A COMPARISON OF SEISMIC LIFE CYCLE COSTS ON EARTHQUAKE RESISTANT BUILDING VERSUS BASE ISOLATED BUILDING

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Summary

In order to maintain the sustainable development, the structural safety of building against big earthquakes is one of significant factors, especially the design lifetime is longer. In this study, the seismic performance of building is quantitatively evaluated from the aspect of the expected loss due to many scenario earthquakes. The seismic life cycle cost during the design lifetime is defined by adding the expected loss to the initial cost. The seismic life cycle costs of ten story R/C buildings which are located in Tokyo, Nagoya and Sendai respectively are calculated in order to compare the earthquake resistant building with the base isolated building. As the design lifetime is longer, the seismic life cycle cost of base isolated building is smaller than that of earthquake resistant building even if the earthquake resistant building takes part in the seismic insurance. It is numerically confirmed that the increment of initial cost of base isolated building can be cancelled because the base isolated building makes it possible to decrease the expected loss. The seismic risk management harmonizing with the environment should be established in the future.

1. Introduction

In the field of the construction industry, it becomes more serious problem to reduce the environment impact as much as possible. According to the CO2 emission in Japan, the amount of that due to the construction activity is approximately one over three in all industries, and this substance is one of reasons to accelerate the global warming. In order to protect the global environment, it is necessary to establish the sustainable buildings. For one method to fulfill this concept, it is considered to make the design lifetime of buildings longer than that of usual existing buildings so as to reduce construction wastes by demolition. As the design lifetime is longer, the buildings which are located at relatively high seismicity may suffer serious structural damages during their lifetime. The sustainable development is to be interrupted even if the environment load due to waste heat or waste water and so on has decreased by the energy conservation. Because the structural safety of buildings is one of critical factors to maintain the sustainability, the structural types which have higher seismic performance should be selected. The seismic performance of base isolated buildings is relatively higher than that of earthquake resistant buildings, but the initial costs of base isolated buildings tend to be more expensive than that of earthquake resistant buildings. This factor may be an obstacle to select the base isolated structure because the initial cost is a big concern as well as the structural safety for building owners. Therefore, the seismic life cycle cost, which is obtained by adding the expected loss during the design lifetime to the initial cost, is defined in this study. At this time, the seismic loss due to the damage of furniture is also considered because the assets value of furniture is to be important as well as buildings. The purpose of this paper is to calculate the seismic life cycle cost of both base isolated buildings and earthquake resistant buildings, and to quantitatively examine the superiority of base isolated buildings from the standpoint of the seismic life cycle cost. On the other hand, for a risk hedge in terms of earthquake resistant buildings, the seismic insurance system, which is operated by the Japanese government, is prepared. The seismic life cycle cost of earthquake resistant buildings with the seismic insurance is also calculated to compare with each other.

2. Analytical Method for Evaluating Seismic Life Cycle Cost

The expected loss of buildings for the design lifetime can be evaluated through both the seismic hazard at construction sites and the seismic loss of buildings. The details of the analytical procedures for the seismic life cycle cost are described as follows.

2.1 A Set of Scenario Earthquakes

Many earthquakes which are located at inland and sea should be appropriately considered in order to calculate the probabilistic seismic hazard at construction sites. The seismic source models consist of three types, which are plate boundaries, inland active faults and background earthquakes. For the plate boundary sources, the Pacific Ocean plate and the Philippine Sea plate are modeled. For the active faults, several major tectonic lines are modeled as vertical plate sources, and others are modeled as line sources. The background sources are prepared to evaluate historical earthquakes which are not related to the plate boundary sources and the active faults. A set of scenario earthquakes, which can represent the characteristics of these seismic sources, are proposed. Each scenario earthquake has the seismic information, which consists of a location of source, a distribution of magnitude and annual occurrence rate with respect to each magnitude. In this study, about twenty-eight thousand scenario earthquakes throughout Japan are generated.

2.2 Seismic Intensity at Construction Sites

Seismic intensity at a construction site due to each scenario earthquake is calculated by the attenuation model. The representative parameters of this model are the magnitude of a scenario earthquake and the shortest distance from a hypocenter. The median of seismic intensity is calculated through this model, and the uncertainty of estimation is modeled by lognormal distribution.

