Post-Earthquake Damage Evaluation for R/C Buildings

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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. Moreover, seismic response analyses of SDF systems were carried out and it is shown that the intensity of ultimate ground motion for a damaged RC building structure can be evaluated conservatively based on the *R*-index in the Guideline.

Keywords: Post-earthquake damage evaluation; Residual seismic capacity; R/C building

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 damage due to the 1995 Hyogoken-Nambu (Kobe) earthquake and seismic response analyses of SDF systems.

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2. Post-earthquake Damage Evaluation

2.1 Residual seismic capacity ratio, *R*

In the Damage Evaluation Guideline, damage level of a building structure is evaluated by residual seismic capacity ratio *R*, which is defined as the ratio of post-earthquake seismic capacity to the original capacity. Seismic Evaluation Standard[2)], which is most widely applied to existing reinforced concrete buildings in Japan, is employed to evaluate the seismic capacity of a building. In the Seismic Evaluation Standard, seismic performance of a building is expressed by the *Is*-index. The basic concept of *Is*–index appears in **APPENDIX**. Residual seismic capacity ratio *R* is given by Eq.(1).

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

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

2.2 Estimation of post-earthquake seismic capacity

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 Post-earthquake Damage Evaluation Guideline[1].

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).

$$\eta = \frac{E_r}{E_t} \tag{2}$$

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

The Post-earthquake Damage Evaluation Guideline recommends values for seismic capacity reduction factor η shown in **Table 2** based on the author's experimental and analytical results[3,4].

Table 1. Damage Class For RC Structural Members[1]

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.

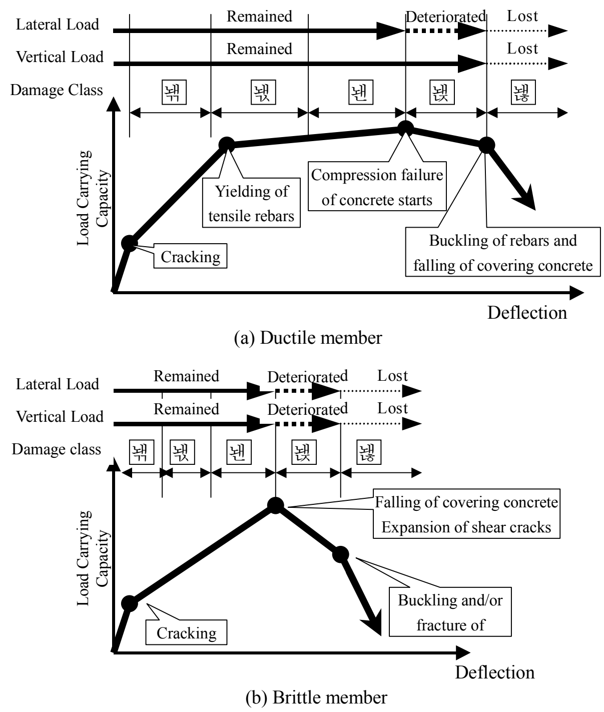

Fig. 1. Idealized lateral force-displacement relationships and damage class

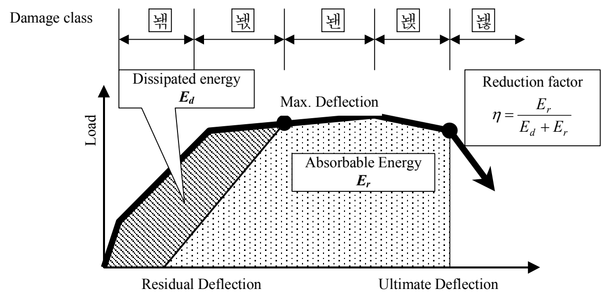

Fig. 2. Seismic capacity reduction factor η

Table 2. seismic capacity reduction factor η

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	

2.3 Approximation of lateral strength and ductility in members

One of main purposes of damage level classification is to grasp the residual seismic capacity as soon as possible just after the earthquake, in order to access the safety of the damaged building for aftershocks and to judge the necessity for repair and restoration. For this purpose, need of detailed and complicated procedure, i.e. calculation of strength and ductility of structural member based on material and sectional properties, reinforcing details etc, is inconvenient. Accordingly, a simplified method was developed by approximated lateral strength and ductility. Following assumptions were employed in the approximation.

