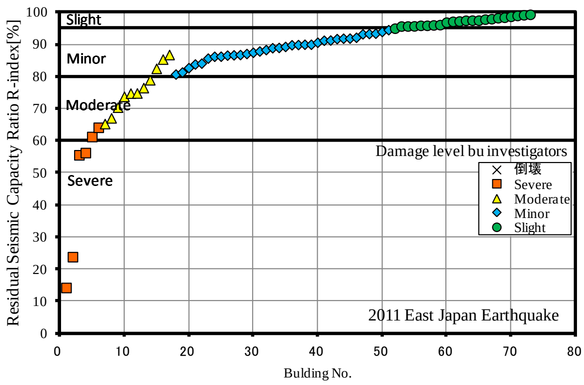
The proposed damage evaluation method was applied to reinforced concrete buildings damaged due to the 1995 Hyogo-Ken-Nambu (Kobe) Earthquake and the 2011 East Japan Earthquake. The residual seismic capacity ratio, R-index, of about 140 reinforced concrete buildings damaged due to the Kobe Earthquake and about 70 buildings due to the East Japan Earthquake are shown in Figure 5a, b together with the observed damage levels from field surveys by experts such as professors. The horizontal lines in Figure 5a, b 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 Figure 5a, 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 Figure 5b, 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 3d 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 Figure 6 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 3b, 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 3 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





(a) 1995 Kobe Earthquake *(b) 2011 East Japan Earthquake*

Figure 5: 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

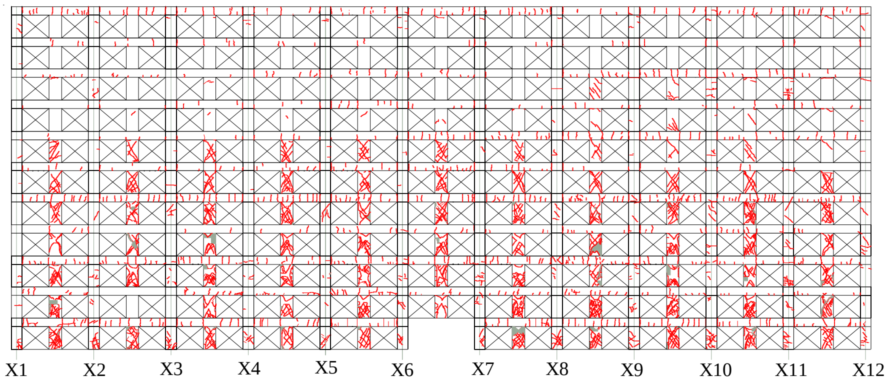


Figure 6: Elevation of a frame with crack map of a residential building damaged due to the 2011 East Japan Earthquake

4 CONCLUSIONS

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

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