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SCALE EFFECT ON MECHANICAL BEHAVIOR OF LEAD RUBBER BEARINGS FOR SEISMIC ISOLATION

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Abstract

Seismically-isolated buildings isolate a superstructure from the ground, greatly improving the safety of the buildings during an earthquake and enabling the site to be used immediately after an earthquake. This technology has been used in earthquake-prone countries around the world. To establish a seismically-isolated structure, isolators are required to support the building for a long time and be deformed significantly in the horizontal direction during an earthquake. A typical isolator is a lead rubber bearing (LRB) containing a lead plug. LRBs are made by pressing lead plugs into the center of laminated rubber bearings. They act as isolators and absorb seismic energy through the plastic deformation of lead. As a result, the response deformation of the base-isolated building can be suppressed, and the shaking can be converged early. One major concern in the Japanese structural engineering community is that seismically-isolated structures in Japan will shake over a long duration due to the occurrence of long-period ground motion, and that response deformation will increase considerably. The capability of LRBs to suppress deformation and to absorb energy has been experimentally demonstrated. However, the LRBs used were smaller specimens because no experimental apparatus in Japan can vibrate a full-sized specimen at actual speeds and with actual displacement.

The authors decided to test whether or not the characteristics of a full-sized test specimen could be evaluated with a smaller one. Three types of test specimens with diameters of 500, 800, and 1200 mm, respectively, will be used to examine the scale effect on deformation suppression and energy absorption in this research. The experiment will be conducted with the experimental equipment of the National Center for Research on Earthquake Engineering, Bi-Axial Dynamics Testing System (BATS), in Taiwan. The authors plan to give a large number of cyclic deformations to the LRBs. In this paper, the preliminary simulation analysis results are presented. In the analysis, a thermal-mechanical coupled behavior analysis of LRBs was performed. These results show the state of heat conduction changes as the size of the LRBs changes. The authors believe that the difference in the behavior of heat conduction and the scale effect on the mechanical behavior of LRBs can be demonstrated in the test. Experiments conducted using a reduced specimen are expected to produce useful information such as how far the behavior of a real size specimen can be reproduced.

Keywords: seismic isolation, lead rubber bearing, thermal-mechanical coupled behavior, scale effect

1. Introduction

Long-period and long-duration ground motions have been a great concern in Japan since the 2011 Tohoku Earthquake, when ground motions lasting more than five minutes were observed across a wide area of Japan. Previous research has predicted that very large subduction earthquakes in the Nankai and Tokai regions of Japan will produce similar long durations, strong ground shaking with long-period characteristics. Therefore, the possible impacts of these events to long-period structures such as seismically-isolated buildings have become a major concern in the Japanese structural engineering community. The most commonly used seismic isolation devices in Japan are elastomeric isolation bearings. A number of bearing types exhibit hysteretic damping performances, eliminating the need for separate dampers. However, such ground motions might induce excessive and numerous cyclic deformations in elastomeric isolation bearings. In particular, a large number of cyclic deformations will cause the performance of seismic isolation devices to deteriorate due to fatigue or internal heat generation [1]. This phenomenon is understood as a thermal-mechanical coupled behavior [2]. Since April 2017, the Japanese Ministry of Land, Infrastructure, Transport and Tourism (MLIT) has obliged structural engineers to consider how the long-period earthquake ground motion caused by an earthquake in the Nankai Trough would impact the design of a seismically-isolated building constructed in that area [3].