(1) Vertical members are categorized into five members and normalized lateral strengths $\overline{C}$ of the five categories are assumed as shown in **Table 3**. These values were evaluated from cross section area and average shear stress for typical low-rise reinforced concrete buildings in Japan.

(2) Ductility factor F of each vertical member is assumed 1.0.

(3) The original and residual capacities of a building are estimated by the summation of the original and residual capacities of vertical members in the damaged story. Therefore residual seismic capacity ratio R is calculated by Eq.(3).

$$R = \frac{\sum \eta \overline{C} F}{\sum \overline{C} F} \quad (3)$$

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 recent earthquakes such as 1995 Hyogo-ken-nambu Earthquake. Objective buildings include 10 moment frame structures and 2 wall-frame structures[5].

Approximated value of Residual seismic capacity ratio R_1 was compared with accurate value R_2, which was evaluated from calculated lateral strength and ductility based on material and sectional properties, reinforcing details, in **Figure 3**. From the figure, approximated value R_1 agrees with accurate value R_2 not only for frame structure but also for wall-frame structure.

The residual seismic capacity ratio R of about 150 reinforced concrete school buildings, including above mentioned buildings, are shown in **Figure 4** 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 4** are borders between damage levels proposed in the Damage Evaluation Guideline[1].

[slight] R□95 (%)
[minor] 80□$R < 95$ (%)
[moderate] 60□$R < 80$ (%)
[severe] $R < 60$ (%)
[collapse] $R \approx 0$

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 about 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.

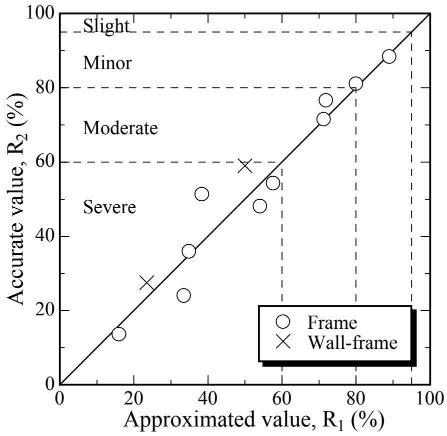

Fig. 3. Comparison R_1 and R_2

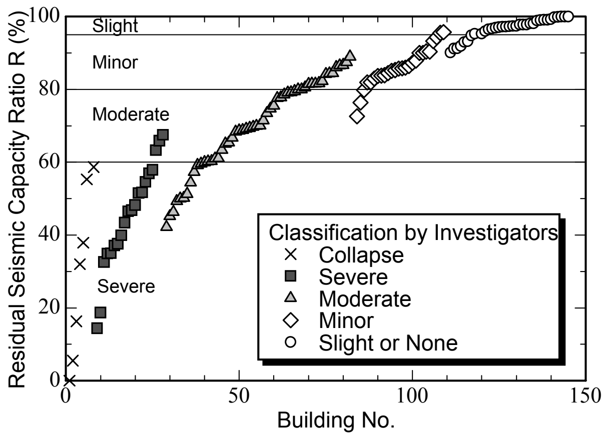

Fig. 4. Residual seismic capacity ratio R and damage level classification

Table 3. Categories of vertical members and normalized lateral strengths $\overline{C}$

	Column	Wall without boundary column	Column with side wall	Wall with boundary columns
Section	60cm, 60cm	15cm, 240cm	15cm, 240cm	15cm, 480cm
Shear stress τ	1 N/mm^2	1 N/mm^2	2 N/mm^2	3 N/mm^2
$\overline{C}$	1	1	2	6

