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Durability of Rubber Isolators by Long-Duration Ground Motion due to Large Earthquakes

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ABSTRACT :

In Japan, the Tokai earthquake and the Tonankai earthquake are expected to occur in the near future. Due to these earthquakes, the possibility of suffering from a big shake is pointed out in the big city around the Pacific Ocean coast. It is expected that the vibration continues for a long time especially in high rise buildings and seismic isolated buildings with a long natural period. The response displacement of seismic isolated building become greater than the design displacement, and the re-verification of the energy dissipation capacity of isolation devices is required.

In this research, the dynamic experiments of lead rubber bearings (LRB) and high damping rubber bearings (HDR) carried out to verify the energy absorption capacity. In the experiments, the repetition of 200 cycles or more and the maximum shear strain of 200% was examined (the total loading time is 600 seconds). The maximum temperature of the center of HDR (LRB) specimen reached over 80 (100) Celsius in accumulated displacement about 70m. The hysteretic characteristics were changing in the experiment along with the repetition (remarkably decrease in the yield force and the equivalent stiffness), and it was clarified that the energy dissipation capacity was decreasing as the temperature increasing. The characteristics of the specimen almost returned to the initial state after the temperature had decreased. The influence that the change in these hysteretic characteristics gave to the maximum response in seismic isolated building was verified by the response analysis. As the results, it was shown that it was important to evaluate the change in the hysteretic characteristics of isolation devices appropriately.

KEYWORDS: Seismic Isolation, Rubber Bearing, Dynamic Tests, Response Analysis

1 INTRODUCTION

Since the 1995 Hyogo-ken Nanbu Earthquake, seismic isolated buildings have dramatically increased. The seismic isolation system has become frequently applied to apartment buildings other than disaster-prevention facilities such as hospitals, so the period of seismic isolated building has become long.

Meanwhile, when the 2003 Tokachi-oki Earthquake occurred, a petroleum tank in Tomakomai was damaged by sloshing of liquid by a long-period ground motion. The duration time of this type ground motion is long and its dominant periods are also long. When the 2004 Niigata Chuetsu Earthquake and the 2007 Niigata Chuetsu-oki Earthquake occurred, large earthquake motions were observed at the neighborhood of epicenter. The velocity response spectrums and the energy spectrums of these earthquake motions are shown in Fig. 1. The velocity level of response spectrum that is taken into consideration at earthquake-resisting design in Japan is approximately 100 cm/s. The observed earthquake motions exceeded this level for design.

In this study, firstly, we carried out the dynamic experiments, presuming the long-duration ground motion. The lead rubber bearing and the high damping rubber bearing were used in this experiment. It showed how the hysteresis characteristics of rubber bearing are changed by being deformed repeatedly for 200 cycles or more. Based upon the experimental results, the maximum response of seismic isolated building was validated by time history analysis.

2 RESPONSE PREDICION BASED ON ENERGY BALANCE

It can be presumed that seismic isolation layers of seismic isolated building can absorb all earthquake input energy.

The characteristics of seismic isolation layers are presumed to be able to be shown in the bilinear type as shown in Fig. 2. Equation (1) was obtained as energy equilibrium equation in seismic isolation layer.

$$W_e + W_p = E \tag{1}$$

W_e of Equation(1) is the elastic vibration energy, and it is obtained in Equation (2) as the energy absorbed by the linear spring (Isolator) K_d shown in Fig. 2(b). δ_{max} is the maximum displacement of seismic isolation layer.

$$W_e = \frac{1}{2} K_d \delta_{max}^2 \tag{2}$$

W_p is the elasto-plastic strain energy, which is equivalent to the absorbed energy by the entire elasto-plastic spring (damper) as shown in Fig. 2(c). If the yield load and accumulated plastic deformation of damper are Q_d and δ_p, respectively, Equation (3) is obtained.

$$W_p = Q_d \delta_p \tag{3}$$

The energy input E of the earthquake is converted to the equivalent velocity V_E by Equation (4).

