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ULTIMATE SEISMIC RESPONSE OF A BASE-ISOLATED BUILDING CONSIDERING RANDOMLY RUPTURED ISOLATORS

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Abstract

There has been increasing research interest about rupture of isolators caused by ultimate response of base-isolated buildings due to long-period ground motion exceeding design earthquakes. We conducted seismic response analysis considering the rupture event of rubber bearings and tried to grasp the response characteristics of seismic isolation system and superstructure. As a result of the analysis considering the presence or absence of rupture and the distribution of rupture strain, it was confirmed that the acceleration response can be reduced by the model in which the rubber bearings ruptured or the model with variation in rupture strain. There is a possibility that the acceleration response can be reduced by controlling the rupture of rubber bearings.

Keywords: seismic isolation; isolator; rupture event; rupture strain

1. Introduction

Seismic isolation technology has developed along with learning sereve experiences against frequent earthquakes, and the base-isolation technique has been widely used in the commercial buildings. On the other hand, recently, there has been increasing research interest about the large response of base-isolated buildings due to long-period ground motion exceeding design earthquakes. To avoid hard stop of moat wall impacts or rupture of rubber bearing in the ultimate deformation of isolation layer, some types of isolation devices have been proposed recently. Higuchi et al. [1,2] and Yoshida et al. [3] proposed new seismic isolation devices that combined rubber bearings and sliding bearings. These seismic isolation devices have a two-shift mechanism such that the rubber bearings work within design level earthquakes, and for exceeding the design earthquake the sliding bearings work only in very large deformation. By changing the natural period according to the response magnitude, the whole vibration system cannot reach to resonate completely between the ground motion and the seismic isolation system.

Such behavior of seismic isolation devices using these combined bearings can be realized in the same way by considering breaking or rupture of rubber bearings [4,5]. In the ruptured case, there might be a concern about a loss in the vertical dead load capacity after the rupture of the rubber bearings. For the concern, previous studies by shaking table tests [6-8] have already confirmed that the vertical capacity of rubber bearings is still maintained even after some of the bearings are ruptured. Another concern is that the response characteristics of the seismic isolation system at the time of rupture and after the rupture is not clarified enough, in order to permit the breaking and rupture of the rubber bearing in seismic design. For example, it is necessary to confirm the influence of the rupture event of rubber bearings and its distribution of rupture strain on the seismic isolation system and superstructure.

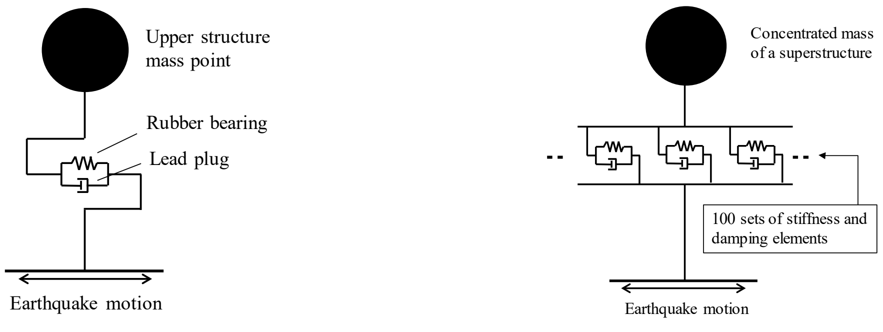
In this study, we carry out seismic response analysis of base-isolated system with lead rubber bearings (LRBs), in order to grasp the response characteristics at the time and after the rupture of rupture of rubber bearings. In the analysis, the model is referred to previous shaking table tests considering rupture events of LRBs. In Chapter 3, we will analyze the seismic response in consideration of the presence or absence of a rupture event deterministically. Here, we investigate the effect of the rupture event of rubber bearings on the seismic isolation system and the response of buildings and inner equipment in the superstructure. In Chapter 4, we will analyze the seismic response when multiple rubber bearings have some distribution in the rupture strain probabilistically. Here, we evaluate the effect of distribution in rupture strain of each rubber bearings on the response characteristics of the seismic isolation system. In Chapter 5, we summarize the findings in the paper, and discuss future issues.

2. Analysis model

2.1 Base-isolated building model

The model of the base-isolated building has a one-mass assuming that the superstructure is a rigid body, as shown in Fig.1. Assume that the weight of the superstructure is supported only by lead rubber bearings (LRBs) and that the dead load always keeps in constant. In order to simulate a seismic response of seismic isolation systems that take into account the rupture of rubber bearings, we refer to a specimen used in the shaking table test conducted at E-Defense in 2008 [9]. In the shaking table test, LRBs that are one-third scale bearings in the size of a real isolator were used. In this study, we applied a similarity law to those scale models and set up a rubber bearing model equivalent to the real size of 1600 mm in diameter. Table 1 shows the basic specifications of the rubber bearing.

In the simulation, the two types of models are employed in Fig.1. In the first model as shown in Fig.1(a), the effect of the presence or absence of a rupture event is examined on the response characteristics of a building assuming that consolidate the seismic isolation layer with a single spring, therefore all rubber bearing breaks simultaneously. In the second model as shown in Fig.1(b), the effect of distribution in rupture strain of rubber bearings will be examined on the response characteristics of buildings assuming a model with 100 rubber bearings shown in Fig.1 (b). In the second model, the rubber bearings can break non-simultaneously.



