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RESIDUAL SEISMIC CAPACITY EVALUATION FOR REINFORCED CONCRETE BUILDINGS CONSIDERING EFFECTS OF CHARACTERISTICS OF STRUCTURE AND EARTHQUAKE RESPONSE SPECTRUM

構造特性と地震動応答スペクトル形状を考慮した被災 RC 造建物の残存耐震性能評価

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Abstract:

構造特性と地震動応答スペクトル形状が応答スペクトル法における被災 RC 造建物の残存耐震性能に及ぼす影響を検討した。最初に，地震動応答スペクトルの周期と傾きをパラメータとした地震動モデルを作成し，建物の一質点系モデルにおいて地震動応答スペクトル形状が残存耐震性能に及ぼす影響を評価した。次に，建物の強度と塑性率をパラメータとした建物モデルを作成し，構造特性が建物の残存耐震性能に及ぼす影響を評価した。最後に，以上の検討結果に基づく，耐震設計法と復旧の方案を提案した。

Keywords ***: residual seismic capacity ratio, earthquake response spectrum, structural characteristic, strength・deformation・damping***
耐震性能残存率，応答スペクトル，構造特性，強度・変形・減衰

1. Introduction

To restore an earthquake damaged community as quickly as possible, a well-prepared reconstruction plan is 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 in the case of aftershocks. So some researchers in Japan have proposed some methods to evaluate the residual seismic capacity of reinforced concrete structures based on residual seismic capacity ratio *R-index*, by considering failure mechanism. Residual seismic capacity ratio *R-index*, is evaluated by considering collapse mechanism and seismic capacity reduction factor η. Fig. 1 shows a conceptual diagram of the lateral force-displacement curve and a definition of the η factors. The η factor is defined as the ratio of residual energy dissipation capacity, E_r, to original energy dissipation capacity, $E_d + E_r$, and can be calculated by Eq. (1). However, definition of η doesn't consider the earthquake response and although there are degradations of strength, deformation and energy dissipation for damaged member, η factor is effected by them comprehensively. Thus η factor cannot be adapted for evaluation of seismic capacity by equivalent linearization method, time history response analysis and so on.

$$\eta = \frac{E_r}{E_r + E_d} \tag{1}$$

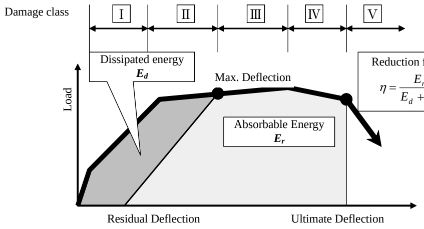

Fig.1 Seismic capacity reduction factor

Where, E_d: dissipated energy. E_r: residual energy dissipation capacity

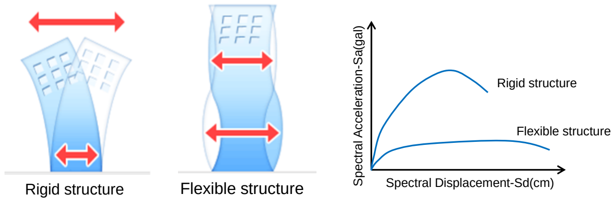

Fig.2 Flexible vs. rigid structure

On the other hand, since the Great Kanto earthquake in the year of 1923, the argument of flexible structure vs. Rigid structure has last for many years (see Fig.2). The purpose of this argument is to separate the periods of earthquake and building. The Japanese Standard for Seismic Evaluation of Existing Reinforced Concrete Buildings (JBPDA) [1] proposed evaluation method of seismic capacity by using indexes of strength and ductility. However, even when both flexible structure and rigid structure are evaluated with same seismic capacity, they were still damaged in different levels in past earthquake. But the current evaluation method can't evaluate the effect of structure characteristics on residual seismic capacity.

Based on the above background, this thesis investigated residual seismic capacity of damaged RC buildings using Capacity Spectrum Method and evaluated the effects of characteristics of structure and earthquake response spectrum on residual seismic capacity. Furthermore, the principles of selecting and scaling a target spectrum, seismic design and retrofiting of existing buildings were proposed.