$$E = \frac{M V_E^2}{2} \tag{4}$$

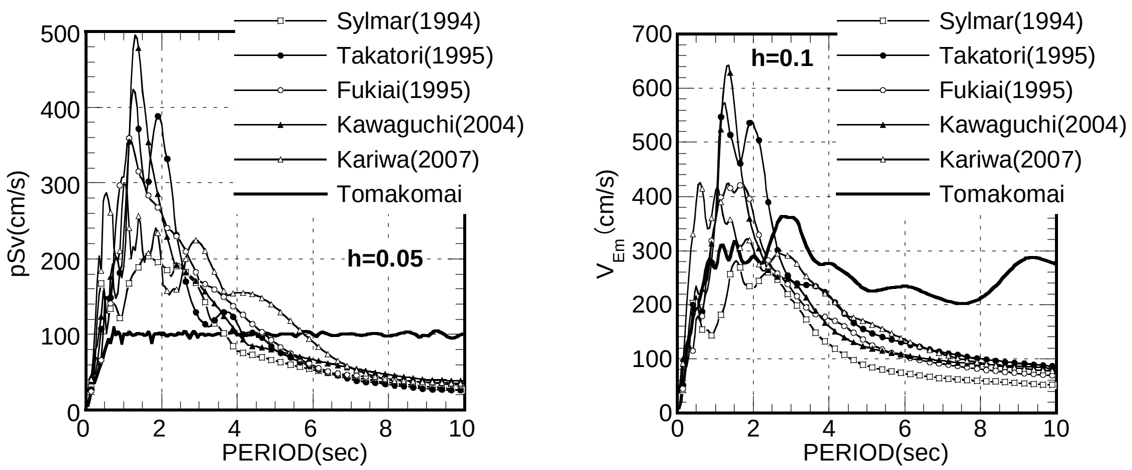
Substitute Equations (2)-(4) to Equation (1) and sort out it with Equations (5) and (6), then Equation (7) is obtained.

$$T_d = 2\pi \sqrt{\frac{M}{K_d}} \tag{5}$$

$$\alpha_s = \frac{Q_d}{Mg} \tag{6}$$

where, M : the total mass of building, g : the acceleration of gravity

$$\frac{4\pi^2}{T_d^2} \delta_{max}^2 + 2g\alpha_s \delta_p = V_E^2 \tag{7}$$



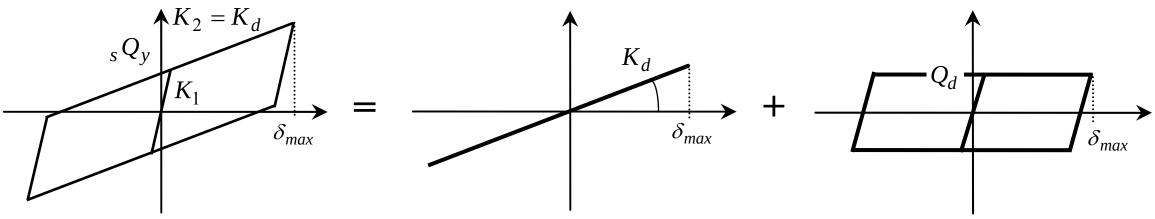
(a) Velocity Response Spectrum (b) Energy Spectrum

Fig.1 Response Spectrum of Observed Ground Motions

Equation (7) shows that the period of isolator T_d and the yield shear coefficient of the damper α_s are largely related to the response characteristics of seismic isolated structure. δ_p / δ_{max} affects the accuracy of response prediction. All earthquake input energy is absorbed by damper ultimately. Therefore $W_p = E$, and the accumulated plastic deformation of damper δ_p is obtained in the simple form like Equation (8).

$$\delta_p = \frac{V_E^2}{2g\alpha_s} \tag{8}$$

The relationship between the accumulated plastic deformation of damper δ_p and V_E is shown in Fig. 3. It shows that when α_s is small, the accumulated plastic deformation necessary to absorb earthquake energy becomes very large.