(a) Concentrated spring model (Chapter 3) (b) Distributed springs model (Chapter 4)
Fig. 1 －Vibration models

Table 1 －Basic specifications of LRBs

	Test	Analysis
Rated load (t)	100	1000
Diameter (mm)	505	1600
Total thickness of rubber (mm)	72	228
Horizontal natural period (s)	1.6	2.8

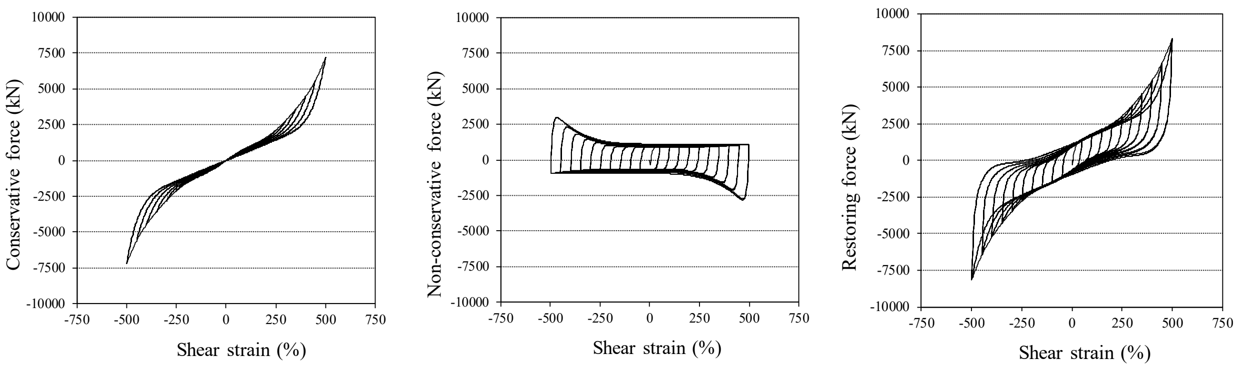
2.2 Restoring force of rubber bearings

The equation of motion of the one-mass vibration model [5] is expressed as equation (1). In this analysis, the restoring force $q(x, \dot{x})$ of the rubber bearing is expressed as the sum of the conservative force and the non-conservative force as shown in equation (2).

$$m\ddot{x} + q(x, \dot{x}) = -m\ddot{x}_g \tag{1}$$

$$q(x, \dot{x}) = q_C(x) + q_N(x, \dot{x}) \tag{2}$$

The conservative force $q_C(x)$ is a force corresponding to the elastic strain energy and it depends only on the displacement. A duffing type model shown in Fig.2(a) is employed for the conservative force $q_C(x)$, which can the hardened response of rubber bearing with a smooth curve. The non-conservative force $q_N(x, \dot{x})$ mainly represents a force dependent on the damping mechanism. A hysteretic model shown in Fig.2(b) is employed for the Non -preserving force $q_N(x, \dot{x})$ that can be modelled as the elastoplastic properties of the lead plug.



(a) Conservative force model (b) Non-conservative force model (c) Restoring force model

Fig.2 —Restoring force characteristics of rubber bearings

2.3 Constitutive law of ruptured and post-ruptured rubber bearings

Since the two deformations of pre-ruptured and post-ruptured rubber bearings are completely different from one another, we employed an analysis model proposed by Hiraki and Kanazawa [5]. In this model, we treat the ruptured rubber bearing in two coordinate axes, that is, in a member coordinate displacement axis and in the overall displacement axis, where those two coordinates are independent one another. In addition, we assume that there is no change in the characteristics of the conservative force and the non-conservative force before and after the rupture of the rubber bearings.

2.4 Rupture conditions and analysis cases

We assume that the shear strain at rupture of the rubber bearing is 500% where horizontal rupture displacement is 1140 mm. Also, in the distributed spring model, different rupture strains are statistically given to 100 rubber bearings. In this study, we use the log-normal distribution [10] which is widely used as the distribution of such statistical values, and set the value of rupture strain as follows.

2.4.1 Rupture strain in log-normal distribution

Of all the parameters governed in the structural properties of the rubber bearing, only the rupture strain is set as a random variable associated with a log-normal distribution. The probability density function (PDF) of the log-normal distribution for the random variable X is expressed by equations (3) and (4). Here, ζ is the standard deviation, and X_m is the median.

$$f(X) = \frac{1}{\zeta X\sqrt{2\pi}} exp\left[-\frac{1}{2}\left(\frac{ln\,X-\lambda}{\zeta}\right)^2\right] \quad (3)$$

$$X_m = e^{\lambda} \quad (4)$$

2.4.2 Rupture strain distribution using uniform random numbers

In equations (3) and (4), the combination of 100 strains that satisfies the given PDF is determined in the following two steps. First, we generate uniform random numbers in the interval (0,1] for the total number of rubber bearings. Second, a random variable is set by associating this random number with a rupture strain via a cumulative distribution function of a log-normal distribution. By using the scheme, a set of random rupture strains, where one set of 100 or 50 strains are determined can be set, as most similar to the log-normal distribution. However, 100 random numbers corresponding to a total of 100 rubber bearings are not enough to satisfy uniformity statistically. Therefore, we prepare 20 sets of distribution of rupture strains for 100 isolators and perform Monte Carlo simulation.

