REPARABILITY DEMAND SPECTRUM OF R/C BUILDINGS DUE TO THE LIFECYCLE SEISMIC LOSS ESTIMATION

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SUMMARY

The performance-based seismic design procedure has aimed to define and estimate the multiple type of building performance using quantified parameters. Especially the performance of reparability relates to the quantified parameter such as seismic economic loss, and the well-established method for assessing and estimating the quantified parameter is needed at first. Moreover it should be also important that the engineer using the procedure is capable of developing preliminary designs that have the desired performance. The performance-based seismic design in the next generation therefore should address the development of design guidance that assists the engineer to design the desired performance including reparability. Then, in this research, the idea of the reparability demand spectrum for R/C buildings is proposed. The reparability demand spectrum is visualized from the expected running cost to repair a building structure damaged by earthquakes through its lifetime, where the equivalent repairing running cost is converted to the relation of spectral base shear coefficients and spectral yield displacements by means of the single-degree of freedom nonlinear time history analysis. Finally the availability of the proposed method is further investigated its practical use for the preliminary seismic design in the future.

1. INTRODUCTION

The present seismic design of building structures in Japan reflects the idea of performance-based design. In general, the seismic performance of buildings can be distinguished into three major states. There are called as "immediate occupancy (IO)", "life safety (LS)" and "collapse prevention (CP)" respectively. As long as only these performances are considered in the seismic design, the performance-based seismic design procedure might be established easily, because these performance limitations are estimated by physical or engineered parameters such as strength or displacement. On the other hand, the performance-based seismic design is aim to be an owner-friendly expression as building owners are especially interested in their building assets. To satisfy the building owner, the "reparability" performance could be important. The reparability performance in the performance-based seismic design should be represented by the expected economic loss of the building after earthquakes. Then many recent approaches to the performance-based design are aim to logically evaluate the seismic economic loss. The Pacific Earthquake Engineering Research Center (PEER) has proposed the underlying probabilistic framework of the seismic loss estimation [Moehle and Deierlein 2004]. According to this framework, the results of seismic economic loss could be expected and evaluated. Although it is very important for an owner-friendly expression to develop the procedure of seismic loss estimation, it may not be enough to preliminarily design a building structure. In fact, the ATC-58 project suggests that the future phase of

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its project will focus on the development of design guidance to assist the engineer in efficiently identifying designs providing the desired performance [Hamburger et al. 2004].

In this paper, a study on estimating the EARC is demonstrated. And the concept of "seismic reparability demand spectrum" due to the EARC is proposed. It is investigated whether the "seismic reparability demand spectrum" can indicate the physical or engineered parameters of a building as useful structural demand spectrum for the preliminary seismic design.

2. PROCEDURE TO EVALUATE THE EXPECTED ANNUAL REPAIRING COST

To evaluate the lifecycle seismic economic loss of a building constructed in high seismic zone, the damage due to medium to major earthquakes is not negligible, because it is probable that the building will suffer many earthquakes in the course of its life. In order to estimate the seismic performance of a building through its life, "expected value of annual repair cost (EARC)" is one of measurements used to represent the damage control performance. EARC (unit: currency / year) is defined as a total repair cost of a building expected in its life length, divided by the designed life length in year. To estimate the life cycle repair cost, all the specifications to a building design as well as a set of models including (i) a model for earthquake history in the life length, (ii) models for simulating non-linear structural response, (iii) models for correlating the structural response to damage of the building component, (iv) Repairing policy scenario, and (v) models for correlating the damage of the component to repair cost according to the properties of the building element, are necessary. The whole set of the scheme is depicted in Fig. 1.
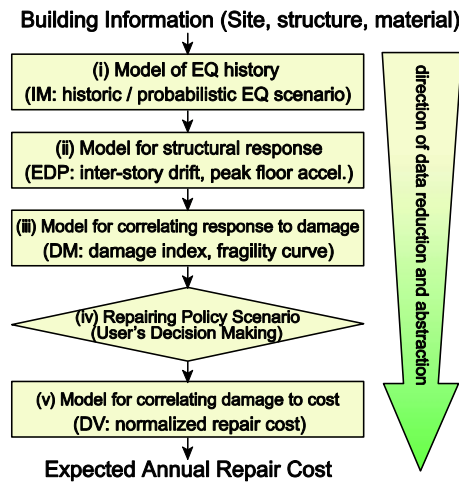