(a) Total System (b) Isolator (c) Damper

Fig.2 Restoring Force Characteristics of Isolation System

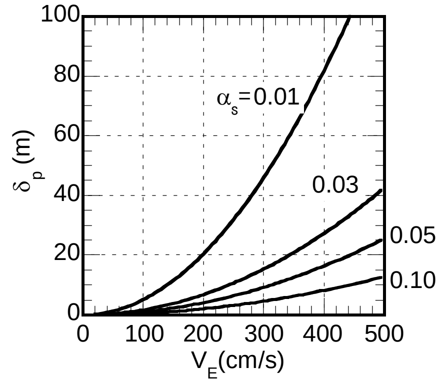


Fig.3 Relationship between Energy Input and Cumulative Plastic Deformation

3 EXPERIMENTS OF RUBBER BEARINGS

In order for the energy absorption capacities of lead rubber bearing and high damping rubber bearing to be confirmed, the dynamic experiment with 200 cycles was conducted. The compressive shear tests were carried out in each test specimen. The compressive stress (surface pressure) was kept at 8N/mm^2 constantly during the test, and the experiment was repeatedly performed at 200% shear strain for 200 cycles. The accumulated deformation was approximately 70m. The input waveform was a sine curve and the frequency was 0.33 Hz. The heat distribution within the rubber bearing was measured with a thermo couple at the experiment. In order for the heat conduction through the experiment equipment to be prevented, a heat insulation board (10mm thickness) was placed between the test specimen and experimental equipment.

3.1 Lead Rubber Bearing (LRB)

Fig. 4 shows the section plan and Table 1 shows the specification of the specimen. The material of rubber of LRB is natural rubber and that of HDR is high-damping rubber. The diameter of test specimen is 225mm and the total rubber thickness is 44mm. The diameter of the lead plug is equivalent to 1/5 the external diameter of the rubber bearing.

The shape factors in the table were calculated by the following equations:

$$\text{Primary shape factor} \quad S_1 = \frac{D}{4t} \qquad \text{Secondary shape factor} \quad S_2 = \frac{D}{nt} \tag{9}$$

where, D: Diameter of rubber bearing, n: Number of rubber layers, t: Thickness of a rubber layer

Fig. 5 shows the relationship between horizontal displacement and horizontal load obtained by the experiment. The hysteresis characteristics are the largest at the first cycle, and the hysteresis loop (yield load) becomes reduced with increasing the repeated cycles. The same experiment using the same specimen for 200 cycles was repeated four times on different days. 800 cycles tests were performed in total, but there were no marked changes in the hysteresis characteristics up to 600 cycles at least. As stated above, the characteristics of rubber bearing change by being repeatedly deformed, but, when it was deformed again after it was left for more than one day, the characteristics of rubber bearing showed the same ones as before. It is considered that the characteristics of rubber bearing return to original ones.

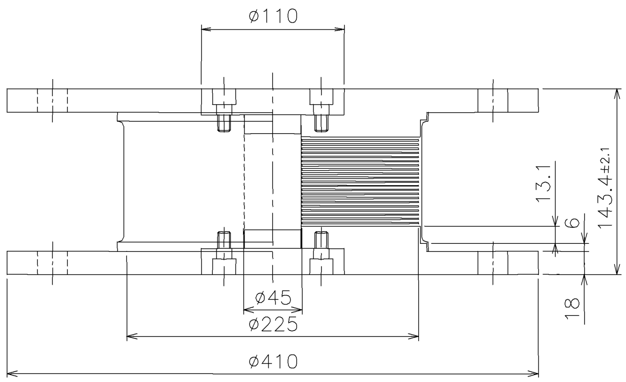


Fig.4 Section Plan of LRB Specimen

Table 1 Specification of the Specimens

Specimen	LRB	HDR
Rubber Material	Natural Rubber (G=0.39N/mm^2)	High Damping Rubber (G=0.62N/mm^2)
Diameter	φ225mm	
Diameter of Lead Plug	φ45mm	—
Rubber Sheet	2.0mm×22 layers=44.0mm	
Steel Plate	1.2mm×21 layers	
Shape Factor	S_1=28.1, S_2=5.11	

Fig. 6 and Fig.7 show the changes of K_d and Q_d caused by the increase of hysteresis absorption energy W_p. From these figures, the ratio of change of K_d was -5.4% at the third cycle of 200 cycles and that of Q_d was -41.7%. From these results, it revealed that although the change of K_d (stiffness after yield) on the hysteresis curve was small, the yield load largely decreased. It decreased approximately to -30% at around the first 10 cycles, in particular, so you should pay special attention to this point in establishing a restoring force model for response analysis.