4. Calibration of R-Index with Seismic Response of SDF Systems

4.1 Outline of Analysis

In the Damage Evaluation Guideline[1], the seismic capacity reduction factor η was defined based on absorbable energy in a structural member, which was evaluated from an idealized monotonic load-deflection curve as shown in **Figure 2** and accordingly the effect of cyclic behavior under seismic vibration was not taken into account. Therefore nonlinear seismic response analyses of a single-degree-of-freedom (SDF) system were carried out and validity of the residual seismic capacity ratio R in the Guideline was investigated through comparison of responses for damage and undamaged SDF systems.

Residual seismic capacity ratio based on seismic response, R_{dyn}, was defined by the ratio of the intensity of ultimate ground motion after damage to that before an earthquake (**Figure 5**). The ultimate ground motion was defined as a ground motion necessary to induce ultimate limit state in a building and the building would collapse.

$$R_{dyn} = \frac{A_{di}}{A_{d0}} \tag{9}$$

where, A_{d0}: intensity of ultimate ground motion before an earthquake (damage class 0)

A_{di}: intensity of ultimate ground motion after damage (damage class “i”)

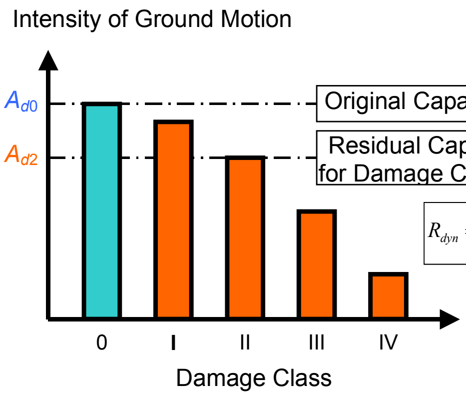

Fig. 5. Residual seismic capacity ratio based on seismic response R_{dyn}

4.2 Analytical Model

A new model was used to represent the hysteresis rule of the SDF systems; i.e., Takeda-pinching model was modified in order that shear resistance deterioration occurs after some plastic displacement (**Figure 6**). Yield resistance F_y was chosen to be 0.3 times the gravity load. Cracking resistance F_c was one-third the yielding resistance F_y. Initial stiffness K_e was designed so that the elastic vibration periods T were 0.1, 0.2, 0.3, 0.4, 0.5 and 0.6sec. The secant stiffness at the yielding point, K_y, and the post-yielding stiffness, K_u, were 30 and 1 percent of the initial stiffness, respectively.