Figure 1: Layered expression of models for the process of estimation of the life cycle cost

2.1 Input Ground Motion

To evaluate the EARC, a life cycle history of input ground motion is necessary. But it is not feasible to obtain exact time histories of earthquake record including multiple events in the life cycle of a particular building. Hence the following simplified methodology is used to synthesize an earthquake input from the available information in this study.

Based on the statistics of extremes theory, an expected extreme value of peak base velocity confirmed to hazard curve (as Eq.1 in Fig.2) in this study [Dan and Kanda 1986] is used to determine the target base velocities. A series of peak velocity is created such that it fits the probabilistic distribution using the plotting position equation [Hazen 1930]. The plotting position formula is represented by

$$F(x) = \frac{i - \alpha}{N + 1 - 2\alpha} \tag{2}$$

where, N: total number of years in record, i: rank in descending order (i.e. from highest to lowest), x: value of i_{th} data, $F(x)$: exceedance probability, α: constant number, calculated by Eq. 3 to define the exceedance probability

of largest earthquake in life cycle as P % in life-cycle years,

$$\alpha = \frac{N + (N+1)\ln(1-P)}{N + 2\ln(1-P)}$$ (3)

and, P: 10% is used in this study. The set of earthquake peak velocities in order are shown in Fig. 3. It is assumed that the effective earthquakes are limited from the biggest to the fourth magnitude of these velocities for the sake of estimating the life cycle reparability. And these moderate to major earthquakes are selected. In this case, the sequence of earthquake can be 24 (= 4!) cases as to the earthquake occurrence order. All order is operated for evaluating EARC in this study.
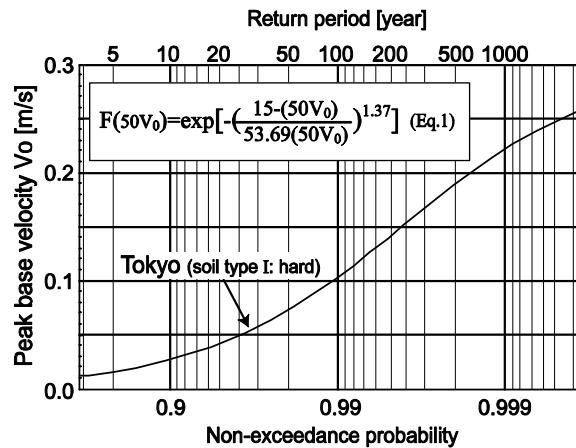

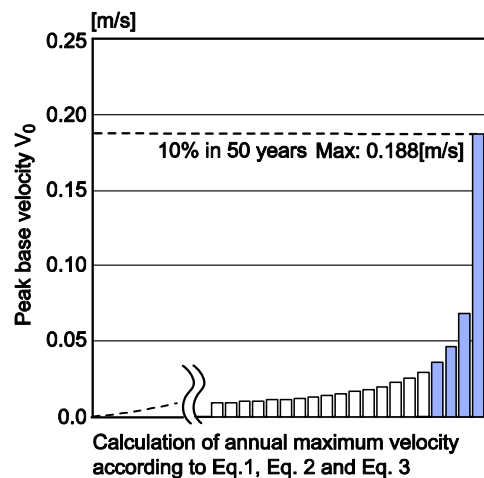**Figure 2: Seismic hazard curve at Tokyo**

Figure 3: Selection from the life cycle earthquake peak velocity set

This series of peak velocity is used as a target to modify an input base accelerogram. Four artificial earthquake motions are synthesized such that it should fit the design spectra defined by a specification in the cabinet order of the Minister of Land, Infrastructure and Transport Japan, while the phase characteristic of Kobe 1995 (NS), El Centro 1940 (NS), Hachinohe 1968 (EW), and Tohoku Univ. 1978 (NS) are used. They are factored such that peak ground velocity should match to each target peak velocity.