A typical isolator is a lead rubber bearing (LRB) containing a lead plug. LRBs are made by pressing lead plugs into the center of laminated rubber bearings. They were invented in New Zealand and have been used worldwide. 30% of isolated building in Japan use LRBs. In addition to their role as isolators, they absorb seismic energy through plastic deformation of lead. As a result, the response deformation of the base-isolated building can be suppressed, and the shaking can be converged early. The capability of LRBs to suppress deformation and absorb energy has been experimentally demonstrated. However, in many cases, the LRBs used were smaller specimens because no experimental apparatus in Japan can vibrate a full-sized specimen at actual speeds and with actual displacement [4]. There are very few cases in which tests can be conducted on full-sized LRBs. The authors do not believe that the performance of a full-seized product can be evaluated from the test results of a scaled specimen. Therefore, the testing of different sized LRBs are planned to examine the scale effect on deformation suppression and energy absorption. The experiment will be conducted with the experimental equipment of the National Center for Research on Earthquake Engineering in Taiwan. Currently, the test specimens are being manufactured. In parallel with the arrangement of the tests, the analytical studies of the scale effect have also been conducted to predict the test results of the LRBs by the authors. A numerical analysis model has been carefully constructed for the different LRB sizes. Thermal-mechanical coupled behavior analysis of LRBs has been performed. In this paper, the results obtained from the preliminary analysis conducted prior to the test are presented.

2. Numerical analysis model for thermal-mechanical coupled behavior

2.1 Analysis flow

The numerical analysis consists of a thermal conductivity analysis and seismic response analysis. Both analyses are performed interactively by updating their parameters at each time step increment. The seismic response analysis uses nonlinear hysteresis models specialized for elastomeric isolation bearings [5]. The thermal conductivity analysis employs a finite volume method. This model is applicable to various types of elastomeric isolation bearings with hysteretic damping.

Fig. 1 shows the flowchart of the thermal-mechanical coupled analysis. First, the mechanical properties of the elastomeric isolation bearing are updated by using the temperature obtained in the previous analysis step. Then, seismic response analysis is conducted at a certain time step by using the updated mechanical properties of the bearing. Accordingly, an energy increment absorbed by an elastomeric isolation bearing, ΔE, is calculated at the end of the time increment in the seismic response analysis. The seismic response analysis employs the Newmark-β method as a time integration method [6]. Next, ΔE is distributed to the heat generation parts in the bearing, and thermal conductivity analysis is conducted. For numerical analysis stability, a time increment for the thermal conductivity analysis is preferably between one fifth and one tenth of that of the seismic response analysis. Accordingly, the temperature of the heat generation parts for the next analysis step is obtained. This procedure is repeated until the end of the input ground motion. The model presented here was implemented in the OpenSees program [7].

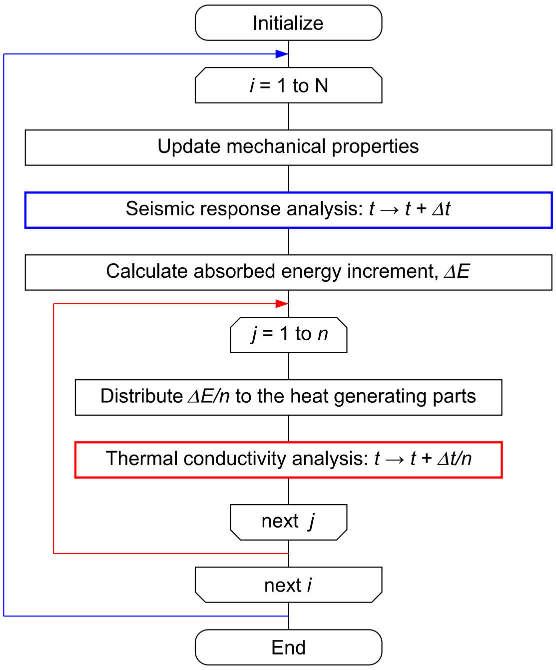


Fig. 1 – Flowchart of thermal-mechanical coupled analysis

2.2 Seismic response analysis

The latest nonlinear hysteresis model optimized in accordance with the LRBs is used in the seismic response analysis for seismically-isolated buildings [8]. Some modifications were made to the hysteresis model so that the change in the mechanical properties due to temperature changes could be considered. As shown in Fig. 2, the hysteresis model is used to evaluate the restoring force of elastomeric isolation bearings by combining elastic and hysteretic components separately. The affect of temperature on the restoring force, F, is expressed using Eq. (1).

$$F = F_e + c_h(T)\, F_h \tag{1}$$

where F_e and F_h are the elastic and hysteretic components of the restoring force at standard temperature (usually at 20°C), respectively, and c_h is the coefficient for the hysteretic component of the restoring force at temperature T (°C) in the lead plug inserted at the center of the bearing.