2.3 Evaluation of Seismic Fragilities of Buildings

2.3.1 Seismic Fragility Curves of Superstructures

The superstructure is reduced to the shear lumped mass system, and earthquake response analysis due to several simulated seismic waves is carried out in order to obtain the relations between seismic intensity and relative story displacement for each story. Semi-continuous relations are calculated, and these relations are modeled by the following regression equation :

$$\delta = d_1 \times a^{d_2} \tag{1}$$

where a is seismic intensity, δ is response relative story displacement, d_1 and d_2 are coefficients of regression. The shape of seismic fragility curves is modeled by lognormal distribution, and the limit relative story displacement with respect to the each level of damage is assumed. At that time, the lognormal expectation and lognormal standard deviation of seismic fragility curves are evaluated by the following equations :

$$\lambda_a = \frac{1}{d_2} \times \left(\lambda_R - \ln d_1\right) \tag{2}$$

$$\zeta_a = \frac{1}{d_2} \times \zeta_R \tag{3}$$

where λ_a , ζ_a are the parameters of seismic fragility curves, and λ_R , ζ_R are the parameters of limit relative story displacements.

2.3.2 Seismic Fragility Curves of Base Isolated Story

The relation between seismic intensity and relative story displacement at base isolated story is calculated in the same way of superstructure. The shape of seismic fragility curves is modeled by lognormal distribution, and that of base isolated story is evaluated through the limit relative story displacement. When the response displacement at base isolated story exceeds the limit displacement, the whole building including the base isolated story is assumed to collapse.

2.3.3 Seismic Fragility Curves of Furniture

In order to represent the damage of furniture, the overturning behavior is focused on. The seismic fragility curves of furniture at each story are evaluated through both floor response acceleration and floor response velocity based on Kaneko’s method. The relations between seismic intensity and floor response acceleration and velocity at each story are calculated in the same way. It is confirmed that the sliding behavior of furniture tends to be predominant, and the furniture does not overturn when the width-height ratio of furniture is relatively smaller than the coefficient of friction with the floor. Therefore, the overturning probability of furniture is evaluated on condition that the furniture does not slide.

2.4 Expected Loss of Buildings due to a Scenario Earthquake

As the damaged probability of buildings and furniture is calculated through each seismic fragility curve, the seismic loss distributions of buildings can be obtained by the event tree analysis in order to consider various damaged modes. The expectation and standard deviation of the distribution are calculated by the following equations :

$$\mu_C = \sum_{k=1}^{K} (P_k \times C_k) \tag{4}$$

$$\sigma_C = \sqrt{\sum_{k=1}^{K} \left\{ P_k \times (C_k - \mu_C)^2 \right\}} \tag{5}$$

where P_k is damaged probability of k-th damaged mode, C_k is repair cost of k-th damaged mode. The seismic loss disribution is modeled by the beta distribution which has both upper and lower bounds, and the upper bound is given by the assets value. When the seismic loss of earthquake resistant buildings with seismic insurance is calculated, the repair costs are given by subtracting the paied seismic insurance money. At that time, the seismic loss ditribution due to a scenario earthquake is calculated by weighting integraion with respect to the distribution of seismic intensity. The expected loss $E[C|S]$ and its variance $Var[C|S]$ due to a scenario earthquake S are calculated through the following equations :

$$E[C|S] = \int \left\{ \mu_{C|a} \times f_A(a) \right\} da \tag{6}$$

$$Var[C|S] = E[Var(C|A)] + Var[E(C|A)] \tag{7}$$

where $f_A(a)$ is the probability density function of the seismic intensity at a construction site, $Var(C|A)$ is the conditional variance, and $E(C|A)$ is the conditional expectation.

