13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 203

# LIFE CYCLE ECONOMIC LOSS DUE TO SEISMIC DAMAGE OF NONSTRUCTURAL ELEMENTS

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## SUMMARY

Buildings should have long lifetime to reduce $CO_2$ emission and to save energy for the environmental conservation. If the life length of a building is aimed to be longer, the impact of medium to large earthquake is higher, in particular in high seismic zones. Thus the evaluation of life cycle economic loss considering accumulation of repair cost in life length is important to facilitate decision making for the choice of seismic performance target in performance-based seismic design.

This paper reports the investigation on factors affecting the repair cost in terms of life cycle economic loss. Economic loss is defined as the repair cost necessary for maintenance of the functionality of a building. The repair cost stems from repair cost of structural members as well as nonstructural components. If nonstructural elements were not adequately designed, sometimes the repair cost for nonstructural components may exceed the repair cost for structural members. However, the impact of repair cost of the nonstructural components on the total life cycle cost is not well recognized.

To simulate the damage and repairing process as well as total repair cost in life length of a building, a building structure is modeled as a simple system of multiple masses and shear springs with non-linear hysteresis model. Assumptions are made that structural damage is represented in Park's damage index and nonstructural damage depends on attained maximum inter-story drift or peak floor acceleration. It is also assumed that nonstructural components don't affect the structural response in this paper. Then the accumulated repair costs in life cycle are evaluated.

It is revealed that the increase of ductility capacity of the structural system changes the nonstructural repair cost. It is also revealed that the ratio of the repair cost for nonstructural components to the total repair cost is depending on the type of the structural system.

## INTRODUCTION

One of the most anticipated to the performance based earthquake engineering is its ability to design and maintain building facilities with predictable performance. The performance is evaluated by limit states for multiple performance objectives, and they should be defined quantitatively like an economic loss or

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downtime. To estimate seismic reparability performance, the quantitative evaluation of repair cost is needed.

In high seismic zone, loss estimation of nonstructural components is very important for building designers and owners, because the percentage of repair cost of damage due to earthquake loss by nonstructural components is large. Kanda and Hirakawa [1] reported the ratio of seismic loss for structural components, nonstructural components and their contents of 210 R/C buildings suffering from the 1995 Hyogo-ken Nanbu earthquake. It says that the percentage of nonstructural components loss becomes 40% of total seismic loss. Miranda [2] reported the result of cost comparison of structural, nonstructural and their contents of typical buildings. The typical ratio of the costs for each component of buildings is summarized in Fig. 1.

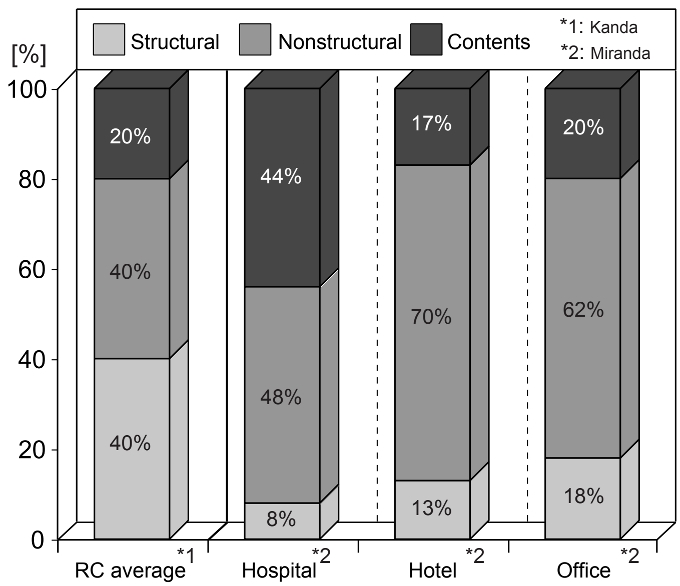



Figure 1: Seismic repair cost comparison of each component

It is revealed from the figure that the loss of nonstructural components has a big impact on seismic repair performance after a major earthquake.