The coefficient c_h was previously identified as Eq. (2) [9].

$$c_h(T) = 1.0 - (T/327.5)^{0.4+0.25(T/327.5)} \tag{2}$$

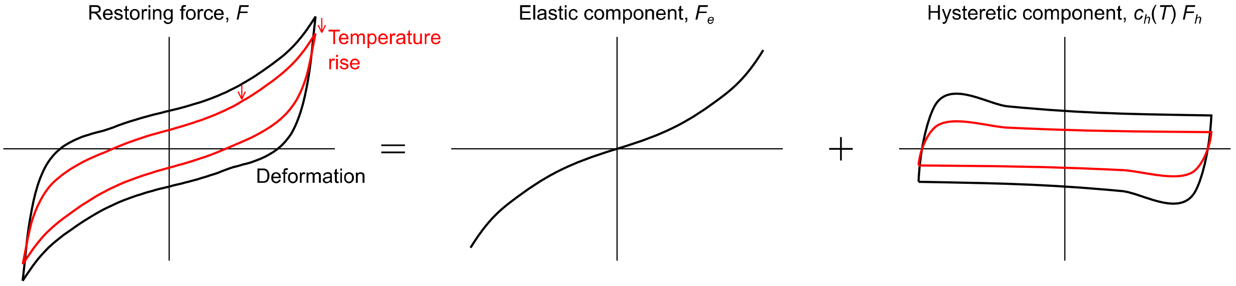


Fig. 2 – Concept of hysteresis model for LRB considering temperature change

2.3 Thermal conductivity analysis

A finite volume method is used for the thermal conductivity analysis. Fig. 3 shows a cross-sectional view of an axisymmetric two-dimensional model for a typical cylindrical elastomeric isolation bearing. In consideration of symmetry in the height direction, only the upper half of the bearing is modeled. The rubber part and inner steel plate part are modeled by using separate cells. Heat is generated only in the lead inserted in the center of the bearing. The material constants used for this analysis are summarized in Table 1.

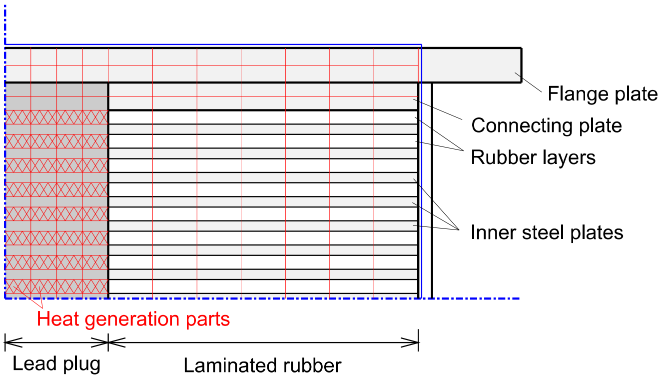


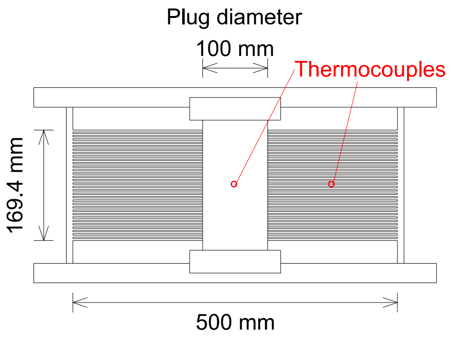
Fig. 3 – Axisymmetric models for thermal conductivity analysis

Table 1 – Material constants for thermal conductivity analysis

Material	**Thermal conductivity [W/(m·K)]**	**Density [g/cm^3]**	**Specific heat capacity [J/(g·K)]**
Lead	35.2	11.33	0.130
Rubber	0.13	1.04	1.90
Steel	59	7.86	0.473

