# REPARABILITY DEMAND SPECTRUM OF R/C STRUCTURES DUE TO THE LIFE CYCLE SEISMIC LOSS

Noriyuki TAKAHASHI[1], Yoshiaki NAKANO[2] and Hitoshi SHIOHARA[3]

**ABSTRACT**: The performance-based seismic design procedure has aimed to define and estimate the multiple type of building performance using quantified parameters. Especially the reparability performance relates to the quantified parameter such as seismic economic loss. Therefore the target of a reparability performance can define based on the economical rationality. On the other hand, the target of a safety performance is concerned with a human life and sometimes conflicts with its economical rationality. In this paper, the example of this conflicting is quantitatively shown by using the reparability demand spectrum. And it shows that the considering of multiple earthquakes occurred in the life cycle of buildings makes the evaluation of safety and reparability without conflicting.

***Key Words:*** *Performance-based seismic design, Reparability, RC Structure*

## 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. As of now, 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 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 next 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).

[1] Research Associate, Institute of Industrial Science, The University of Tokyo
[2] Professor, Institute of Industrial Science, The University of Tokyo
[3] Associate Professor, Dept. of Architecture, Faculty of Engineering, The University of Tokyo

In this paper, a concept of "reparability demand spectrum" obtained from "expected value of annual repairing cost (EARC)" is introduced. Then the mutual relation of safety and reparability performance is demonstrated by reparability demand spectra. And how to clear the conflicting between the target of safety performance and the target of reparability performance is investigated for the preliminary seismic design in the future.

## 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. 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 **Figure 1.**

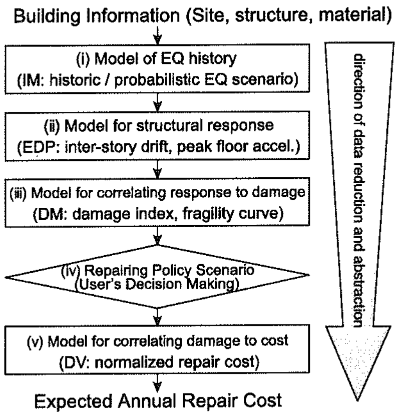



**Figure 1.** Layered expression of models for the process of estimation of the life cycle cost

### *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 length of a particular building. Hence the following simplified method is used to synthesize an earthquake input from the available information.

An expected value of peak velocity on engineering bedrock at Tokyo as the hazard curve (NIED 2006) is used to determine the target velocities on engineering bedrock in **Figure 2.**

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

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

where, $N$: total number of years in record, $i$: rank in descending order (i.e. from highest to lowest), $x_i$: value of $i_{th}$ data, $F(x_i)$: annual probability of exceedance, $\alpha$: constant number, calculated by Equation

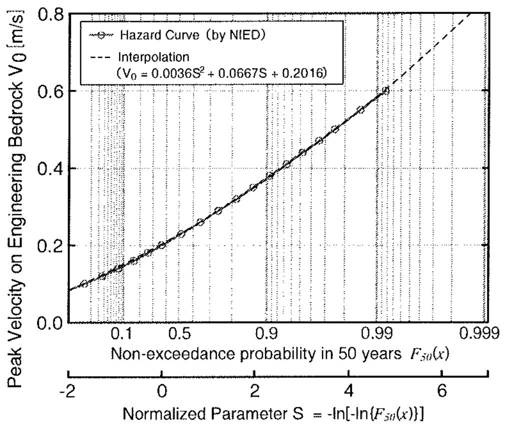



**Figure 2.** Seismic hazard curve at Tokyo

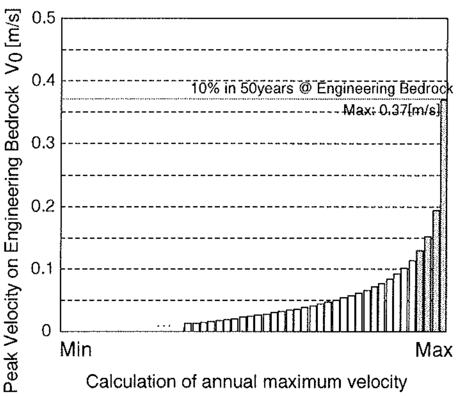



**Figure 3.** Selection from the peak velocity set

(2) to define the probability of exceedance for the largest earthquake as $P(i)\%$ in life-cycle years,

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

and, $P(i)$: $i_{th}$ data's probability of exceedance in $T$ years. The set of earthquake peak velocities on engineering bedrock are shown in **Figure 3** and **Table 1**. 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.

