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IMPACT OF R/C BUILDING COMPONENTS ON ITS SEISMIC REPARABILITY DUE TO THE LIFE CYCLE ECONOMIC LOSS

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ABSTRACT:

Loss estimation of a building due to earthquake events in its life length is important to facilitate the decision making of the building owner to choose the reasonable seismic performance. In high seismic zone, the lifecycle economic loss due to earthquakes is particularly significant because the occurrence probability of medium to large earthquake, that is to say the probability of repairing the building damage, is high. Thus this paper reports the investigation on the life cycle economic loss of R/C building under a variety of conditions. Lifecycle economic loss is defined as the expected annual repairing cost (EARC) of structural members and nonstructural components damaged by earthquakes. To simulate the damage and repairing process of buildings, two scenarios of earthquake events are postulated and three building structures are modeled as multi-mass shear spring system. Structural damage is assumed to be represented in Park's damage index and nonstructural damage is assumed to be governed by the maximum inter-story drift or peak floor acceleration. Based on these models, the lifecycle economic loss for two lifecycle earthquake scenarios, three structural types, and five building members/components are illustrated.

KEYWORDS: Lifecycle economic loss, Nonstructural components, Reparability performance

1. INTRODUCTION

A key feature of performance-based seismic design is an owner-friendly expression of performance. Many building owners are interested in their building assets. To satisfy the building owner, reparability performance must be predicted and defined not only qualitatively but also quantitatively. Thus the reparability performance should be represented in the expected economic loss of the building after earthquakes.

Figure 1 summarizes some of the available data that illustrate the seismic loss comparison of building components (Hirakawa and Kanda 1997, Taghavi and Miranda 2002). It implies that loss estimation of nonstructural components is most important for building designers and owners because the loss of nonstructural components occupies much of the seismic loss.

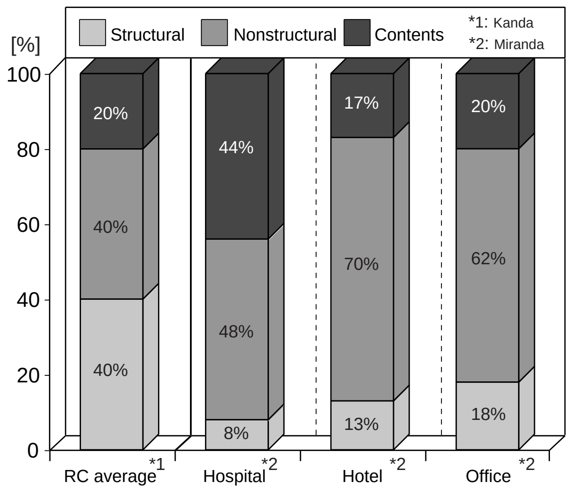


Figure 1 Seismic loss comparison of each building component

Hirakawa et al. investigated the ratio of seismic loss of structural components, nonstructural components, and contents over 210 R/C buildings after the 1995 Hyogo-ken Nanbu earthquake and concluded that the loss of nonstructural components becomes 40% of total seismic loss. Taghavi et al. also investigated the seismic loss comparison of structural, nonstructural, and contents of some typical buildings and concluded that the loss of nonstructural components has a large effect on seismic repair performance. But it must be noted that this seismic loss was obtained through one major earthquake. Considering the lifecycle of buildings, multiple earthquake events including moderate to major earthquakes may occur and cause multiple damage states come into existence sequentially. In consequence, the ratio of seismic loss of each building's components would be different from the loss obtained through one major earthquake.
In this paper, a concept of expected annual repair cost (EARC) is introduced as a convenient indicator of reparability performance based on the lifecycle seismic loss. Then simple application of the expected value of annual repair cost is demonstrated. And the ratio of the repair cost for nonstructural components to the total repair cost for different structural systems will be explained.