2.2 Modelling of Structural Response

A single-degree-of-freedom system representing a reinforced concrete building structure is used for the prediction of a displacement response time history. Responses are calculated by step-by-step integration of the equation of motion using the computer software "SDF" [Otani 1981]. The tri-linear backbone curve and Takeda hysteresis model [Takeda et al. 1970] are used. Viscous damping factor proportional to instantaneous stiffness is

assumed to be 2%. The cracking strength is assumed to be one third of yeilding strength and the secant stiffness at yeilding point is assumed to be 30% of the linearly elastic stiffness. The post yield stiffness is assumed to be 1% of the linearly elastic stiffness. These common properties are used for all cases reported in this paper. And some structural parameters are prepared such as the base shear coefficient C_0 of 0.1 to 0.6, the ductility capacity µ of 1 to 10, and the fundamental natural period T of the building based on the secant stiffness at yeilding point is assumed to be 0.05, 0.1, 0.3, 0.5, 1.0, 3.0, 5.0 sec respectively.

2.3 Modelling of Damage

To simulate the process of the accumulation of the damage due to a series of multiple events, the damage accumulation model by Park et al. is used [Park et al. 1985], because it is one of the simplest model which consists of limited parameters in SDOF analysis. The dissipation of hysteretic energy in this model is considered as follows,

$$D = \frac{\delta_M}{\delta_u} + \frac{\beta}{Q_y \cdot \delta_u} \int dE \tag{4-1}$$

where, D: damage index, δ_M: maximum displacement under earthquake, δ_u: ultimate displacement under monotonic loading, Q_y: yield point strength, β: non-negative parameter to explain the failure of structural member subjected to cyclic loading, dE: incremental absorbed hysteretic energy. By the definition, the damage index D of unity means a collapse. As Park suggested the constant value β of 0.05 showed good correlation to failure in structural tests of reinforced concrete member with remarkable ductility. And the value of 0.05 is used for the value of β in this study.

2.4 Repairing Policy Scenario

The first term of the damage index D defined by the Eq. 4-1 is related to the maximum attained displacement response. It is assumed that this damage is reparable immediately, whereas the second term of the Eq. 4-1 is assumed that damage accumulates and is not reparable by repairing work except through an exchange of structural component with new one. Thus, the assumption on repairing policy is summarized as follows.

The damage represented by the first term in Eq. 4-1 is assumed to be repaired after an earthquake event in which the displacement exceeds the specific point displacement. Generally the making decision of the specific point should depend on the building owner, but in this paper, the specific point is set to the yielding point. When the structure is repaired, the first term in Eq. 4-1 is cancelled and the initial stiffness of the strucutre is also recovered to linearly elastic one. If the structure is unrepaired, its initial stiffness degrades to orient to the maximun displacement. Hereafter, the repaired damage represented by the first term in Eq. 4-1 is denote Repaired Damage index D_R, i.e. :

$$D_R = \frac{\delta_M}{\delta_u} \tag{4-2}$$

When the damage index D (including the accumurating damage) exceeds unity, then the structure is totally replaced and full repair cost is added but the accumulation of damage is cancelled to zero.

2.5 Modelling of Repairing Cost R Due to Repaired Damage Index D_R

Four different types of monotonically increasing functions shown in Fig. 4 are used to model the relation between the damage repair index D_R and the repairing cost index R. Hereafter, the model is called "repairing cost model" in this paper. The repairing cost index R is a normalized cost by the cost for replacing building components with new one. When the damage index D_R exceeds unity, the repairing cost index R is assumed to be one. As long as the damage index D_R takes below unity, the convex curve (a) in Fig. 4 is represented by Eq. 5.

$$R = -\left(\frac{1-D_R}{1-\gamma}\right)^3 + 1 \qquad (\gamma < D_R < 1) \tag{5}$$

where, γ denotes (δ_c/δ_u) and δ_c is the cracking displacement. This type of repairing cost increase immediately

provided maximum displacement response exceeds the specific (yielding) point displacement. The bilinear curve (b) in Fig. 4 is the simplest model which assumes that the repairing cost R is linearly proportional to repairing damage index D_R, except the repairing cost remains zero as far as maximum displacement smaller than the specific (yield) displacement.

