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POST-EARTHQUAKE CAPACITY EVALUATION OF REINFORCED CONCRETE BUILDINGS BASED ON SEISMIC RESPONSE ANALYSIS

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SUMMARY

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 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 and seismic response analyses of SDF systems. 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.

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 (JBPDA 2001a) originally developed in 1991 was revised 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

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of Existing RC Buildings (JBPDA 2001b), and their validity through calibration with observed damage due to the 1995 Hyogoken-Nambu (Kobe) earthquake and seismic response analyses of SDF systems.

OUTLINE OF DAMAGE EVALUATION GUIDELINE

First, structural damage is surveyed and damage of structural members is classified in the most severely damaged story. The residual seismic capacity ratio index R is then calculated and damage rating of the building structure, i.e., [slight], [minor], [moderate], [severe], and [collapse] is made. Necessary actions are finally determined comparing the intensity of the ground motion at the building site, building damage rating, and required seismic capacity against a future earthquake.

Damage Classification of Structural Members

Damage of columns and shear walls is classified based on the damage definition shown in **Table 1**. As was reported in the past earthquake in Japan, typical damage is generally found in vertical members, and the Guideline is essentially designed to identify and classify damage in columns and walls rather than in beams. Columns and walls are classified in one of five categories I through V as defined in **Table 1**. **Figure 1** schematically illustrates the load carrying capacity, load-deflection curve, and member damage class.

Table 1: Damage Class For RC Structural Members

Damage Class	Observed Damage on Structural Members
I	Visible narrow cracks are found (Crack width is less than 0.2 mm)
II	Visible clear cracks on concrete surface (Crack width is about 0.2 - 1 mm)
III	Local crush of covering concrete Remarkable wide cracks (Crack width is about 1 - 2 mm)
IV	Remarkable crush of covering concrete with exposed reinforcing bars Spalling off of covering concrete (Crack width is more than 2 mm)
V	Buckling of reinforcing bars Cracks in core concrete Visible vertical and /or lateral deformation in columns and/or walls Visible settlement and/or inclination of the building

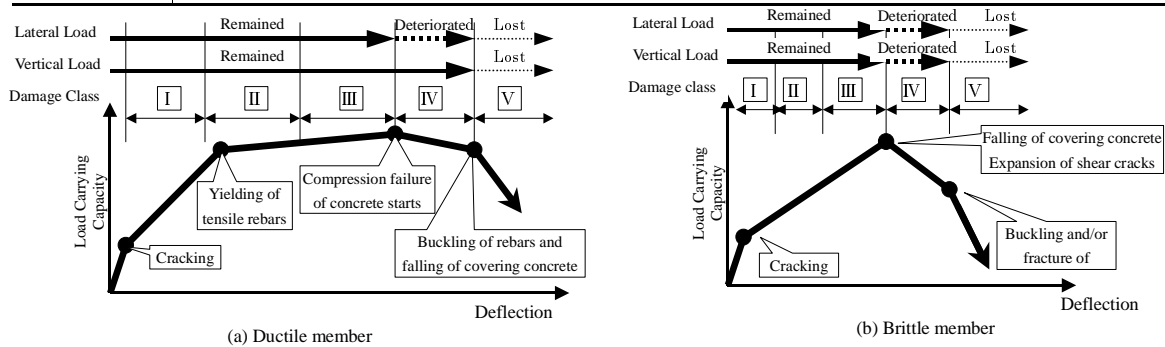


Figure 1: Lateral Load – Deflection Relationships and Damage Class

Residual Seismic Capacity Ratio Index R

A residual seismic capacity index R, which corresponds to building damage, is defined by as the ratio of seismic capacity after damage to that before an earthquake (i.e., the ratio of the residual capacity to the original capacity).

$$R = \frac{D_{Is}}{Is} \times 100 \quad (1)$$

where, Is: seismic capacity index of structure before earthquake damage

D_{Is} : seismic capacity index of structure considering deteriorated member strength

Is-index can be calculated based on the Standard for Seismic Evaluation (JBPDA, 2001b), which is most widely applied to evaluate seismic capacity of existing buildings in Japan. The basic concept of the Standard to calculate Is-index appears in APPENDIX. The Guideline recommends to calculate D_{Is} -index for a damaged building in the analogous way for pre-event buildings, considering seismic capacity reduction factor η defined as the ratio of the absorbable hysteretic energy after earthquake to the original absorbable energy of a structural member as illustrated in Fig. 2. Table 2 shows the values of the reduction factor η in the Guideline.