In this paper, the ratio of the repair cost for nonstructural components occupying in the total repair cost due to the structural system will be discussed. A concept of “expected value of annual repair cost” [3] is applied as an indicator of the performance of a building protecting from property loss based on the concept of the life cycle economic loss. Then simple application of the “expected value of annual repair cost” to non-structural components is demonstrated.

## PROCEDURE TO EVALUATE ANNUAL REPAIR COST

### Outline

In evaluating the life cycle economic loss of a building constructed in high seismic zone, damage due to medium to major earthquakes is not negligible, because it is probable that building suffers many earthquakes in its life length. To estimate the seismic performance of a building through its life length, “Expected value of Annual Repair Cost (EARC)” is one of measurements 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. 2.

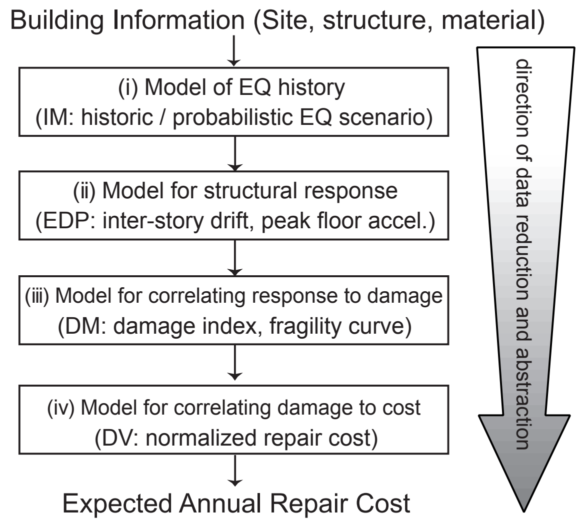



Figure 2: Estimation process of EARC

**Input ground motion**

To evaluate life cycle damage in cost, a life cycle history of input ground motion is necessary. Of course, 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 method is used to systhesize an earthquake input from information available currently in this study.

Based on the theory of probability, expected extreme value of peak base velocity conformed to hazard curve [4] in this study is used to determine the target base velocities in Fig. 3.

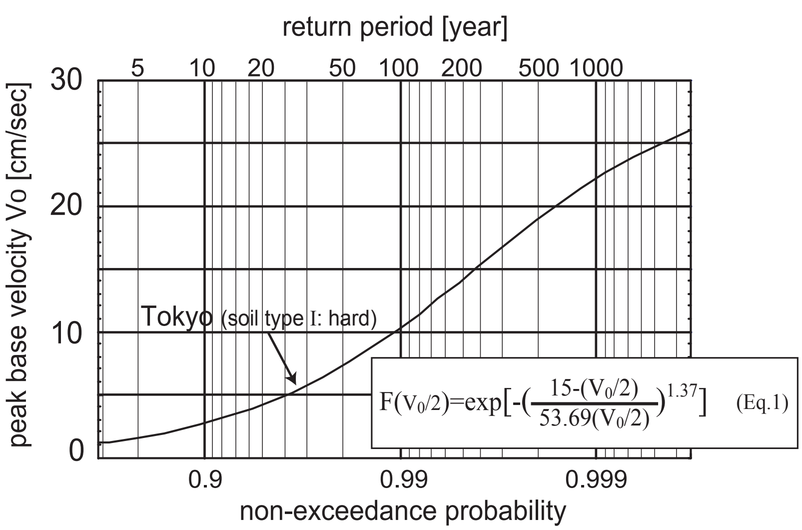



Figure 3: Seismic hazard curve at Tokyo

A series of peak velocity is created such that it fits the probabilistic distribution using the plotting position equation. Plotting position formula is represented by

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

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, $\alpha$: constant number, calculated by Eq.3 to define the exceedance probability of largest earthquake in life cycle as $P$ % in life-cycle years,

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

and, $P$: 10% is used in this study. The sequence of earthquake is rearranged in random order. This series of peak velocity is used as a target to modify an input base accelerogram. An example of life cycle earthquake scenario is shown in Fig. 4.