2.5 Seismic Life Cycle Costs of Buildings

When the occurrence of each scenario earthquake is assumed to be the stationary Poisson process, the expectation of occurrence number of a scenario earthquake for the design lifetime T is obtained by multiplying the annual occurrence ratio ν by the design lifetime T. The expected loss L_T for the design lifetime with respect to all selected scenario earthquakes is evaluated through the following equation :

$$L_T = \sum_{i=1}^{N} \left\{ (\nu_i \times T) \times E[C|S_i] \right\} \tag{8}$$

where N is the total number of all selected scenario earthquakes. Therefore, the seismic life cycle cost of buildings for the design lifetime is given by the following equation :

$$SLCC = C_I + C_F + L_T \tag{9}$$

where C_I is the initial cost and C_F is the assets value of furniture. In the case of the earthquake resistant buildings with the seismic insurance, the seismic life cycle cost of that is given by the following equation :

$$SLCC = C_I + C_F + L_T + S_T \tag{10}$$

where S_T is the seismic insurance premium which should be paid.

3. Analytical Conditions

For the construction sites, Tokyo, Nagoya and Sendai, the seismic hazard of which is different with each other, are selected. In order to examine that the different seismic hazard influences on the seismic life cycle cost, the soil conditions and the analytical model of buildings are same for all construction sites. The details of the analytical conditions are described as follows.

3.1 Analytical Conditions for Calculating Seismic Intensity

The scenario earthquakes, the magnitude of which is greater than five, are selected. The seismic intensity at engineering bedrock is calculated through Annaka's attenuation model. The uncertainty of its model is given by the lognormal distribution, the lognormal standard deviation of which is assumed to be 0.5. The response spectrum at engineering bed rock is defined by that of AIJ recommendations. The acceleration response spectrum in terms of soil type one is selected. The method, which fits response spectrum due to simulated seismic waves for this target spectrum, is adopted. Several simulated seismic waves are generated by the following method, which is defined by multiplying waves fit for the target spectrum by the Jennings type enveloped function in proportion to the level of magnitude. In addition, the level of seismic intensity at engineering bed rock is changed. As a result, the thirty-nine simulated seismic waves at engineering bed

Table 1 Soil Profile for Surface Layer

Thickness of Layer (m)	Velocity of S Wave (m/s)	Weight per Unit Volume (kN/m^3)	Type of Soil
5	120	14.0	Cohesive Soil
1	180	18.0	Cohesive Soil
6	260	20.0	Sandy Soil
10	395	20.0	Sandy Soil

Table 2 Parameters of Seismic Fragility Curves for Limit Drift Angle

	Minor	Intermediate	Major	Collapse
Median	1/300	1/150	1/75	1/50
Lognormal Standard Deviation	0.4	0.4	0.4	0.4

rock are generated. In order to obtain the simulated seismic waves at ground surface, equivalent liner responses are carried out with respect to the soil profile in Table1.

3.2 Analytical Models

3.2.1 Analytical Model for Earthquake Resistant Building

The ten story R/C building, in which the area of each floor is 1000 square meter, and the total floor area is 10000 meter square, is set for the analytical model. The first natural period is 0.7 sec and the yielding base shear coefficient is 0.3. The vertical distribution of yielding shear coefficient is assumed by Ai distribution which is defined by Japan building code. The yielding drift angle is one over one hundred fifty with respect to all stories. Takeda model is used for the hysteresis restoring force characteristic. The first damping ratio is 3 percent, and the damping matrix is given in proportion to the stiffness matrix.

3.2.2 Analytical Model for Base Isolated Building

This earthquake resistant building is converted into the base isolated building, the natural period of which is 3.55sec. The hybrid base isolated system, which consists of the natural rubber and the hysteresis damper, is adopted. The yielding shear coefficient is 0.05, and the yielding displacement is 1 cm.

3.2.3 Analytical Model for Furniture

The shape of furniture is assumed to be a rectangular prism. The height of furniture is 200 cm, and the width is 50 cm. The distribution of coefficient of friction between the furniture and the floor is modeled by normal distribution, the expectation of which is 0.4, the standard deviation is 0.2.

3.3 Set of Seismic Fragility Curves

Minor, intermediate, major and collapse damages are used for representing the damaged sates of superstructure. The medians and lognormal standard deviations of limit drift angles with respect to the each level of damage are shown in Table 2. The median and lognormal standard deviation of limit relative story displacement at base isolated story are 60cm and 0.3. In the case of furniture, the lognormal standard deviation of seismic fragility curves is assumed to be 0.3.