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

where, E_d : dissipated energy, E_r : residual absorbable energy,

E_t : entire absorbable energy ($E_t = E_d + E_r$).

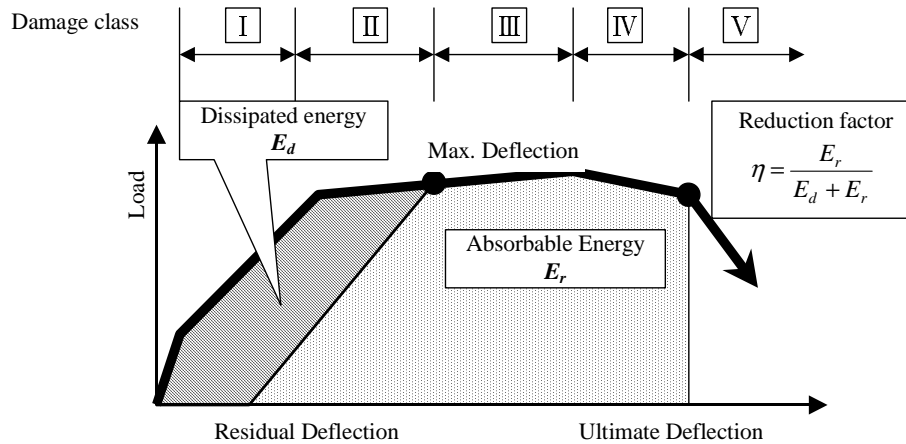


Figure 2: Definition of Seismic Capacity Reduction Factor η

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	

The values in **Table 2** were determined based on authors' several experimental results. Comparison between the reduction factor of the Guideline and experiments are shown in **Fig. 3**. The results four ductile beam specimens (Maeda and Bun-no 2001) and three column specimens (Jung and Maeda 2002) were shown in the figure. The η values in the Guideline generally correspond to the lower bound of the test results. It is noted, however, that available data related to residual capacity is still few, especially for brittle column and wall members, and more efforts should be directed toward clarifying residual performance of damaged members.

D/S -index for a damaged building can be calculated from residual member strength reduced by the reduction factor η and the original member ductility, and then residual seismic capacity index R is evaluated.

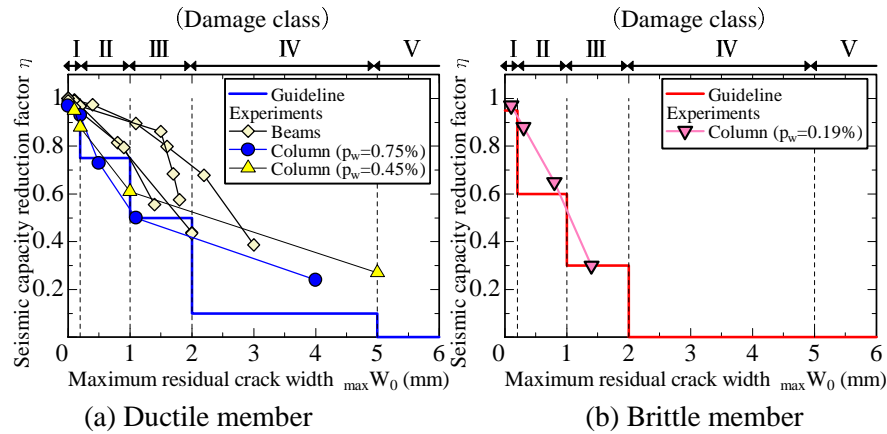


Figure 3: Comparison of Seismic Capacity Reduction Factor η and Experimental results

Damage Rating of Building

The residual seismic capacity ratio index R can be considered to represent damage sustained by a building. For example, it may represent no damage when $R = 100\%$ (100% capacity is preserved), more serious damage with decrease in R , and total collapse when $R = 0\%$ (no residual capacity). To identify the criteria for damage rating, R values of 145 RC school buildings that suffered 1995 Kobe Earthquake are compared with observed damage and judgments by experts as shown in **Fig. 4**. The Guideline defines the damage rating criteria shown below.