$$R = \left(\frac{D_R - \gamma}{1 - \gamma} \right) \qquad (\gamma < D_R < 1) \qquad\qquad (6)$$

The sigmoid curve (c) in Fig. 4 is expressed by Eq. 7. This curve lies between the convex curve given by Eq. 5 and the concave curve given by Eq. 8.

$$R = -\left(\frac{1}{1 - \gamma} \right)^3 \cdot (D_R - \gamma)^2 \cdot (2D_R + \gamma - 3) \qquad (\gamma < D_R < 1) \qquad\qquad (7)$$

The concave curve (d) is represented by Eq.8.

$$R = \left(\frac{D_R - \gamma}{1 - \gamma} \right)^3 \qquad (\gamma < D_R < 1) \qquad\qquad (8)$$

This curve may be represented a characteristics of damage which increased rapidly just before it reaches to the ultimate ductility.

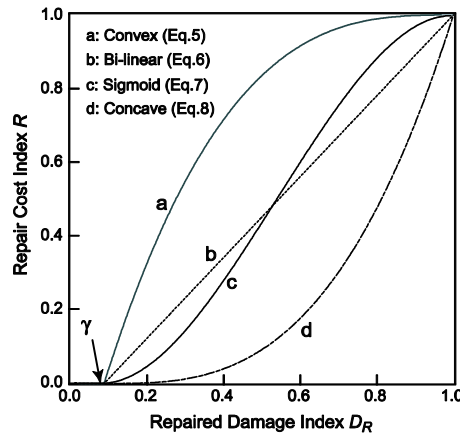**Figure 4: Repairing cost models**

2.6 Expected Value of Annual Repairing Cost Index

Finally, the total repair cost index R is calculated as a sum of the total required repair cost index R through the life cycle of the building. EARC is defined as the total repair cost index divided by life length of a building in year. EARC is evaluated with 50 years in this study. To average the effects of the different earthquake characteristic through the life cycle, EARC obtained from four different artificial earthquake motions are averaged in the result.

3. CALCULATION RESULTS OF EARC

Fig. 5 shows the calculated EARC for each repairing cost model and fundamental natural period T of buildings. This vertical axis means EARC value and two horizontal axes mean the capacity of ductility ratio μ and base shear coefficient C_0 respectively. It is recognized that the case of building period T of 0.1sec takes the highest value of EARC comparing to the other fundamental natural period T in this research. For the reference, the values of EARC (in case of μ=4 and C_0=0.2) are shown in Fig. 5. And it is also recognized that lower ductility capacity and weaker base shear make the value of EARC higher. However Fig. 5 shows the reparability

