Multi-cyclic Dynamic Loading Experiment of Full-scale Devices for Seismic Isolation against Long-Period Earthquake Motions -Preliminary study -

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SUMMARY:
The authors have conducted full-scale multi-cyclic dynamic loading experiments on a sliding bearing with a diameter of 800 millimetres and on an oil damper with a maximum damping force of 1,000 kN. The world's largest 3-D full-scale shaking table named "E-Defense" was used for the experiments. A large reaction beam was constructed over the shaking table and the bearing used in the experiment was placed on the table. The table was then lifted up to the reaction beam in displacement control mode until 5,000 kN of axial force had been introduced on the bearing. The table was then shaken in a horizontal direction. Sinusoidal excitations with amplitude of 400 mm were applied such that the cumulative displacement reached from 50 m to 100 m. It is clarified that the several techniques devised to ensure accurate and safe execution of the experiment worked well and that accurate experimental data have been obtained.

Keywords: Full-scale dynamic loading test, Base isolation, Sliding bearing, Hydraulic damper, Long-period ground motion

1. INTRODUCTION

In recent years, long-period earthquake motions caused by subduction zone earthquakes around Japan and their impact on super high-rise buildings and base-isolated buildings have attracted great public concern and interest in Japan. In particular, the 2011 Great East Japan Earthquake brought about long-period ground motions in the Kanto plain, which caused large displacement response in super high-rise buildings and base-isolated buildings lasting for several minutes. With the Tokai, Tonankai, and Nankai earthquakes, or even a coupling of more than one of them, expected to occur in the near future [Headquarters for Earthquake Research Promotion, 2012, Review meeting for mega-earthquake along Nankai Trough, 2012], the Kanto, Nobi and Osaka plains will be exposed to long-period ground motions of larger amplitude. It is therefore very important and essential to verify the safety of seismic isolation systems against long-period earthquake motions.

To assess this issue, we have conducted full-scale multi-cyclic dynamic loading experiments on a sliding bearing measuring 800 millimetres in diameter and on an oil damper with a maximum damping force of 1,000 kN. Sinusoidal excitation at a frequency of 0.25 Hz was applied to these devices in the horizontal direction. The excitation was 0.4 m in amplitude, 0.628 m/s in peak velocity and continued such that the cumulative displacement of the devices was 50 m to 100 m (exceeding that expected of a base-isolated building during long-period earthquakes) [Shimizu Corporation et. al. 2010]. As for the sliding bearing, an axial load of 5,000 kN was applied simultaneously.

To make possible this full-scale dynamic loading experiment, the world's largest 3-D full-scale shaking table (named "E-Defense" and constructed by the National Research Institute for Earth Science and Disaster Prevention in Japan (NIED)) was used. A large reaction beam was constructed over the shaking table and the bearing used in the experiment was placed on the shaking table with load cells underneath it. The table was then lifted up into contact with the reaction beam in displacement control mode until an axial force of 5,000 kN had been introduced on the bearing and

then oscillated in the horizontal direction. Several techniques were devised to ensure an accurate experiment as well as its safe execution.
The preliminary results of this full-scale multi-cyclic loading experiment are presented and discussed along with details of the experimental set-up.

2. DYNAMIC LOADING EXPERIMENT USING LARGE SHAKING TABLE

2.1. Experimental set-up

The full-scale multi-cyclic dynamic loading experiments were carried out on a sliding bearing measuring 800 mm in diameter and on an oil damper with a maximum damping force of 1,000 kN. A large reaction beam, comprising main and sub beams, was constructed over the corner of the shaking table, as shown in Figure 2.1 and Photo 2.1. The elastic sliding bearing used in the experiment was set down on the shaking table with thirty-one load cells underneath it. The table was then lifted up in displacement control mode to the reaction beam until an axial force of 5,000 kN had been introduced on the bearing. Multi-cyclic loading of the elastic sliding bearing was carried out in the direction of the main beam axis, while in the case of the oil damper it was in the direction of the sub beam axis, as

