8th Pacific Conference on Earthquake Engineering

5 -7 December 2007, Singapore

Mutual Relation of Safety and Reparability for R/C Structures in Seismic Design

N. Takahashi & Y. Nakano

Institute of Industrial Science, The University of Tokyo, Japan.

H. Shiohara

Department of Architecture, Faculty of Engineering, The University of Tokyo, Japan.

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 repairing cost demand spectrum. Particularly two types of parameter for R/C buildings (failure mechanism and repairing cost model) are studied. When the poor-safety structure with soft story mechanism is converted to the structure with beam-collapse mechanism, its safety performance is approved but its reparability performance is deteriorated. However, considering the multiple earthquakes occurred in the life cycle of buildings, this conflicting in the evaluation of safety and reparability performance is cleared up.

1 INTRODUCTION

A key feature of the performance-based seismic design is an owner-friendly expression of performance. Especially, building owners are interested in their building assets. To satisfy the building owner, the "reparability" performance must 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 evaluate the seismic economic loss not only empirically but also logically. The Pacific Earthquake Engineering Research Center (PEER) has proposed the 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 important for an owner-friendly expression to develop the procedure of seismic loss estimation, it may not be enough to design a building structure preliminarily. 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 providing the desired performance in design (Hamburger 2004).

In this paper, a concept of "reparability demand spectrum" obtained from "expected value of annual repair cost (EARC)" is introduced as the assistance of seismic design. Then the mutual relation of safety and reparability performance is demonstrated by reparability demand spectra. In addition, 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.

2 PROCEDURE TO EVALUATE THE EXPECTED ANNUAL REPAIR 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)” can be one of measurements to represent the damage control performance. EARC (unit: currency / year) is defined as a total repair cost of a building through its service life dividing by the year of its service life. 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**.

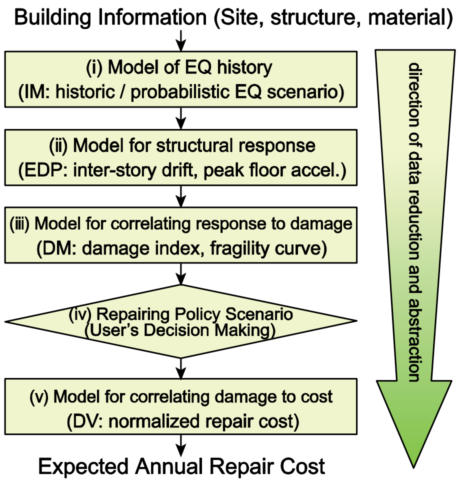

Figure 1. Layered expression of models for the process of estimation of the life cycle cost

2.1 Input Ground Motion

To evaluate the EARC, a scenario of input ground motion through the service life of building is necessary. But it is not feasible to obtain exact time histories of earthquake records including multiple events in the life length of a particular building. Hence, the following simplified method is used to synthesize the input ground motions from the available information.

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

A series of peak velocities is created such that it fits the probabilistic distribution according to 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, 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, α: constant number calculated by Equation (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 is shown in **Figure 3** and **Table 1**. It is assumed that the effective earthquakes for estimating reparability are limited from the biggest to the fourth magnitude of these velocities. That is to say, moderate and major earthquakes are selected and minor earthquakes are neglected. 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.

This series of peak velocities on engineering bedrock is multiplied by the magnification factor G_s for a hard soil, which is defined in the cabinet order No. 1457 Vol.7-2 by the Minister of Land, Infrastructure and Transport (MLIT) Government of Japan, in order to get the peak ground velocities.

These obtained peak ground velocities are the target to modify an input base accelerogram. Four artificial earthquake motions are synthesized such that it should fit the design spectra defined by 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 of peak ground velocity.