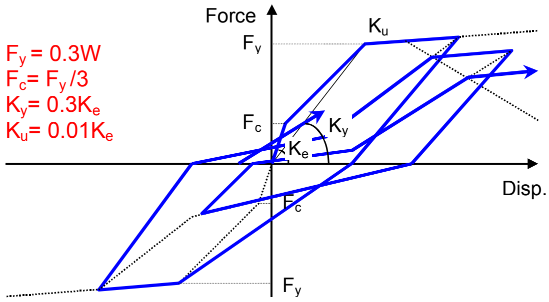

Figure 6: Hysteretic model

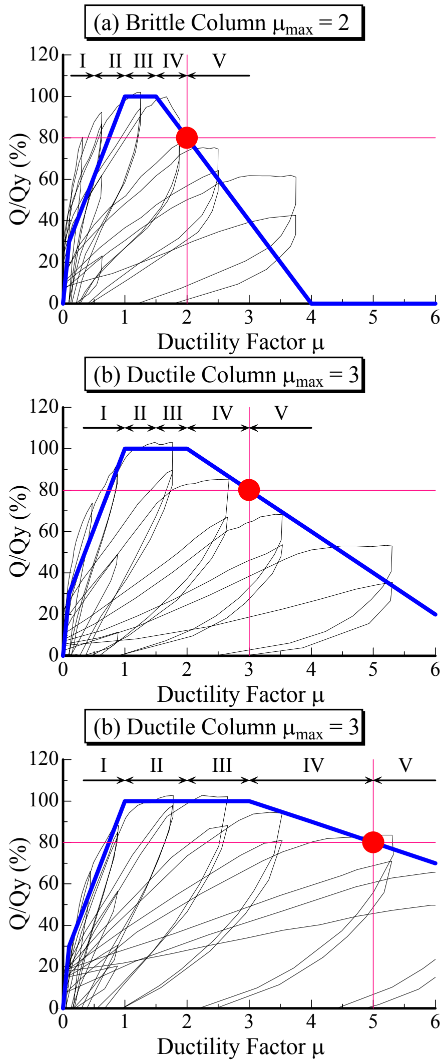

Fig. 7. Envelope curve and damage class

Three systems with different ultimate ductility μ_{max} were assumed as shown in **Figure 7** based on authors' column test results[6]. **Figure 7(a)** represents a brittle structure of which ultimate deflection is 2 times yielding deflection (μ_{max} =2). **Figure 7(b)** and **(c)** represent ductile structures with μ_{max} =3 and 5, respectively. The relationship between deflection and damage class was determined in accordance with authors' experimental results as shown in **Figure 7**. The yield resistance F_y started to deteriorate as shown in **Figure 7** after deflection reached to the region of the damage class IV.

4.3 Method of Analyses

Four observed earthquake accelograms were used: the NS component of the 1940 El Centro record (ELC), the NS component of the 1978 Tohoku University (TOH), the NS component of the 1995 JMA Kobe (KOB), and the N30W component of the 1995 Fukiai recode (FKI). Moreover, two simulated ground motion with same elastic response spectra and different time duration was used. Acceleration time history and acceleration response spectra are shown in **Figure 8** and **Figure 9**, respectively. The design acceleration spectrum in the Japanese seismic design provision was used as target spectrum and Jennings-type envelope curve was assumed in order to generate the waves. A simulate wave with short time duration is called Wave-S and with long time duration Wave-L. The equation of motion was solved numerically using Newmark-β method with β = 1/4.

