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EQUIVALENT SEISMIC LOSS SPECTRUM FOR A PERFORMANCE BASED DESIGN OF SUSTAINABLE R/C BUILDINGS

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ABSTRACT

The present performance-based seismic design procedure has aimed to define and estimate the building performance in multiple levels using quantified parameters. Though this approach is very important for the improvement of performance-based seismic design procedure, it may be inefficient unless the engineer using the procedure is capable of developing preliminary designs that have the desired performance. The next generation performance-based seismic design therefore should address the development of design guidance that assists the engineer to design the desired performance including a reparability.

In this research, the idea of the equivalent seismic loss spectrum is proposed. The equivalent seismic loss spectrum is visualized from the expected running cost to repair a building structure damaged by earthquakes throughout its lifetime. Then the proposed method is applied to R/C building structures, where the spectrum is shown as the relation between the expected seismic repair cost and the physical parameters related to structural performance.

Introduction

The present seismic design of building structures 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.

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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 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 concept of "expected value of annual repairing cost (EARC)" is introduced as a convenient indicator of the reparability performance of a building through its life cycle. Additionally simple application of the EARC is demonstrated, and the concept of "equivalent seismic loss spectrum" is also proposed. It is investigated whether the "equivalent seismic loss spectrum" can indicate the physical or engineered parameters of a building as useful structural demand spectrum for the preliminary seismic design.

Procedure to Evaluate the Expected Annual Repairing Cost

In evaluating the life cycle economic loss of a building constructed in high seismic zone, the damage due to medium to major earthquakes is not negligible, as 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, and (iv) 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.

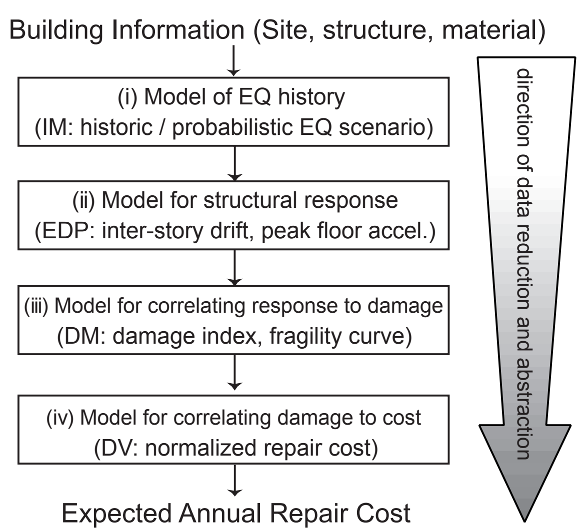


Figure 1. Layered expression of models for the process of estimation of the life cycle cost

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 time length 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 in this study (Dan and Kanda 1986) is used to determine the target base velocities in Fig. 2.

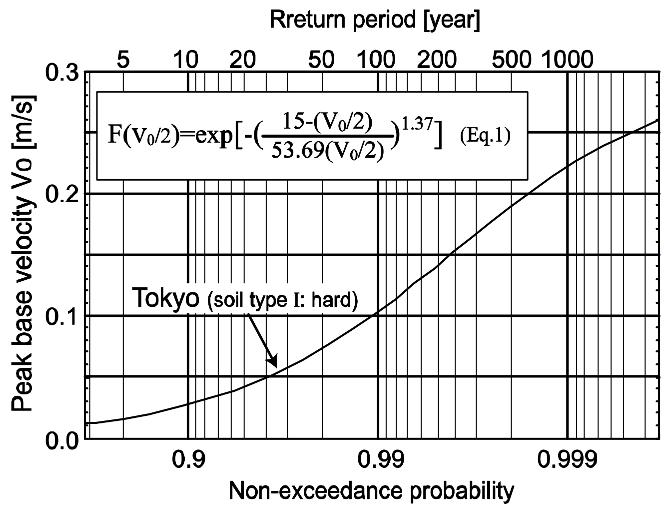


Figure 2. Seismic hazard curve at Tokyo

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,

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

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 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.