3.4 Set of Assets Value

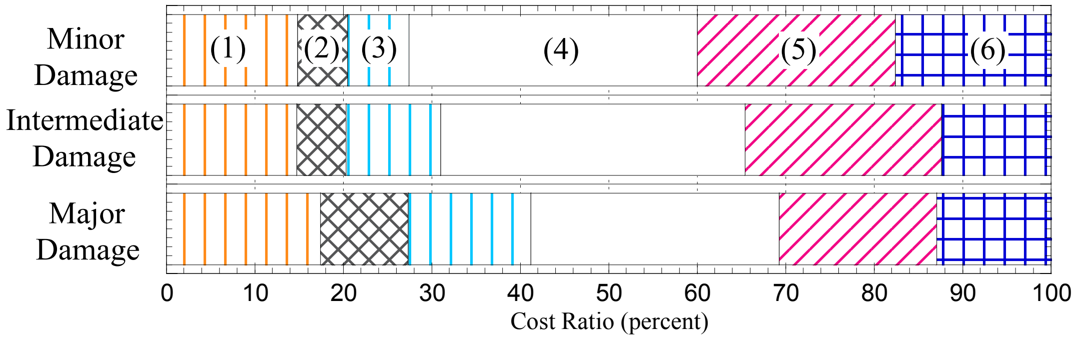
The initial cost of earthquake resistant building is 182000 yen per unit area, and that of base isolated building is assumed to be five percent higher than that of earthquake resistant building. The assets value of furniture is assumed to be 100000 yen per unit area for both buildings. Therefore, the total assets value of earthquake resistant building is 2.82 billion yen, and that of base isolated building is 2.911 billion yen.

3.5 Repair Costs of Buildings

We investigated the repair costs of buildings suffered from the 1995 Hyogo-Ken-Nanbu earthquake, and made out the database of repair costs. The total number of investigated buildings is twenty-seven, and this database consists of eighteen R/C buildings, in which this number includes steel encased reinforced concrete buildings, and nine steel buildings. On the other hand, this database consists of fourteen minor damaged buildings, ten intermediate damaged buildings, and three major damaged buildings respectively. The repair costs per unit area, which are obtained by the repair cost of the whole building over the total floor area, are calculated with respect to each building. The expectations of repair cost per unit area, which are calculated through the repair costs for all buildings, are shown in Table 3. The cost ratios of each building work, which are normalized by the total amount of the repair costs of each building work, are shown with respect to each level of damage in Fig.1. It is found that the cost ratio of skeleton work is around ten percent, that of finishing work is approximately thirty percent, and that of equipment work is about twenty percent regardless of the difference of level of damage. Therefore, it is significant to enhance the seismic

Table 3 Expectation of Repair Costs per Unit Area (yen)

Minor	Intermediate	Major
38,800	87,400	119,000



(1) : temporary work, (2) : demolition work, (3) : skeleton work, (4) : finishing work, (5) : equipment work, (6) : other work, content of which consists of general overheads and design fee etc.

Fig.1 Cost Ratio of Each Building Work

Table 4 Paid Seismic Insurance Money Due to the Damage

Minor Damage	five percent of seismic insrurance money
Intermediate Damage	fifty percent of seismic insurance money
Major Damage	whole of seismic insurance money

Table 5 Seismic Risk Premium Per One Thousand Yen

Tokyo	Nagoya	Sendai
1.58 yen	1.22 yen	0.63 yen

performance of the finishing materials as well as that of the skeleton in order to decrease the seismic loss effectively. In this study, the repair costs per unit area for earthquake resistant buildings are given by these expectations in Table 3. In the case of base isolated buildings, the whole building including the base isolated story is assumed to collapse when the response displacement at base isolated story exceeds the limit displacement. Therefore, the repait cost of this case is given by the total assets value, namely 2.911 billion yen.