2. PROCEDURE TO ESTIMATE EARC

2.1. Outline

To estimate the seismic loss of a building constructed in high seismic zone, damage due to medium to major earthquakes is not negligible. Then expected annual repair cost (EARC) would be a good measurement to estimate the reparability performance. EARC (unit: currency/year) is defined as a total repair cost of a building expected in its life length, divided by the life length in year.
In order to estimate EARC, models such as (i) earthquake history in the life length, (ii) non-linear structural response, (iii) correlation between the structural response and damage to building components, and (iv) correlation between the damage and repair cost for different building elements, are necessary. The whole set of the scheme is depicted in Figure 2.

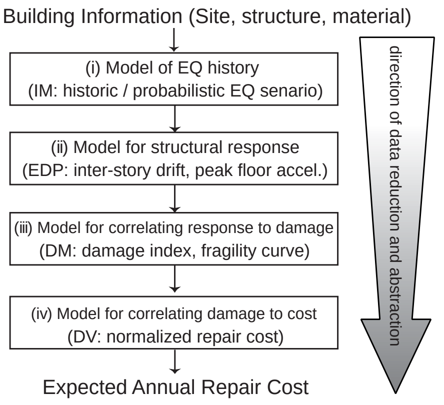


Figure 2 Estimation process of EARC

2.2. Input ground motion

To estimate the lifecycle seismic loss, the scenario of earthquake events through lifecycle is necessary. But it is not feasible to establish the exact time histories of future earthquake records. In this study, the following simplified method is used to systhesize an earthquake input from currently available information.
Based on the seismic hazard curve proposed by National research Institute for Earth science and Disaster prevention (NIED), peak velocities of ground motion on engineering bedrock are calculated. A series of peak velocities through lifecycle is created such that they fit the probabilistic distribution using the plotting position equation. Plotting position equation is represented by

$$F(x) = \frac{i - \alpha}{N + 1 - 2\alpha} \tag{2.1}$$

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. In this paper, α is calculated as Eqn. 2.2 to define the probability of exceedance for the largest earthquake as $P(i)$% in lifecycle years,

$$\alpha = \frac{(N+1)\ln(1-P(i))+iT}{2\ln(1-P(i))+T} \tag{2.2}$$

and, $P(i)$: i_{th} data's probability of exceedance in T years. The sequence of earthquake is rearranged in a random order. This series of peak velocity is used as a target to modify an input base accelerogram. Figure 3 shows the seismic hazard curve in Tokyo proposed by NIED (NIED 2005). Figure 4 shows examples of lifecycle earthquake senario. In this study, it is assumed that only four earthquakes from the largest are effective to estimate reparability as shown hatched in Figure 4. EARC are then estimated for all possible 24 sets (= 4!) of the earthquake occurrence order.

