Heat-Mechanics Interaction Behavior of Laminated Rubber Bearings under Large and Cyclic Lateral Deformation

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ABSTRACT :

Base-isolation devices attached to base-isolated buildings can be subjected to larger and more cyclic deformation than anticipated as a result of long-period ground motion caused by strong earthquakes occurring in oceanic trenches. For the lead rubber bearings (LRB) and high damping rubber bearings (HDB) of damping mechanisms, the seismic energy they absorb is fundamentally transformed into thermal energy, so heat is generated causing high temperatures in the lead plug and the high damping rubber. The deterioration of damping characteristics in line with rising temperatures is a serious concern, but there is a lack of experimental data on the relationship between increased temperatures and the mechanical characteristics of rubber bearings. Based on this background, dynamic loading tests were conducted using full-scale and reduced-scale rubber bearing specimens under large deformation conditions assuming long-period ground motion to ascertain the effects of increased temperatures on the mechanical behavior of rubber bearings. The results of tests show that the temperature of the lead plug shows a rapid increase, the hysteretic curve in the force-deformation relationship becomes smaller and the yield load becomes lower with cyclic loading.

KEYWORDS: Base Isolation, Laminated Rubber Bearing, Long-period Ground Motion, Rising Temperature, Loading Test

1. INTRODUCTION

Base-isolation devices attached to base-isolated buildings can be subjected to larger and more cyclic deformation than anticipated due to long-period ground motion caused by strong earthquakes in oceanic trenches [1]. The seismic energy absorbed by the lead rubber bearings (LRBs) and high damping rubber bearings (HDBs) of damping mechanisms is fundamentally transformed into thermal energy. This leads to heat generation, which causes high temperatures in the lead plug and the high-damping rubber.
The deterioration of damping characteristics in line with rising temperatures is a serious concern, but there is a lack of experimental data on the relationship between increased temperatures and the mechanical characteristics of rubber bearings. To confirm the effects of higher temperatures caused by larger and more cyclic deformation on the mechanical properties of rubber bearings, dynamic loading tests were conducted using full-scale and reduced-scale LRB and HDB models and by applying sine waves and earthquake response waves.

2. EXPERIMENTAL METHODS

Lead rubber bearings and high-damping rubber bearings were tested in this study. The specimens were a full-scale model with a diameter of 1,000 mm and a total rubber thickness of 200 mm, and 1/2 and 1/4 reduced models. The reduced models were prepared by reducing the values of diameter, rubber layer thickness and internal steel plate thickness on the same scale of contraction to avoid changing the heat transfer properties. The specifications of the specimens are shown in Table 1. Sine waves and earthquake response waves were applied in the horizontal direction by retaining constant axial stress (vertical load / sectional area of rubber). The axial stress was set at 3 MPa for the full-scale model and 5 MPa for the reduced scale models. The parameters of the sine waves were period T, shear strain γ (horizontal deformation / total rubber thickness) and number of repetitions. The sine wave cases are listed in Table 2. The parameters of the sine wave cases were determined assuming actual earthquakes in Cases 1 to 3 and ultimate strong earthquakes in Cases 4 and 5, and considering the law of similarity on heat transfer mentioned later in Cases 6 and 7. The number of repetitions for the full-scale model was reduced by the performance limitation of the loading equipment. The earthquake response waves were the response displacement waveforms determined from the results of earthquake response analyses on a base-isolated building. The seismic motions input for the analyses were waves recorded in the past, including those during direct-hit earthquakes and long-period earthquakes, simulated earthquake waves used in structural design, and those caused by an assumed large earthquake. The earthquake response wave cases are listed in Table 3. Preliminary analyses showed that the input energy was much larger when the sine waves were applied than when the earthquake response waves were applied. Basic property tests were performed before and after the loading tests using a sine wave with parameters of T = 100 seconds, γ = 100% and three repetitions. The loading equipment for the reduced models is shown in Figure 1.