2. Residual Seismic Capacity Evaluation using Capacity Spectrum Method

2.1 Introduction of Capacity Spectrum Method

The Capacity Spectrum Method (CSM), a performance-based seismic analysis technique, can be used for a variety of purposes. CSM method is used in Acceleration-Displacement Response Spectrum format (ADRS) (see Fig.3). The procedure compares the capacity of the structure (in the form a pushover curve) with the demands on the structure (in the form of response spectra). The graphical intersection of the two curves approximates the response of the structure. In order to account for non-linear inelastic behavior of the structural system, effective viscous damping values are applied to linear-elastic response spectra similar to inelastic response spectra. Effect viscous damping value F_h is calculated by Eq. (2).

$$F_h = 1.5/1 + 10h \tag{2}$$

h: damping factor

$$h = 0.05 + 0.25\left(1 - 1/\sqrt{\mu}\right) \tag{3}$$

μ: ductility factor

2.2 Seismic Capacity Index

In Japanese Guidelines for performance evaluation of earthquake resistant reinforced concrete buildings [2], Seismic Capacity Index *α* is defined as the ratio of capacity spectrum strength (S_{a1}) and demand spectrum strength (S_{a2}) as Eq. (4), shown in Fig.4.

$$\alpha = \frac{S_{a1}}{S_{a2}} \tag{4}$$

2.2 Residual Seismic Capacity Evaluation Method

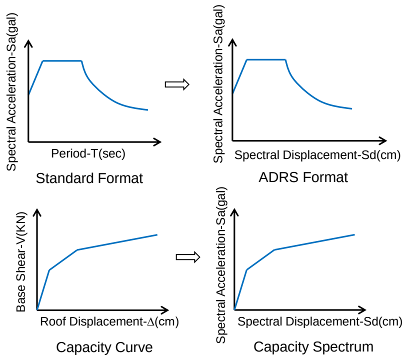

Fig.3 Capacity Spectrum Method

In this thesis, residual seismic capacity index *R-index* is evaluated by the ratio between seismic capacity index of damaged building (α') and seismic capacity index of building with no damage(α), shown in Fig.5. The green line is capacity curve after building was damaged, and seismic capacity index of damaged buildings can be calculated by Eq. (5). So *R-index* can be evaluated by Eq. (6).

$$\alpha' = \frac{{}_D S_{a1}}{{}_D S_{a2}} \tag{5}$$

$$R = \frac{\alpha'}{\alpha} \tag{6}$$

3. Effect of earthquake response spectrum Characteristic on Residual Seismic Capacity

3.1 Earthquake response spctrum characteristic model

In the study of GENG Shuwei [3], shape of earthquake response spectrum with period band longer than 0.864s is studied which is based on the ground motion records of west American and Taiwan Ji-Ji obtained by digital earthquake observing system. Based on these records with consideration of 5% damping, period within 6s, earthquake response spectrum S_a-S_d curve have been formulated into six types of F1~F6. S_a-S_d curve of F3 shown in Fig.6 is closest to the real response. The design earthquake response spectrum in Japanese code [2] is shown in Eq. (8) and Fig.7. Based on Eq. (7), (8), S_a-S_d curve is set into three stages of rising line, maximum strength and descent line which is shown in Fig.8. Formula of rising line and maximum strength is same with Eq. (8) of period $T \leq 0.16$, $0.16 < T \leq 0.864$. Based on Eq. (7), formula of descent line is set as Eq. (9).

Slope characteristic model (see Fig.9) and Period characteristic model (see Fig.10) were set.

$$\begin{aligned}
F3 &= a + \left(S_{a\max} - a\right)\left(\frac{T - 0.04}{T_1 - 0.04}\right)\left(0.04 \leq T < T_1\right) \\
F3 &= S_{a\max}\left(T_1 \leq T < T_2\right) \\
F3 &= S_{a\max}\left(\frac{T_2}{T}\right)^b \left(T_2 \leq T < 6.0\right)
\end{aligned} \tag{7}$$

$$\begin{aligned}
S_a &= 480 + 4500T(T \leq 0.16) \\
S_a &= 1200(0.16 < T \leq 0.864) \\
S_a &= 1036.8/T(0.864 < T)
\end{aligned} \tag{8}$$

$$S_a = S_{a\max} \cdot (\beta_T / T)^{\gamma} \tag{9}$$

$$T = 2\pi\sqrt{\frac{S_d}{S_a}} \tag{10}$$

T : ultimate period
β_T : descent point period
$S_{a\max}$: maximum strength value
γ : slope influence factor

3.2 Building Model

Analyzing building models is shown in Fig.11. Basis share coefficient is Q_y/W =0.3; maximum acceleration is 300gal; cracking yielding strength is one-third of maximum strength; yielding deformation angle is 0.5%; cracking deformation angle is 0.05%; ultimate ductility factor is 4.