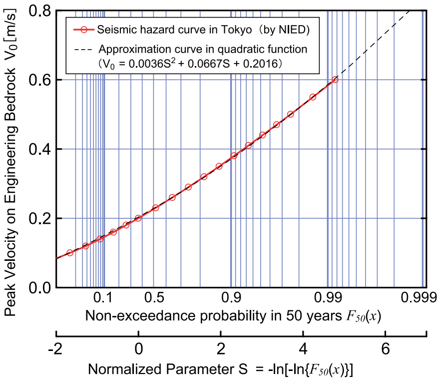


Figure 3 Seismic hazard curve in Tokyo

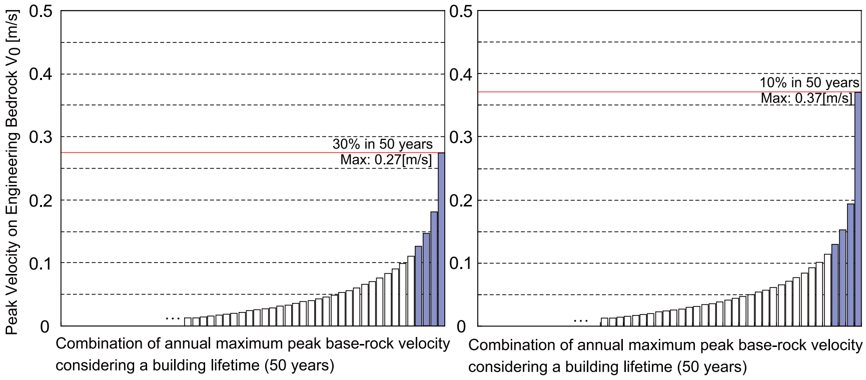


Figure 4 Example of earthquake senario for life cycle

Assuming the building located on the engineering bedrock, four artificial earthquake motions are generated such that they should fit the design spectra defined by the cabinet order of the Minister of Land, Infrastructure and Transport (MLIT) Government of 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 their peak velocities should match to each of the four target peak ground velocities as already disccussed in Figure 4.

2.3. Models in structural analysis

A multi-mass shear spring system representing a reinforced concrete building structure is used for predicting a displacement response history. The Takeda hysteresis model (Takeda et al. 1970) is used for each story. Viscous damping factors proportional to instantaneous stiffness are assumed to be 5%. The cracking strength is assumed to be one third of yielding strength and the secant stiffness at yielding point is assumed to be 30% of the linearly elastic stiffness. The third stiffness after yielding is assumed to be 1% of the linearly elastic stiffness.

2.4. Model of damage

2.4.1. Structural components damage model

The process of the accumulation of damage due to a series of multiple events are not usually considered. But damage such as a hysteretic fatigue of reinforcing bars would be not repaired completely. Such cumulative damage must have a significant effect on the lifecycle repair performance. Thus the lifecycle repair cost is estimated considering the accumulation of damage. Park et al. (Park et al. 1985) proposed a damage model which considers the dissipation of hysteretic energy as follows:

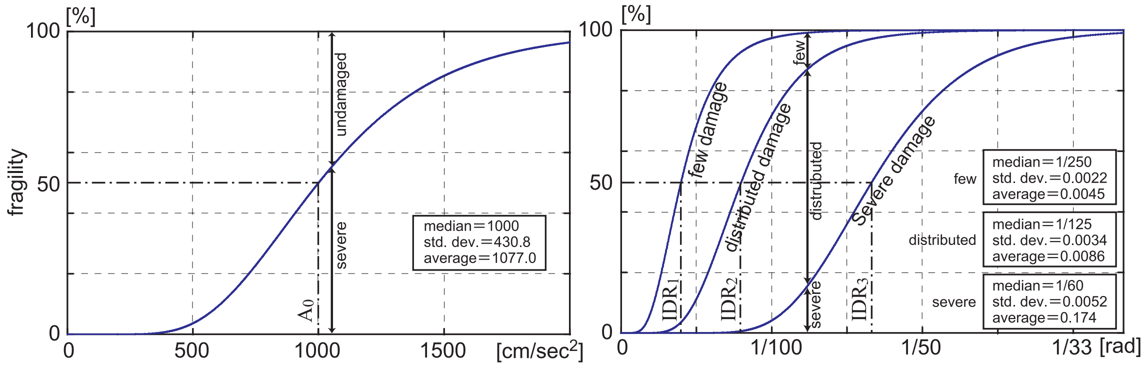
$$D = \frac{\delta_M}{\delta_u} + \frac{\beta}{Q_y \delta_u} \int dE \tag{2.3}$$

where, D: damage index, δ_M: maximum deformation 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. Damage index D of unity means collapse. The value of 0.05 is used for β as in this study.