The items measured were the horizontal force, horizontal deformation and the temperature of the specimens. The temperature of the rubber bearings was measured by installing thermocouples to the specimens. The points of temperature measurement in the central section are shown in Figure 2 for the 1/2-scale LRB specimen and the 1/2-scale HDB specimen as examples. In the LRB, the temperature was measured at fifteen points in total: three within the lead plug (P1 to P3), four within the rubber at a height of 1/2 (RC1 to RC4), four within the rubber at a height of 1/4 (RQ1 to RQ4), and four at the flange (MT1 to MT4). The temperature was measured in the HDB at ten points in total: three within the rubber at a height of 1/2 (C1 to C3), three within the rubber at a height of 1/4 (Q1 to Q3), one near the flange (T1), and three on the upper surface of the flange (F1 to F3).

Table 1 List of specimens

Kind of rubber bearing	LRB			HDB	
Kind of rubber	Natural rubber G0.4			High damping rubber X0.6	
Contraction scale	Full-scale	1/2-scale	1/4-scale	1/2-scale	1/3-scale
Outer diameter D (mm)	1000	510	255	500	300
Lead diameter (mm)	200	102	51	-	-
Rubber layer thickness t (mm)	8	4.08	2.04	3.4	2.0
Number of rubber layers	25	25	25	30	30
Total thickness of rubber h (mm)	200	102	51	102	60
Thickness of internal steel plate (mm)	4.3	2.2	1.1	3.1	1.8
Shape factor (S=D/4tr)	31	31	31	35.7	37.5
Secondary shape factor (S_2=D/h)	5	5	5	4.9	5

Table 2 Sine wave cases

Case number	Period T (second)	Shear strain γ (%)	Number of repetition	
			Full-scale model	Reduced model
1	3	50	40	100
2	3	100	20	50
3	5	100	20	50
4	3	200	10	100
5	5	200	10	100
6	12	50	40	-
7	0.75	50	-	40

Table 3 Earthquake response wave cases

Case number	Name of seismic wave	Maximum velocity* (mm/s)	Maximum displacement* (mm)
8	JMA KOBE NS	906	284
9	K_net TOMAKOMAI_NS×1.5	497	425
10	MEXICO SCT1	836	325
11	BCJ L2	758	428
12	JSCA KOKUJI	447	232
13	SANNOMARU EW	711	354

*Values are at the full-scale model

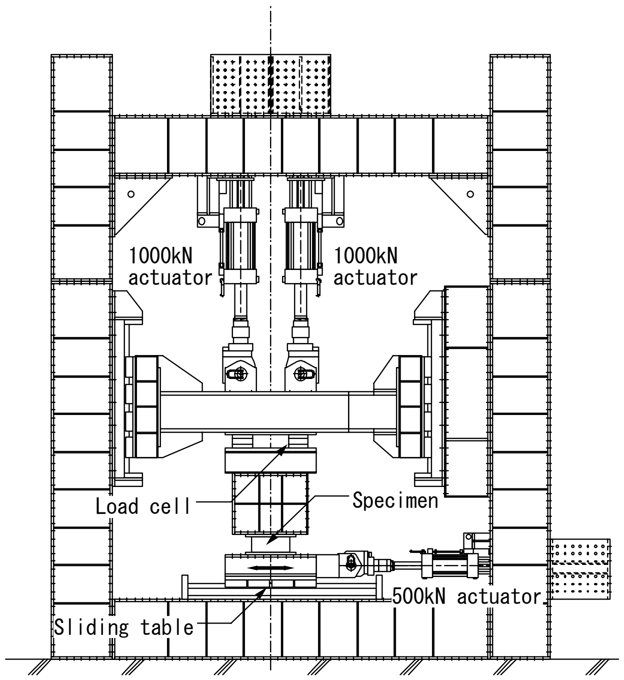
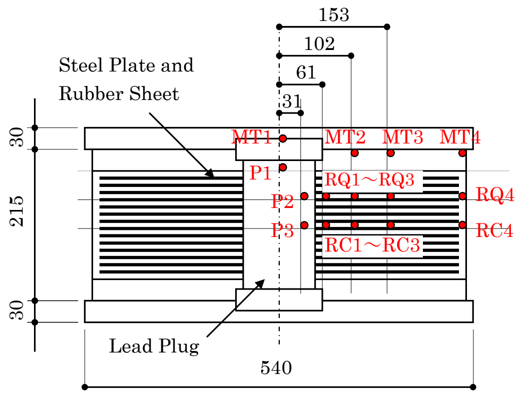
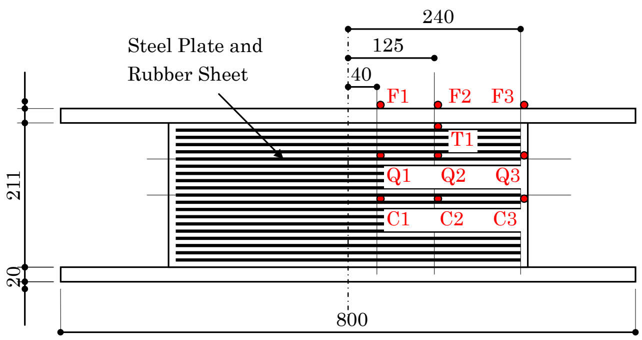