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

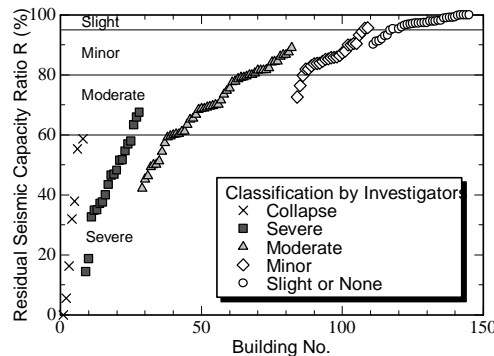


Figure 4: Residual Seismic Capacity Ratio R vs. Observed Damage

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.

CALIBRATION OF R INDEX WITH SEISMIC RESPONSE OF SDF SYSTEMS

Outline of Analysis

In the Damage Assessment Guideline, 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 **Fig. 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 (**Fig. 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.

$$R_{dyn} = \frac{A_{di}}{A_{d0}} \quad (3)$$

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”)

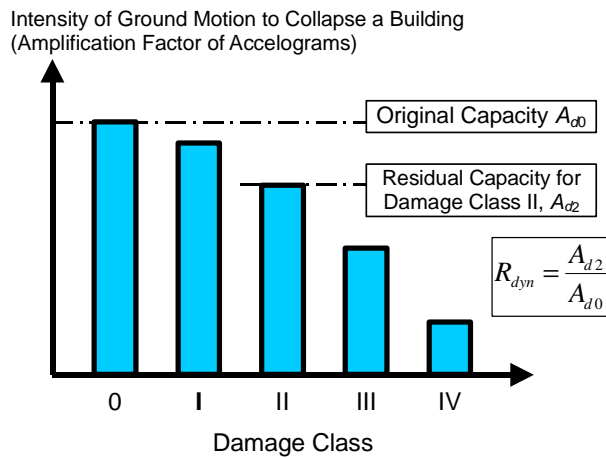


Figure 5: Residual Seismic Capacity Ratio based on Seismic Response R_{dyn}

Analytical Model

Three models were used to represent the hysteresis rules of the SDF systems; i.e., Takeda model, Takeda-pinching model and resistance-deteriorating model (**Fig. 6.a, b, and c**). Force-deflection properties were chosen common among the models. 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 for a series of models was designed so that the elastic vibration periods T were 0.2, 0.3, 0.4, 0.5, 0.6, 0.8 and 1.0sec. 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.

Three systems with different ultimate ductility μ_{max} were assumed as shown in **Fig. 7** based on authors' column test results (Jung and Maeda 2002). **Figure 7.a** represents a brittle structure of which ultimate

deflection is 2 times yielding deflection ($\mu_{max} = 2$). **Figure 7.b and c** represent ductile structures with $\mu_{max} = 3$ and 5, respectively. The relationship between deflection and damage class was determined in accordance with authors' experimental results as shown in **Fig. 7**. In case of resistance-deteriorating model, the yield resistance F_y was deteriorated as shown in **Fig. 7** after deflection reached to the region of the damage class IV.