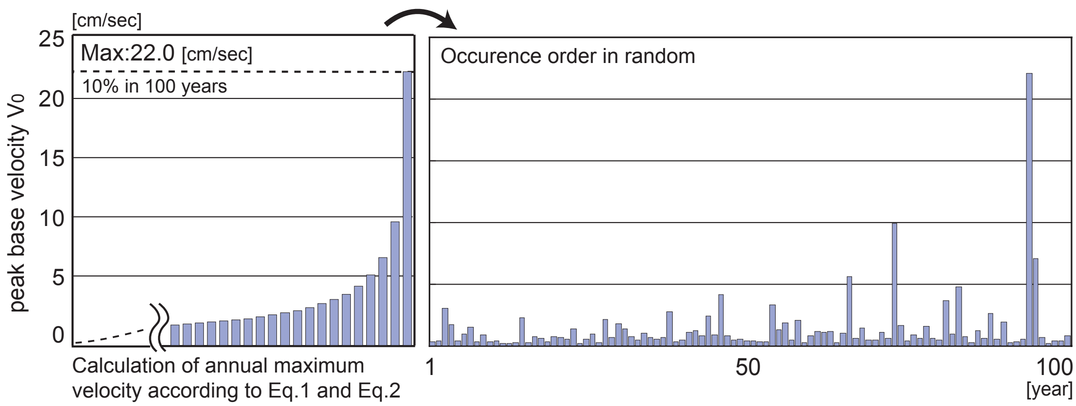



Figure 4: Example of earthquake scenario for life cycle

Four artificial earthquake motions are synthesized such that it should fit the design spectra defined by a specification in the cabinet order of 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.

**Model for structural response**

A multi-mass shear spring system is used for simulating a reinforced concrete building structure to obtain a displacement response history. Responses are calculated by step-by-step integration of the equation of motion by Newmark's $\beta$ method. Tri-linear backbone curve and Takeda hysteresis model (Takeda et al. [5] 1970) are used for each story. 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 third stiffness after yielding is assumed to be 1% of the linearly elastic stiffness.

**Modeling of damage**

*Structural components damage model*

To simulate the process of the accumulation of damage in structural components due to a series of multiple events, the damage accumulation model by Park et al. [6] is used, in which dissipation of hysteretic energy is considered as follows,

$$D = \frac{\delta_M}{\delta_u} + \frac{\beta}{Q_y \delta_u} \int dE \qquad \text{(Eq.4)}$$

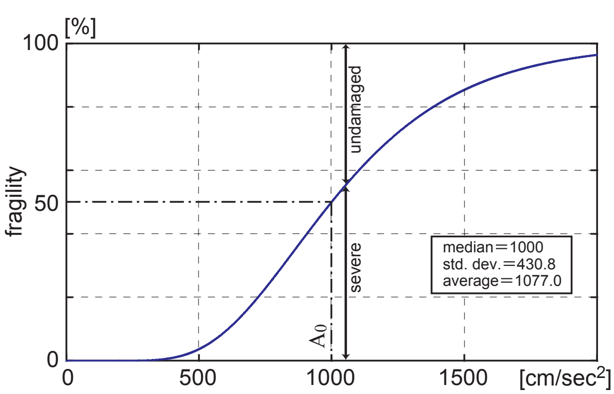
where, $D$: damage index, $\delta_M$: maximum deformation under earthquake, $\delta_u$: ultimate displacement under monotonic loading, $Q_y$: yield point strength, β: non-negative parameter to explain the failure of structural member subjected to cyclic loading, $dE$: incremental absorbed hysteretic energy. By the definition, 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. So value of 0.05 is used for the value of β in this study.

*Nonstructural components damage model*

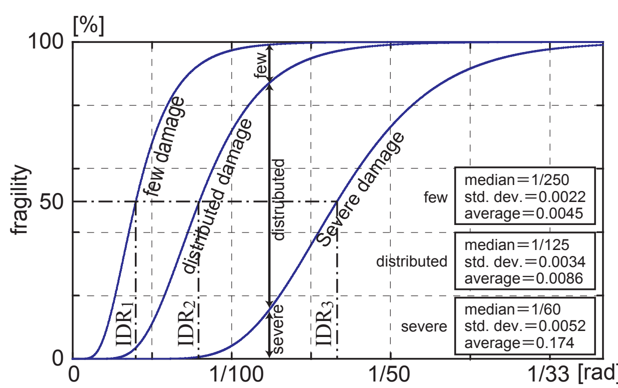
Two types of damages to nonstructural components are identified in this paper. One type is the damage governed by the peak floor acceleration (PFA). The other type is the damage governed by the maximum inter-story drift ratio (IDR).