Figure 1 Loading equipment for the reduced models



(a) 1/2 scale LRB specimen



(b) 1/2 scale HDB specimen

Figure 2 Points of temperature measurement at the central section

3. RESULTS

3.1. Method for Estimating the Hysteresis Characteristics of Rubber Bearings

Changes in characteristics were estimated based on the yield load Q_d and the stiffness K_d after yielding defined on the relationship between horizontal force Q and horizontal deformation δ. Q_d and K_d are represented by the following equations:

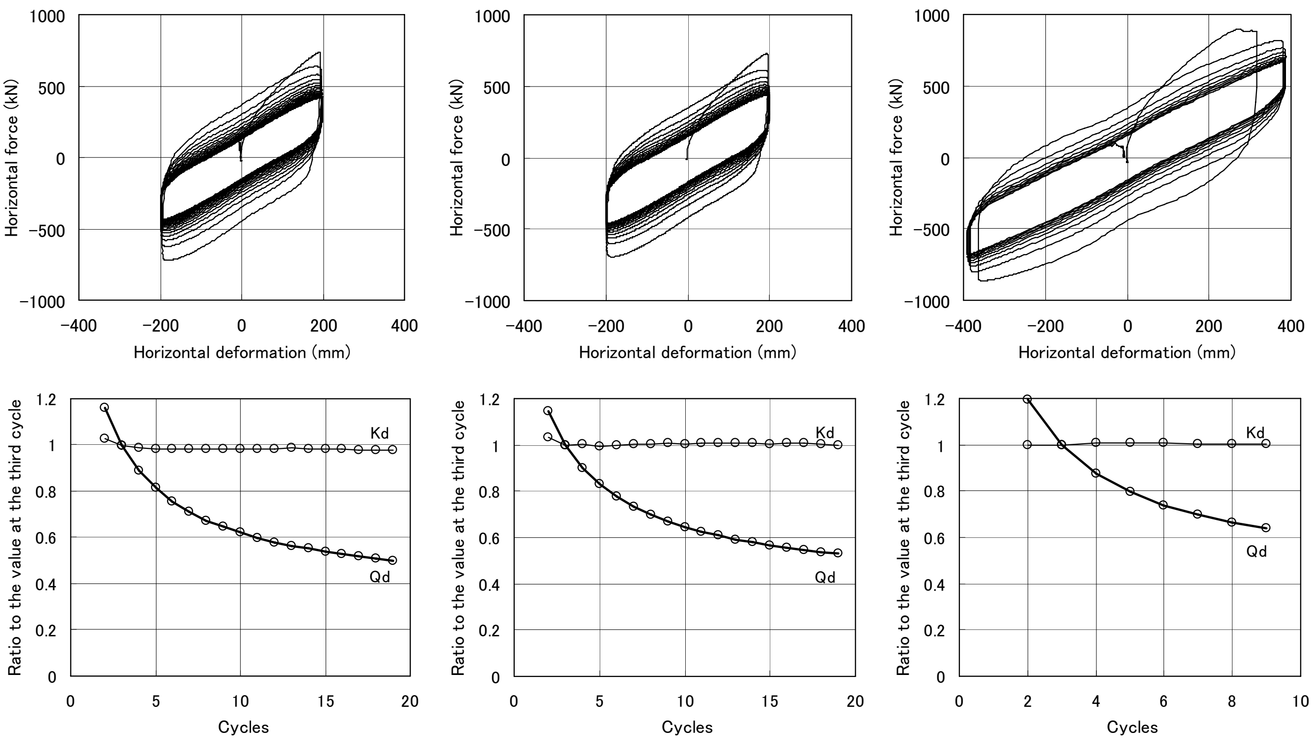
$$Q_d = \left(|Q_{d+}| + |Q_{d-}|\right)/2 \tag{3.1}$$