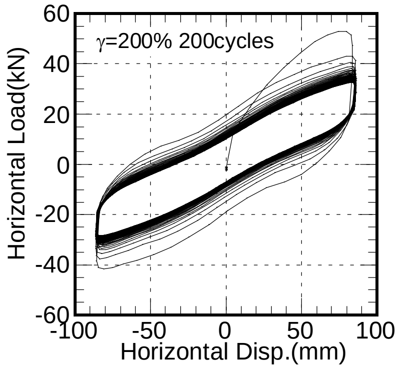


Fig.5 Hysteresis Loop of LRB

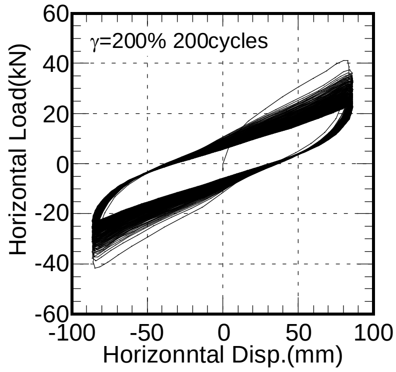


Fig.9 Hysteresis Loop of HDR

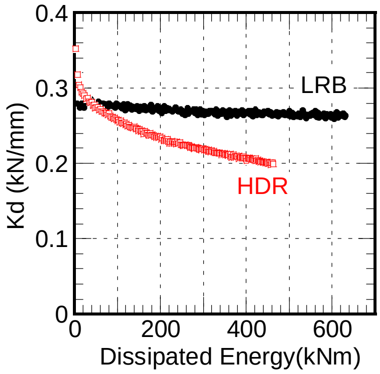


Fig.6 Variation of K_d

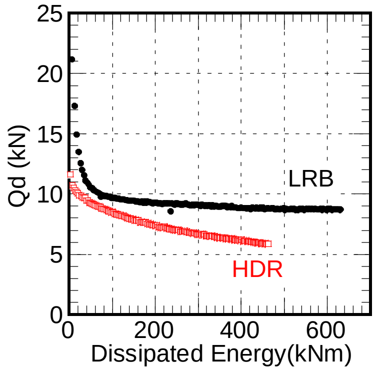


Fig.7 Variation of Q_d

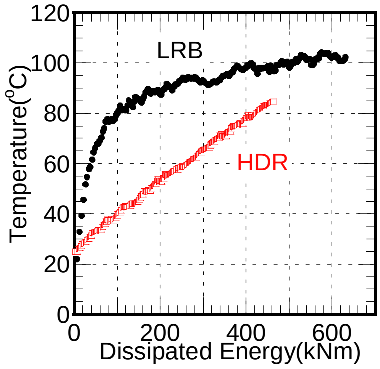


Fig.8 Variation of Temperature

Fig. 8 shows the relationship between the temperature measured at the upper part of lead plug and the absorbed energy. The temperature measured at the upper part of lead plug reached 100℃ at the maxim and it rapidly decreased after the completion of vibration input. The melting point of lead is approximately 320℃, so the temperature of the lead plug might not have reached the melting point.

3.2 High Damping Rubber Bearing (HDR)

The shape of the test specimen of HDR is nearly the same as that of LRB shown in Fig. 4 and Table 1. Fig. 9 shows the hysteresis characteristics of the test specimen of HDR. The horizontal stiffness of the hysteresis curve decreased with the repetition of the test and the hysteresis loop area also reduced in size. The equivalent stiffness, K_{eq}, decreased with the increased repetition of the test, and the equivalent viscous damping constant, H_{eq}, changed only in the range from 0.17 to 0.15.

Commonly, an equivalent viscous damping constant H_{eq} is obtained by the following equation:

$$H_{eq} = \frac{1}{4\pi}\frac{W}{\Delta W} \tag{10}$$

where, W : hysteresis loop of one cycle, ΔW : elastic energy $\left(=\frac{1}{2}K_{eq}\delta_{\max}^2\right)$

From the above equation, hysteresis loop W is expressed by the following equation:

$$W = 4\pi \cdot H_{eq} \cdot \Delta W = 2\pi\delta_{\max}^2 \times K_{eq} \cdot H_{eq} \tag{11}$$

In other words, the hysteresis loop of high damping rubber bearing (energy absorption capacity) is proportional to H_{eq} and K_{eq}.. Even if H_{eq} is constant, if equivalent stiffness decreases, it is necessary to make sure that energy absorption capacity decreases.

The period of seismic isolated building is lengthened because of the decrease of equivalent stiffness, and subsequent decrease of energy absorption capacity is caused by the decrease of hysteresis loop area. These factors possibly lead to the increase of response deformation. You should be careful in establishing the restoring force characteristics used in the response evaluation in the case where the loading is being repeatedly applied.