3.6 Set of Seismic Insurance

The buildings which are used only for residential purpose can take part in the seismic insurance system which is operated by the Japanese government. The precondition of this seismic insurance system is such that we should take part in the fire insurance. The maximum seismic insurance money of buildings is fifty million yen, and that of furniture is ten million yen. We select the seismic insurance money from thirty to fifty percent of the fire insurance within the maximum seismic insurance money. The seismic insurance money which will be paid due to the level of damage is shown in Table 4. The seismic insurance premium depends on the region, the structural type, the building year and the seismic performance. In the case of earthquake resistant buildings, it is set that the maximum seismic insurance money is selected at fifty percent of fire insurance, the non-wooden category is selected for the structural type and the building year is after 1981. At that time, the seismic insurance premium with respect to each construction site is shown in Table 5 on condition that the seismic insurance money is one thousand yen.

4. Analytical Results

4.1 Some Results

When the peak acceleration is selected for the index of seismic intensity, the seismic hazard curves at engineering bed rock are calculated as shown in Fig.2. The seismic hazard in Nagoya is higher than that of other regions when the annual exceedance probability is approximately lower than 10^{-2}. Through the equivalent liner analysis for the surface layer, several simulated seismic waves at ground surface are generated. As a result, the relation between peak acceleration at engineer bed rock and peak ground acceleration is obtained in Fig.3, and this relation is represented by the regression curve. The relations It is confirmed that the earthquake responses of base isolated building are smaller than that of earthquake

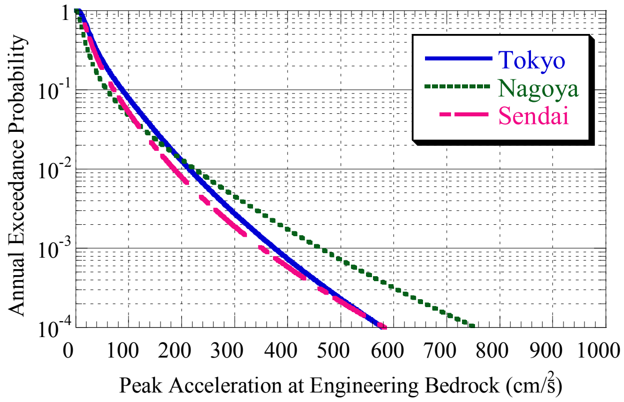


Fig.2 Seismic Hazard Curves at Engineering Bed Rock

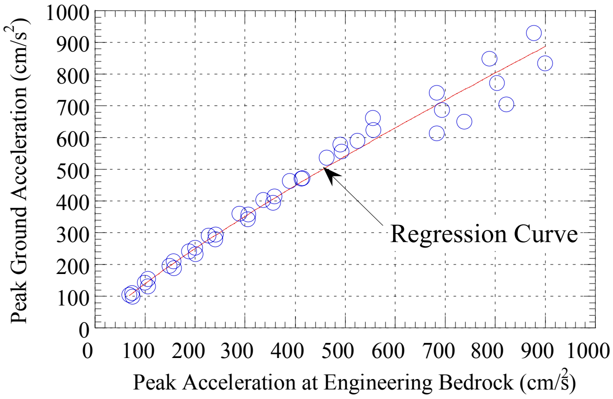
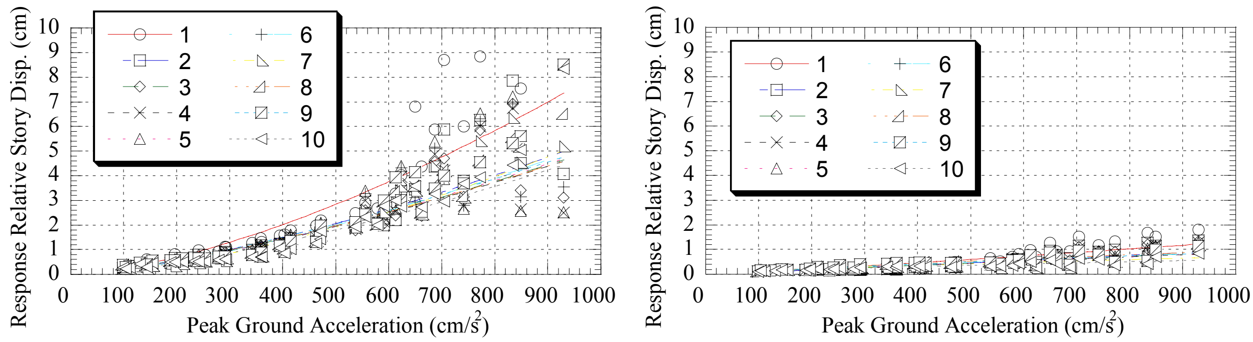
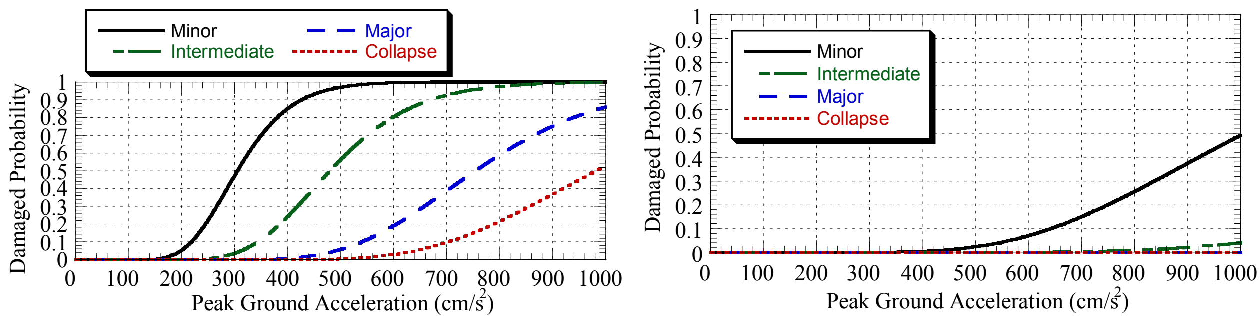