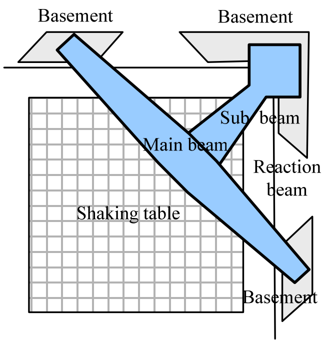
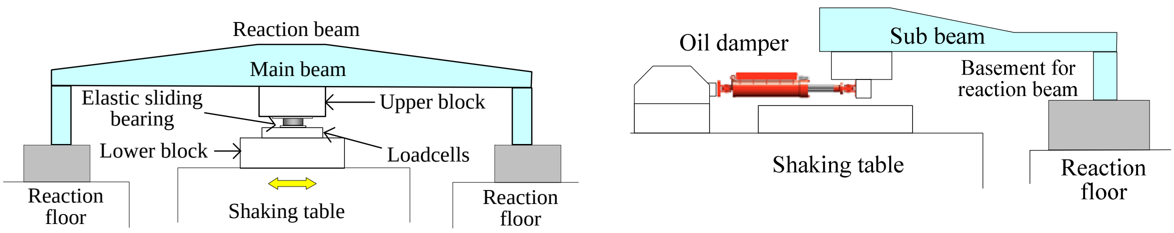


Figure 2.1. Layout of reaction beam

Photo 2.1. Reaction beam in place over shaking table



(a) Elastic sliding bearing (b) Oil damper

Figure 2.2. Experimental set-ups for multi-cyclic loading

Photo 2.2. Cotters on reaction beam

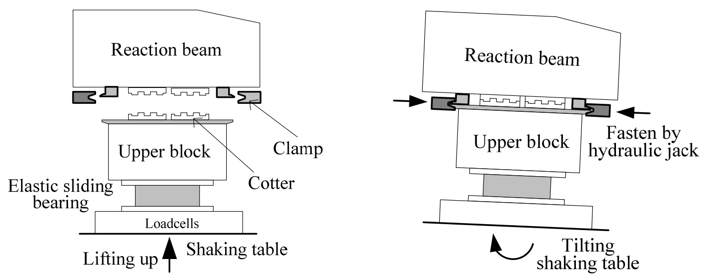


Figure 2.3. Introduction of axial force on the bearing

shown in Figure 2.2.
The shear force of the sliding bearing is transmitted to the reaction beam using four interlocking cotters attached beneath the reaction beam and on the upper block of the sliding bearing, as shown in Photo 2.2. The shaking table is lifted until the cotters interlock. The upper block and the reaction beam are then fastened with clamps using hydraulic jacks so that the cotters cannot come apart as a result of the overturning moment induced by the shear force on the bearing. Next, the axial force is introduced on the bearing by further lifting the shaking table; this may cause some inclination in the reaction beam. To cancel any such eccentric axial pressure on the bearing, the shaking table is tilted. This procedure is illustrated in Figure 2.3. A steel plate of 220 mm thickness is placed under the bearing in order to transmit the axial and shear force to the thirty-one load cells.
The experimental set-up for the oil damper is shown in Figure 2.2.(b); the main body of the oil damper is connected to the shaking table with a pin joint and is exposed to the table excitations such that the seismic responses of the damper are similar to those of one installed in an actual base-isolated building. The piston is connected to the reaction beam with a pin joint and does not move. In an ordinary test for an oil damper before shipping, the piston is excited in a testing machine and the main body of the damper is not subjected to excitation.

2.2. Excitation conditions

The excitation conditions for the elastic sliding bearing and the oil damper are listed in Table 2.1 and Table 2.2, respectively, where the main beam and sub beam axes are defined as u and v, respectively, as shown in Figure 2.1. The fundamental excitation is applied before and after the main multi-cyclic excitations and earthquake excitations so as to evaluate the change in characteristics of the sliding bearing and oil damper. The multi-cyclic excitations are conducted at intervals of about one minute, an operational requirement due to the limitation of oil supply for the shaking table. The excitation waveforms for the earthquake excitations are calculated by the seismic response analysis of a one-degree-of-freedom building subjected to long-period ground motions anticipating the Tokai, Tonankai and Nankai coupled earthquake [Ohsaki Research Institute Inc. 2012].