Fig. 6 and Fig. 7 show the changes of K_d and Q_d caused by the increase of hysteresis absorption energy. Comparing to LRB, K_d and Q_d of HDR are mildly decreasing.

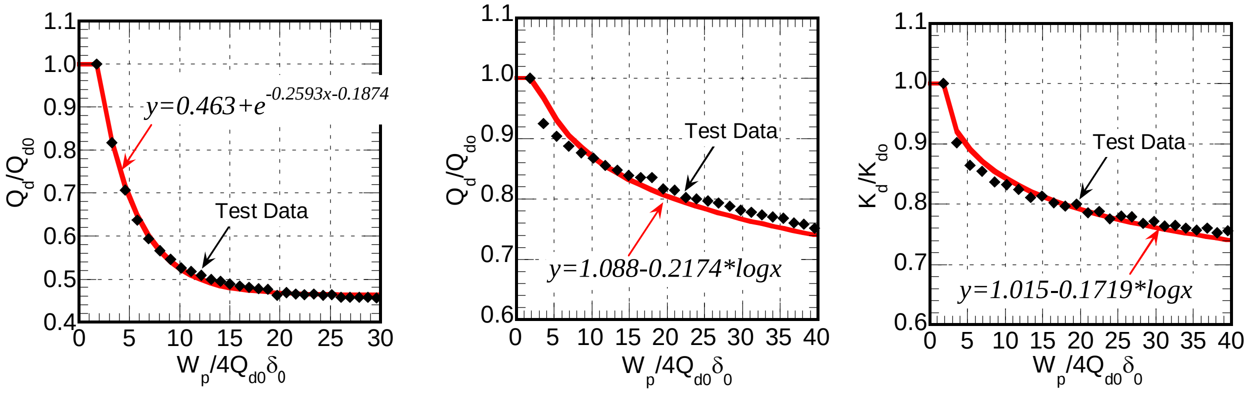
Temperature of HDR is measured with the thermo couple at the central part, the position of approximately 1/2 of the radius of the rubber bearing and the surface of the rubber. Fig. 8 shows the results of measuring the temperature at the central part of the rubber bearing. The temperature in the radial direction becomes higher toward the central part and becomes lower toward the surface. The temperature of the central part of rubber reaches about 80℃ at maximum, but stays below the melting point of rubber.

4 TIME HISTORY RESPONSE ANALYSIS

It was revealed by the dynamic experiments of rubber bearing that the energy absorption capacity is decreasing. In order for these changes of characteristics affecting earthquake response to be confirmed, time history response analysis was performed. The analytical model was a one-degree-of-freedom model consisting of seismic isolation layer only. The seismic isolation layer has the bi-linear characteristic as shown in Fig. 2.

In modeling of restoring force characteristics of LRB, the horizontal stiffness K_d was fixed, and the yield load Q_d was changed. The relationship between yield load and hysteretic absorption energy W_p is shown in Fig. 10(a). The hysteretic absorption energy is standardized by being divided by $4Q_{d0}\delta_0$. Q_{d0} is the initial yield load and δ_0 is assumed as D/S_2. In other words, δ_0 show the deformation equivalent to the thickness of total rubber layers, and it is equivalent to the hysteresis loop area for one cycle of damper shown in Fig. 2(c).

In modeling of HDR hysteresis loop, both the horizontal stiffness and yield load were changed as shown in Fig. 10(b)(c). A model like these is called a dependency model. For the purpose of comparison, an analysis was performed by the model maintaining primary characteristics, which is called a constant model.



(a) Q_d for LRB Model (b) Q_d for HDR Model (c) K_d for HDR Model

Fig.10 Dependency of Hysteresis Loop

Table 2 Conditions of rubber bearing to be used in the analytical model

Compressive Stress σ (N/mm^2)	6	8	10	15
Diameter D (m)	1.0			
Mass M (ton)	480.8	641.1	801.4	1202.1
Axial Load Mg (kN)	4712	6283	7854	11781
Stiffness K_d (kN/m)	1570.7			
Period T_d (sec)	3.48	4.01	4.49	5.50
Initial Yield Force for LRB Q_{d0} (kN)	251			
$\alpha_s = Q_{d0}/Mg$	0.053	0.040	0.032	0.021
Initial Yield Force for HDR Q_{d0} (kN)	208			
$\alpha_s = Q_{d0}/Mg$	0.044	0.033	0.027	0.018