The former type of damage governed by PFA occurs in components which are attaching to the structure by hanging or self-supporting on one point or single track. If the PFA exceeds a critical acceleration $A_0$, the component separates or falls down and will be broken. So it is assumed that this type of comoponent has two damage state, “undamaged” and “severe.” The other type of damage governed by IDR occurs in components which attach to the structure with multiple points or lines. So this type of nonstructural components would have several critical value of IDR representing damage state limit. Therefore, it is assumed that this type of comoponent has multiple damage state. In this paper, this damage state is devided by four levels and defined as “undamaged”, “few”, “distributed” and “severe.”

It is assumed that the fragility curve in Fig. 5 defines the ratio of the number of element in all over the building in specific damage state for each nonstructural component type. Since the nonstructural component the damage of which is governed by PFA has two damage state, this type of components takes one fragility curve as shown in Fig. 5(a). In the case of nonstructural component which damage governed by IDR, it takes several fragility curves as shown in Fig. 5(b), because it has several intergradations of damage state. A lognormal distribution was then fitted to the points to give the fragility curve.




(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

**Repairing policy**

*Repairing policy for structural components*

Assumption on repairing policy of structural components is made as follows. The damage represented by the first term in Eq.4 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 $D_R$, whereas the second term of the Eq.4 is assumed that damage accumulates and is not reparable by repairing work except through an exchange of structural component with new one. As the number of earthquake events increase, the damage index $D$ including the accumulated damage exceeds unity, then the structure is totally replaced and full repair cost is added but the accumulation of damage is cancelled to zero.

*Repairing policy for nonstructural components*

The nonstructural damage is visible and sensitive for building owners, so these damage are assumed to be repaired immediately.

**A model correlating damage to repair cost**

Models correlating between damage to repair cost are prepared for each component type. Hereafter the structural repair cost index $R_S$ represents a normalized cost by the cost for replacing structural components with new one in each story. The nonstructural repair cost index $R_N$ for each nonstructural components represents a normalized cost as same as the structural repair cost index.

If structural repaired-damage index $D_R$ is smaller than $\gamma$ corresponding to the cracking point, the structural repair cost index $R_S$ is zero. Once the value of $D_R$ exceeds $\gamma$, the structural repair cost index $R_S$ is assumed to be calculated using Eq.5. When the structural damage index $D$ exceeds unity, the structural repair cost index is assumed to be 1. Nonstructural repair cost indices $R_N$ for each damage state are assumed as shown in Table 1 based on the investigation of repair cost in R/C buildings reported by Kanda [7].

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

<table>
<tr><th>Type of Components</th><th colspan="3">Normalized repair cost index</th></tr>
<tr><td>Structural components</td><td colspan="3">$R_S = \left(\dfrac{D_R - \gamma}{1-\gamma}\right) \quad (0<R_S \leq 1) \qquad \text{(Eq.5)}$</td></tr>
<tr><td rowspan="2">Nonstructural components damage governed by PFA</td><td colspan="3">Damage state: severe</td></tr>
<tr><td colspan="3">$R_N$=0.4</td></tr>
<tr><td rowspan="2">Nonstructural components damage governed by IDR</td><td>Damage state: few</td><td>Damage state: distributed</td><td>Damage state: severe</td></tr>
<tr><td>$R_N$=0.1</td><td>$R_N$=0.16</td><td>$R_N$=0.4</td></tr>
</table>

**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 $R_S$ and $R_N$ through the life cycle of the building. Expected value of annual repair cost index is defined as the total repair cost index $R$ divided by life length of a building in year. EARC is evaluated with 100 years in this study. To average the effects of the different earthquake characteristic through the life cycle, EARC obtained from four different artfitial earthquake motions are averaged in result.