Fig.3 Relation between Peak Acceleration at Engineering Bed Rock and Peak Ground Acceleration

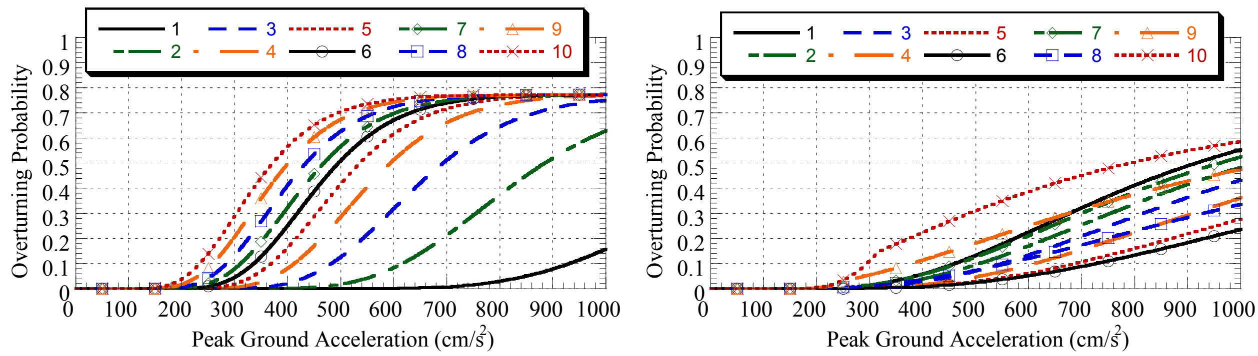


(a)Earthquake Resistant Building *(b)Base Isolated Building*

Fig.4 Relations between Peak Ground Acceleration and Response Relative Story Displacement



