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Post-Earthquake Damage Evaluation for R/C Buildings Based on Residual Seismic Capacity

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ABSTRACT

In this paper described is the basic concept of the Guideline for Post-earthquake Damage Assessment of RC buildings, revised in 2001, in Japan. This paper discusses the damage rating procedures based on the residual seismic capacity index R, the ratio of residual seismic capacity to the original capacity, that is consistent with the Japanese Standard for Seismic Evaluation of Existing RC Buildings, and their validity through calibration with observed damage due to the 1995 Hyogoken-Nambu (Kobe) earthquake. Good agreement between the residual seismic capacity ratio and damage levels was observed.

1. INTRODUCTION

To restore an earthquake damaged community as quickly as possible, well-prepared reconstruction strategy is most essential. When an earthquake strikes a community and destructive damage to buildings occurs, quick damage inspections are needed to identify which buildings are safe and which are not to aftershocks. However, since such quick inspections are performed within a restricted short period of time, the results may be inevitably coarse. In the next stage following the quick inspections, damage assessment should be more precisely and quantitatively performed, and then technically and economically sound solution should be applied to damaged buildings, if rehabilitation is necessary. To this end, a technical guide that may help engineers find appropriate actions required in a damaged building is needed, and the Guideline for Post-earthquake Damage Evaluation and Rehabilitation [1] originally developed in 1991 was revised in 2001 considering damaging earthquake experience in Japan.

The Guideline describes damage evaluation basis and rehabilitation techniques for three typical structural systems, i.e., reinforced concrete, steel, and wooden buildings. Presented in this paper are outline and basic concept of the Guideline for reinforced concrete buildings. This paper discusses the damage rating procedures based on the residual seismic capacity index that is consistent with the Japanese Standard for Seismic Evaluation of Existing RC Buildings [2], and their validity through calibration with observed real damage.

2. BASIC CONCEPT OF POST-EARTHQUAKE DAMAGE EVALUATION

2.1 Residual Seismic Capacity Ratio

In this paper, damage level of a building structure was evaluated by residual seismic capacity ratio R, which is defined as the ratio of post-earthquake seismic capacity to the original capacity. The Seismic Evaluation Standard [2] was employed to evaluate the seismic capacity of a building. In the Seismic Evaluation Standard, the seismic performance index of a building is expressed by

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the Is-index. Residual seismic capacity ratio R is defined using Eq.(1).

$$R = 100 \times {}_D Is / Is\,(\%) \quad (1)$$

where, Is: original seismic performance index, ${}_D Is$: post-earthquake seismic performance index

2.2 Estimation of Post-Earthquake Seismic Capacity of Building

The original seismic performance Is-index of a building can be calculated from lateral resistance and deformation ductility of structural members in accordance with the Seismic Evaluation Standard [2]. On the other hand, residual resistance and deformation ductility in the damaged structural members are needed to be evaluated in order to quantify post-earthquake seismic performance index ${}_D Is$. Idealized lateral force-displacement relationships for ductile and brittle columns are shown in Figure 1 with damage class defined in Table1. Table 1 shows damage classification of structural members in the Guideline [1].

Table 1. Damage Class for RC Structural Members

Damage class	Description of damage
I	Visible narrow cracks on concrete surfaces. Crack widths are less than 0.2 mm.
II	Visible cracks on concrete surface. Crack widths range about 0.2-1 mm.
III	Localized crushing of concrete cover. Noticeable wide cracks. Crack widths range about 1-2 mm.
IV	Crushing of concrete with exposed reinforcing bars. Spalling of covering concrete. Crack widths are greater than 2 mm.
V	Buckling of reinforcing bars. Cracks in core concrete. Visible vertical deformation in columns, walls or both. Visible settlement, inclination of the building or both.

In the Seismic Evaluation Standard, most fundamental component for Is-index is E_0-index, which is basic structural seismic capacity index calculated from the product of strength index(C), and ductility index (F). Accordingly, deterioration of seismic capacity was estimated by energy dissipation capacity in lateral force-displacement curve of each member, as shown in Figure 2. Seismic capacity reduction factor η is defined by Eq.(2).

$$\eta = Er/Et \quad (2)$$

where, E_d : dissipated energy, E_r : residual absorbable energy, E_t : entire absorbable energy (E_t = E_d + E_r).