2.4.3 Analysis case settings

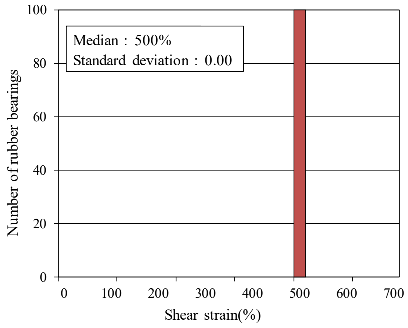
Table 2 shows a list of analysis cases set in this study. Model 1 is a model that does not consider rupture, and models 2 to 5 are models that consider rupture. Further, among the models considering the rupture, models 3 to 5 are the models considering the distribution in the rupture strain. In Chapter 3, we use models 1 and 2 to investigate the effect of rupture on response characteristics. In Chapter 4, in order to evaluate the effect of the distribution of rupture strain on the response properties, we analyse the cases of models 2 to 4 where the median X_m is fixed at 500% and the standard deviation ζ is changed, and the case of model 5 where the standard deviation ζ is fixed at 0.1 and two types of median X_m are set. Fig.3 shows an example of the rupture strain distribution in each cases. As shown in Fig.3(d), only model 5 has two peaks in the rupture strain distribution.

2.5 Input ground motion

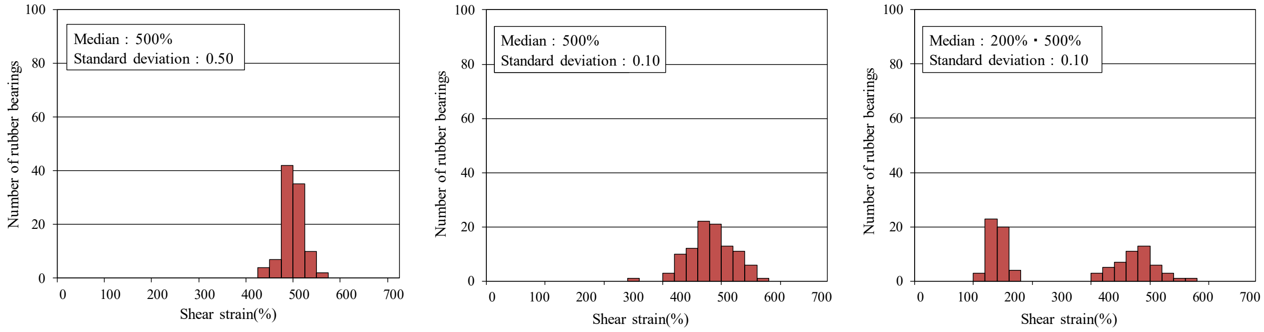
We normalize the strong motion record of El Centro NS (1940) [11] to the maximum velocity of 0.5 m/s for the seismic response analysis, and use the waveforms multiplied by the constant coefficients.

Table 2 －Break conditions for each model

	Consideration of rupture	Median Xm(%)	Standard deviation ζ
Model 1	No	－	－
Model 2	Yes	500	0.00
Model 3	Yes	500	0.05
Model 4	Yes	500	0.10
Model 5	Yes	200,500	0.10



(a) Model 2



(b) Model 3 (c) Model 4 (d) Model 5

Fig.3 －Example of rupture strain distribution

3. Influence of rubber rupture on response of seismic isolation system and superstructure

3.1 Analysis overview

In this chapter, we conduct seismic response analysis to investigate the response characteristics of the seismic isolation system due to rupture of the rubber bearing. Here, we compare two kinds of response of Model 1 without rupture and Model 2 with rupture, where the rupture strain of Model 2 is set to 500%.

We also calculate the floor response spectrum (at damping constant 10%) using the time history response waveform of the building mass calculated by the seismic response analysis in order to examine the effect of the rubber rupture event on the response of the superstructure.

3.2 Analysis result

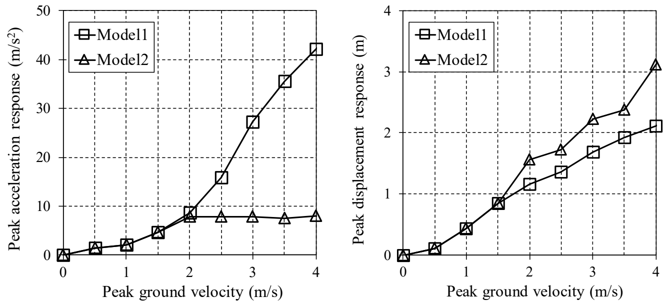
3.2.1 Response on seismic isolation system

Table 3 shows the ruptured results of the rubber bearings of each model, and Fig.4 shows the relationship between the input peak ground velocity and the maximum response. Focusing on the transition of the maximum acceleration of Fig.4(a), it can be seen that in the model 2, when the rubber bearings breaks, the increase in the maximum acceleration has leveled off in 2.0 m/s of input velocity. This reason is that the maximum load becomes constant due to rupture. As shown in Fig.6 the response acceleration at the peak ground velocity is set to 3.0 m/s, where it can be observed that the acceleration response of the model 2 is maximum when the rubber bearings ruptured, and the response thereafter is smaller than that of the model 1. Next, focusing on the maximum displacement in Fig.4(b), it can be seen that the maximum displacement of the model 2 is larger than that of the model 1 within the range of the peak ground velocity of 2.0 m/s or more. According to the load-displacement relationship at the peak ground velocity of 3.0 m/s shown in

Fig.5, it can be seen that the center of the vibration of the displacement is shifted to the minus-side after the rubber ruptured. From this point of views, it is considered that the maximum displacement of Model 2 after rupture increased due to the bias of displacement vibration.