3.3 Analyzing Result

Based on Capacity Spectrum Method, considering performance reduction ratio of strength (R_s), deformation (R_d) and damping (R_h), effect of slope characteristic is shown in Fig.12. Effect of period characteristic is shown in Fig.13. The performance reduction ratios are shown in Table 1, which were concluded in Yoshihiro ITO's research [4]. At damage level I, II, III, R-index becomes larger while slope factor γ becomes smaller; at damage level IV, R-index becomes smaller while γ becomes smaller; when decent point period becomes longer, it affect R-index: at damage level I, II, III, R-index becomes larger, at damage level IV, R-index becomes smaller.

4. Effect of Structure Characteristic on Residual Seismic Capacity

4.1 Damage Case of Two Buildings

Based on Hamood ALWASHALI's research [5], a three storied RC building of an elementary school in Sendai city constructed in 1974 is studied (see Fig.14), which considered the relation between seismic capacity index I_s and damage level of the damaged RC buildings. Results are shown in Table 2. Building (W) and (E), with similar seismic capacity, are damaged at different level after earthquake. Building (W) with higher strength was damaged slightly, and building (E) with higher ductility was damaged moderately.

4.2 Building Model

Analyzing building models are set as Single-Degree-of-Freedom models.

Strength Models take strength as parameter: Basis share coefficient is Q_y/W =0.3; maximum acceleration is 300gal, 400gal, 500gal; cracking yielding strength is one-third of maximum strength

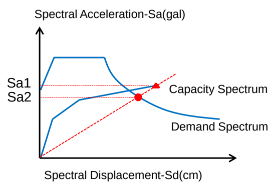

Fig.4 Seismic Capacity Index

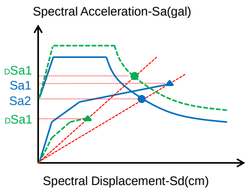

Fig.5 Residual Seismic Capacity

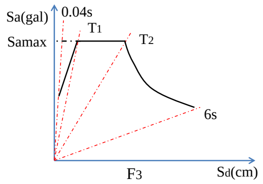

Fig.6 Spectrum of F3

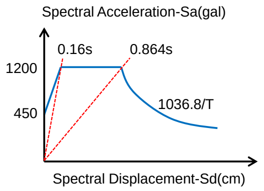

Fig.7 Standard earthquake response spectrum

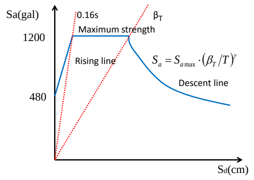

Fig.8 Earthquake response spectrum model

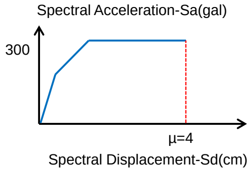

Fig.11 Building model

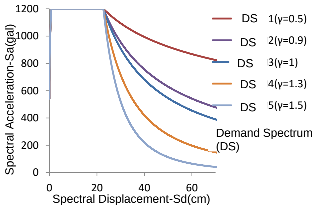

Fig.9 Slope factor model

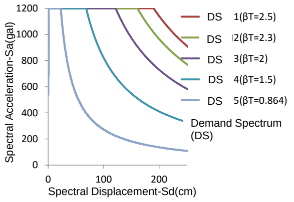

Fig.10 Descent point period model

Table 1

Bending failure

Damage level	η	η_s	η_d	η_h
I (slight)	0.95	1.00	1.00	0.95
II (minor)	0.75	1.00	0.95	0.80
III (moderate)	0.5	1.00	0.85	0.75
IV (severe)	0.1	0.60	0.75	0.70

Shear failure

Damage level	η	η_s	η_d	η_h
I (slight)	0.95	1.00	1.00	0.90
II (minor)	0.6	1.00	0.85	0.70
III (moderate)	0.3	1.00	0.70	0.60
IV (severe)	0	0.40	0.50	0.50