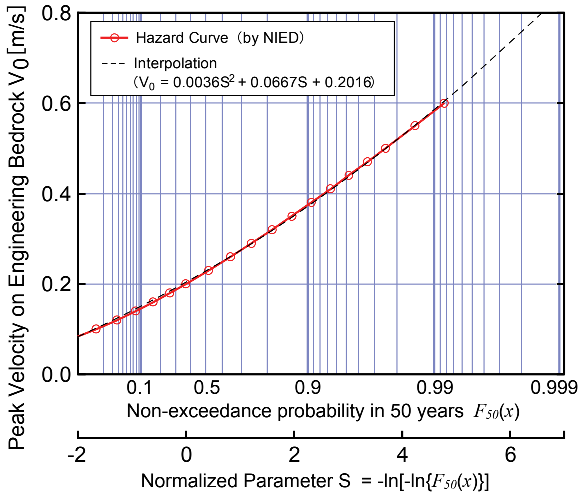

Figure 2. Seismic hazard curve at Tokyo

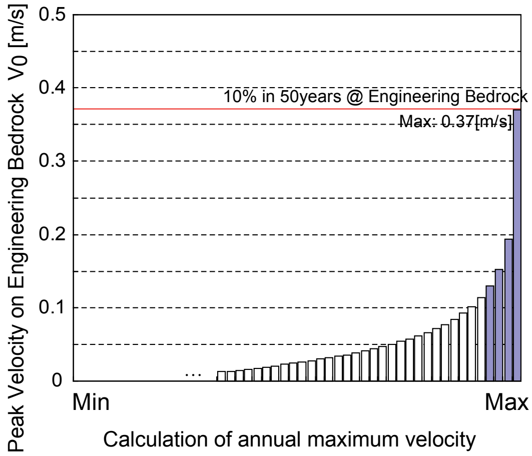

Figure 3. Selection from the peak velocity set

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%

2.2 Modelling of Structural Response

A single-degree-of-freedom system representing 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 2%. The cracking strength is assumed one third of yielding strength and the secant stiffness at yielding point is assumed 30% of the linearly elastic stiffness. The post yield stiffness is assumed 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 μ of 1 to 8, and the fundamental natural period T_y of the building based on the secant stiffness at yielding point is assumed to be 0.05, 0.1, 0.3, 0.5, 1.0, 3.0 and 5.0 sec respectively.

2.3 Modelling of Damage

To simulate the process of the damage accumulation due to a series of multiple events, the damage evaluation model (i.e. damage index model) by Park et al. is used (Park et al. 1985). The simple model consists of limited parameters in SDOF analysis. The dissipation of hysteretic energy 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, 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. Thus 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 Equation (3) is related to the maximum attained displacement. It is assumed that this damage is reparable immediately. The second term of the Equation (3) is assumed that damage accumulates. That is, the second term of the Equation (3) is not reparable by repairing work except an exchange of structural component with new one.

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 could exceed unity. Then the structure is totally replaced and repair cost is fully added. But the accumulation of damage is cancelled to zero.

2.5 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 normalized by the cost for replacing building components with new one.

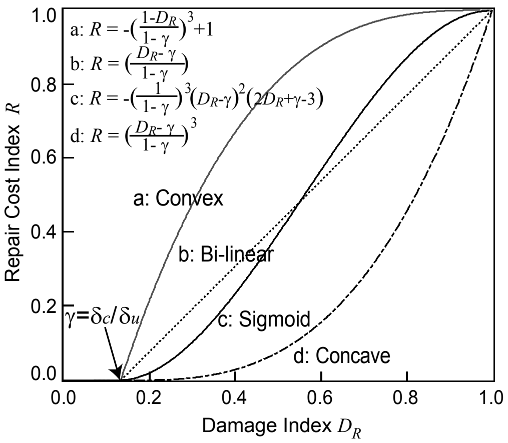

Figure 4. Repair cost models

When the damage index D_R exceeds unity, the repair cost index R is assumed one. In **Figure 4**, γ denotes (δ_c/δ_u) and δ_c is the cracking displacement. The convex curve (a) in **Figure 4** represents the type of repair cost increase immediately if the maximum displacement response exceeds the limit displacement of unrepaired (= yield displacement in this paper). The bi-linear curve (b) in **Figure 4** is the simplest model, which assumes that the repair cost R is linearly proportional to the repairing damage index D_R, except the repair cost remains zero because the maximum displacement is 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 that increased rapidly just before it reaches to the ultimate ductility.