## BUILDING PARAMETER

### Structural parameter

A seven-story reinforced concrete building is used as an example in this paper. The structural model is a multi-mass shear spring system with vertical distribution of a seismic story shear coefficient according to $A_i$ distribution [8]. Hereafter, three model buildings are considered with three levels of ductility capacity $\mu_i$ as a building parameter. Other building parameters such as floor mass $m_i$, inter-story height $h_i$, yeilding inter-story drift $\delta_{yi}$ are common for all the buildings. The design strength of the all model buildings are determined such that they should satisfy the Newmark's design criteria [9], which determines a yeilding story shear $Q_y$ for each ultimate ductility capacity $\mu$ from the linearly-elastic base shear $Q_e$ having an equivalent energy dissipation. Newmark's design criteria is defined as,

$$Q_y = \frac{1}{\sqrt{2\mu - 1}} Q_e \tag{Eq.6}$$

where, $Q_e$: linearly-elastic base shear. When the earthquake resistance of a building rely on heavily inelastic displacement capaciy, this building is defined as "ductile type building." If the earthquake resistance of a building rely on primally strength, this building is hereafter called "strong type building." A building having a midium characterlistic is called as "standard type building." Story shear coefficients $C_i$, yeilding story shear $Q_{yi}$ and secant stiffness at yeilding point $k_{yi}$ for each type building are listed in Table 2.

Table 2: Assumption on structural parameter

| Ultimate ductility $\mu_i$ | Floor | $C_i$ | $Q_{yi}$ [kN] | $k_{yi}$ [kN/m] |
|---|---|---|---|---|
| 1.5 Strong type building | 7 | 0.71 | 3473 | 173674 |
| | 6 | 0.58 | 5719 | 285965 |
| | 5 | 0.52 | 7603 | 380173 |
| | 4 | 0.47 | 9208 | 460413 |
| | 3 | 0.43 | 10565 | 528278 |
| | 2 | 0.40 | 11691 | 584583 |
| | 1 | 0.37 | 12596 | 629816 |
| 2 Standard type building | 7 | 0.58 | 2836 | 141805 |
| | 6 | 0.48 | 4670 | 233489 |
| | 5 | 0.42 | 6208 | 310410 |
| | 4 | 0.38 | 7519 | 375926 |
| | 3 | 0.35 | 8627 | 431337 |
| | 2 | 0.32 | 9546 | 477310 |
| | 1 | 0.30 | 10284 | 514243 |
| 4 Ductile type building | 7 | 0.38 | 1857 | 92833 |
| | 6 | 0.31 | 3057 | 152855 |
| | 5 | 0.28 | 4064 | 203211 |
| | 4 | 0.25 | 4922 | 246101 |
| | 3 | 0.23 | 5648 | 282376 |
| | 2 | 0.21 | 6249 | 312473 |
| | 1 | 0.20 | 6733 | 336651 |

Common parameter: $m_i$=500000[kgf], $h_i$=3[m], $\delta_{yi}$=1.5[cm]

It is assumed that all the building have almost the same seismic safety performance. However, seismic reparability performance with nonstructural components is unpredictable at this stage.

**Nonstructural parameter**

In this paper, three typical nonstructural components the damage of which are governed by IDR, i.e. (a) PCa exterior walls, (b) ALC exterior walls and (c) gypsum board, are examined. And two typical nonstructural components the damage of which are governed by PFA, i.e. (d) book shelf and (e) refrigerator, are examined. To determine the fragility curve, the median value and coefficient of variation is required. So the assumption on the median value and coefficient of variation for the fragility curve of a typical nonstructural component is made as listed in Table 3 and 4.

Table 3: Assumption on median value parameter for fragility curve

| Nonstructural components | Median IDR (few damage) | Median IDR (distributed damage) | Median IDR (severe damage) |
|---|---|---|---|
| (a) PCa exterior walls | 1/300 | 1/120 | 1/40 |
| (b) ALC exterior walls | 1/180 | 1/90 | 1/40 |
| (c) Gypsum board | 1/250 | 1/50 | 1/15 |
| | Median value of $A_0$ [cm/sec$^2$] | | |
| (d) Book shelf | 180 | | |
| (e) Refrigerator | 380 | | |