$$K_d = \left(|K_{d+}| + |K_{d-}|\right)/2 \tag{3.2}$$

Q_{d+} and Q_{d-} represent positive and negative forces at δ = 0, and K_{d+} and K_{d-} represent the inclination of the line connecting points that have values of γ = ±50%. The properties of the rubber bearings were estimated by standardizing the Q_d and K_d values at each cycle by those at the third cycle.

3.2. Results for the Lead Rubber Bearings

The Q - δ relationships of the full-scale LRB specimen are shown in Figure 3 for sine wave cases 2 to 4, together with changes in Q_d and K_d at each cycle. The figures show that the hysteresis curves were similar to those represented by a bi-linear model, but the area surrounded by the curves decreased as the number of repetitions increased. Q_d values dropped sharply soon after the start of loading, becoming about 60% of the third-cycle values by the time of the tenth cycle. At the end of loading (after 20 cycles), Q_d values became about 50% of those seen at the third cycle. On the other hand, repetition caused no changes in K_d values. The Q - δ relationship of the full-scale LRB specimen is shown in Figure 4 for when the Sannomaru response waveform



(a) Sine wave Case 2 (b) Sine wave Case 3 (c) Sine wave Case 4

Figure 3 Q-δ relationships, and changes in Q_d and K_d at each cycle during sine wave cases (full-scale LRB)

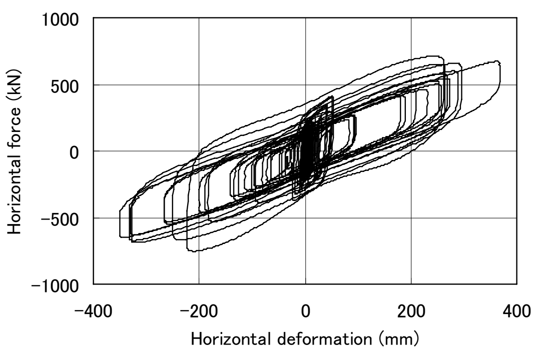
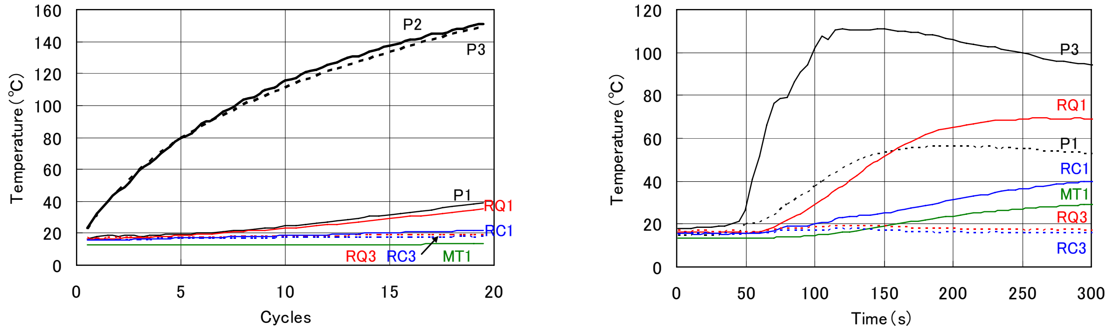