2.6 Expected Value of Annual Repair 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 (years) of a building. EARC is evaluated for 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 DEMONSTARATION OF REPARABILITY DEMAND SPECTRUM

Firstly, EARC is drawn in 3-Dimension graph, which has three 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 from 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 conventional 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 the 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 structural types 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 μ is 4 (in the case 1) or 8 (in the case 2) 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 type is the structure with soft story mechanism which ultimate ductility μ is 2 (in the case 1) or 4 (in the case 2) and repair cost model is assumed (d) concave curve**.**

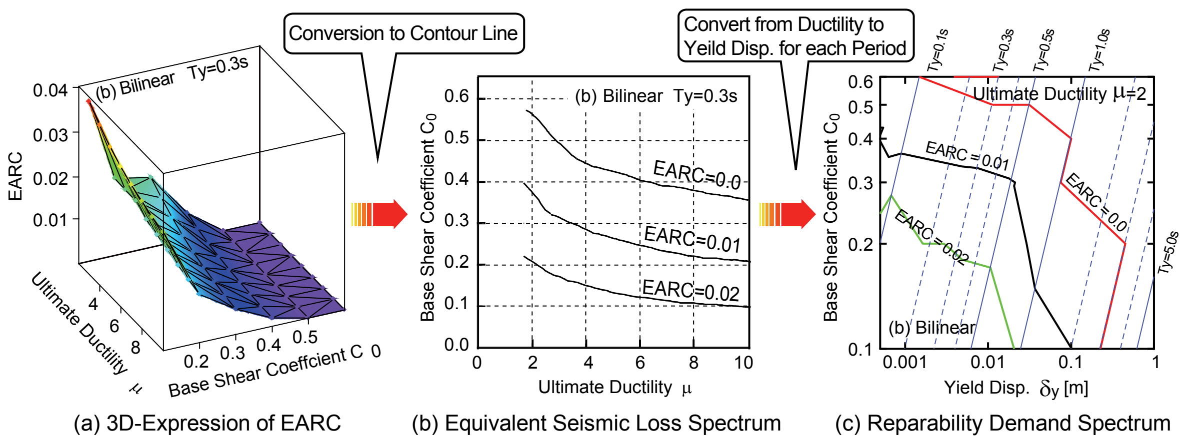

Figure 5. Concept of conversion from EARC to reparability demand spectrum

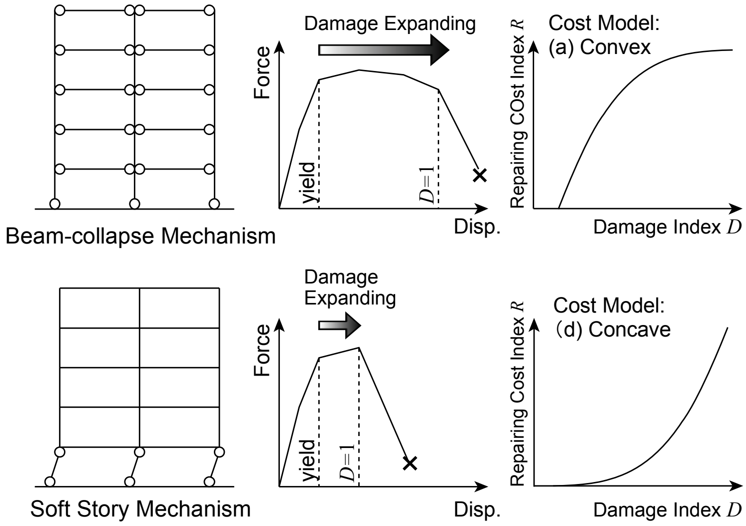

Figure 6. Assumption of ultimate ductility and repair cost model in each collapse mechanism

In **Figure 7**, the example of reparability performance and safety performance demand spectra of these structural types, 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.