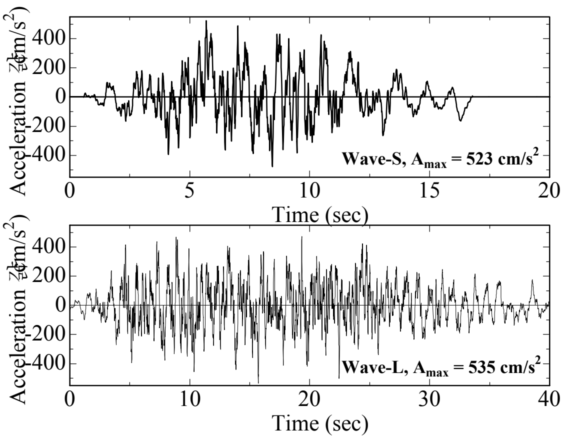

Fig. 8. Time history of simulated ground motions

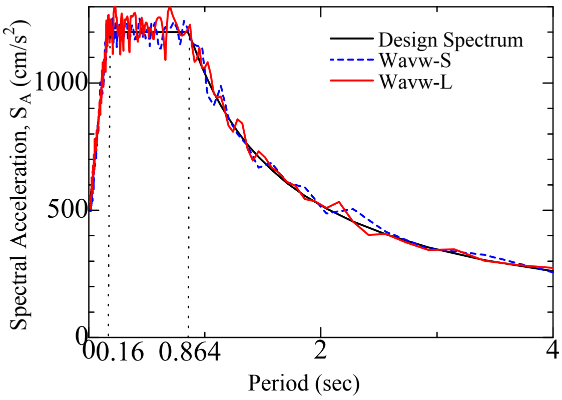

Fig. 9. Acceleration spectrum of simulated ground motions

4.4 Analytical Results

To investigate the relationship between maximum displacement response and intensity of the ultimate ground motion, parametric analyses were run under the six ground motions with different amplification factors. The results for a system with μ_{max} =3 and T =0.2 sec. under ELC and Wave-S are shown in **Figure 10**. Thick lines indicate results before damage. Ductility factor μ increases with increase in the amplification factor. The lower bound of amplification factor for damage class V is assumed to correspond to intensity of ground motion which induce failure of the structure, and is defined as the intensity of ultimate ground motion before damage, A_{d0}. Ultimate amplification factor for damaged structure, A_{di}, was estimated from analytical results for systems damaged by pre-input. For example, first ductility factor μ =2 (damage class III) was induced to a system using amplified ground motion, and then additional ground motion was inputted continuously to find the ultimate amplification factors for damage class III, A_{d3}, by parametric studies (**Figure 11**). 0 cm/s^2 acceleration was inputted for 5 seconds between the pre-inout and second ground motion in order to reduce vibration due to the pre-input.

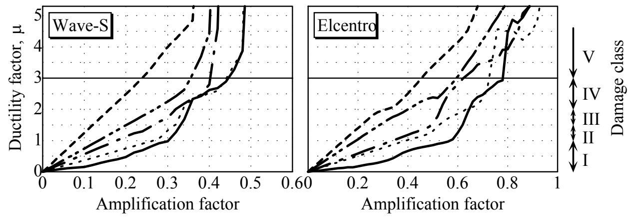

Fig. 10. Amplification factor vs. maximum ductility factor

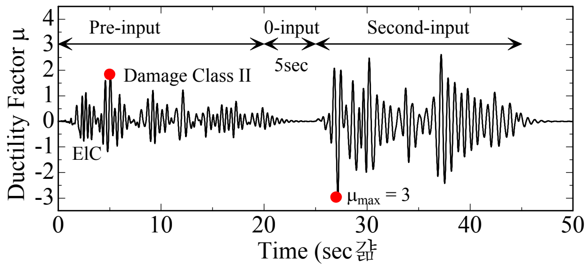

Fig 11. Response time history for a system damaged by pre-input

The residual capacity ratio index R_{dyn}, obtained from analyses of systems with different initial period T under the six ground motions, was shown in **Figure 12**. The reduction factor η in the Guideline (**Table 2**), which is correspond to the R value for a SDF system, was also shown in the figure. As can be seen from the figure, R_{dyn} values based on analyses are ranging rather widely and R-index in the Guideline generally corresponds to their lower bound, although some of analytical results R_{dyn}–index for damage class I are lower than values in the Guideline. Therefore, The Guideline may give conservative estimation of the intensity of ultimate ground motion for a RC building structure damaged due to earthquake.