performance in terms of the quantitative expression as EARC, it may still be uncomfortable for engineers to preliminarily design the building structure. It is desired that the limitations of the reparability performance should be recognized as physical or engineered parameters, for instance a strength or displacement. Then in the next chapter, EARC is converted to the expression by engineered parameters.
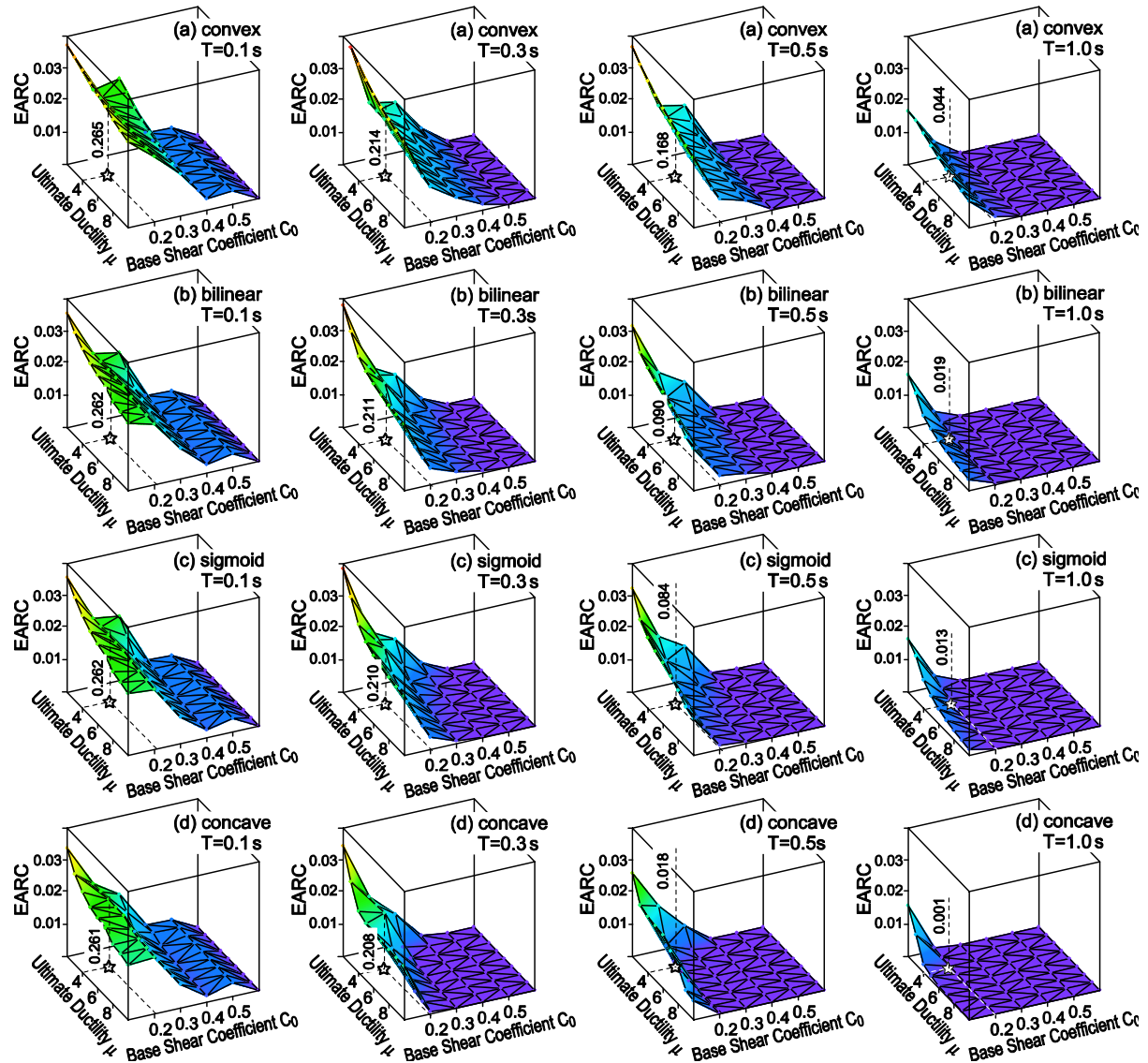

Figure 5: Calculating results of EARC

4. CONVERSION FROM EARC TO REPARABILITY DEMAND SPECTRUM

Firstly EARC is converted to the equivalent seismic loss spectrum. The equivalent seismic loss spectrum is obtained by drawing the contour lines of EARC. Secondly, combining the equivalent seismic loss spectrum data of each fundamental natural period T, the equivalent seismic loss spectrum is converted to the seismic reparability demand spectrum with respect to each ductility ratio. Then the reparability performance limitations can be described using the strength and displacement capacity of the structure. This concept of a converting from the EARC to the seismic reparability spectrum is illustrated in Fig. 6.