SFCs at First Story

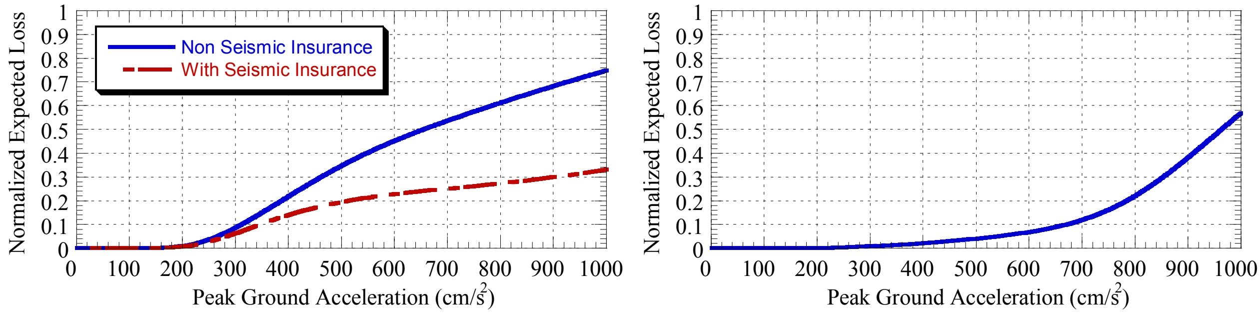


SFCs of Furniture

(a)Earthquake Resistant Building *(b)Base Isolated Building*

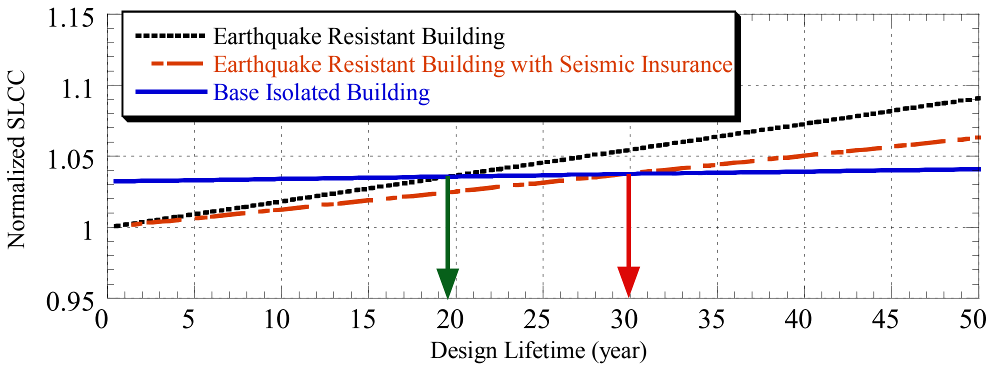
Fig.5 Seismic Fragility Curves

resistant building. The seismic fragility curves are calculated through both these earthquake responses and limit states. For example, the seismic fragility curves of buildings at first story and that of furniture at each