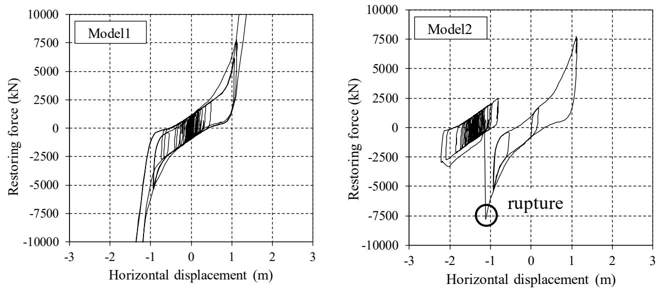
Table 3 —Presence or absence of rupture in LRBs (× is ruptured)

Model	Input peak ground velocity (m/s)						
	1.0	1.5	2.0	2.5	3.0	3.5	4.0
Model1	-	-	-	-	-	-	-
Model2	-	-	×	×	×	×	×



(a) Peak acceleration response (b) Peak acceleration response

Fig.4 —Relationship between maximum response and input level



(a) Model1 (b) Model2

Fig.5 —Load-displacement relationship (at maximum input speed of 3.0 m/s)

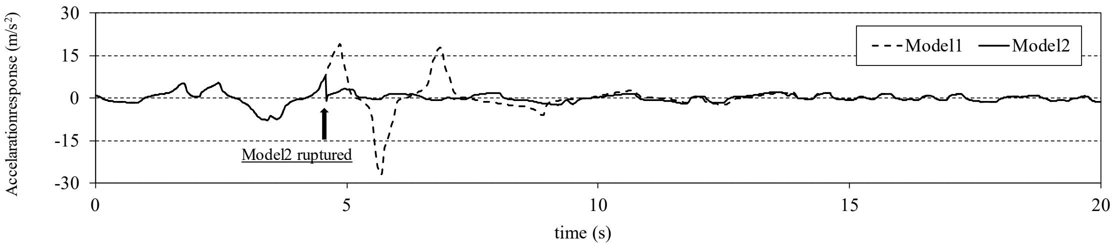
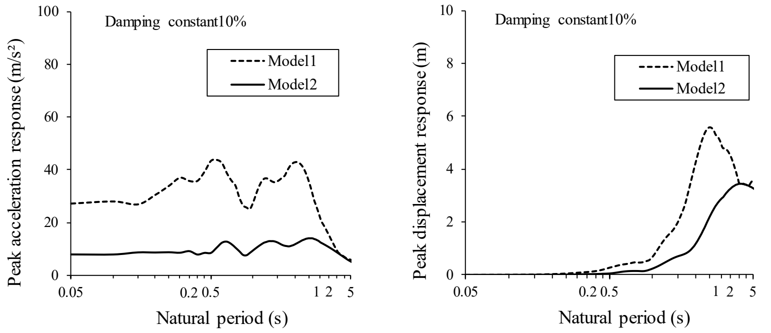


Fig.6 —Time history of Response acceleration (Input velocity is 3.0 m/s)

3.2.2 Floor response spectrum

Fig.7 shows the floor response spectrum at the peak ground velocity of 3.0 m/s. It can be seen that, for all response values, the response of model 2 is lower than the response of model 1 in the range of the natural period of 4.0 s or less. In particular, it can be seen that the maximum acceleration is reduced to about 1/3 around the peak period of the natural cycle of 0.5 s and 2.0 s. This suggests that the rupture event of the rubber bearings does not always have negative influence to the building response, and that the response can be reduced by controlling the rupture.



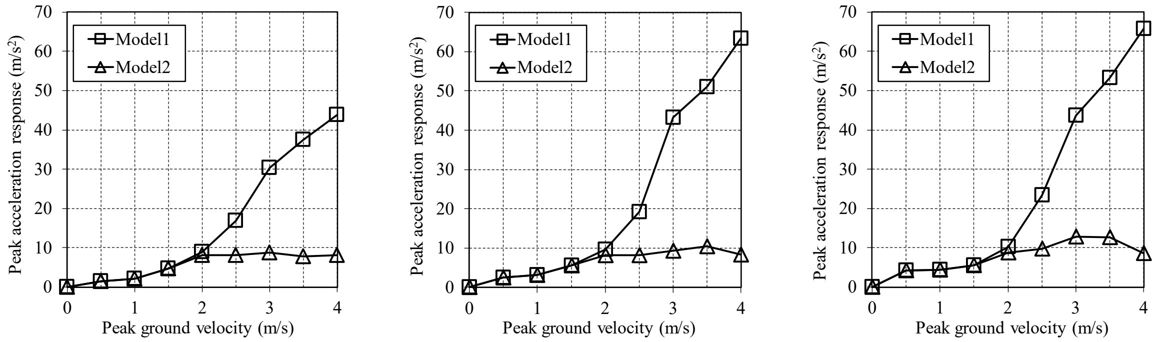
(a) Peak acceleration response (b) Peak displacement response
Fig.7 —Floor response spectrum (Input ground velocity is 3.0 m/s)