In Fig. 7, examples of the seismic reparability demand spectrum are shown. When the ductility capacity becomes large, the equivalent seismic reparability spectrum that indicates life safety (e.g. EARC = 0.2) and seismic reparability spectrum that indicates life safety (e.g. EARC = 0.2) and seismic reparability (e.g. EARC = 0.1) lies on the lower left. On the contrary, however the ductility capacity becomes large, the equivalent seismic
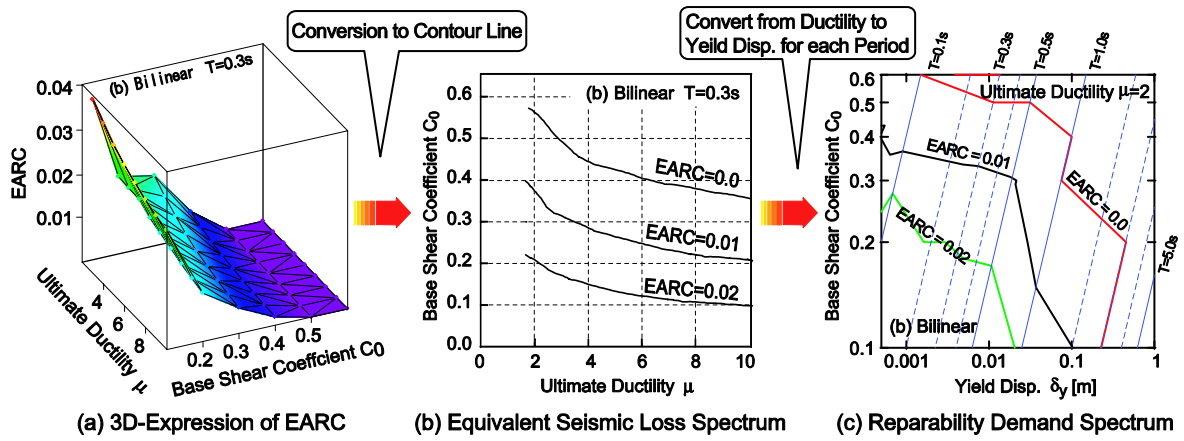
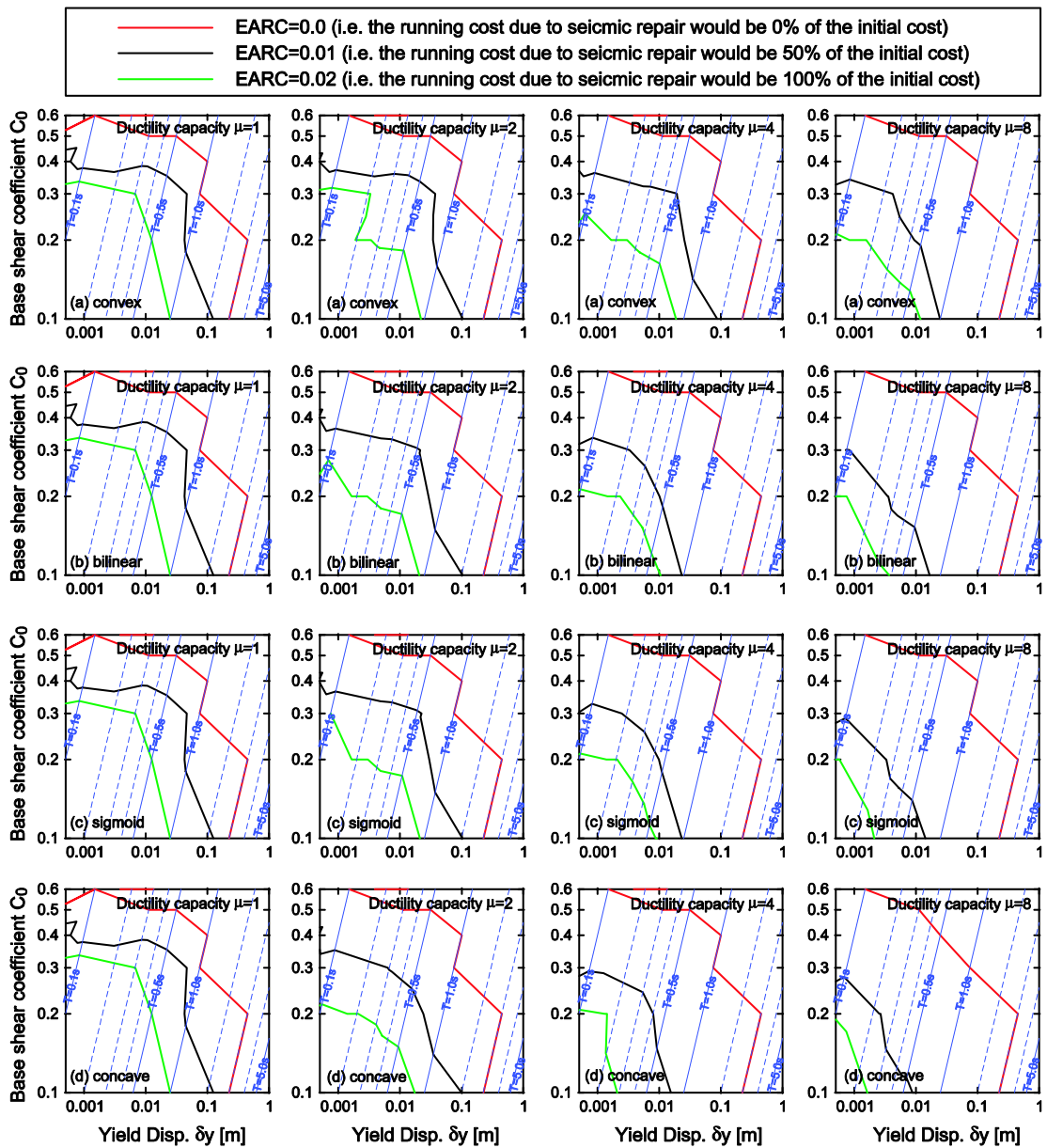Figure 6: Concept of conversion from EARC to reparability demand spectrum