**Table 1.** A set of probability of exceedance on earthquake occurrence in life cycle

| Descending Order of Earthquake | $i$=1 | $i$=2 | $i$=3 | $i$=4 | ··· | $i$=50 |
|---|---|---|---|---|---|---|
| Annual Probability of Non-Exceedance $F_X(x_i)$ | 0.998 | 0.978 | 0.957 | 0.937 | ··· | 0.002 |
| Return Period $r(i)$ (year) | 475 | 44.6 | 23.4 | 15.9 | ··· | 1.00 |
| Probability of Exceedance in 50years $1\text{-}F_{50}(x_i)$ | 10.0% | 67.4% | 88.2% | 95.7% | ··· | 100% |

This series of peak velocities on engineering bedrock is multiplied by the magnification factor $G_s$ for a hard soil defined in the cabinet order No. 1457 Vol.7-2 by the Minister of Land, Infrastructure and Transport (MLIT) Government of Japan to get the peak ground velocities. And these obtained peak ground velocities are used as the 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 MLIT, 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 their peak velocities should match to each target peak ground velocity.

***Modelling of Structural Response***

A single-degree-of-freedom system representing a RC 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 0.8, the ductility capacity $\mu$ of 1, 2, 4 and 8, and the fundamental natural period $T_y$ 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 and 5.0 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,

$$D = \frac{\delta_M}{\delta_u} + \frac{\beta}{Q_y \cdot \delta_u} \int dE \tag{3}$$

where, $D$: damage index, $\delta_M$: maximum displacement under earthquake, $\delta_u$: ultimate displacement under monotonic loading, $Q_y$: yield point strength, $\beta$: 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 $\beta$ 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 $\beta$ in this study.

***Repairing Policy Scenario***

The first term of the damage index $D$ defined by the Equation (3) is related to the maximum attained displacement. It is assumed that this damage is reparable immediately, whereas the second term of the Equation (3) is assumed that damage accumulates. That is, the Equation (3) 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 Equation (3) is assumed to be repaired after an earthquake when the displacement exceeds the yielding point displacement. The stiffness is also recovered to linearly elastic one. If the maximum attained 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. :

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

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 Repair Cost Index R due to Repaired Damage Index $D_R$***

Four different types of monotonically increasing functions shown in **Figure 4** are used to model the relation between the damage repair index $D_R$ and the repair cost index $R$. Hereafter, the model is called "repair cost model" in this paper. The repair 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 repair cost index $R$ is assumed to be 1. In **Figure 4,** $\gamma$ denotes $(\delta_c/\delta_u)$ and $\delta_c$ is the cracking displacement. The convex curve (a) in **Figure 4** represents the type of repairing cost increase immediately provided maximum displacement response exceeds the yielding point displacement. The bi-linear curve (b) in **Figure 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. The sigmoid curve (c) in **Figure 4** shows the characteristic between the convex curve (a) and the concave curve (d). The concave curve (d) in **Figure 4** represents the characteristics of damage, which increased rapidly just before it reaches to the ultimate ductility.

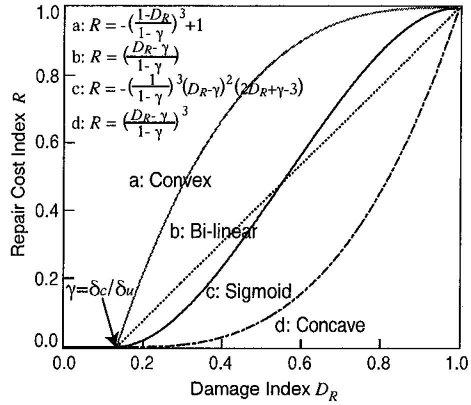



**Figure 4.** Repairing cost models

***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.

## DEMONSTARATION OF REPARABILITY DEMAND SPECTRUM

Firstly EARC is drawn in 3-D graph, which has 3 axes (ultimate ductility in x-axis, base shear coefficient in y-axis and EARC in z-axis). At the next step, EARC is converted to the equivalent seismic loss spectrum. The equivalent seismic loss spectrum is obtained by drawing the contour lines of EARC. At last, combining the equivalent seismic loss spectrum data of each fundamental natural period $T_y$, the equivalent seismic loss spectrum is converted to the reparability demand spectrum in 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 **Figure 5.**

The past seismic design with the beam-collapse mechanism is aim to save all survival space in the building structure without concentration of damage and collapse on a specific layer during big earthquake. Although this beam-collapse mechanism denotes a good safety performance, it often shows the less reparability performance because of a large amount of repairing cost by multi-pronged damaged area. In this paper, two structures with different collapse mechanism and repair cost model shown in **Figure 6** are examined. One is the structure with beam-collapse mechanism which ultimate ductility $\mu$ is 4 and repair cost model is assumed to be (a) convex curve, because its repair cost becomes high in the early stage of damage expanding due to a cost of temporary scaffold etc. Another one is the structure with soft story mechanism which ultimate ductility $\mu$ is 2 and repair cost model is assumed to be (d) concave curve.