2.4 Verification analysis

A simulation analysis using a scaled LRB was conducted to verify the numerical analysis method described in this section. The design of the specimen is shown in Fig. 4. The test was conducted by using the test facilities owned by the manufacturers [4]. Assuming that the LRB was installed in a concrete structure, 12.7-mm-thick heat insulators were installed on the outer ends of the top and bottom flange plates. A sinusoidal cyclic horizontal loading test was carried out under the conditions of a constant vertical pressure of 2.5 MPa, frequency of loading of 0.25 Hz, and shear strain amplitude of 200%. The number of horizontal loading cycles was 35. The vertical pressure was less than the design pressure of 15 MPa due to the performance of the test facilities. Thermocouple sensors were inserted into the lead plug and laminated rubber part.



Thickness

Rubber layers: 33 × 3.0 mm = 99.0 mm

Inner steel plates: 32 × 2.2 mm = 70.4 mm

Fig. 4 – Design of scaled LRB for verification analysis

Figs. 5 and 6 show the experimental and analytical results. The temperature at the center of the lead plug reached 223°C at the end of the 35 cyclic loadings. However, the temperature at the laminated rubber part did not rise. This fact shows that the generated heat was not easily diffused from the lead plug to the outer laminated rubber part within the duration of the earthquake. The analysis result showed good agreement with the experimental test result. The analysis predicted the degradation of the shear force in the hysteresis loops well. The change in measured temperatures at the lead plug and laminated rubber part were also captured well by the analysis.