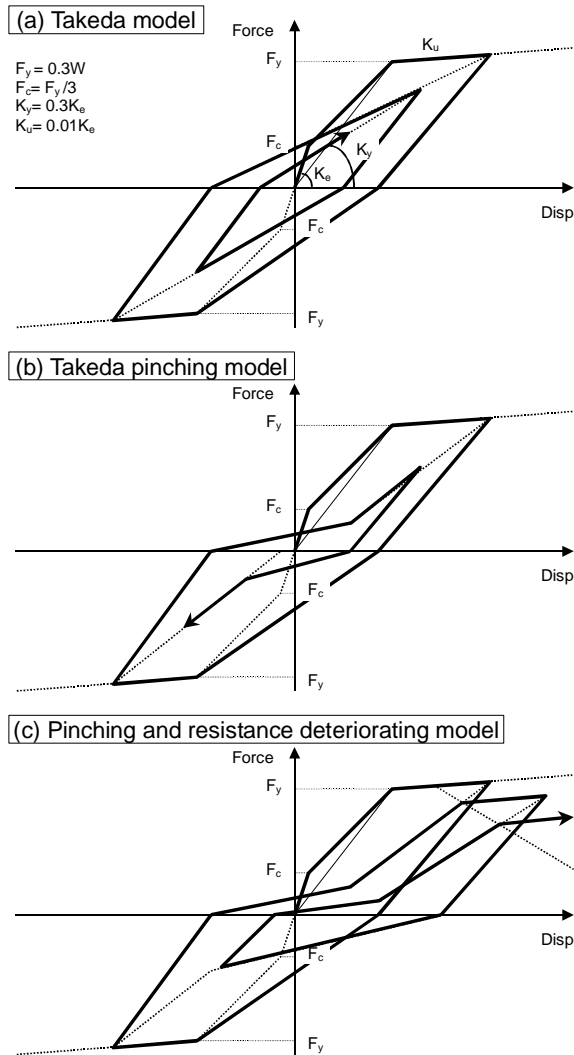


Figure 6: Hysteretic Models

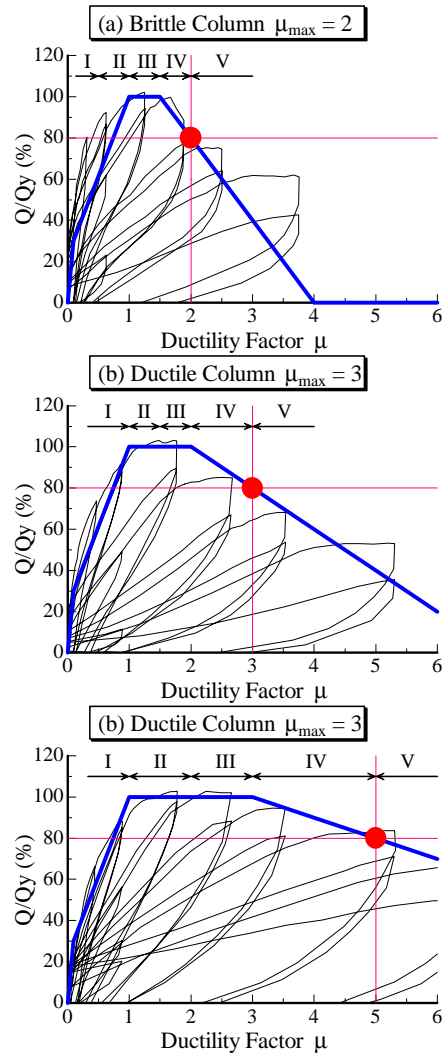


Figure 7: Envelope Curve and Damage Class

Method of Analyses

Four observed earthquake accelerograms 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 Fukiui record (FKI). Moreover, ten simulated ground motions with same elastic response spectra were used for analysis. Five of them, which are named Wave-S1 to S5 have short time duration of 20sec. and others, which are named Wave-L1 to L5, have long time duration of 120sec. The example of acceleration time history and acceleration response spectra are shown in **Fig. 8** and **Fig. 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. The equation of motion was solved numerically using Newmark- β method with $\beta = 1/4$.

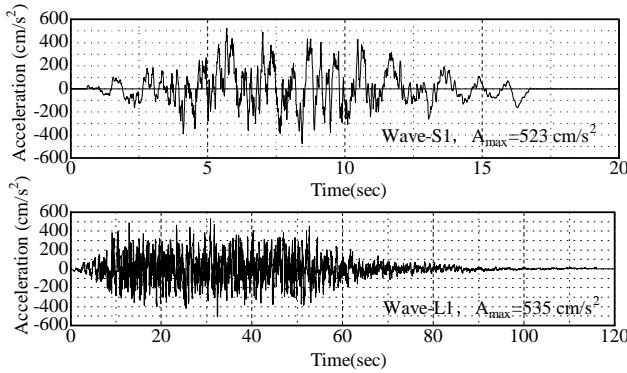


Figure 8: Time History of Simulated Ground Motions

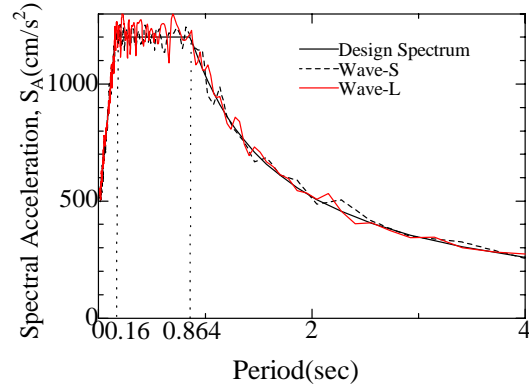


Figure 9: Acceleration Spectrum of Simulated Ground Motions

Analytical Results

To investigate the relationship between maximum displacement response and intensity of ground motion, parametric analyses were run under 14 ground motions with different amplification factors. The results for a system with $\mu_{max} = 3$ and $T = 0.2$ sec. under ELC and Wave-S are shown in **Fig. 10**. Thick lines indicate results before damage. Ductility factor μ increases with increase in the amplification factor. The upper bound of amplification factor for damage class IV 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 $\mu = 2$ (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 (**Fig. 11**). 0 cm/s^2 acceleration was inputted for 5 seconds between the first and second ground motion in order to reduce vibration due to the first input.