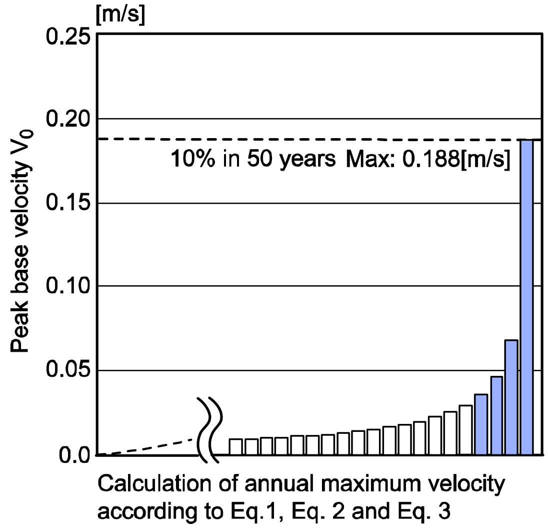


Figure 3. Selection from the life cycle earthquake peak velocity set

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.

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 study.

In this research, some structural parameters are prepared such as the base shear coefficient C_0 of 0.1 to 0.6, the ductility capacity μ of 2 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 sec respectively.

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 the simple model which consists of limited parameters in SDOF analysis. The dissipation of hysteretic energy in this model is considered as follows,

$$D = \frac{\delta_M}{\delta_u} + \frac{\beta}{Q_y \cdot \delta_u} \int dE \qquad (4\text{-}1)$$

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.

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 yielding point displacement. The stiffness is also recovered to linearly elastic one. If maximum response displacement is smaller than yielding point displacement, it is left unrepaired. Hereafter, the repaired damage represented by the first term is denote Repaired Damage index D_R, i.e. :

$$D_R = \frac{\delta_M}{\delta_u} \qquad (4\text{-}2)$$

As the number of earthquake events increase, the accumulated damage index D exceeds unity, then the structure is totally replaced and full repair cost is added but the accumulation of damage is cancelled to zero.

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 1. Thus a convex curve (a) in Fig. 4 is represented by Eq. 5.

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

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 yielding point displacement.

The bi-linear 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 yield displacement.

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

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.

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

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

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

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

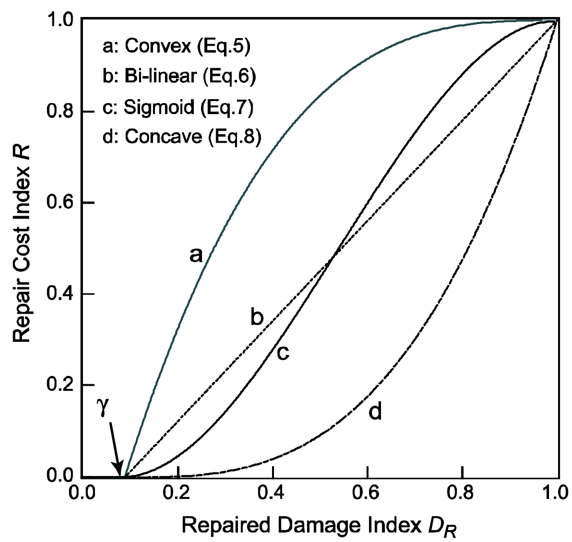


Figure 4. Repairing cost models

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.