For the preparation of an analytical model, the rubber bearing with the diameter of 1m was presumed, and the situation where the rubber bearing is supporting a given load was modeled. Table 2 shows K_d and Q_d of rubber bearings used for the analysis. The secondary shape factor S_2 is presumed as 5 (δ_0 =0.2m). The compressive stress (surface pressure) σ of the rubber bearing was changed in the range of 6N/mm^2 to 15N/mm^2. The period T_d and yield shear coefficient α_s calculated in Equations (5) and (6) are also shown in Table 2.

For response analysis, an artificial earthquake wave and the waveform observed at the Japan Meteorological Agency (JMA) in Kawaguchi-machi at the time of the 2004 Niigata-ken Chuetshu Earthquake were used. The artificial earthquake wave was prepared with the phase information of waveform observed at Tomakomai when the 2003 Tokachi-Oki Earthquake occurred. Fig. 11 shows time historical waveforms. It revealed that although the acceleration of artificial earthquake wave is not large, it continues for a long period of time.

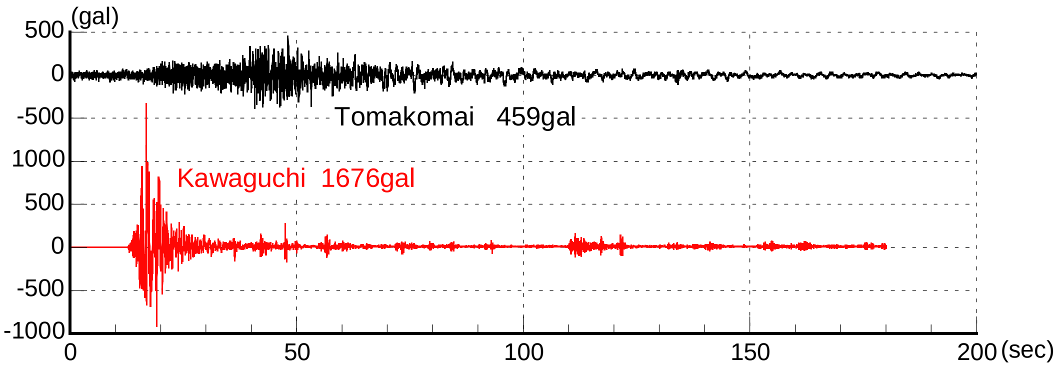


Fig.11 Input Earthquake Wave for Dynamic Analysis

Table 3 shows the maximum displacement of seismic isolation layers obtained from the response analysis. According to the analysis results, where the dependence of characteristics of both LRB and HDR were taken into consideration, the ratio of the results of Tomakomai wave analyzed by the dependency model and the constant model became 1.1-1.3. The reason why the ratio of response of HDR is smaller than that of LRB is that the characteristic change of HDR is more moderate than that of LRB, as clearly shown in Fig. 10. Meanwhile, there was no change in the maximum response displacement in the case of Kawaguchi wave.

As shown in Fig. 12 and 13, in the case of Tomakomai wave, many repeated deformations are generated, but in the case of Kawaguchi wave, the repetitions are very few. The cumulative plastic deformation of Tomakomai wave is in the range of 10m to 28m, but Kawaguchi wave is less than 6m. The hysteretic absorption energy W_p of Kawaguchi wave is only 4-6 times of $4Q_{d0}\delta_0$. Meanwhile, that of Tomakomai wave is 10-25 times.

Table 3 The maximum displacement obtained from analysis (m)

(a) Analysis Results of LRB

Input Motion	TOMAKOMAI			KAWAGUCHI		
Hysteresis Model	Dependency Model (A)	Constant Model (B)	Ratio (A/B)	Dependency Model (A)	Constant Model (B)	Ratio (A/B)
σ=6 N/mm^2	0.224 (10.2)	0.171	1.31	0.769 (5.9)	0.769	1.00
σ=8 N/mm^2	0.308 (15.8)	0.271	1.14	0.716 (4.5)	0.713	1.00
σ=10 N/mm^2	0.386 (21.0)	0.305	1.27	0.650 (4.1)	0.646	1.01
σ=15 N/mm^2	0.630 (27.9)	0.503	1.25	0.647 (3.7)	0.647	1.00