Table 4 —Range of period in Fig.8

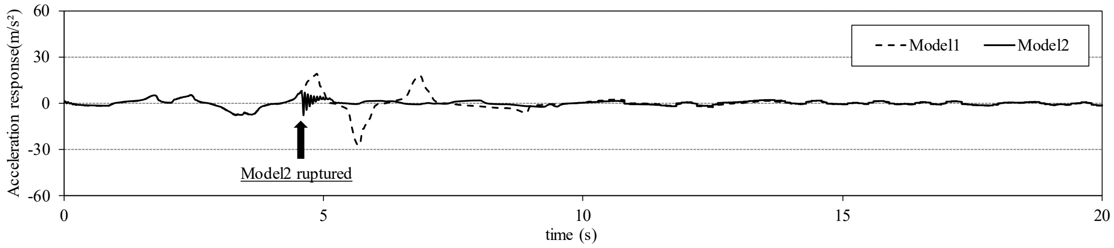
	Period range	Target
(a)	0.05 s ~ 0.20 s	Furniture and equipment
(b)	0.20 s ~ 0.50 s	RC structure
(c)	0.50 s ~ 1.00 s	Steel structure

Next, in order to clarify the characteristics of the floor response spectrum, we analyze the response value for each specific natural period range. As shown in Table 4, three ranges of natural periods are set with considering for the structure and facilities on the superstructure. We pick up the maximum value of the response spectrum of acceleration within each natural period range and investigate the relation with the peak ground velocity. Fig.8 shows the result. It can be seen that all of the graphs in Fig.8 show a tendency of increase similar to the maximum acceleration of the building mass as shown in Fig.5. Comparing 8(a) to (c) in detail, the model 1 in which no rupture occurs tends to have a slightly larger maximum acceleration response as the natural period becomes longer. In addition, the response value is about 30% larger in the natural period of 0.5 to 1.0 s than one in the natural period of 0.05 to 0.20 s. This tendency also appears in Model 2 when rupture occurs, and when compared at a flat portion of 2.0 m/s or more where the response peaks, the response value of the natural period of 0.5 to 1.0 s is only about 30% different from that of the natural period of 0.05 to 0.20 s. As described above, it was confirmed that even when the rupture occurred, the response of the superstructure was stable without being excessive response in all periodic region.

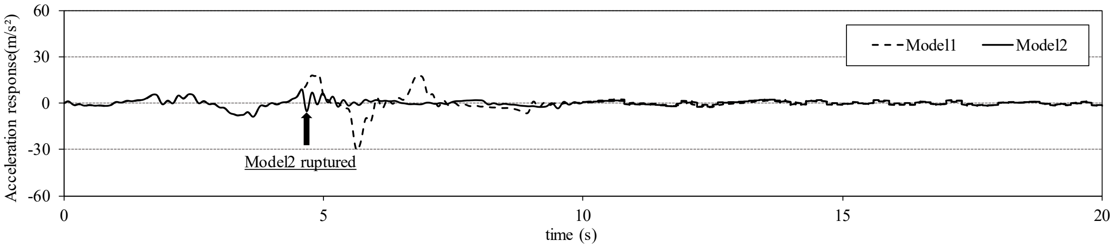
In order to discuss the fact further, Fig.9 shows the response acceleration history of the added one-mass system model calculated in the process of calculating the floor response spectrum. The response values of the model with four periods are shown in the subtitle, which are the boundaries of the setting range of the natural period in Table 4. In the graph of 0.05 s or 0.20 s such as in a short natural period added system, the free vibration waveform can be clearly appeared at the time of rupture. It is considered that these free vibrations are caused by the sudden change of acceleration at the building mass generated at the time of rupture (see Fig.6). On the other hand, as shown in Fig.9 (iv), the maximum value of the response acceleration occurs before the rupture where this maximum response have no causal relationship with rupture. As stated above, it can be confirmed that the acceleration on the superstructure does not become excessively larger at the moment of the rupture.



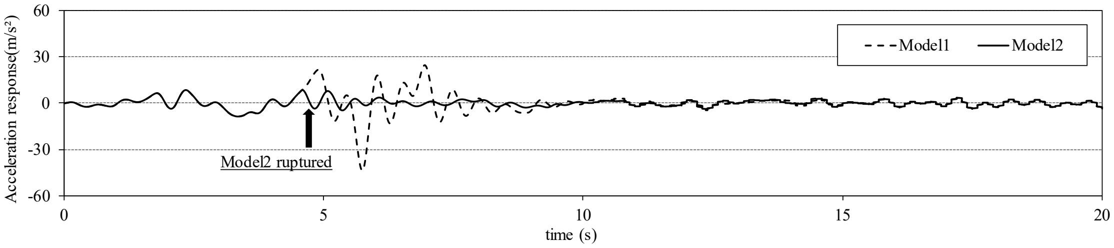
(a) Natural period 0.05 s ~ 0.20 s (b) Natural period 0.20 s ~ 0.50 s (c) Natural period 0.50 s ~ 1.00 s
Fig.8 —Relationship between floor response spectrum values and input level