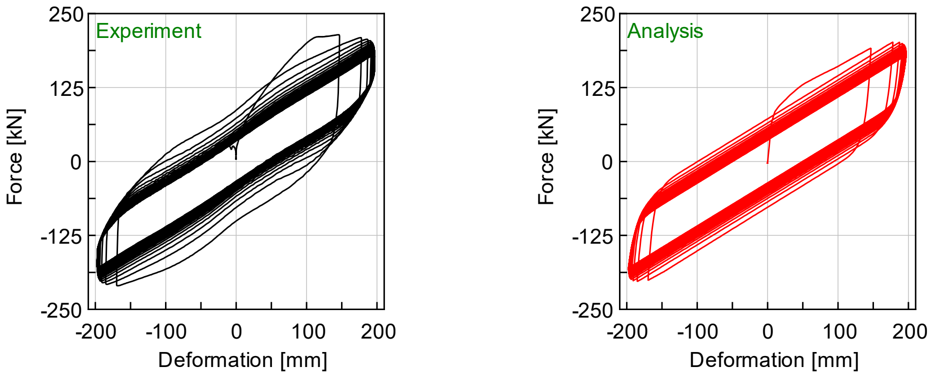


Fig. 5 – Force-deformation relationships obtained from verification analysis

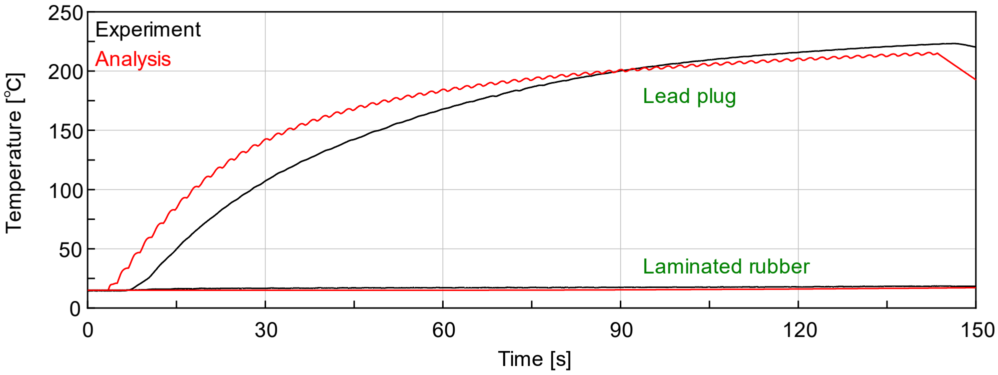


Fig. 6 – Temperature change obtained from verification analysis

3. Test plan for lead rubber bearings

3.1 Design of LRBs

One of the purposes of the test is to examine the scale effect on thermal-mechanical coupled behavior under a large number of cyclic deformations caused by long-duration earthquake ground motions. Three LRBs with diameters of 500 mm (Type S), 800 mm (Type M), and 1200 mm (Type L), respectively, were carefully designed to meet with the requirements of this research. Fig. 7 shows the design of the largest LRB (Type L). The dimensions of each LRB type are summarized in Table 2. The thickness of the rubber sheets, inner plates, and diameter of the lead plug were scaled in accordance with the scale factor of the rubber sheet diameters. The LRBs are currently being manufactured by Wuhan Hirun Engineering Equipment Co., Ltd in China. Thermocouple sensors will be inserted into the lead plug and laminated rubber part and be delivered to the National Center for Research on Earthquake Engineering, Bi-Axial Dynamic Testing System (BATS) in Taiwan.

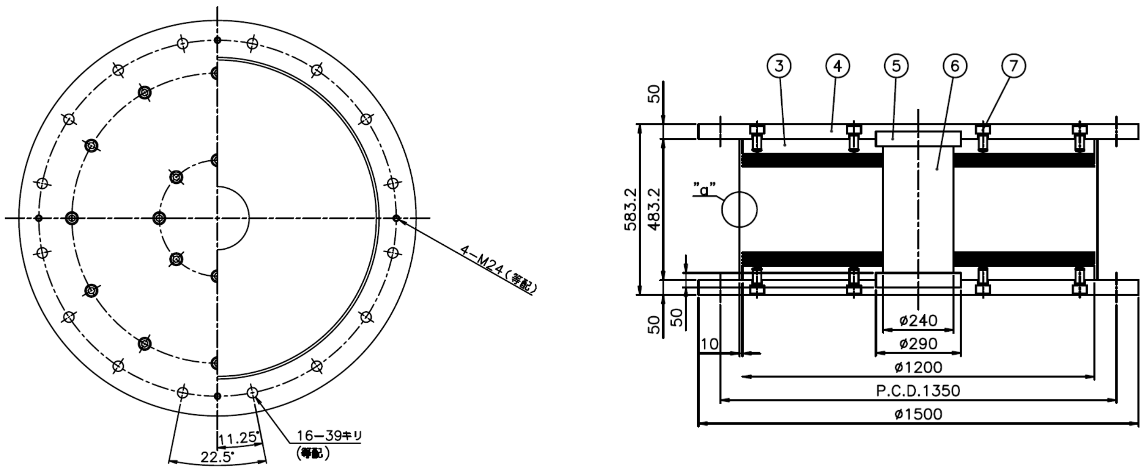


Fig. 7 – Design of LRB (Type L)

Table 2 – Dimensions of LRBs

Bearing type	**Diameter of rubber** (mm)	**Thickness of rubber sheet** (mm)	**Thickness of inner plate** (mm)	**Number of rubber sheets**	**Total rubber thickness** (mm)	**Diameter of lead plug** (mm)
L	1200	9.6	6.0	25	240	240
M	800	6.4	4.0	25	160	160
S	500	4.0	2.5	25	100	100

3.2 Test program

The test program is summarized in Table 3. Three LRBs of each scaled design (nine in total) will be used for the test. The experiment will be conducted with the experimental equipment of the BATS.

First, a compression and shear-compression test as a basic performance test will be conducted for every LRB. The compressive pressure is 10 MPa, and the shear strain is 100% during the basic performance test. Next, a cyclic loading and large deformation test will be performed to evaluate the ultimate performance. The cyclic loading test will be conducted under 30–40 cycles with a shear strain of 100% and 200% with 10-MPa compressive stress. Moreover, the large deformation test will be performed under cyclic loading up to 300 or 400% shear strain under 10 or 20-MPa compressive stress. The frequency of loading will be determined in accordance with the performance of the experimental equipment and the preliminary analysis result on the scale effect described in the following section.