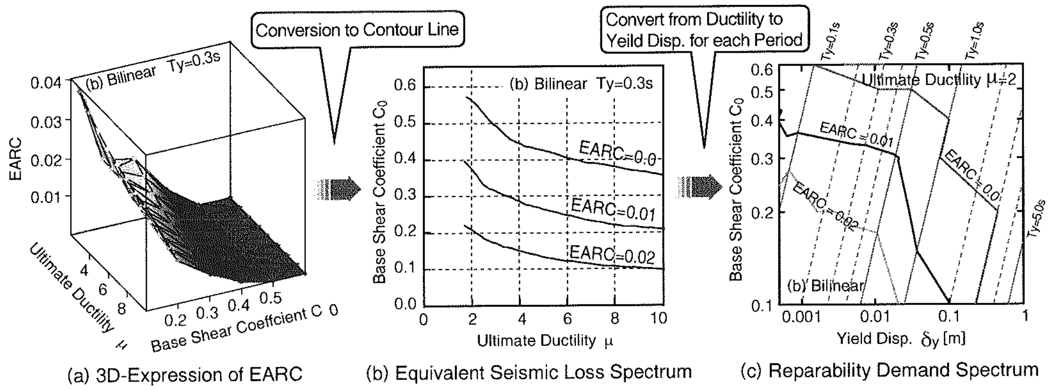



**Figure 5.** Concept of conversion from EARC to reparability demand spectrum

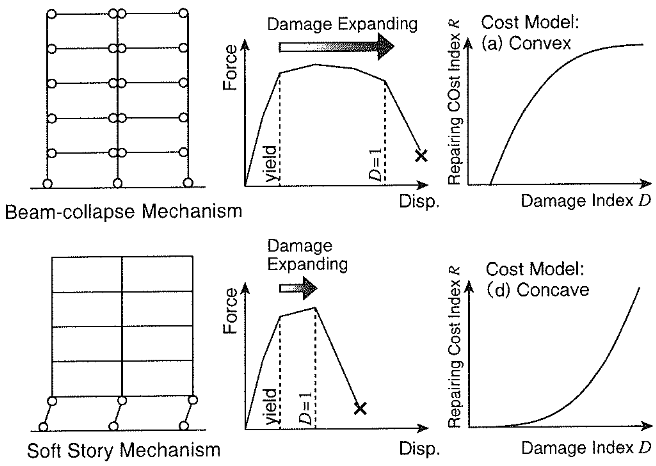



**Figure 6.** Assumption of ultimate ductility and repair cost model in each collapse mechanism

In **Figure 7**, the example of reparability performance and safety performance demand spectra of these structures, that is obtained from one specific ground motion defined its occurrence probability corresponding each performance, is expressed. When the specific ground motion is defined as 2% in 50 years, the reparability demand spectrum indicating safety performance (assumed to be EARC=0.02) of the beam-collapse mechanism structure lies on the lower left side than that of the soft story mechanism structures. It means that the beam-collapse mechanism structure needs less base shear coefficient than that of the soft story mechanism structure for satisfying the target of safety. But when the specific ground motion is defined as 10% in 50 years, the reparability demand spectrum indicating seismic reparability (assumed to be EARC=0.01) of the beam-collapse mechanism structure lies on the higher right side than that of the soft story mechanism structures. It means that the beam-collapse mechanism structure needs more base shear coefficient than that of the soft story mechanism structure for satisfying the target of reparability. This conflicting of safety performance and reparability performance between the beam-collapse mechanism structure and the soft story mechanism structures is also shown when the specific ground motion is defined as 5% in 50 years instead of 2% in 50 years.

In **Figure 8**, lifecycle earthquake scenarios, which contain the maximum earthquake with 10% in 50 years of probability of exceedance or 2% in 50 years of probability of exceedance, are applied to the structures shown in **Figure 7**. The conflicting of safety performance and reparability performance described in the foregoing paragraph was not seen in **Figure 8**. It means that the safety performance is evaluated as the extensional reparability performance because the accumulation of minor to moderate damage is taken into consideration for the safety limitation. That is, when the sum of repair cost index $R$ through its lifecycle becomes one (e.g. EARC=0.02) or more, it is regarded as the limitation of safety performance in real life, not the limitation of collapse. If the detailed collapse process of a structure can be experimentally and analytically explicated, it is expected that the relation of the safety limit and the collapse limit in the form of demand spectrum.