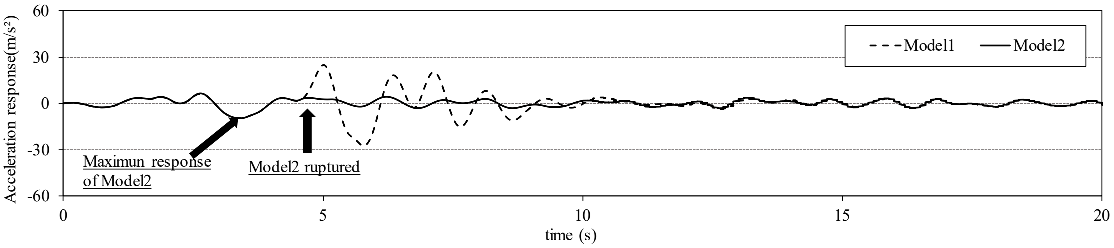
(i) Natural period 0.05 s



(ii) Natural period 0.20 s



(iii) Natural period 0.50 s



(iv) Natural period 1.0 s

Fig.9 —Response acceleration of added mass (Input velocity of 3.0 m/s)

4. Effect of distributed rupture strain on response of seismic isolation system

4.1 Analysis overview

In this chapter, we conduct seismic response analysis with considering probabilistically-distributed rupture strain described in Fig.3 and section 2.4, in order to evaluate the effect of the distribution of rupture strain of rubber bearing on the response of seismic isolation system. In Section 4.2, we will discuss the distribution in rupture strain assuming the manufacturing error of the rubber bearings. In Section 4.3, we will discuss the distribution in rupture strain when rubber bearings that rupture occur in very small strain will be employed as a design method.

4.2 Effect on the standard deviation

In this section, we analyzed on the models 2 to 4 as prescribed in Table 2. We fixed the median value at X_m = 500% and used the three types of log-normal distribution in which the standard deviation was changed, $\zeta = 0$, 0.05 and 0.10. In Model 2 where $\zeta = 0$, a deterministic analysis was performed only for one case, since there was no distribution in the rupture strain and the number of the sample is one case.

Fig.10 shows the results of the time history response analyses, summarizing the 20 calculation results for each model. In Model 3 and Model 4, the tendencies that the number of ruptures is growing with input can be observed slower than that in Model 2. When the input velocity is 2.0 m/s, the almost half numbers of LRBs are remained with non-ruptured in Model 3 and Model 4, whereas the rupture occurs completely in the deterministic analysis of Model 2. With considering the relations between input velocity and ruptured status, we will discuss peak response characteristics associated with rupturing LRBs.

Focusing on the peak acceleration response as shown in Fig.10(ii), the upper-limits are clearly observed for larger inputs, that is, in the input ranges of 2.0m/s or more, as already discussed in Chapter 3. It is also observed that the values of those upper-limits tend to be gradually smaller with increasing standard deviation in rupture strains. Alternatively, peak displacement and residual displacement might not be related with standard deviation in ruptured strains, however, Model 2 where the ruptured strains are set deterministically, gives lager displacements rather than the probabilistic models of Model 3 and Model 4. These results indicate that the seismic isolation members must not to have the same performance value in the event of a rupture, and it is suggested that the maximum response value can be reduced by having some distribution.