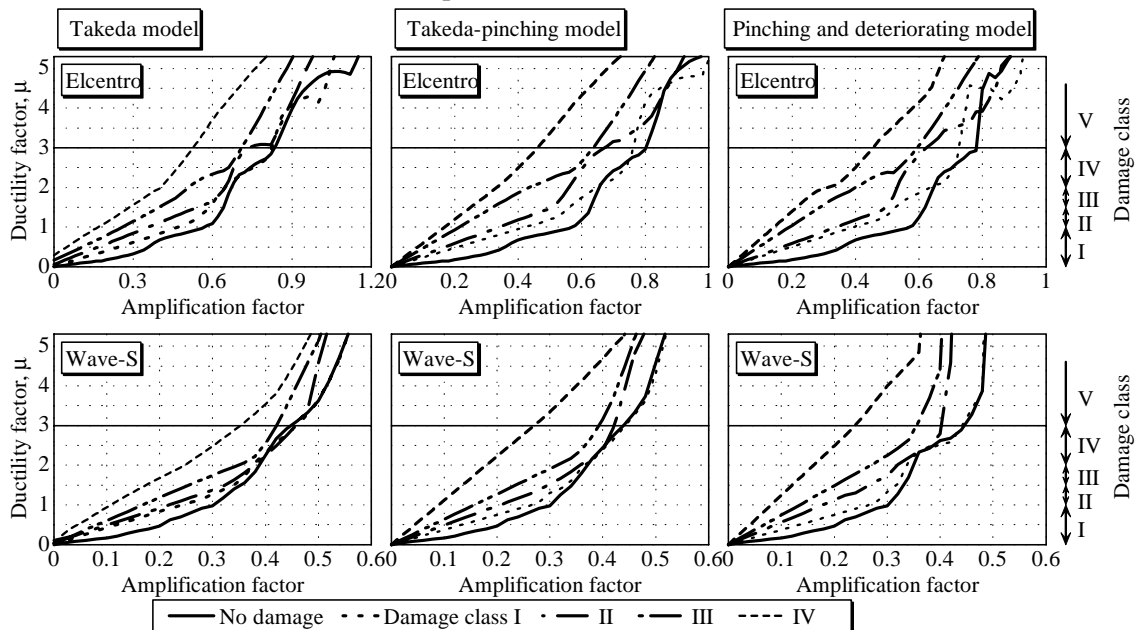


Figure 10: Amplification Factor vs. Max. Ductility Factor

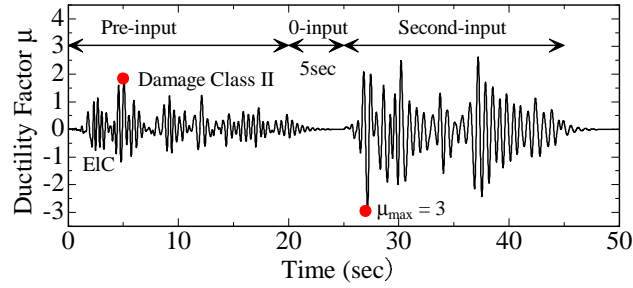


Figure 11: Response Time History for a System Damaged by Pre-input

Effects of the three hysteretic models on the residual seismic capacity ratio index R_{dyn} are compared in **Fig. 12**. It can be seen from the figures that R_{dyn} -index is generally lowest considering both pinching and lateral resistance deterioration (Pinching and resistance- deteriorating model). Although the results only for $T=0.2$ sec. under TOH and Wave-S were shown in the figures, the general tendency was almost same for the other period T and ground motions. Therefore, in the following discussion, the pinching and resistance-deteriorating model was used.