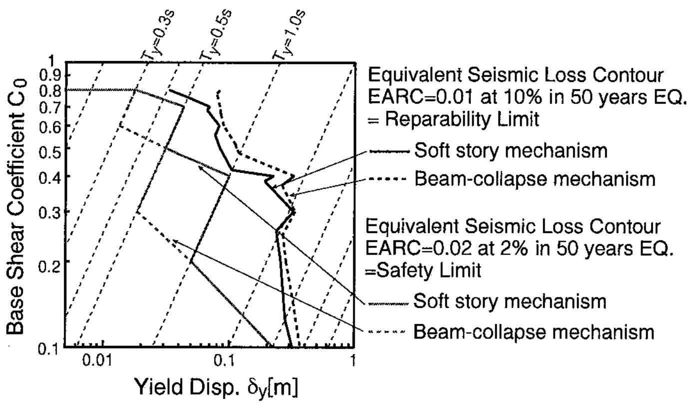
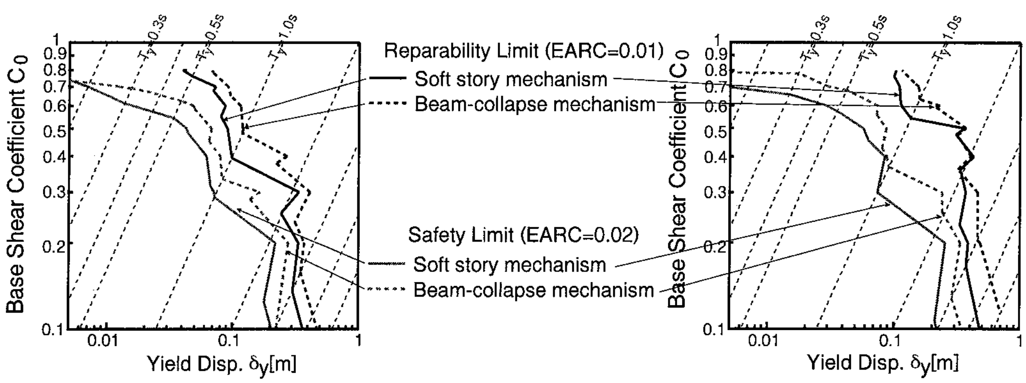



**Figure 7.** Conflicting of safety and reparability in reparability demand spectrum




(a) Life cycle EQs with 10% in 50 years EQ as the maxmum

(b) Life cycle EQs with 2% in 50 years EQ as the maxmum

**Figure 8.** Reparability demand spectrum based on the lifecycle earthquakes

## CONCLUDING REMARKS

The concept of the EARC and the reparability demand spectrum based on the EARC was proposed. And the reparability demand spectrum was also demonstrated by different collapse mechanism structures (beam-collapse mechanism and soft story mechanism) and different input ground motion scenarios (one specific ground motion and lifecycle earthquakes).

The conflicting of safety performance and reparability performance between the beam-collapse mechanism structure and the soft story mechanism structures was shown when the specific ground motion was used. But this conflicting was dissolved when the lifecycle earthquake scenario was adopted, because the safety performance was evaluated as the extensional reparability performance by means of considering the accumulation of minor to moderate damage for the safety performance.

## REFERENCES


Hamburger, R., Rojan, C., Moehle, J., Bachman, R., Comartin, C. and Whittaker, A. (2004): "The ATC-58 Project: Development of Next-generation Performance-based Earthquake Engineering Design Criteria for Buildings", *Proceedings of the 13th world conference on eathquake engineering*, Paper No. 1819.

Hazen, A. (1930): "*Flood Flows, A Study of Frequencies and Magnitudes*", John Wiley & Sons, Inc., New York.

Moehle, J. and Deierlein, G. (2004): "A Frameworl Mothodology for Performance-based Eathquake Engineering", *Proceedings of the 13th world conference on eathquake engineering*, Paper No. 679.

National Research Institute for Earth Science and Disaster Prevention (2006): "Japan Seismic Hazard Information Station", http://www.j-shis.bosai.go.jp/

Otani, S., (1981): "Hysteresis Model of Reinforced Concrete for Earthquake Response Analysis", *Journal, Faculty of Engineering*, University of Tokyo, Series B, Vol.XXXVI-II, No.2, September 1981, pp.407-441.

Takeda, T., Sozen, M. A. and Nielsen, N. N. (1970): "Reinforced concrete response to simulated earthquakes", *Journal, Structural Division*, ASCE, Vol.96, No.ST 12, pp.2557-2573.