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

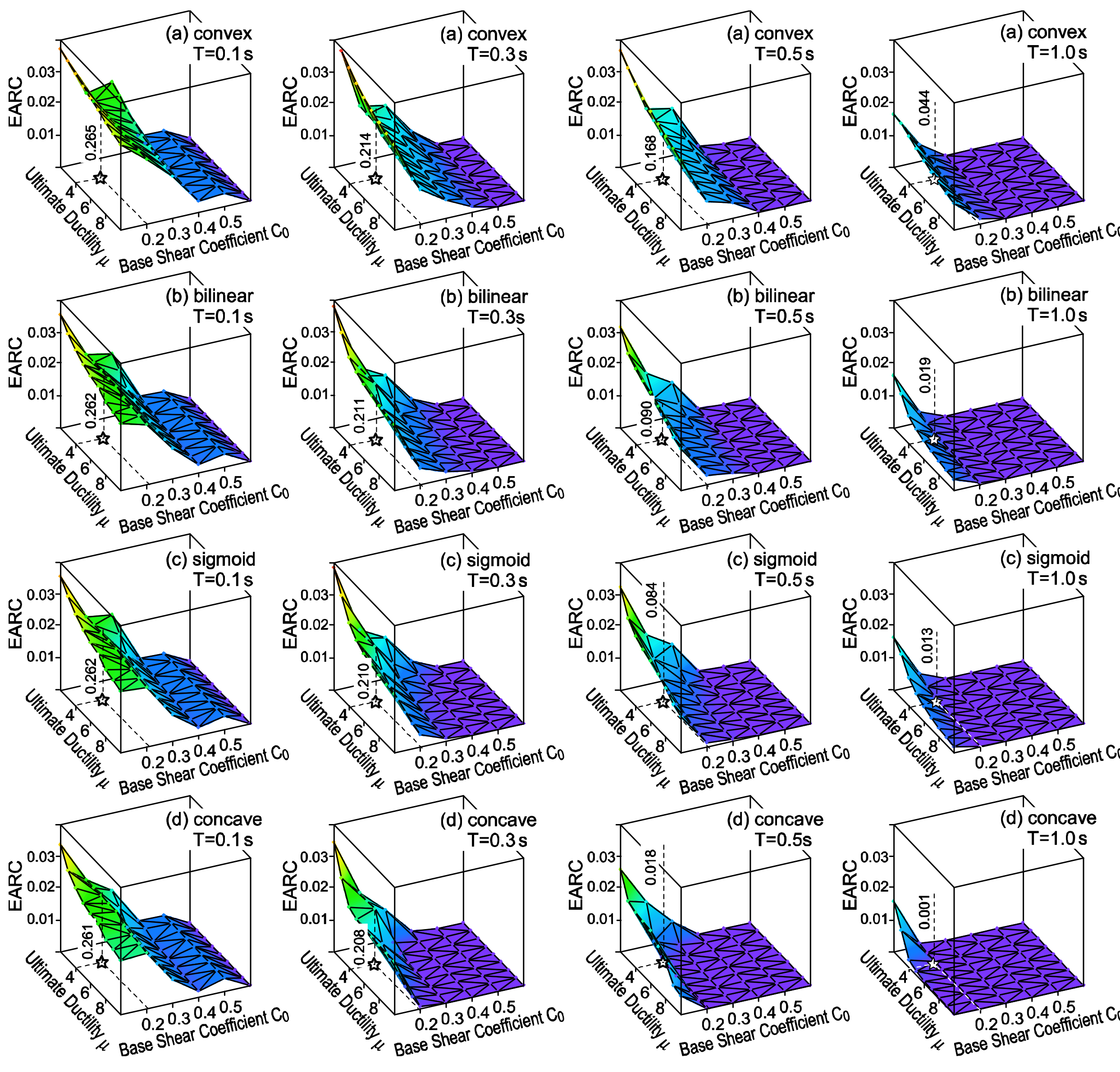


Figure 5. Calculating results of EARC

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.

Equivalent Seismic Loss Spectrum

Equivalent seismic loss spectrum is obtained by drawing the contour lines of EARC. Using the fundamental natural period T of buildings, the ultimate ductility ratio is calibrated into