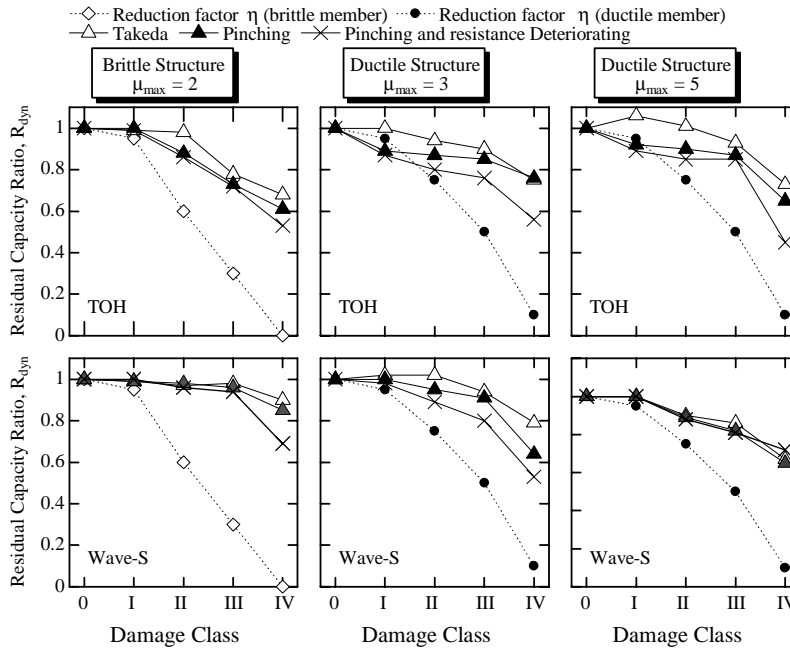


Figure 12: Comparison of R_{dyn} Indices between Three Hysteretic Models

The residual capacity ratio index R_{dyn} , obtained from analyses of systems with different initial period T for six ground motions; four observed earthquake accelerograms, Wave-S1 and Wave-L1, was shown in **Fig. 13**. **Fig. 14** shows the comparisons between the mean value of R_{dyn} index for the fourteen ground motions, together with the reduction factor η proposed in the Guideline for damage class III and IV (Table 2) with respect to the initial T . The η values in the Guideline were determined as one value without considering the change in the period.

As can be seen from **Fig. 13**, the residual capacity ratio index 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. Most of mean values in Fig.14 are also higher than the value in the Guideline even though there exists lower value in the

region of short period. Therefore, The Guideline may give conservative estimation of the intensity of ultimate ground motion for a RC building structure damaged due to earthquake.