Figure 7: Reparability demand spectrum

reparability spectrum that indicates immediate occupancy (e.g. EARC = 0.0) lies on almost the same place as long as using the same repairing cost model. It implies that the performance as to the life safety and the reparability is dominated by its structural strength and also its ductility capacity. On the other side, the performance as to the immediate occupancy is not dominated by its structural ductility capacity.

A concept of using the seismic reparability demand spectrum for preliminary seismic design is shown in Fig. 8. In Fig. 8, the ductility capacity μ, the fundamental period of structure T and the repairing cost model (b) in Fig. 4 are used as common parameters. The intersecting points of the reparability demand spectra and the line of the fundamental period of structure T show the structural strength demand for each performance. In the case of its ductility capacity μ=2, the structural strength demand in terms of base shear coefficient C_0 goes to 0.50 for the performance as to the immediate occupancy, 0.33 for the performance as to the reparability which aims to EARC=0.01 and 0.19 for the performance as to the life safety, respectively. In the case of its ductility capacity μ=4, the structural strength demand in terms of base shear coefficient C_0 goes to 0.50, 0.26 and 0.17 as same as the case of μ=2. Since any reparability demand spectrum that aims to the building owner desiring performance in terms of EARC is available, the structural strength or ductility demand is also available in the same way of Fig. 8.
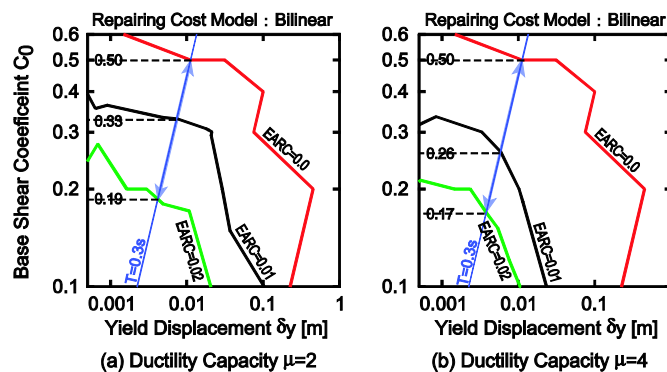

Figure 8: Example of using the reparability demand spectrum for a preliminary design

5. CONCLUDING REMARKS

The concept of the EARC and the seismic reparability demand spectrum based on the EARC was proposed. And it was also demonstrated that the seismic reparability demand spectrum could indicate the structural demand related to the desired performance. It is revealed that the performance as to the life safety and the reparability is dominated by its structural strength and also its ductility capacity. On the contrary, the performance as to the immediate occupancy is not dominated by its structural ductility capacity.

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