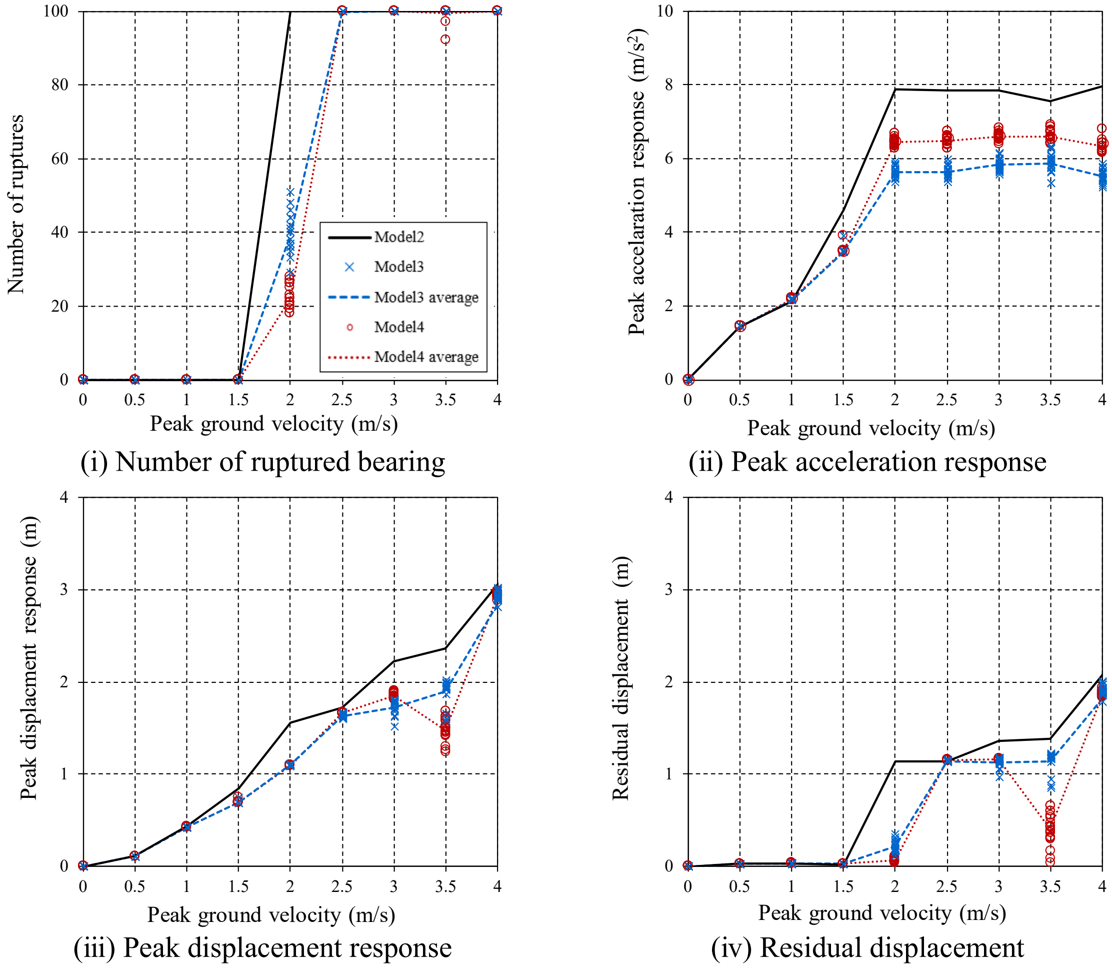


Fig.10 —Response results comparing with the standard deviation is changed

4.3 Effect on distributions with one-median or two-median

The ruptured response of Model 4 and Model 5 will be discussed on two different distributions in rupture strain, where Model 4 has one-peak distribution as shown in Fig.3(c), whereas Model 5 has two-peak distribution as shown in Fig.3(d). In Model 5, a log-normal distribution is used in which the standard deviations are fixed at $\zeta = 0.1$, and the medians are set to X_m = 200% and 500%.

Fig.11 shows the results of the response analyses, summarizing 20 results for each model. As shown in Fig.11(i), in Model 5 the input range when some of the LRBs are ruptured but all LRBs are not ruptured, is greater than that in Model 4. Especially it is notable that in input velocity 2.5m/s, all LRBs are completely ruptured in Model 4, but some of the LRBs have not ruptured in Model 5; that is, the isolation layer in Model 4 is stronger than that in Model 5, in the sense that the input acceleration level is greater when all LRBs are ruptured, although the half number of LRBs in Model 5 is set to be very small ruptured strain.

This strange effect also appears in peak response. By comparing the maximum accelerations, it can be observed that the upper limit of the Model 5 is smaller than that in Model 4. On the other hand, there is no significant difference between the two models in the maximum displacement and the residual displacement. Focusing on the variation, it is confirmed that the scattering of response in Model 5 is almost similar to that in Model 4. It is suggested that by arranging the rubber bearings having different rupture characteristics and controlling the number of ruptures, it is possible to prevent a sudden increase in the ultimate seismic response of base-isolated building.