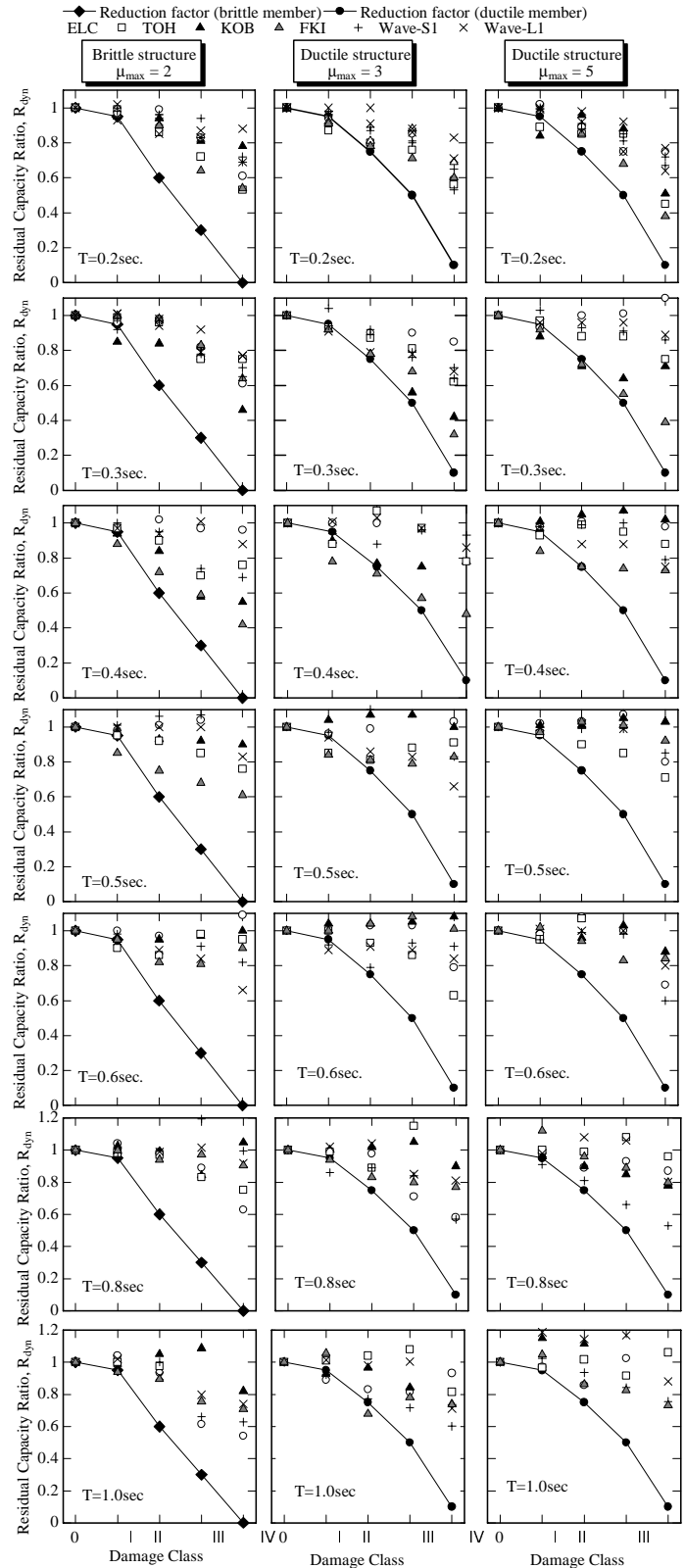


Figure 13:

Residual Capacity Ratio R_{dyn} with values in the Guideline

Comparison of

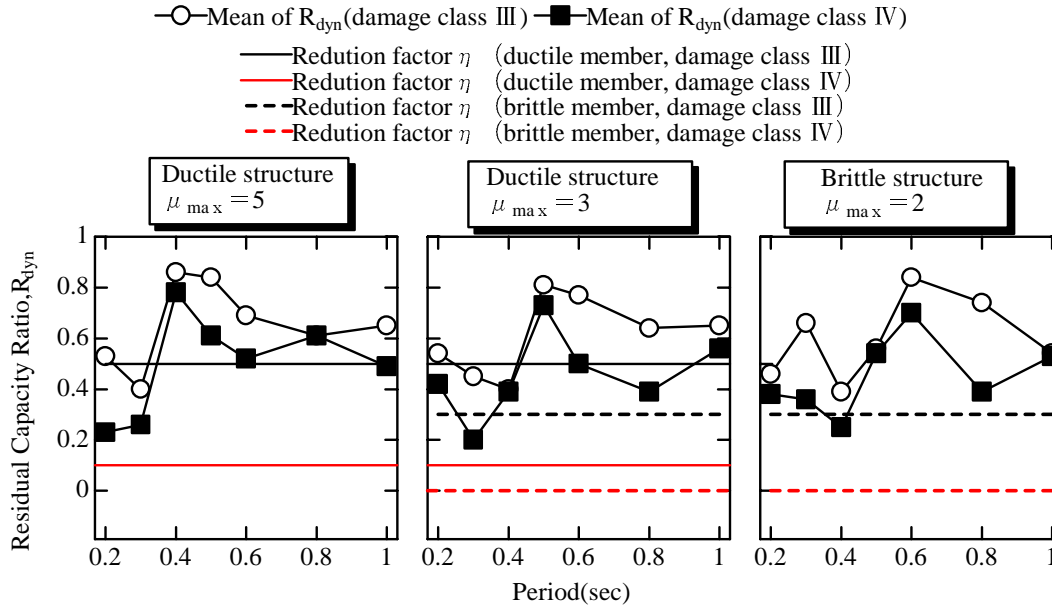


Figure 14: Mean of Residual Capacity Ratio R_{dyn}

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. 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.

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APPENDIX

BASIC CONCEPT OF JAPANESE STANDARD FOR SEIMIC PERFORMANCE EVALUATION

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 I_s -Index for each story and each direction, as shown in Eq. (7)

$$I_s = E_0 \times S_D \times T \quad (7)$$

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 to 1.0

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.