2.4.2. Nonstructural components damage model

The damage to nonstructural components, which are (1) suspended from structural members (e.g. ceiling light), (2) placed on the floor (e.g. refrigerator), and (3) attached on the strtucture (e.g. PC wall), is assumed to be governed by two parameters: the peak floor acceleration (PFA) and the maximum inter-story drift ratio (IDR). The PFA has a marginal acceleration A_0 beyond which such components are separated from structural members or fall down. Therefore, it assumes that this type of comoponent has two damage states: "undamaged" and "severe damaged". On the other hand, the damage governed by IDR would have several IDR value of damage state limit. Since this type of component attaches to the structure with multiple points or lines, the damage state has multiple level such as "partial damage", "serious damage", etc according to the attachmemt conditions.

Since the nonstructural component with damage governed by PFA has one intergradation of damage state, this type components takes one fragility curve such as Figure 5(a). In the case of nonstructural component with damage governed by IDR, it takes several fragility curves such as Figure 5(b) because it has several intergradations of damage state. A lognormal distribution1 is applied to these fragility curves.



(a) Nonstructural components which damage governed by peak floor acceleration

(b) Nonstructural components which damage governed by inter-story drift ratio

Figure 5 Fragility curve examples of nonstructural components

2.5. Assumption on repairing policy

2.5.1. Structural components repairing policy

The first term of the damage index D defined by Eqn. 2.3 is related to the maximum displacement response. The damage represented by the first term in Eqn. 2.3 is fully repaired in its stiffness after an earthquake if the maximum displacement exceeds the yielding point. If the maximum displacement is smaller than yielding point displacement, it is left unrepaired. Hereafter, the repaired damage represented by the first term is expressed as Repaired Damage index D_R.

The second term of the Eqn. 2.3 is related to the dissipated hysteretic energy. This part of damage index called as D_E is assumed to be not reparable by quick repair and accumulated till replaceing the damaged component with new one. As the number of earthquake events increase, the damage index D ($=D_R+\Sigma D_E$) exceeds unity, then the structure is totally replaced and full repair cost is added instead of cancelling the the damage index D ($=D_R+\Sigma D_E$).

2.5.2. Nonstructural components repairing policy

Building owners are sensitive to visible damage to nonstructural components, and such damage should be therefore repaired immediately.

2.6. Models for correlating damage to repair cost

Models for correlating between damage to repair cost are prepared for each component type. The repair cost index R represents the cost normalized by the cost of replacing the damaged components with new one.
If D_R is smaller than γ ($=\delta_c/\delta_u$: δ_c means the cracking point displacement), the structural repair cost index is zero. Once the value of D_R exceeds γ, the structural repair cost index is calculated using one of the monotonically increasing functions. When the damage index D_R exceeds unity, the structural repairing cost index is assumed to be 1.
In the case of nonstructural component, the assumption on the repair cost in this paper is shown in Table 1 according to the repair cost investigation by Kanda (Kanda 1998). The nonstructural repairing cost index is calculated from the summation of Rs in each damage state multiplied by corresponding probabilities in each damage state.

Table 1 Assumption on repair cost index R for each component type

<table>
<tr><th>Type of Components</th><th colspan="3">Normalized repair cost index R</th></tr>
<tr><td>Structural components</td><td colspan="3">$R=\left(\frac{D_R-\gamma}{1-\gamma}\right)$ $(0<R\leq 1)$</td></tr>
<tr><td rowspan="2">Nonstructural components with damage extended by PFA</td><td colspan="3">damage state: severe</td></tr>
<tr><td colspan="3">R=0.4</td></tr>
<tr><td rowspan="2">Nonstructural components with damage extended by IDR</td><td>damage state: few</td><td>damage state: distributed</td><td>damage state: severe</td></tr>
<tr><td>R=0.1</td><td>R=0.16</td><td>R=0.4</td></tr>
</table>

2.7. Expected Annual Repair Cost

After calculating the repair cost index through the lifecycle, expected annual repair cost (EARC) can be estimated. EARC is defined as the sum of repair cost index through the lifecycle divided by life length of a building in year. EARC is estimated with averaging the effects of earthquake characteristics and occurrence order. In this study, it is postulate that life length of buildings is 50 years and discount rate is 4%.