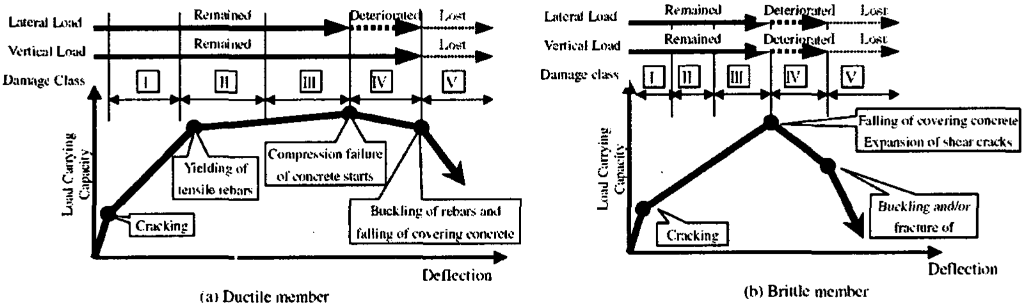


Figure 1. Idealized lateral load-displacement relationships and damage class

2.3 Evaluation of seismic capacity reduction factor based on experimental results

The seismic capacity reduction factor η for flexural members was investigated using test results [1]. Four beam specimens were tested under anti-symmetric bending and axial restraint force applied in proportion to the measured axial elongation. The stiffness constant for the axial force was selected as 1000 kN/cm or 4000 kN/cm, representing the lateral restraint stiffness of columns in prototype frame structures. The shear span ratio was 1.0 or 2.0. The specimens were subjected to two cycles at rotation angles of 1/200, 1/100, 1/67, 1/50, 1/33 rad. after the first cycle at a rotation angle of 1/400 rad.

Figure 3 shows the observed shear force-lateral displacement relations. The relationship between maximum residual crack widths and the lateral displacement is shown in Figure 4. In the experiment, all the flexural crack widths were measured by crack gauges along the top and bottom surfaces of a specimen at the peak in each cycle and at the moment when the lateral force was unloaded. (see Figure 5). Longitudinal bars yielded in each specimen at the rotation angle of the order of 1/200rad. As can be seen in Figure 4, residual crack widths were smaller than 0.2mm, which corresponds to the "damage class I (slight damage)", until flexural yielding occurred in a cycle at 1/200rad. After flexural yielding, the maximum residual crack increased markedly with increase in the lateral displacement.