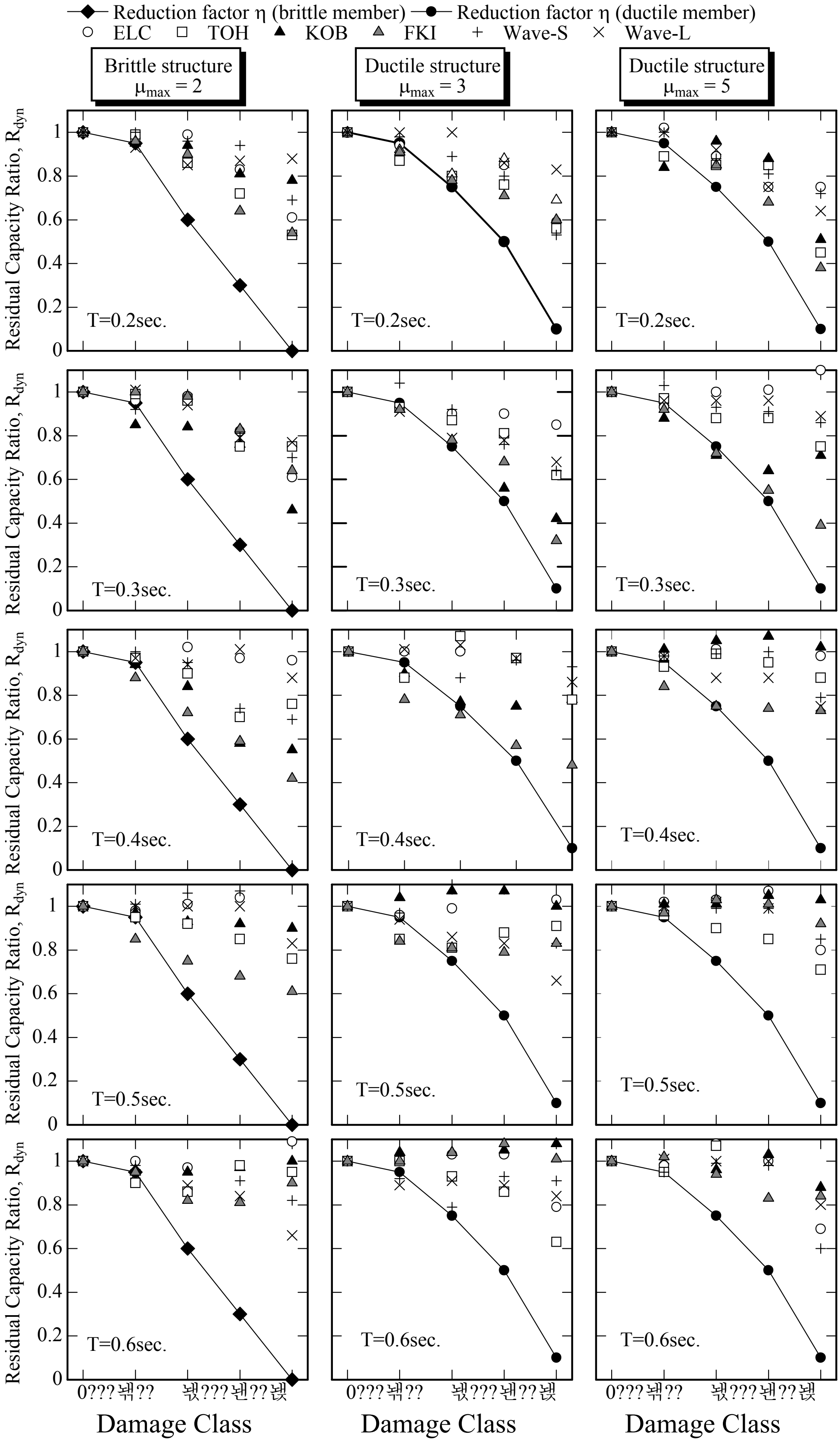

Fig. 12. Comparison of residual capacity ratio R_{dyn} with values in the Guideline

5. 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. Moreover, the validity of the R-index was examined through calibration with seismic response analyses of SDF systems. As discussed herein, the intensity of ultimate ground motion for a damaged RC building structure can be evaluated conservatively based on the R-index in the Guideline. Much work is, however, necessary to improve the accuracy of the post-earthquake damage evaluation, because available data related to residual seismic capacity are still few.

Appendix

-Basic Concept of Japanese Standard for Seismic Evaluation[2)]-

The Standard consists of three different level procedures; first, second and third level procedures. The first level procedure is 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, ultimate lateral load carrying capacity of vertical members or frames are evaluated using material and sectional properties together with reinforcing details based on the 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. (7)

$$Is = E_0 \times S_D \times T \tag{7}$$

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 at the ultimate limit state due to lateral force, i.e., $E_0 = \phi \times C \times F$.

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

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 failed in shear. F is dependent on the failure mode of structural member and their sectional properties such as bar arrangement, member proportion, shear-to-flexural-strength ratio etc. . F is assumed to vary from 1.27 to 3.2 for ductile column, 1.0 for brittle column and 0.8 for extremely brittle short column.

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 straight mode 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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