3. ANALYTICAL PARAMETERS

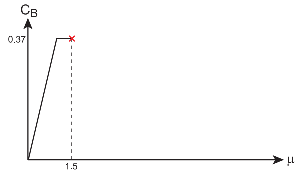
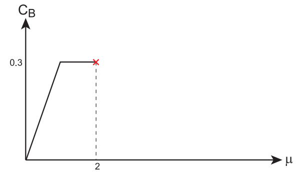
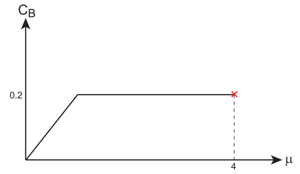
3.1. Structural parameter

Five-story reinforced concrete buildings are examined. The structural model is a multi-mass shear spring system with vertical distribution of a seismic story shear coefficient according to A_i distribution specified in the Japanese building standard law. Three models having different combinations of lateral strength Q_y and ultimate inter-story ductility μ_i are considered. Other parameters such as floor mass m_i, inter-story height h_i, yeilding inter-story drift δ_{yi}, are common. The relation between yeilding story shear Q_y and ultimate inter-story ductility μ is derived from Eqn. 3.1

$$Q_y = \frac{1}{\sqrt{2\mu - 1}} Q_l \tag{3.1}$$

where, Q_y: yeilding story shear, Q_l: linearly-elastic base shear estimated using equal energy criteria, μ: ductility. A list of used assumptions for modeling the yeilding story shear Q_{yi}, story shear coefficient C_i and scant stiffness at yeilding point k_{yi} is shown in Table 2.
As shown in Table 2, their fundamental response characteristics are ranging from relatively brittle building (Type A) to ductile building (Type C).

Table 2 Assumption on structural parameter

Ultimate ductility μ_i	Floor	C_i	Q_{yi} [kN]	k_{yi} [kN/m]
 1.5 (Type A: strength)	5	0.62	3052	152604
	4	0.52	5053	252649
	3	0.45	6676	333776
	2	0.41	7984	399178
	1	0.37	9002	450094
 2 (Type B: standard)	5	0.51	2492	124600
	4	0.42	4126	206287
	3	0.37	5451	272527
	2	0.33	6519	325928
	1	0.30	7350	367500
 4 (Type C: ductility)	5	0.33	1631	81570
	4	0.28	2701	135047
	3	0.24	3568	178411
	2	0.22	4267	213370
	1	0.20	4811	240585

Common parameter: m_i=500000[kgf], h_i=3.5[m], δ_{yi}=2[cm]

3.2. Nonstructural parameter

In this paper, PC exterior walls, ALC exterior walls and gypsum board are represented as the typical nonstructural components with damage governed by IDR, and refrigerator are represented as the typical nonstructural component with damage governed by PFA. To establish their fragility curves, median value and coefficient of variation are assumed as shown in Table 3 and Table 4.

Table 3 Assumption on median value for fragility curve

nonstructural components	median IDR (few damage)	median IDR (distributed damage)	median IDR (severe damage)
PC exterior walls	1/300	1/120	1/40
ALC exterior walls	1/180	1/90	1/40
gypsum board	1/250	1/50	1/15
	median value of marginal acceleration A_0 [cm/sec^2]		
refrigerator	380		

Table 4 Assumption on coefficient of variation for fragility curve

nonstructural components type	coefficient of variation for each intergradations of damage state		
nonstructural component with damage according to IDR (e.g. PC exterior walls, ALC exterior walls, gypsum board)	undamaged to few	few to distributed	distributed to severe
	0.5	0.4	0.3
nonstructural component with damage according to PFA (e.g. refrigerator)	undamaged to severe		
	0.4		

4. CALCULATION RESULTS

EARC is calculated due to two lifecycle earthquake scenarios discussed in section 2.2. Figure 6 illustrates the calculated result of EARC for each component. In the case of lifecycle earthquake scenario with exceedance probability of 30% in 50 years as the maximum earthquake, EARC of nonstructural components with damage governed by IDR is low in building type A and high in building type C except the 3rd floor. But EARC of nonstructural component with damage governed by PFA is high in building type A and low in building type C. In the case of lifecycle earthquake scenario with exceedance probability of 10% in 50 years as the maximum earthquake, EARC of nonstructural components with damage governed by IDR is high in building type A. Nortworthy is the increase in EARC on the 2nd and 5th floor of building type A. It indicates that the 2nd and 5th storey of building type A have become soft storey through the lifecycle.