Table 3 – Test program

Category		**Compressive stress** (MPa)	**Shear strain** (%)	**Number of cycles**	**Number of specimens**		
					L	**M**	**S**
Basic test	Compression	0–30	-	3	3	3	3
	Compressive shear	10	±50–±250	3	3	3	3
		20	±50–±250	3	3	3	3
Ultimate test	Cyclic	10	±100	40	1	3	3
			±200	30	1	-	-
	Large deformation	10	±250–±400	3	1	1	1
		20			1	2	2

4. Preliminary analysis

4.1 Analytical case

One of the purposes of this test is to examine the scale effect on the mechanical behavior of LRBs. Three types of scaling laws are introduced to the test, shear strain rate, displacement rate and thermal condition. If the scaling law that provides the same shear strain rate to every type of bearing is applied, the frequency of loading for each type of bearing should be the same value. In the scaling law that provides the same displacement rate to every type of bearing, the frequency of loading should be proportional to the scale factor of each type of bearing. In the scaling law that makes the thermal condition of every type of bearing equal, the frequency of loading needs to be proportional to the square of the scale factor of each type of bearing [10]. This relationship is derived from the governing equation for heat conduction described as Eq. (3):

$$\frac{\rho c}{\lambda}\frac{\partial\theta}{\partial t}=\frac{\partial^2\theta}{\partial x^2}+\frac{\partial^2\theta}{\partial y^2}+\frac{\partial^2\theta}{\partial z^2} \tag{3}$$

where ρ is density, c is specific heat, λ is thermal conductivity, and θ is temperature.

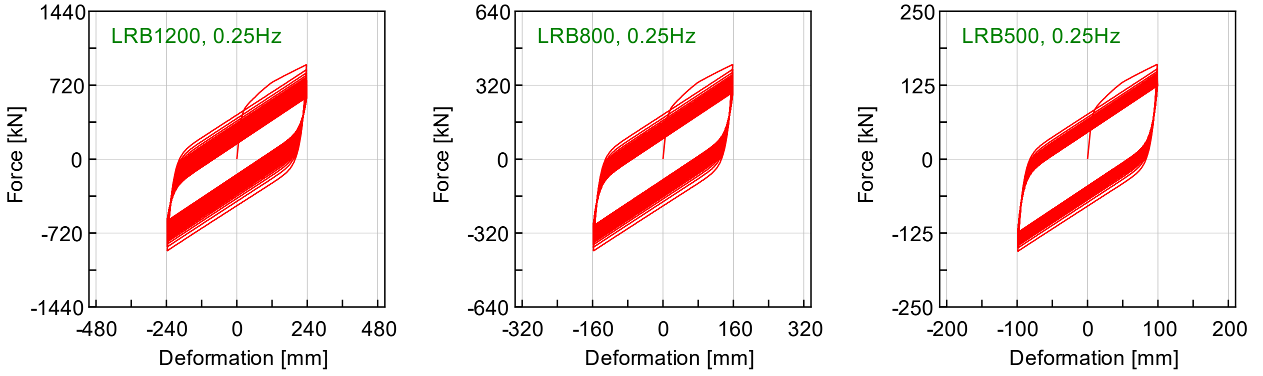
The frequencies of loading for each type of bearing are summarized in Table 4, which were calculated on the basis of the frequency condition of loading of 0.25 Hz for the real size LRB; Type L (1200-mm dia.). In the preliminary analysis, two types of scaling laws, shear strain rate and thermal condition, were examined. In total, five cases of preliminary analysis were conducted.