(b) Analysis Results of HDR

Input Motion	TOMAKOMAI			KAWAGUCHI		
Hysteresis Model	Dependency Model (A)	Constant Model (B)	Ratio (A/B)	Dependency Model (A)	Constant Model (B)	Ratio (A/B)
σ=6 N/mm^2	0.291 (9.6)	0.252	1.15	0.800 (5.0)	0.798	1.00
σ=8 N/mm^2	0.337 (13.1)	0.320	1.05	0.754 (4.1)	0.751	1.00
σ=10 N/mm^2	0.388 (16.8)	0.339	1.14	0.687 (3.8)	0.686	1.00
σ=15 N/mm^2	0.633 (23.8)	0.567	1.12	0.628 (3.4)	0.628	1.00

Note: The value in parenthesis shows the cumulative plastic deformation δ_p.

5 CONCLUSIONS

It revealed that both the lead rubber bearing and the high damping rubber bearing produce heat by repeated cyclic loading, and that the change of stiffness after yield is small, but the yield load decreases early in LRB and that the equivalent viscous damping constant does not change so much, even though the equivalent stiffness decreases in HDR.

Test specimens themselves were not crippled by the heat generation and continued to have enough energy absorption capacity. It revealed that, because the mechanisms of heat generation of LRB and HDR are different, the manners of the temperature increase are also different, and that the changing trends of hysteresis loops of LRB and HDR caused by repetition are also different.

In order to correctly evaluate the earthquake response of seismic isolated buildings, it is indispensable to make models of hysteresis characteristics of seismic isolation devices correctly. From the analytical results of changing the restoring force model based on experiment, when the response causes many repetition as in the case of long-period ground motion, it is very important to appropriately make the model of restoring force characteristics according to presumed response deformation and the number of repetition (accumulated deformation).

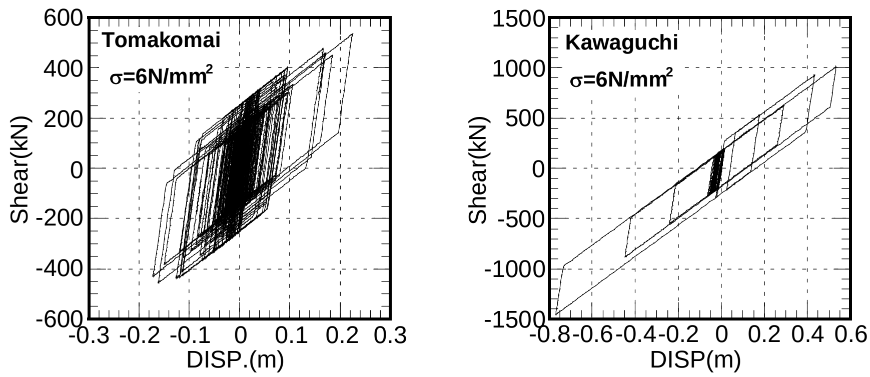


Fig.12 Analysis Results for LRB Model (Compressive Stress σ=6N/mm^2)

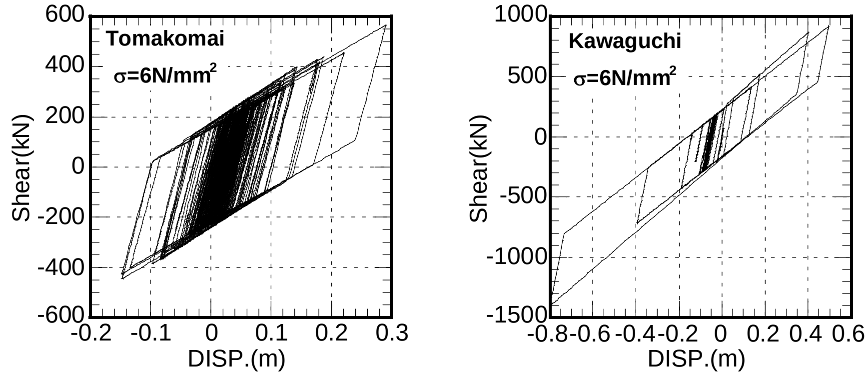


Fig.13 Analysis Results for HDR Model (Compressive Stress σ=6N/mm^2)