Figure 4 Q-δ relationship during earthquake response wave cases (full-scale LRB, Sannomaru waveform)



(a) Sine wave Case 2 (b) Sannomaru waveform

Figure 5 Temperature changes of full-scale LRB specimen

was applied. The figure shows that the hysteresis curve indicated strong nonlinearity, and the force at $\delta = 0$ tended to decrease with repetition. Hysteresis curves whose single amplitude exceeded 200 mm were extracted from Figure 4, and their force at $\delta = 0$ were determined. The force values obtained were reduced by about 50% from the initial value.

Temperature changes in the full-scale LRB specimen at each cycle are shown in Figure 5(a) for the sine wave Case 2. The temperature of the lead plug at P2 and P3 increased sharply soon after the start of loading. The increase gradually slowed, and the temperature at the end of loading was about 150 ℃. This temperature change corresponded to the reductions in Q_d shown in Figure 3(a). The temperatures on the outermost side of the lead plug (P1), inside the rubber (RC and RQ) and at the flange (MT) started to rise after the increases slowed down at P2 and P3. The temperature inside the rubber was higher at RC1 and RQ1, i.e., the measuring points nearer to the lead plug. This showed that heat was generated within the lead plug and was transmitted to the rubber bearings and flange. Temperature changes in the full-scale specimen are shown in Figure 5(b) for when the Sannomaru response waveform was applied. The principal motion of this waveform was at 50 to 120 seconds, during which the temperature of the lead plug at P3 increased significantly. At 120 seconds when the principal motion finished, the temperature reached its upper limit and started to drop at about 150 seconds. Conversely, at other points including the lead plug point P1, the temperature started to rise after the increase at P3 as in the sine wave cases. The temperature continued to rise even after 120 seconds when the principal motion finished. The temperature was particularly high at RQ1 (the nearest point to the lead plug), reaching as much as 70 ℃. This also showed that heat was generated at the lead plug and transmitted to the periphery.

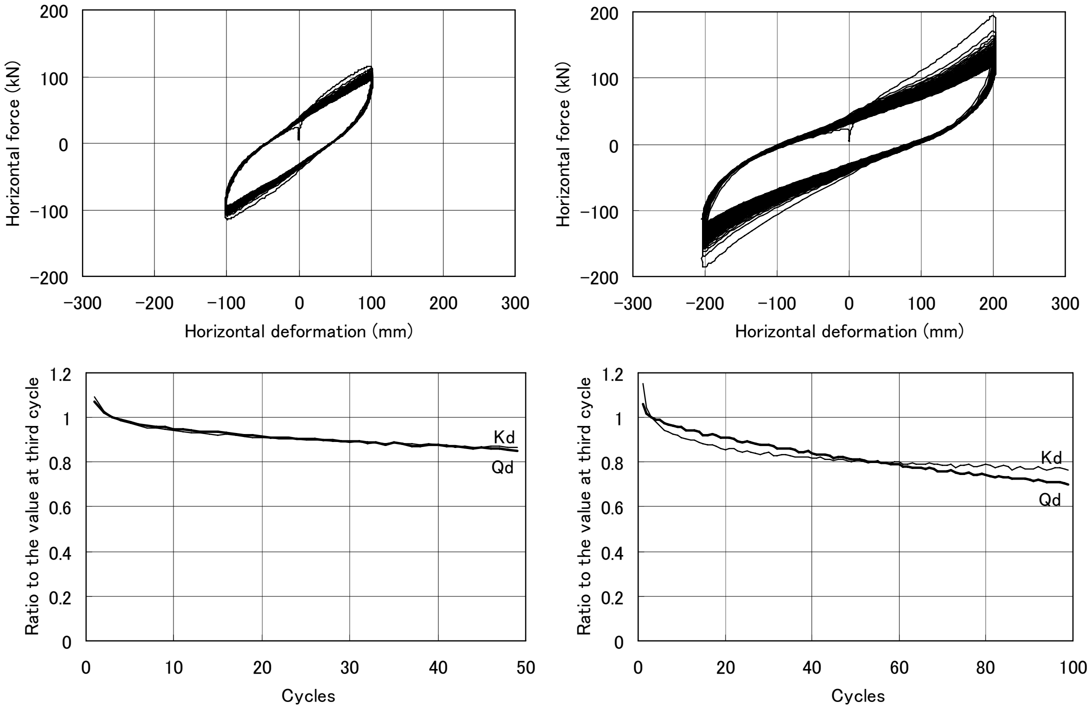
3.3. Results for the High-damping Rubber Bearings