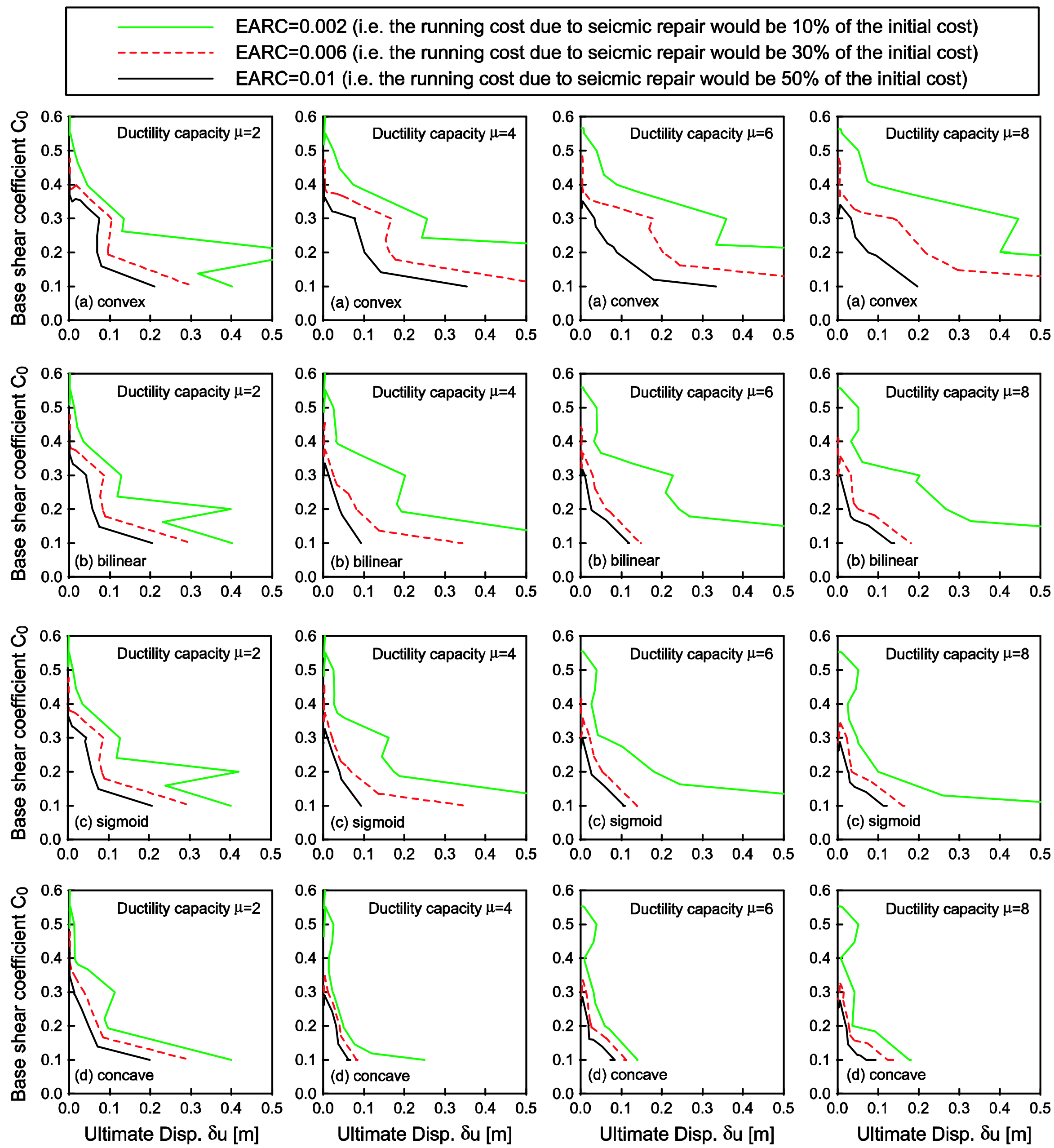
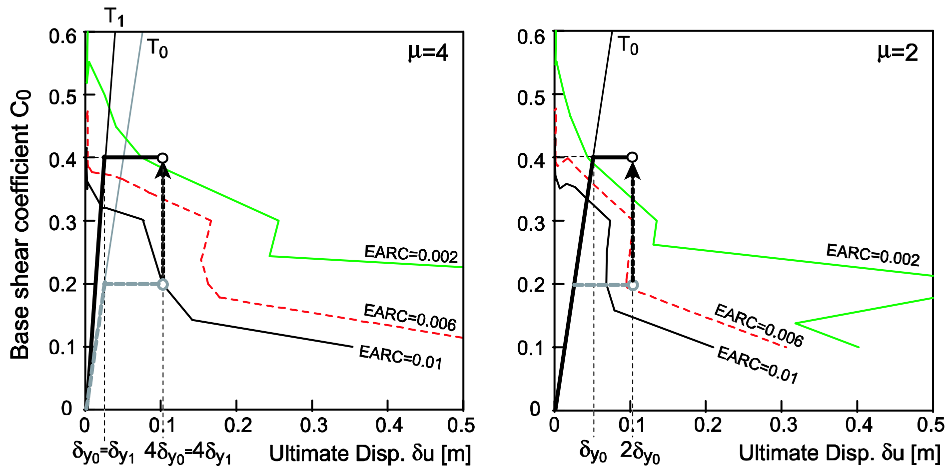