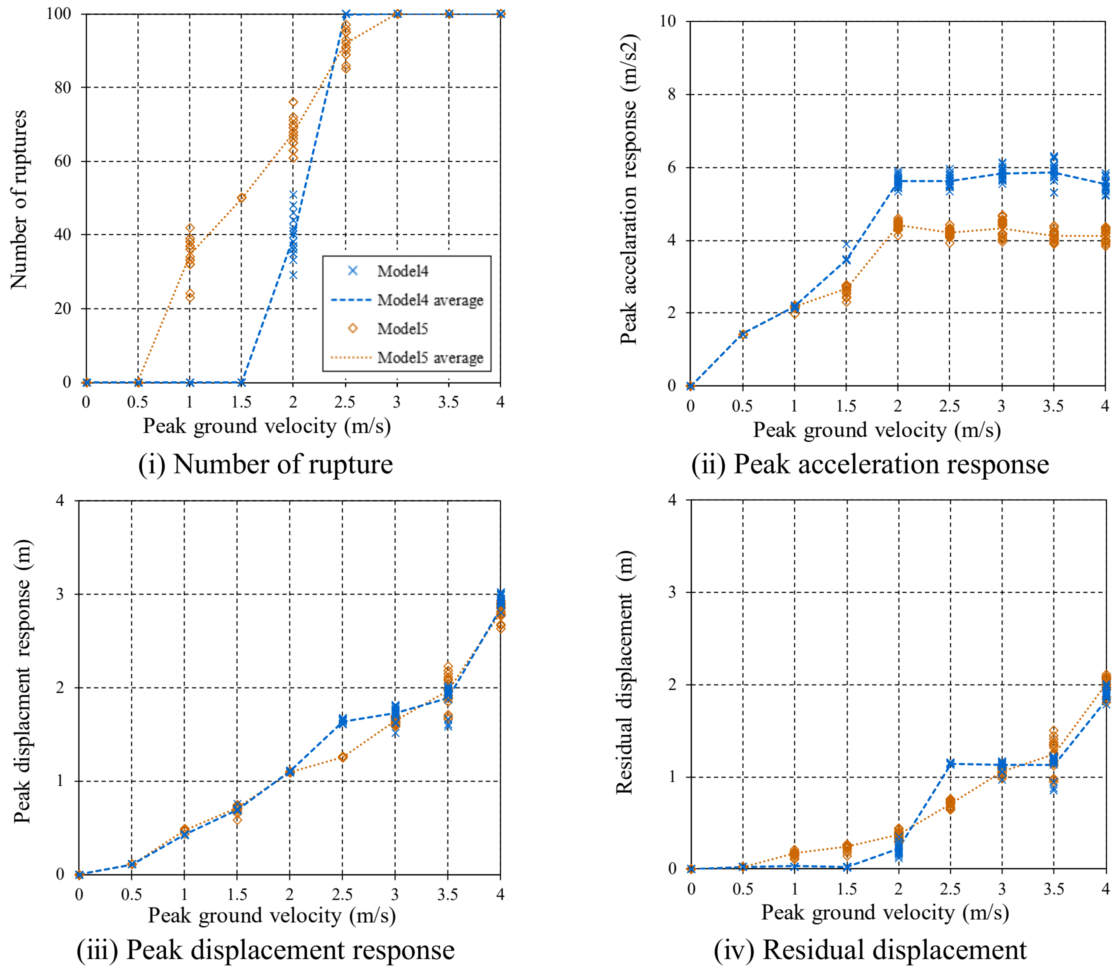


Fig.11 —Response analysis when the type of fracture strain distribution is changed

5. Conclusions

In this study, we performed a seismic response analysis considering the rupture event of the rubber bearing, and analyzed the effect of the presence or absence of a rupture event and the difference in rupture strain distribution on the response characteristics of the seismic isolation system and the superstructure. The main results are summarized below.

1） It is confirmed that the maximum response acceleration tends to peak after breaking and the peak values are constant against the large input acceleration. On the other hand, it is suggested that the maximum displacements tend to increase after the rupture of the rubber bearing, when the center line of vibration has shifted.
2） It is confirmed that the response at the superstructure is reduced by the rupture of the rubber bearing. The fact suggests that the response of superstructure can be controlled by operating the ruptures.
3） The distribution of rupture strain of each rubber bearing must not be always required to be uniform, and it is suggested that the more scattered distribution can reduce the acceleration response of the superstructure.
4） It is found that when two types of rubber bearings are arranged having extremely different breaking characteristics, the maximum acceleration response can be smaller than that when only one type is arranged. But the maximum displacements in the two models are almost the same as each other. There is a possibility that response can be controlled by arranging rubber bearings having different rupture characteristics.
5） However, it was also confirmed that the response displacement of the seismic isolation system became larger when the rupture occurred. Thus, development on vibration control of the response displacement is a future problem.

6. References

[1] H.Hamaguchi, M.Yamamoto, M,Higashino, et al. (2010), A proposal of an isolation system with high safety margin for unexpected input ground motions (Part1) Outline. *Summaries of Technical Papers of Annual Meeting AIJ*, B, II, 437-438.

[2] H.Hamaguchi, T.Wake, M.Yamamoto, et al. (2017), A proposal of an isolation system with higher seismic safety against input ground motions beyond expectations. *Journal of Structural and Construction Engineering* (Transactions of AIJ), pp.1349-1359.

[3] S.Yoshida, Y.Tashiro, A.Ito, et al. (2017), Development of excessive displacement suppression isolator (Part1-3). *Summaries of Technical Papers of Annual Meeting AIJ*, II, 928-932.

[4] T.Hiraki, K.Kanazawa, M.Ikeda, et al. (2016), Development of seismic isolation technology for nuclear plant (Part27), *Summaries of Technical Papers of Annual Meeting AIJ*, II, 1347-1348.

[5] T.Hiraki, K.Kanazawa, H.Kitamura, (2017), Seismic response analysis of a seismic isolation system for evaluating mechanical energy balance. *Journal of Structural and Construction Engineering* (Transactions of AIJ), pp.405-415.

[6] M.Kurimoto, S.Nakae, K.Inaba, et al. (1989), Shaking table test on ultimate behavior of base-isolated structure supported by rubber bearings. *Summaries of Technical Papers of Annual Meeting AIJ*, B, I, 467-468.

[7] A.Matsuda, K.Isida, H.Shiojiri, et al. (1991), Ultimate excitation test of seismic isolation system by shaking table (Part4). *Summaries of Technical Papers of Annual Meeting AIJ*, B, I, 647-648.

[8] H.Mizuuchi, A.Kato, K.Mizukoshi, et al. (1992), Study concept of seismic isolation type plant for FBR (Part15). *Summaries of Technical Papers of Annual Meeting AIJ*, B, I, 1577-1578.

[9] K.Kanazawa, S.Yabana, S.Nagata, et al. (2012), Seismic response of base-isolated structure including rupture state of rubber bearings － Ultimate behavior of large-scale base-isolation system using the E-Defense shake table Part 1－. *Journal of Structural and Construction Engineering* (Transactions of AIJ), pp.1383-1392.

[10] Alfredo.H.S.Ang, et al (2007), Basics of probability and statistics for civil engineering and construction, *Maruzen-Yushodo Company, Limited.*

[11] Building performance standardization association, Representative seismic waves (acceleration data), (http://www.seinokyo.jp/jsh/top/) .