Table 2.1. Excitation conditions for elastic sliding bearing

	Excitation wave	Case	Direction	Period (s)	Pressure N/mm^2	Disp. (mm)	Number of cycles per excitation	Number of excitations (cumulative disp.)
Fundamental excitation	Sinusoidal wave	Sf	u	4	10	100	4	1 (1.6m)
Multi-cyclic excitation	Sinusoidal wave	Smu	u	4		400	5	7 (56.0m)
		Smuv	u+v			u:255 v:255	5	7 (56.0m)
Earthquake excitation	Earthquake response	Seu1	u	-		110	-	(13.0m)
		Seu2				191	-	(13.2m)
		Seuv	u+v	-		u:102 v:85	-	(1.7m)

Table 2.2. Excitation conditions for oil damper

	Excitation wave	Case	Period (s)	Disp. (mm)	Vel. (m/s)	Number of cycles per excitation	Number of excitations (cumulative disp.)
Fundamental excitation	Sinusoidal wave	Of	4	159	0.25	2	1
Multi-cyclic excitation	Sinusoidal wave	Omv	4	400	0.628	4	16 (102.4m)
Earthquake excitation*	Earthquake response	Oev1	-	110		-	(13.0m)
		Oev2		191			(13.2m)
Large displacement and velocity excitation	Sinusoidal wave	Osv1	2.5	300	0.75	2	1
		Osv2		400	1.00		
		Osv3		500	1.25		
		Osv4		600	1.50		

3. VERIFICATION OF EXPERIMENTAL METHOD

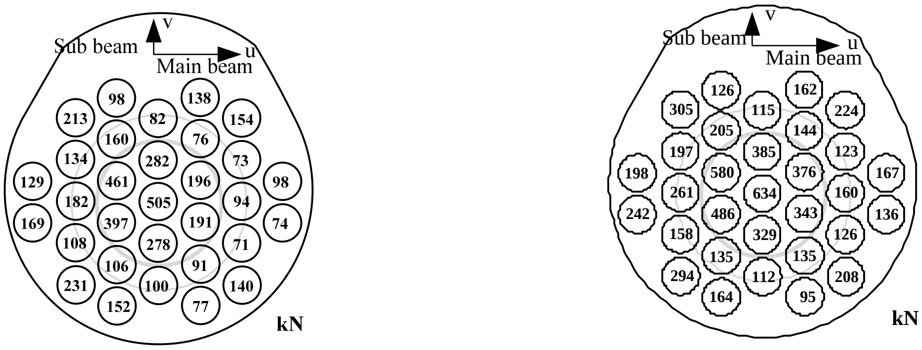
3.1. Axial force on the sliding bearing

The axial force acting on the sliding bearing was measured using the 31 load cells. Upon lifting the shaking table up in displacement control mode until the total axial force on the bearing reached 5000 kN, the shaking table had to be tilted by 1/769 to level the pressure on the bearing. The distribution of axial force on the load cells after levelling is shown in Figure 3.1(a). The axial load on the central load cell is larger than on the other load cells and the centre of the axial load is slightly biased in the direction of the main beam.

3.2. Horizontal excitations

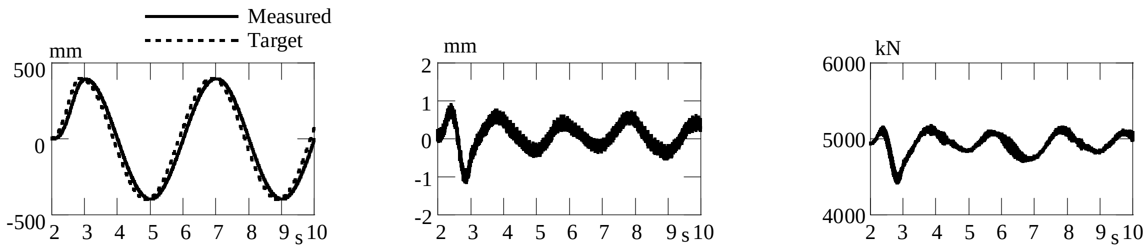
3.2.1. Horizontal and vertical excitation input

Horizontal and vertical excitation displacements are defined near the corner of the shaking table, with the elastic sliding bearing located at a point shifted 3.5 m × 2.5 m from the corner. The displacements are converted to the six degree-of-freedom displacements at the centre of the table surface and these are used as the excitation input for shaking table control. As noted above in section 3.1, an inclination of 1/769 was needed to equalize the load when the full 5000 kN axial force had been introduced. This inclination was maintained while the horizontal excitations were carried out. Prior to the experiment, the vertical displacement of the shaking table resulting from the horizontal excitation was measured with no axial load on the bearing. The sign of this measured vertical displacement was inverted and then used as an input excitation during the experiment to cancel the vertical displacement of the shaking table.