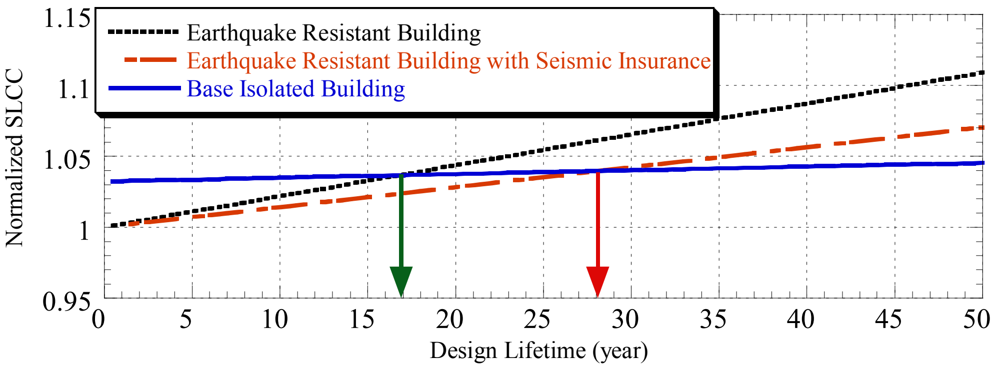


(a)Earthquake Resistant Building *(b)Base Isolated Building*

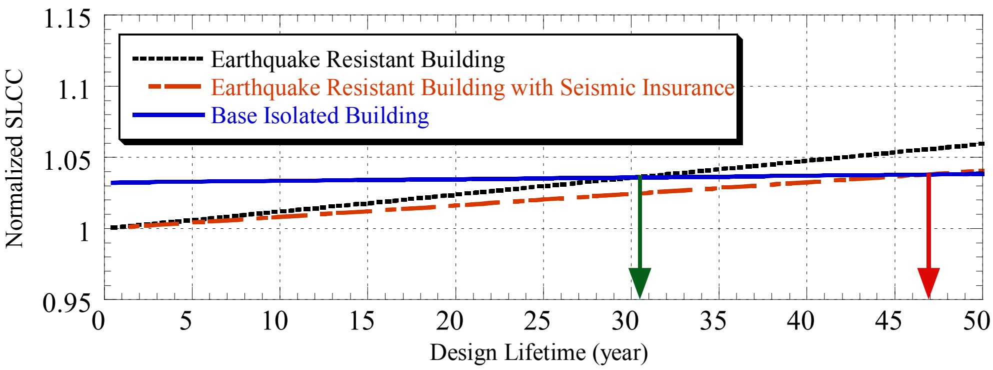
Fig.6 Seismic Loss Curves



(a) Tokyo



(b) Nagoya



(c) SENDAI

Fig.7 Comparison of Seismic Life Cycle Cost

story are shown in Fig.5. In the case of the seismic fragility curves of base isolated building, the damaged probability beyond the intermediate level hardly occurs. According to the seismic fragility curves of furniture of earthquake resistant building, the overturning probability seems to have the upper bound because the overturning probability is evaluated on condition that the furniture does not slide. The seismic loss curves for each case are shown in Fig.6. It is noted that the expected loss is normalized by each assets value, in which

Table 6 Superior period which is defined that the seismic life cycle cost of the base isolated building is smaller than that of the earthquake resistant building. (year)

	Tokyo	Nagoya	Sendai
Earthquake Resistant Building	19.5	17	30.5
Earthquake Resistant Building with Seismic Insurance	30	28	47

the earthquake resistant building is 2.82 billion yen and the base isolated building is 2.911 billion yen respectively. In the case of the earthquake resistant building, the expected loss with seismic insurance is smaller than that of non seismic insurance. Through this seismic insurance system, the earthquake resistant building can effectively transfer the retentive risk.

4.2 Comparison of Seismic Life Cycle Cost

The relations between the design lifetime and the seismic life cycle cost are shown for each construction site in Fig.7. It is noted that the seismic life cycle cost is normalized by the assets value of earthquake resistant building. In the case of the base isolated building, the line of seismic life cycle cost is almost flat, and the expected loss during the design lifetime hardly occurs. Therefore, as the design lifetime is longer, the increment of the initial cost of the base isolated building can be cancelled. The superior period is defined that the seismic life cycle cost of the base isolated building is smaller than that of the earthquake resistant building. The superior period for each construction site is calculated as shown at Table 6. Because the difference of superior period depends on the seismic hazard at each construction site, the superior period of earthquake resistant building in Nagoya is shortest in all constructions. On the other hand, in the case of the earthquake resistant building with seismic insurance, the difference of that also depends on the difference of seismic risk premium in addition to the difference of the seismic hazard. It is found that the superior period with seismic insurance is approximately 1.5 times longer than that of non seismic insurance case in all construction sites. However, as the design lifetime is still longer, the seismic life cycle cost of base isolated building is relatively smaller even if the earthquake resistant building takes part in the seismic insurance. In order to maintain the sustainable development against big earthquakes, the higher seismic performance is needed. The base isolated building, the expected loss of which is smaller than that of the earthquake resistant building, may be selected.

5 Conclusions

In order to maintain the sustainable development harmonizing with the environment, the structural safety is one of important factors as well as the energy conservation and so on. In this study, the seismic performance of building is evaluated from the aspect of the expected loss due to many scenario earthquakes. The seismic life cycle cost is defined by adding the expected loss to the initial cost. The seismic life cycle costs with respect to three different construction sites are calculated in order to compare the earthquake resistant building with the base isolated building. As the design lifetime is longer, the seismic life cycle cost of base isolated building is smaller than that of earthquake resistant building even if the earthquake resistant building takes part in the seismic insurance. Therefore, the increment of initial cost of base isolated building can be cancelled because the base isolated building makes it possible to decrease the expected loss during the design lifetime. In the future, the seismic risk management considering the environment should be established.

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