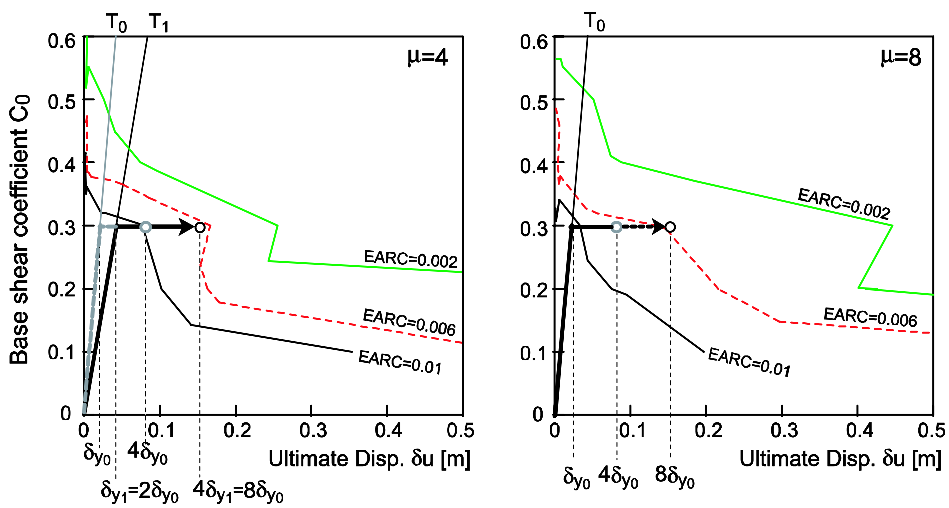
Figure 6. Example of equivalent seismic loss spectrum

the ultimate displacement. Then the reparability performance limitations can be described using the strength and displacement capacity of the structure. Some equivalent seismic loss spectrum are shown in Fig. 6.

In Fig. 6, when the ductility capacity becomes larger, the equivalent seismic loss spectrum lies on almost the same place as long as using the same repairing cost model. It implies that the EARC due to the damage of R/C structure is dominated by its value of ultimate displacement rather than its ductility margin in the high ductility zone. A difference of the equivalent seismic loss spectrum due to the ductility margin tends to appear in the case of low ductility zone and in the case of objective EARC to be small.



(a) In the case of upgrading a strength capacity



(b) In the case of upgrading a displacement capacity

Figure 7. Concept of using the equivalent seismic loss spectrum (with the cost model Eq. 5)

A concept of using the equivalent seismic loss spectrum for preliminary seismic design is shown in Fig. 7. In Fig. 7, it is compared that the manner of changing the engineering parameter in order to satisfy the seismic reparability performance. On the left side of Fig. 7(a) and (b), there are diagram of upgrading the engineered parameter by means of changing the fundamental natural period T and unchanging the ultimate ductility ratio μ. And on the right side of Fig. 7(a) and (b), there are results of upgrading the engineered parameter by means of changing the ultimate ductility ratio μ and unchanging the fundamental natural period T.

In Fig. 7(a), it illustrates the example of upgrading the strength capacity. The result of EARC on the upgraded point has a measurable difference due to the manner of changing the engineering parameter, because the ductility ratio becomes comparatively small value in this case. On the other hand, it illustrates the example of upgrading the displacement capacity in Fig. 7(b), and the result of EARC on the upgraded point has a little difference due to the manner of changing the engineering parameter. It may be caused by the reason that the ductility ratio becomes a comparatively large value in this case.

Concluding Remarks

The concept of the EARC and the equivalent seismic loss spectrum based on the EARC was proposed. And it was also demonstrated that the equivalent seismic loss spectrum can indicate the physical or engineered parameters related to the structural performance.

It is revealed that the equivalent seismic loss spectrum gives almost the same ultimate displacement capacity as long as using the same repairing cost model, when the ductility capacity becomes larger. That is to say that the EARC due to the damage of R/C structure with the high ductility is dominated by its value of ultimate displacement rather than its ductility margin. On the other hand, the equivalent seismic loss spectrum differs owing to the ductility margin in the case of low ductility.

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