(a) 5000kN vertical loading (b) Horizontal excitation for Case Smu

Figure 3.1. Maximum vertical loads on 31 load cells



(a) Horizontal excitation (b) Vertical displacement (c) Variation in axial force

Figure 3.2. Accuracy of horizontal excitation

3.2.2. Accuracy of excitation

Figure 3.2.(a) and 3.2.(b) show examples of shaking table displacement under horizontal excitation plotted against the target value and the vertical induced displacement, respectively, at the point 3.5 m × 2.5 m from the corner. The horizontal displacement coincides with the target value closely. The

vertical induced displacement of the shaking table is minimized. The variation in axial force on the bearing reaches around 500 kN (*i.e.* 10%) at the beginning of excitation and remains within 200 kN thereafter, as shown in Figure 3.2.(c).
The maximum axial forces on the load cells were measured. An example of these measurements for the multi-cyclic loading excitation of Case Smu (defined in Table 2.1.) is illustrated in Figure 3.1.(b). The maximum axial forces on the load cells are well balanced.

4. EXPERIMENTS FOR ELASTIC SLIDING BEARING

4.1. Test specimen

A sectional view of the sliding bearing is shown in Figure 4.1. The bearing comprises a 32 mm steel plate with three layers of 6 mm thick natural rubber on its lower surface and a 2 mm thick layer of PTFE on its upper surface. The elastic sliding bearing is attached to the 220 mm steel plate overlaying the load cells, with a 10 mm thermal insulation board sandwiched between them. A sliding plate made of SUS304 is attached to the upper block with a 10 mm thermal insulation board sandwiched between them, as illustrated in Figure 4.2.

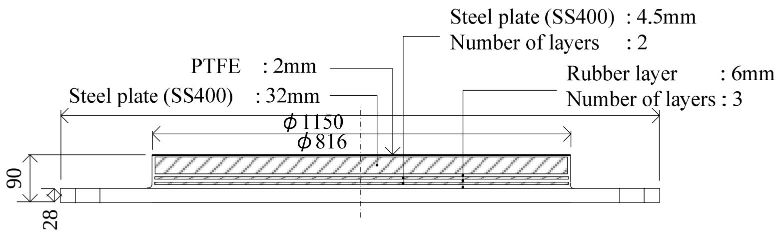


Figure 4.1. Sectional view of elastic sliding bearing

Photo 4.1. Elastic sliding bearing

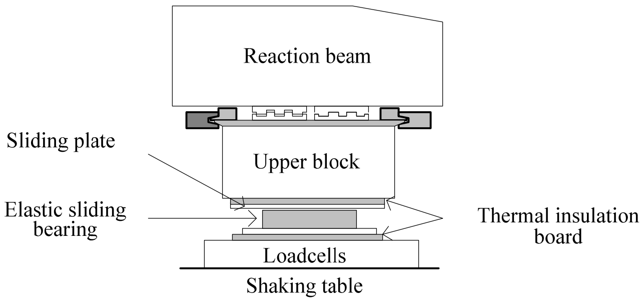


Figure 4.2. Experimental set-up for elastic sliding bearing

4.2. Excitation program and measurement

The series of excitations is listed in Table 4.1. The displacement between the elastic sliding bearing and the sliding plate, the horizontal and vertical deformation of the elastic sliding bearing, and the horizontal and vertical loads are measured. The temperature of the sliding plate, the PTFE and the flange of the elastic sliding bearing is measured with thermocouples. Two radiation thermometers are used to measure the surface temperature of the elastic bearing. The layout for temperature measurement is shown in Figure 4.3.

4.3. Experimental results

The relationships between horizontal load and deformation of the elastic sliding bearing for Case Smu and Case Seu2 are shown in Figures 4.4.(a) and 4.4.(b), respectively. The horizontal load, or the coefficient of friction, gradually decreases. The coefficient of friction, which is evaluated using the third cycle of the horizontal load against deformation relationship in a fundamental excitation, Case Sf, before and after Case Smu, is 0.147 and 0.062, respectively, as shown in Figure 4.5.(a) and 4.5.(b). The method of evaluating the coefficient of friction is illustrated in Figure 4.6.