Table 4: Assumption on coefficient of variation parameter for fragility curve

| Nonstructural components type | Coefficient of variation for each intergradation of damage state | | |
|---|---|---|---|
| Nonstructural component damage governed by IDR e.g. (a), (b), (c) | undamaged to few | few to distributed | distributed to severe |
| | 0.5 | 0.4 | 0.3 |
| Nonstructural component damage governed by PFA e.g. (d), (e) | undamaged to severe | | |
| | 0.4 | | |

## CALCULATION RESULTS OF EARC

Fig. 6 illustrates the calculated EARC for each nonstructural components. The EARC of nonstructural component which damage governed by IDR is approximately same value for each story. On the contrary the EARC of nonstructural component which damage governed by PFA goes larger in the upper story. This tendency is prominent in the strong building. For example, the EARC of (d) book shelf at seventh story is ten times as much as at first story in the strong building.

Fig. 7 shows the change of EARC for each type of building. Concerning the nonstructural component which damage governed by IDR such as (a) PCa exterior walls, the EARC becomes smaller in the strong type building and larger in the ductile building. On the contrary, concerning the nonstructural component which damage governed by PFA such as (d) book shelf, the EARC becomes smaller in the ductile type building and larger in the strong building. As to the structural component, the EARC becomes almost the same value among three buildings.

This result indicates that the repair cost for nonstructural components in a building designed for same seismic safety according to Newmark's design criteria. is not constant. To design new buildings or decide a repairing scheme of existing buildings based on the seismic reparability performance, an appropriate configuration of nonstructural component is important.