Table 4 –Frequencies of loading

Bearing type	**Diameter** (mm)	**Scale factor** λ (= diameter/1200)	Applied scaling law		
			Strain rate $f_{\text{scaled}}=f_{\text{real}}$	**Displacement rate** $f_{\text{scaled}}=\lambda f_{\text{real}}$	**Thermal condition** $f_{\text{scaled}}=\lambda^2 f_{\text{real}}$
L	1200	1.0	0.25 Hz	0.25 Hz	0.25 Hz
M	800	1.5	0.25 Hz	0.375 Hz	0.563 Hz
S	500	2.4	0.25 Hz	0.60 Hz	1.44 Hz

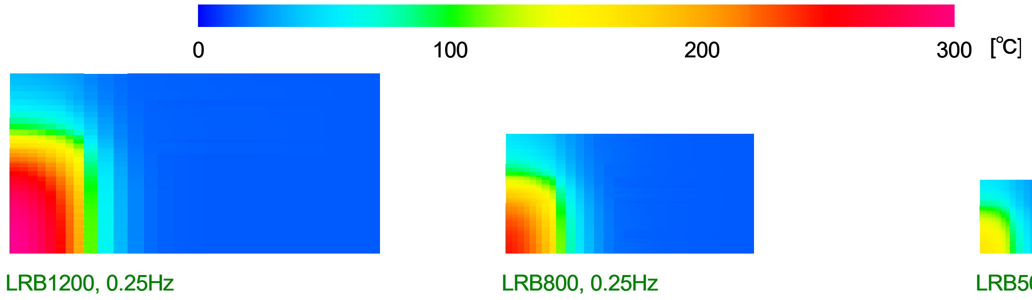
4.2 Analytical results

Figs. 8 and 9 show the analytical results obtained from the analyses in which the scaling law of shear strain rate was applied. The shear strain amplitude was 100%, the frequency of loading was 0.25 Hz, and the number of loading cycles was 30. The force-deformation hysteresis loops shown in Fig. 8 are scaled in accordance with the scale factor of each LRB type. Degradation of the shear force in the hysteresis loops is common, especially as Type L exhibited the most significant degradation of the shear force among the three types. Fig. 9 shows the internal temperature distribution of the LRBs. The heat generated in the lead plug did not conduct to the steel-rubber laminated part around the lead plug so much. The temperature at the center of the lead plug for Type L was the highest, which rose up to 300°C. In general, the amount of generated heat is proportional to the volume of the lead plug, i.e., the cubic of the length, and the amount of diffused heat is proportional to the surface area of the lead plug, i.e., the square of the length. Therefore, the larger the diameter of an LRB, the more easily the generated heat is accumulated in the lead plug, and the temperature significantly increases under the condition of the same shear strain amplitude and frequency of loading. This is the reason that the Type L exhibited the highest temperature and the most significant degradation of shear force.



(a) Type L (b) Type M (c) Type S

Fig. 8 – Force-deformation hysteresis loops obtained from analyses applying scaling law of shear strain rate

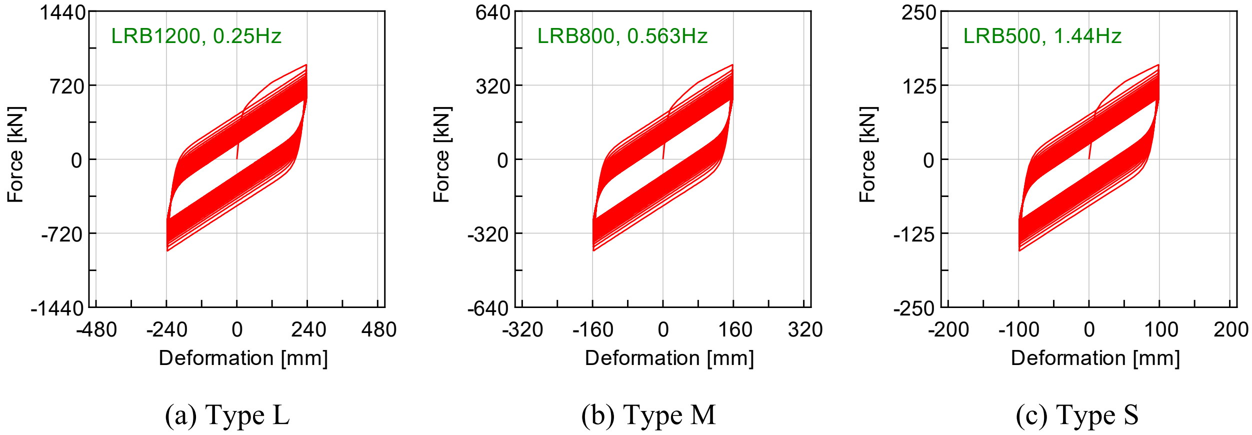


(a) Type L (b) Type M (c) Type S

Fig. 9 – Internal temperature distribution obtained from analyses applying scaling law of shear strain rate