The coefficients of friction evaluated for all 35 cycles of sinusoidal excitation in Case Smu are plotted with respect to accumulated absorbed energy in Figure 4.7. It is observed that the coefficient of friction is higher to some extent at the beginning of each excitation. Thus it seems necessary to consider not only the accumulated absorbed energy but also its dissipation in order to model the observed variations in the coefficient of friction. The coefficient of friction is 0.147 at the beginning, about 1.5 times the design value. This may be due to the pressure dependence of the coefficient of friction, as the pressure on the bearing is 10 N/mm^2, or half of the standard pressure, 20 N/mm^2. The same tendency has been observed in a previous study [Hibino et. al. 2003].

The temperatures at the centre of the sliding plate (A7), of the liner steel plate just beneath the PTFE (B1), and at the centre of the flange (C1) are shown in Figure 4.8. The temperature at point A7 increases to 204 °C and 260 °C at the end of excitation in Case Smu and Case Smuv, respectively.

After the series of excitations listed in Table 4.1., the condition of the PTFE was checked and no damage was observed.

Table 4.1. Series of excitations

	Order of excitations (Case names are defined in Table 2.1)					
1st day	Sf	Seu1	Seu2	Smu	Sf	
2nd day	Sf	Seuv	Smuv	Smuv	Sf	Sf

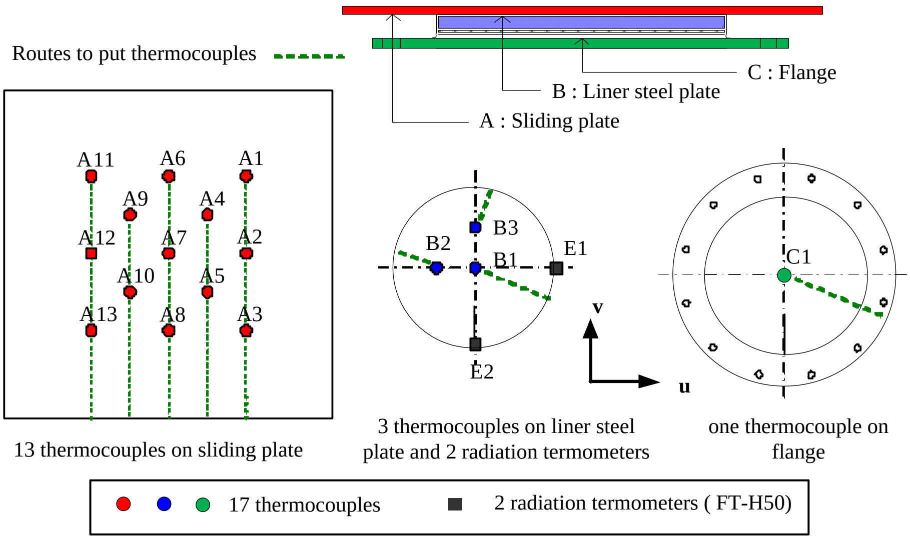
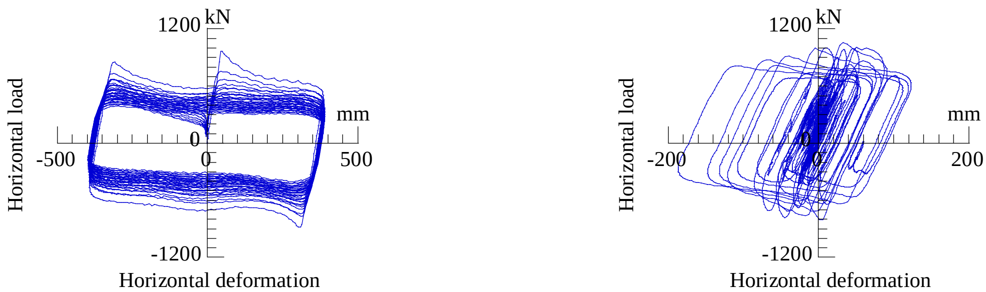


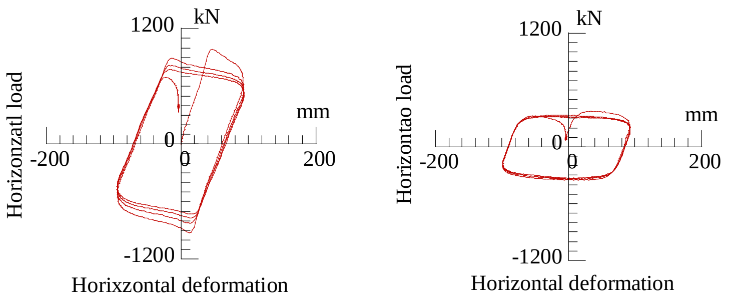
Figure 4.3. Layout for temperature measurement