The Q - δ relationship and changes in Q_d and K_d at each cycle of the 1/2-scale HDB specimen for sine wave cases 2 and 4 are shown in Figure 6. The hysteresis curves were similar to those represented by a bi-linear model, but repetition caused Q_d and K_d values to decrease. Their rate of decrease was similar, and at the end of loading, both values were about 80% of those at the third cycle. The decreases in Q_d were smaller in the HDB than in the LRB. The Q - δ relationship when the Sannomaru response waveform was applied is shown in Figure 7, whose hysteresis curve indicates strong nonlinearity until the termination of loading. As with the LRB, the force at $\gamma = 0$ decreased, but the decrease was smaller than that of the LRB.

Temperature changes in the 1/2-scale HDB specimen at each cycle are shown in Figure 8(a) for sine wave case 4. The temperature increased almost linearly along with the number of repetitions at the 1/2 (C1 and C3) and 1/4 (Q1) heights inside the rubber, rising by about 30 ℃ by the end of loading. Since HDBs absorbs energy by generating heat within the rubber, the temperature increase inside the rubber was almost uniform. On the other hand, the temperature increases were small at the upper surface of the flange (F1) and near the flange (T2), with values of 3 ℃ and 8 ℃, respectively. Temperature changes during loading by the Sannomaru response waveform are shown in Figure 8(b). At 50 to 120 seconds (the duration time of the principal motion), the temperature inside the rubber increased, but the rise was smaller by about 3 ℃ than that in the LRB.

3.4. Comparison of Experimental Results Using the Law of Similarity

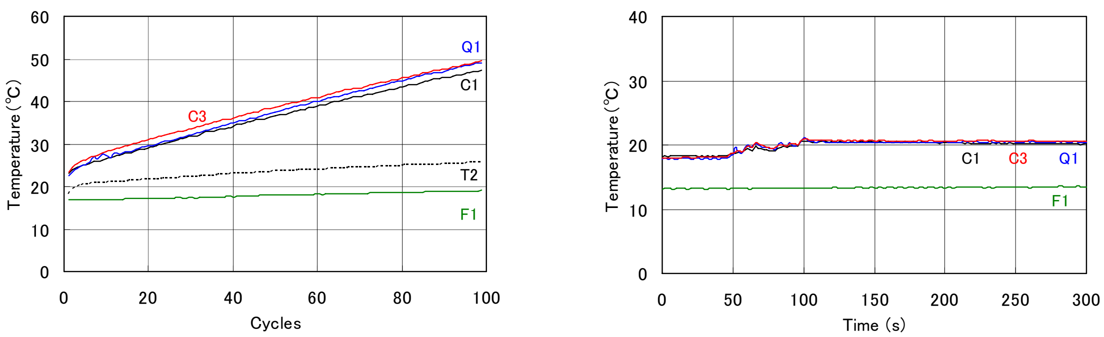
To understand the effects of size on the performance of rubber bearings, the experimental results were