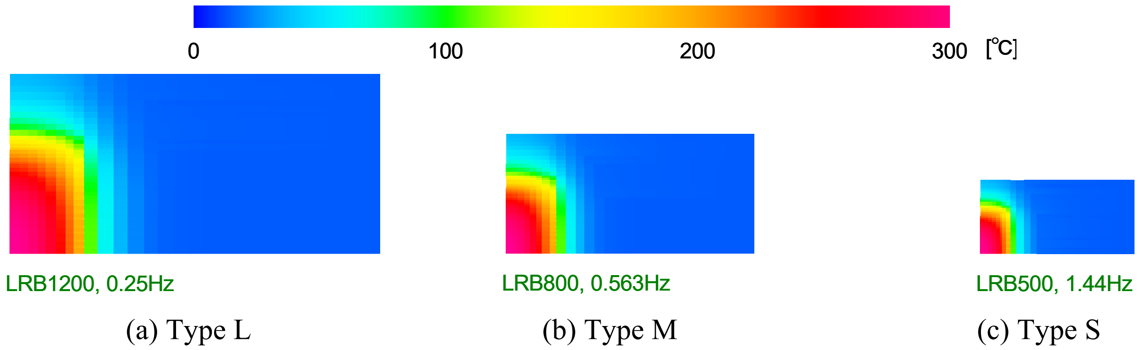
Figs. 10 and 11 show the analytical results obtained from the analyses in which the scaling law of thermal condition was applied. The shear strain amplitude was 100% and number of loading cycles was 30. The loading frequencies summarized in Table 4 were applied. The force-deformation hysteresis loops shown in Fig. 10 are scaled in accordance with the scale factor of the bearing. The shear force in the hysteresis loops of every type of LRB degrades similarly. Fig. 11 shows the internal temperature distribution of the LRBs. The temperature at the center of the lead plug of every type of LRB also rises up to 300°C by the end of the 30 cyclic loadings similarly. This fact shows that a high frequency of loading is required to provide the same heat conditions to a scaled bearing as those to a real scale one.

The analysis results suggest that the thermal-mechanical coupled behavior of the LRBs is strongly dependent on the size of the bearings. The actual behavior of a real size LRB under cyclic loading can not be examined exactly as long as a scaled LRB is used. In other words, the actual behavior is not known unless a full-sized bearing is tested using the test facilities that vibrate the bearing at actual speeds and with actual displacement.



(a) Type L (b) Type M (c) Type S

Fig. 10 – Force-deformation hysteresis loops obtained from analysis applying scaling law of thermal condition



(a) Type L (b) Type M (c) Type S

Fig. 11 – Internal temperature distribution obtained from analyses applying scaling law of thermal condition

5. Conclusion

This research focuses on the thermal-mechanical coupled behavior of LRBs under a large number of cyclic loadings. Tests of LRBs were planned to examine the scale effect on deformation suppression and energy absorption. Three types of LRBs were designed in which the thickness of the rubber sheets, inner plates, and diameter of the lead plug were scaled in accordance with the scale factor of the rubber sheet diameters. In this paper, a preliminary simulation analysis was conducted prior to the test. Two types of scaling laws for the frequencies of cyclic loading were introduced to examine the thermal conditions in the LRBs. The analytical results predicted the state of heat conduction changes over the different LRB sizes. This prediction shows that the actual thermal-mechanical coupled behavior of a real scale LRB under cyclic loading can not be examined exactly as long as a scaled bearing is used. The authors concluded that a full-sized seismic isolation bearing should be tested at actual speeds and with actual displacement to examine the ultimate behavior of the bearing.

6. Acknowledgements

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