(a) Case Smu

(b) Case Seu2

Figure 4.4. Horizontal load and deformation relationships



(a) Case Sf before Case Smu (b) Case Sf after Case Smu

Figure 4.5. Horizontal load and deformation relationships

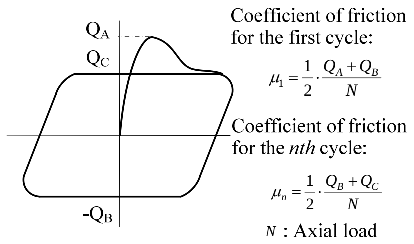


Figure 4.6. Evaluation of coefficient of friction

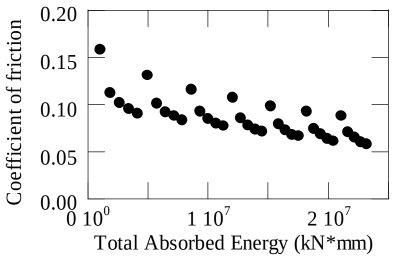


Figure 4.7. Coefficient of friction

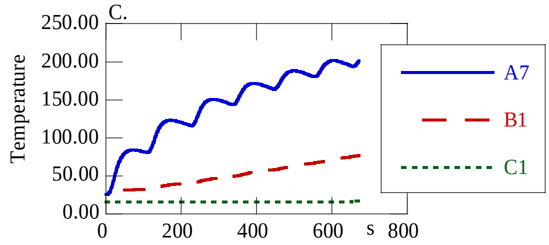


Figure 4.8. Temperature

5. EXPERIMENTS FOR OIL DAMPER

5.1. Test specimen

The damper has a maximum damper force, maximum piston stroke, and maximum allowable piston velocity of 1000 kN, 700 mm, and 1.5 m/s, respectively. The primary and secondary damping coefficients are C1= $2.50 MN \cdot s/m$ and C2= $0.1695 MN \cdot s/m$, respectively, as shown in Figure 5.1.

5.2. Excitation program and measurements

The series of excitations is listed in Table 5.1. The displacement and velocity of the piston are measured with damper force. The oil temperature in the upper oil tank and the surface temperature of the outer cylinder were measured; the layout of thermocouples is illustrated in Figure 5.2. As mentioned in Section 2.1, the main body of the oil damper is connected to the shaking table with a pin joint and is exposed to the table excitations such that the seismic response of the oil damper is similar to that of a damper installed in an actual base-isolated building. The piston is connected to the reaction beam with a pin joint and does not move. In an ordinary test for an oil damper before shipping, the piston is excited by a testing machine and the main body of the oil damper is not subjected to the excitations.

5.3. Experimental results

5.3.1 Multi-cyclic excitation

The relationships between damper force and piston displacement for Case Omv, where 16 consecutive sinusoidal excitations were conducted, are shown in Figure 5.3. Each excitation consists of four sinusoidal waves with a 4-second period and there is a one-minute interval between excitations due to a limitation imposed by the oil supply to the shaking table. The cumulative displacement reached 102.4 m. As is clear from Figure 5.3., there is little change in the relationship between damper force and piston displacement between the beginning and end of the excitation series. Figure 5.4. shows the change in temperature during the excitations. The temperature in the upper oil tank reached 108 °C by the end of the test. The temperature dependence of maximum damper force and of absorbed energy was evaluated. Both maximum damper force and absorbed energy fall with rising temperature, with reductions of 4% and 5% at 108°C, respectively, compared to their initial values at ambient temperature. This confirms that performance degradation is minor.