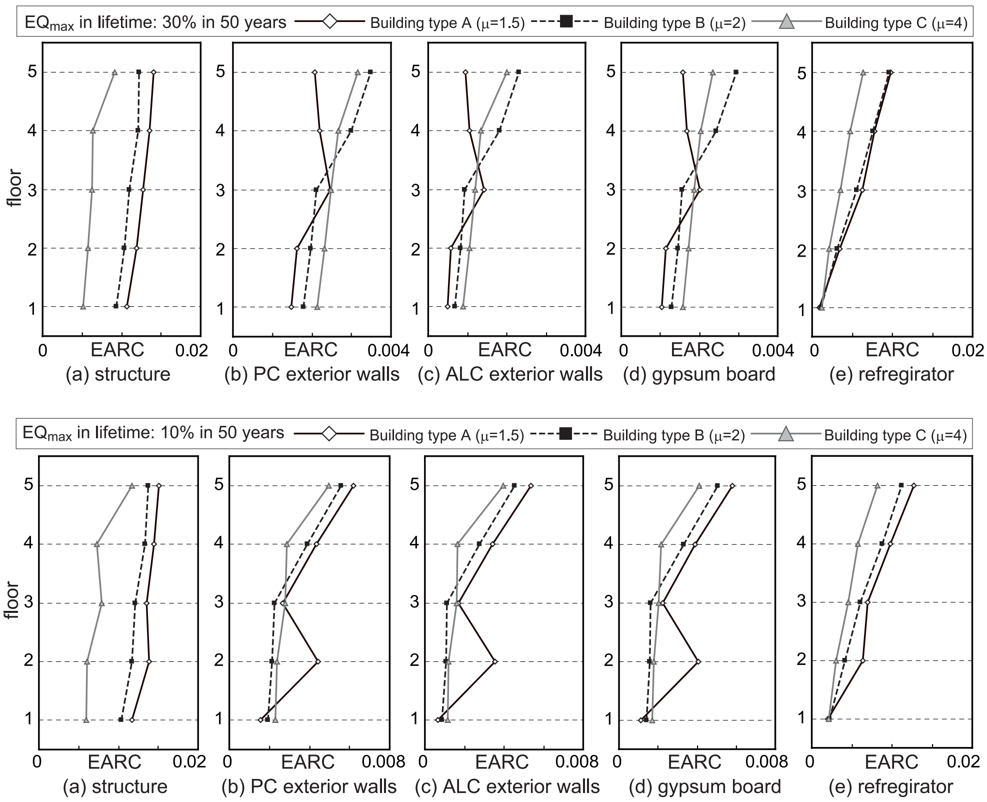


Figure 6 Calculating result of EARC

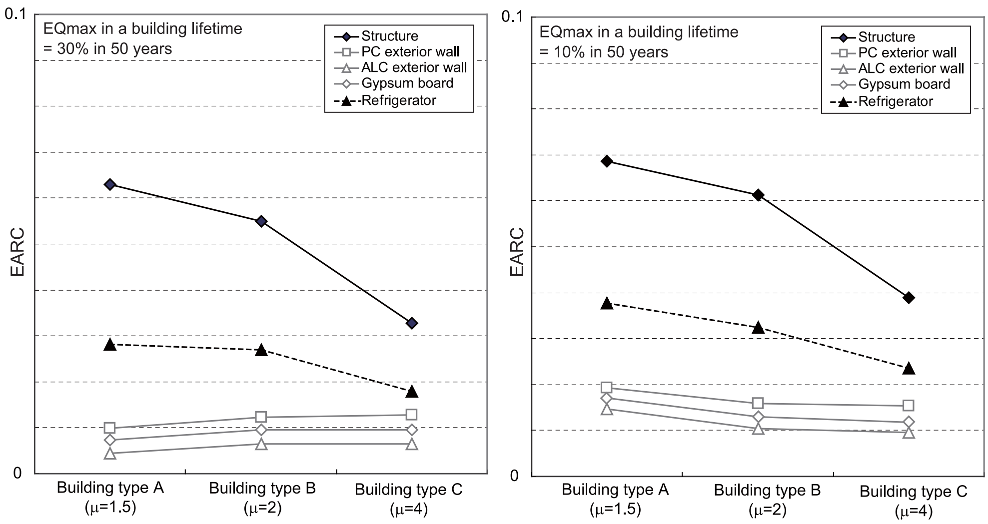


Figure 7 Calculating result of EARC integrating each storey

Figure 7 shows EARC for each component of entire structure. EARC of nonstructural components with damage governed by IDR in building type A differs about 2 times between the lifecycle earthquake scenarios. Figure 8 presents the stacked bar chart of EARC. In the case of lifecycle earthquake scenario with exceedance probability 30% in 50 years as the maximum, total EARC of buiding type A and B is almost same. In the case of lifecycle earthquake scenario with exceedance probability 10% in 50 years as the maximum, total EARC of buiding type A increase more than that of buiding type B.