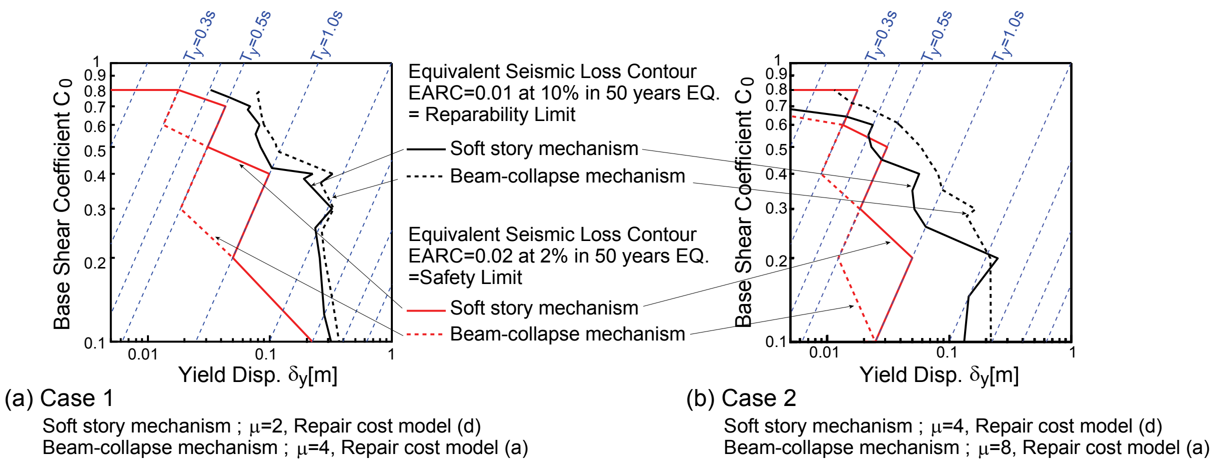

Figure 7. Conflicting of safety and reparability in reparability demand spectrum

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 of the case 1 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 life cycle becomes one (e.g. EARC = 0.02) or more, it is regarded as the limitation of safety performance, not the limitation of collapse. If the detailed collapse process of a structure can be explicated experimentally and analytically, it is expected that the relation of the safety limit and the collapse limit in the form of demand spectrum.

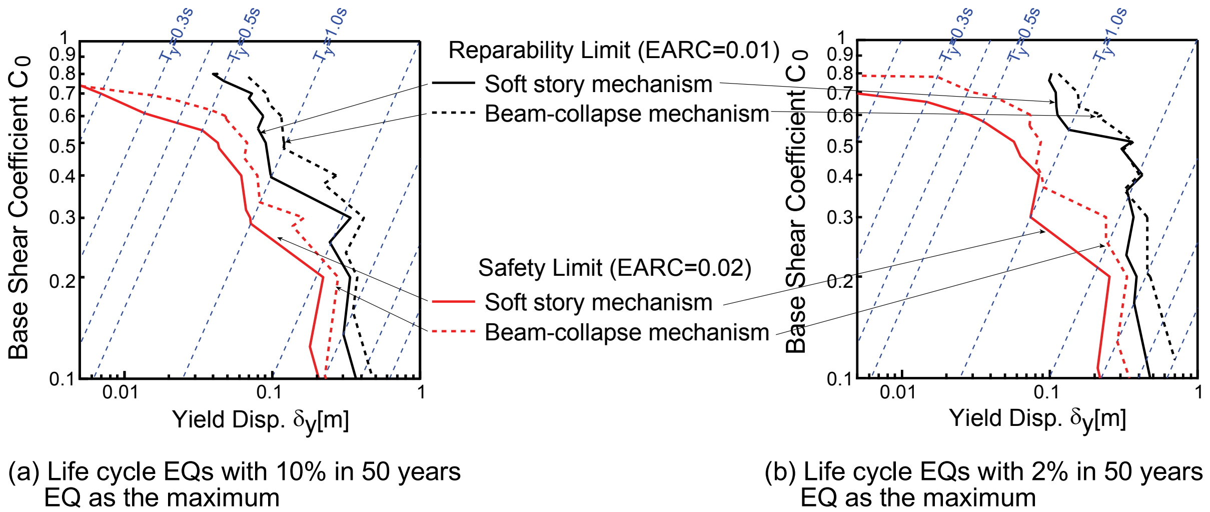

Figure 8. Reparability demand spectrum based on the lifecycle earthquakes

By the way, the conflicting of safety performance and reparability performance is also resolved by using another repair cost model. If the building with beam-collapse mechanism were designed for its damaged area in order to ease its repair work, its repair cost would be reduced in terms of labor cost. In this case, its repair cost model should be changed from (a) convex curve model into another model with low repair cost in the early stage of damage expanding (i.e. (b) bilinear, (c) sigmoid curve and (d) concave curve model). Then the conflicting of safety performance and reparability performance is resolved. The effect of damage control design on the seismic performance will be discussed in the future.

4 CONCLUDING REMARKS

The concept of the EARC and the reparability demand spectrum based on the EARC was proposed. 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 life cycle 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 life cycle 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*, The University of Tokyo, Series B, Vol.XXXVI-II, No.2, September 1981, pp.407-441.

Park, Y. J. and Ang, A. HS. 1985. "Mechanistic Seismic Damage Model for Reinforced Concrete", *Journal of Structural Engineering*, ASCE, Vol. 111, No. 4, pp.722-739

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.