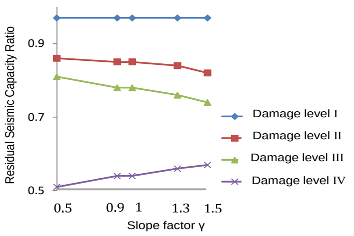

Fig.12 Effect of slope factor

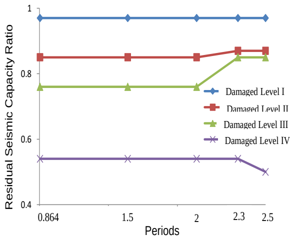

Fig.13 Effect of descent point period

Table 2

Building	C	F	S_D	T	I_s	Damage Level
(W)	0.88	1	0.88	0.98	0.75	slight

Building	C	F	S_D	T	I_s	Damage Level
(E)	0.5	1.75	0.93	0.98	0.8	moderate

Fig.14 Three storied RC building

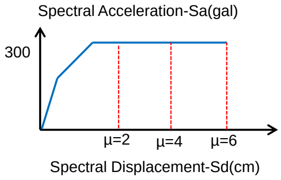

Fig.15 Ductility factor model

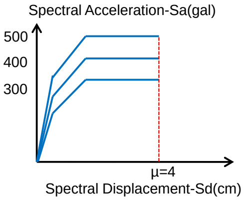

Fig.16 Strength model

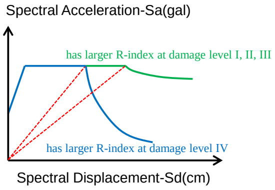

Fig.18 Effect of earthquake response spectrum

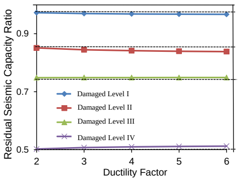

Fig.17 Effect of ductility factor

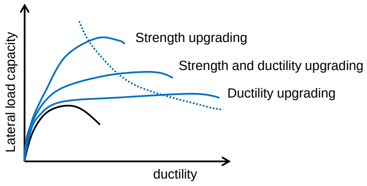

Fig.19 Improvement of seismic capacity

yielding deformation angle is 0.5%; cracking deformation angle is 0.05%; ultimate ductility factor is 4(see Fig.15). Ductility factor Models take ductility factor as parameter: Basis share coefficient is Q_y/W =0.3; maximum acceleration is 300gal, cracking yielding strength is one-third of maximum strength; yielding deformation angle is 0.5%; cracking deformation angle is 0.05%; ultimate ductility factor is varied with 2, 4, 6. (see Fig.16)

4.3 Analyzing Method

Based on standard damand spectrum in Japanese Guidelines [2] by considering the amplifying effect of the second type site which is often used, shown as Eq. (10). Based on (AIJ) Qianqian YAO, Linfei HAO's research [6] by using Capacity Spectrum Method, calculation of *R-index* is formulated by Eq. (11). The result is shown in Fig.17. With regard to SDF model, performance reduction ratios of trength, deformation and damping are supposed to equal with reduction ratios of structural elements shown inTable1.

$$R=\sqrt{R_s}\cdot\frac{\sqrt{R_d}+3R_h\sqrt{R_d}-2.5R_h\Big/\sqrt{\mu_0}}{4-2.5\Big/\sqrt{\mu_0}} \tag{11}$$

R_s: reduction ratio of strength

R_d: reduction ratio of deformation

R_h: reduction ratio of damping

μ_0: ultimate ductility of building

4.3 Analyzing Result

From Fig.17, Even though the tendency is not obvious, we still can see that: 1) At damage level I, II, *R-index* becomes smaller with larger design ultimate ductility factor, 2) At damage level III, IV, *R-index* becomes larger with larger design ultimate ductility factor.

5. Conclusion

1) When buildings are slightly, minor, and moderately damaged, buildings have high residual seismic capacity using earthquake response spectrum with small slope and large descent point period; severely damaged, buildings have higher residual seismic capacity using earthquake response spectrum with large slope and small descent point period (see Fig.18). Based on the above conclusion, we can select earthquake response spectrum with small slope and large descent point period to resist small earthquake, and spectrum with large slope and small descent point period to resist large earthquake.

2) Effect of strength can't be evaluated by CSM. When building is slightly and minor damaged, building with small ductility is evaluated with higher *R-index* than building with large ductility; moderate and severe damaged, building with large ductility is evaluated with higher *R-index* than building with small ductility. There are three methods to improve seismic capacity: strength upgrading, ductility upgrading, strength and ductility upgrading (see Fig.19), and usually we choose to upgrade strength to improve seismic capacity. Based on the effect of ductility, we can design or retrofit building with high strength to resist small earthquake, and building with high ductility to resist large earthquake.

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