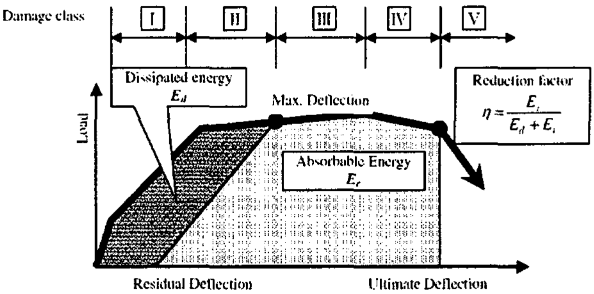


Figure 2. Seismic capacity reduction factor

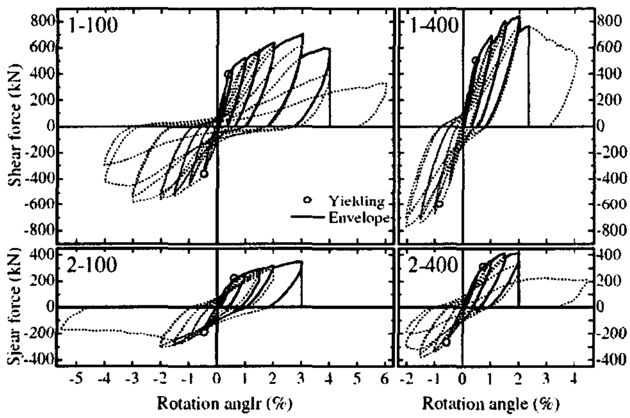


Figure 3. Shear force-lateral displacement relations

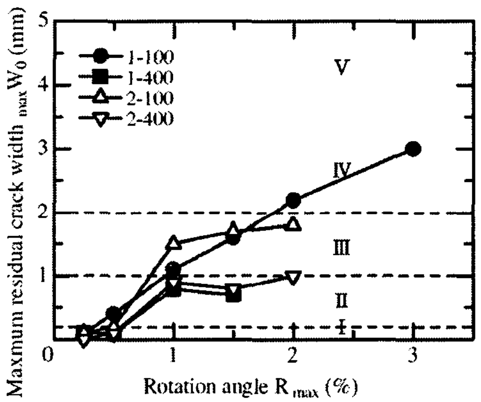


Figure 4. Maximum residual crack width vs. rotation angle

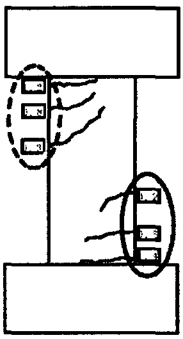
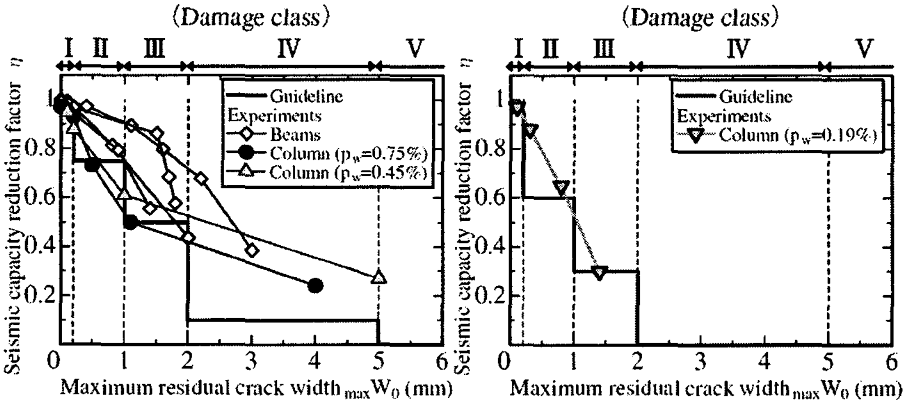


Figure 5. Measurement of crack width



(a) Ductile member **(b)Brittle member**

Figure 6. Maximum residual crack width vs. Seismic capacity reduction factor

When specimens reached maximum lateral force at the rotation angle of 2/100-3/100rad, the maximum residual crack widths were about 2mm and damage class was III or IV. From the test results, the seismic capacity reduction factor η, defined in Figure 2, was evaluated. The entire energy dissipation E_t was calculated from positive envelopes of shear force-lateral displacement curve (see Figure 3). Ultimate displacement was assumed as the rotation angle when shear force decrease to 80% of maximum force. The relationships between seismic capacity reduction factor η and maximum residual crack widths are shown in Figure 6. From the figure, seismic capacity reduction factor η for structural members was determined as shown in Table 2.

3. APPLICATION TO RC BUILDINGS DAMAGED DUE TO RECENT EARTHQUAKES

Table 2. Damage Class for RC

Damage Class	Ductile Column	Brittle Column	Wall
I	0.95	0.95	
II	0.75	0.6	
III	0.5	0.3	
IV	0.1	0	
V	0	0	

The proposed evaluation method was applied to reinforced concrete buildings damaged due to recent earthquakes such as 1995 Hyogo-ken-nambu Earthquake. The residual seismic capacity ratio R of approximately 150 reinforced concrete school buildings are shown in Figure 7 together with damage levels estimated by the engineering judgment of investigators. As can be seen in the figure, no significant difference between damage levels and residual seismic capacity ratio R can be found although near the border some opposite results are observed. The horizontal lines in Figure 7 are borders between damage levels proposed in the Damage Evaluation Guideline.

[slight] $R \geq 95$ (%)　[minor] $80 \leq R < 95$ (%)　[moderate] $60 \leq R < 80$ (%)
[severe] $R < 60$ (%)　[collapse] $0 \fallingdotseq R$

The border between slight and minor damage was set R=95% to harmonize "slight damage" to the serviceability limit state. Almost of severely damaged and approximately 1/3 of moderately damaged buildings were demolished and rebuilt after the earthquake according to the report of Hyogo Prefecture. Therefore, if the border between moderate and severe damage was set R=60%, "moderate damage" may correspond to the reparability limit state.

4. CONCLUDING REMARKS

In this paper, the basic concept and procedure of new Guideline for post-earthquake damage assessment of RC buildings in Japan were 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 and damage levels classified by engineering judgment was observed for relatively low-rise buildings damaged due to 1995 Hyogo-ken Nambu Earthquake.

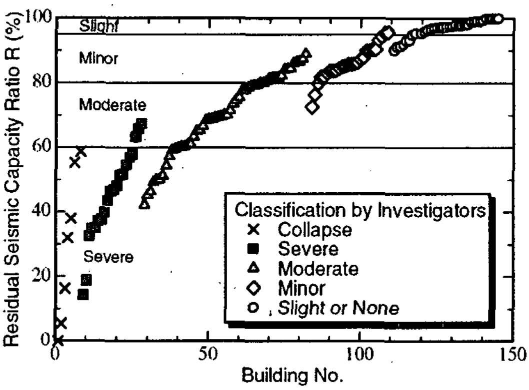


Figure 7. Residual seismic capacity ratio R and damage level classification

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1. The Japan Building Disaster Prevention Association, *Guideline for Post-earthquake Damage Evaluation and Rehabilitation*, 2001. (in Japanese)
2. The Japan Building Disaster Prevention Association, *Standard for Seismic Evaluation of Existing RC Buildings*, 2001. (in Japanese)