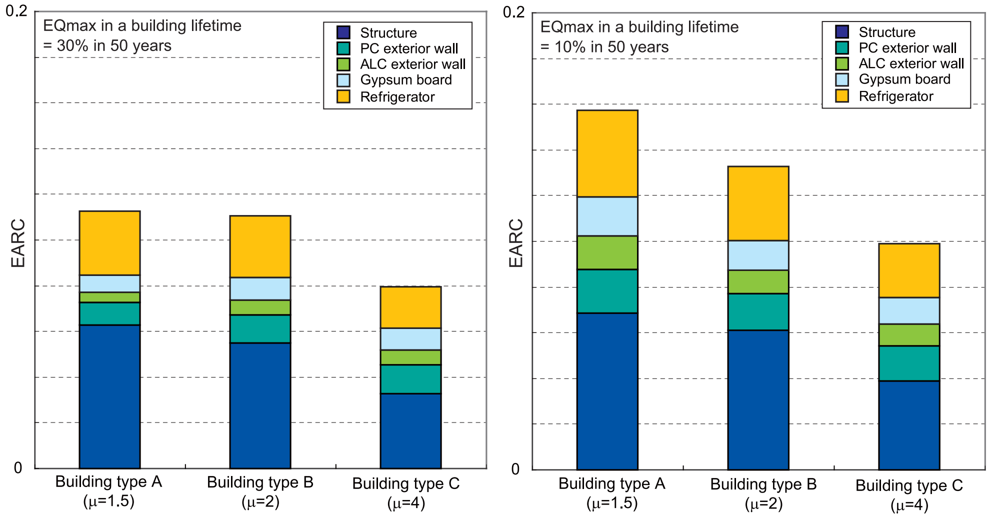


Figure 8 Stacked bar chart of EARC

5. CONCLUDING REMARKS

To estimate the reparability performance of a building including nonstructural components through its life cycle, expected annual repairing cost (EARC) was proposed as a quantitative indicator. The procedure to calculate the EARC was demonstrated by very simple examples. It is revealed that the ratio of the repair cost for nonstructural components to the total repair cost would be changed by the structural seismic resistance mode and the lifecycle earthquake intensity. In particular, a building which depends primarily on its strength to resist an earthquake is sensitive to the lifecycle earthquake intensity.

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