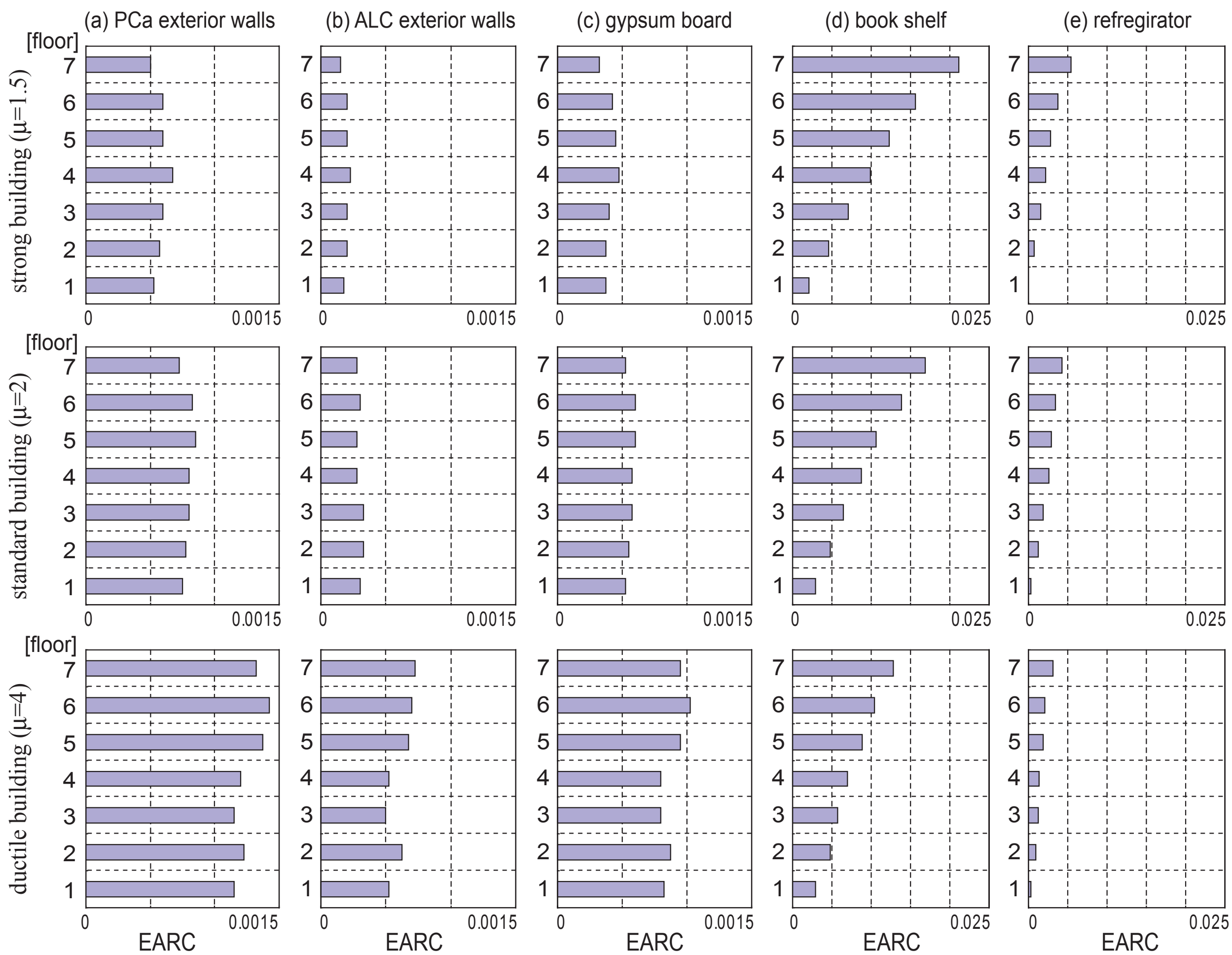



Figure 6: Calculating result of EARC for each nonstructural component

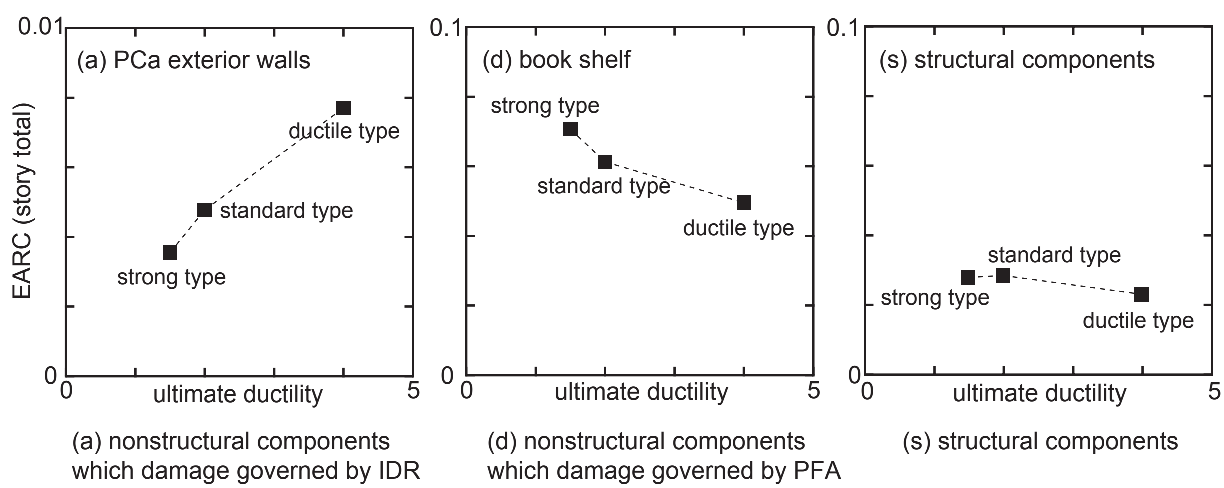



Figure 7: EARC with changes in building models

## CONCLUDING REMARKS

To represent the seismic reparability performance of a building with nonstructural components through its life cycle, "Expected value of Annual Repair cost (EARC)" was applied as a measurement of the damage control performance. The procedure to calculate EARC (unit: currency/year) was demonstrated by a very simple example.

In the case of nonstructural component the damage of which governed by inter-story drift ratio, EARC becomes smaller in the strong type building. On the contrary, in the case of the nonstructural component which damage governed by peak floor acceleration, EARC becomes smaller in the ductile type building. Through the estimation of EARC, it is revealed that the ratio of the repair cost for nonstructural components to the total repair cost will be changed even by the building designed for same seismic vulnerability. So an appropriate configuration of nonstructural component should be considered in order to design a new building based on the seismic reparability performance.

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