(a) Sine wave Case 2 (b) Sine wave Case 4

Figure 6 Q-δ relationships, and changes in Q_d and K_d at each cycle during sine wave cases (1/2-scale HDB)

Figure 7 Q-δ relationship during earthquake response wave cases (1/2-scale HDB, Sannomaru waveform)



(a) Sine wave Case 4 (b) Sannomaru waveform

Figure 8 Temperature changes of full-scale LRB specimen compared among the full-scale, 1/2- and 1/4-scale LRB specimens using the same sine wave case and different sine wave cases considering the law of similarity. As an example of the results under the same sine wave case, temperature changes in the lead plug at P3 and Q_d for sine wave Case 1 (γ = 50%, T= 3 seconds) are shown in Figure 9. In this figure, Q_d values are divided by the cross-sectional area of the lead plug, and the number of repetitions is shown up to 40 cycles to correspond to the full-scale specimen test. As the figure shows, the larger the size of the specimen, the larger the rise in temperature of lead plug and the reduction in Q_d, showing the scale effect in thermo-mechanic behavior. In tests that considered the law of similarity, the period of the sine wave was set to be proportional to the square of the contraction scale of length, according to the law of similarity on heat transfer [2]. Case 1 (γ = 50%, T = 3 seconds) for the 1/2-scale specimen was used as the reference. Case 6 (γ = 50%, T = 12 seconds) for the full-scale specimen and Case 7 (γ = 50%, T = 0.75 seconds) for the 1/4-scale specimen were applied, respectively. Temperature changes in the lead plug at P2 and Q_d at each cycle are shown in Figure 10. The increase in the lead plug temperature for the 1/4-scale specimen was larger than that for other specimens, but the reductions in Q_d displayed a close correlation with each other, showing that the law of similarity on heat transfer applies to LRBs of different sizes.

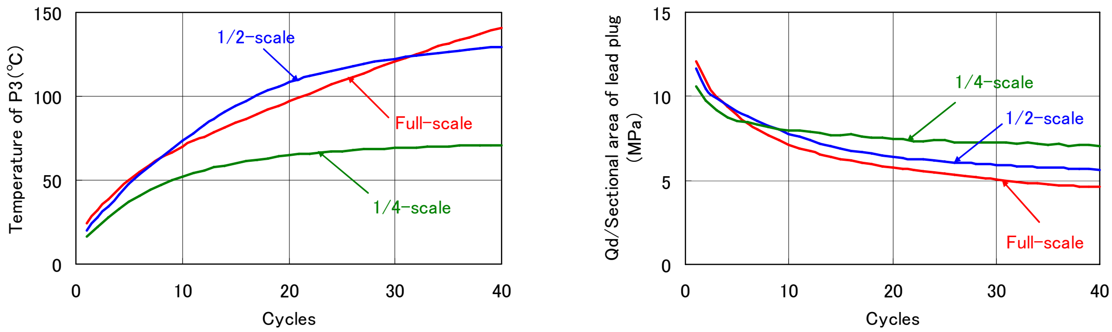


Figure 9 Comparison of lead plug temperature and Q_d between models of different scales under the same loading conditions

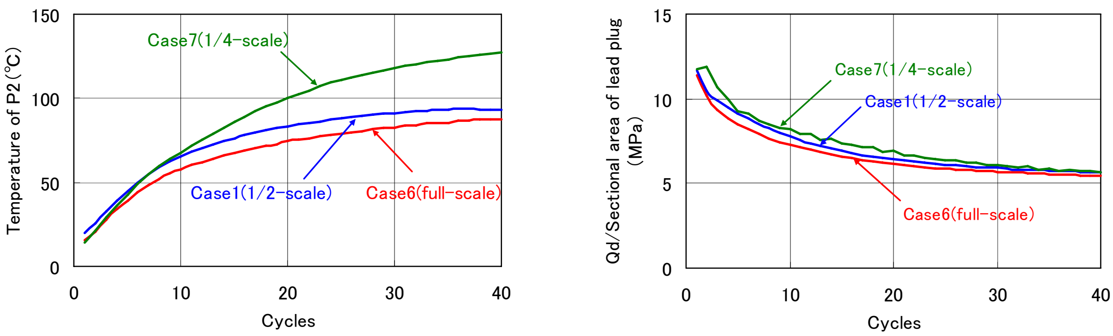


Figure 10 Comparison of lead plug temperature and Q_d between models of different scales under loading conditions determined based on the law of similarity

3.5. Soundness of Lead Rubber Bearings

The inside of the full-scale LRB specimen after the test is shown in Figure 11. No damage was found to the lead plug, but the lead bit the upper and lower rubber layers slightly, and residual deformation was found in the internal steel plate. The total energy input into the specimen was 4.62 × 10^4 kNm, which was equivalent to the amount of energy input by sine waves of γ = 100% and about 243 cycles. The Q - δ relationships obtained from the basic property tests performed before and after the loading tests were compared. The results showed that these relationships remained almost the same, thus confirming that the rubber bearing remained sound.

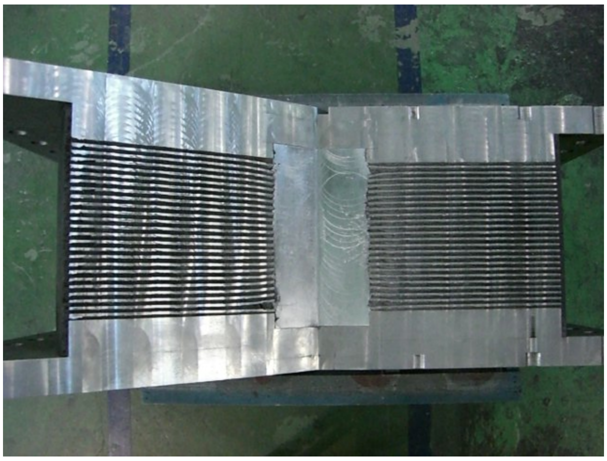


Figure 11 Inside of the full-scale LRB specimen after loading tests

4. CONCLUSION

Dynamic loading tests were conducted on rubber bearings to confirm the effects of increased temperatures caused by larger and more cyclic deformation on their mechanical properties. Full-scale and reduced-scale LRB and HDB models were used, and were loaded by applying sine waves and earthquake response waves. The outcome of this study is summarized below.

The yield load of a full-scale LRB specimen with a diameter of 1,000 mm dropped to about 50% under sine wave input far exceeding the energy of actual seismic motion. The increase in temperature of the lead plug corresponded to the drop in the yield load, and the temperature rose to about 150 ℃. The fact that the temperature started to rise inside the rubber and flange after the temperature increase in the lead plug demonstrated that the heat generated inside the plug was transmitted to the rubber and flange.

In a test using a reduced-scale HDB with diameter of 500 mm, sine wave input caused the yield load to drop to about 80%. The temperature inside the rubber rose uniformly by about 30 ℃. Since HDBs absorb energy by generating heat throughout the rubber, the temperature increase inside the rubber was smaller than that of the LRB, and reductions in the yield load were also smaller.

Under the input conditions (in which the law of similarity was considered), reductions in the yield load were similar regardless of the scale of the specimen. The law of similarity on heat transfer was shown to apply to rubber bearings of different sizes.

The LRB suffered slight residual deformation at the internal steel plate from the input of waves far exceeding the actual energy input during an earthquake, but showed almost no hysteresis curve change and was found to keep its soundness.

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