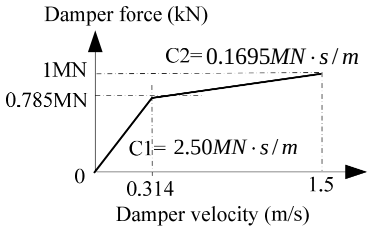


Figure 5.1. Damper force characteristics

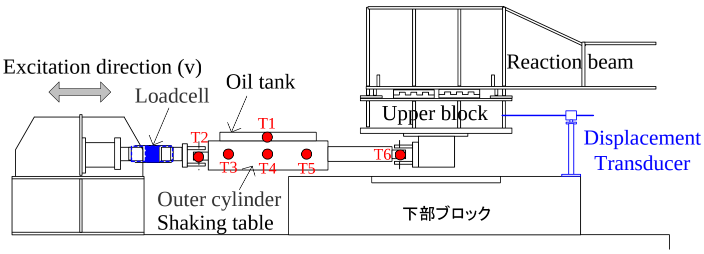


Figure 5.2. Layout of measurement sensors

Table 5.1. Series of excitations

	Order of excitations (Case name is defined in Table 2.2)							
1st day	Of	Omv	Of					
2nd day	Of	Oev1	Oev2	Osv1	Osv2	Osv3	Osv4	Of

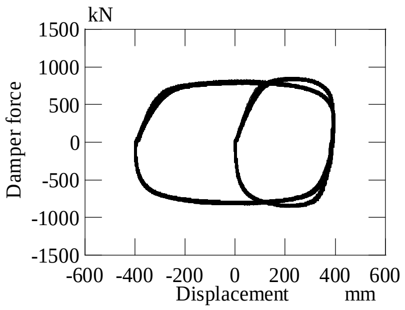


Figure 5.3. Damper force and piston displacement for Case Omv

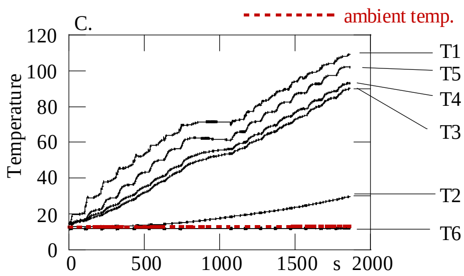


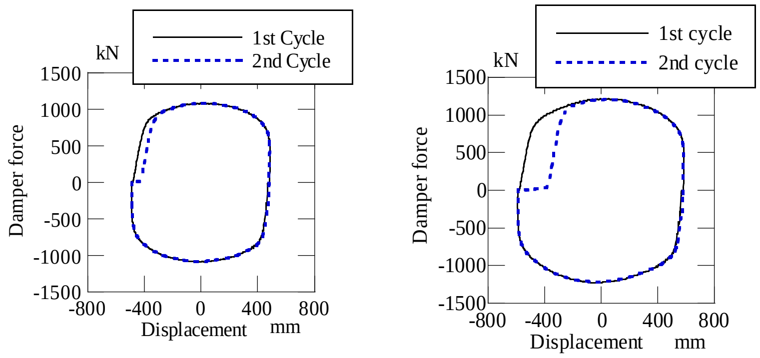
Figure 5.4. Temperature changes

5.3.2 Large displacement and velocity excitation

The relationships between damper force and piston displacement for Case Osv3 and Case Osv4 are shown in Figure 5.5. In these cases, each excitation comprises two sinusoidal waves with a 2.5-second period. The temperatures in the upper oil tank for Case Osv3 and Case Osv4 reached 35.8°C and 49.3°C, respectively. The relationships for the first cycle of excitation are typical for both cases. However, there is some delay in the rise of damper force in the second cycle of excitation, as clearly seen in the time history of damper force plotted in Figure 5.6. This delay in damper force may be caused by a limited flow of oil from the oil tank to the cylinder as well as the shaking of the damper body itself. The maximum damper force during the second cycle, however, is the same as for the first cycle. The reduction in absorbed energy during the second cycle for Case Osv3 and Case Osv4 is 2% and 8%, respectively. The fundamental excitation, Case Of, was applied several minutes after completing Case Osv4 and this confirmed that the relationship between damper force and piston displacement had recovered to normal.

6. CONCLUSIONS

The authors have conducted full-scale multi-cyclic dynamic loading experiments on a sliding bearing measuring 80 centimetres in diameter and on an oil damper with a maximum damping force of 1,000 kN. It is clarified that the several techniques devised to ensure accurate as well as safe execution of the experiment worked well and accurate experimental data were obtained.



(a) Case Osv3 (125 cm/s) (b) Case Osv4 (150 cm/s)

Figure 5.5. Damper force and piston displacement relationship

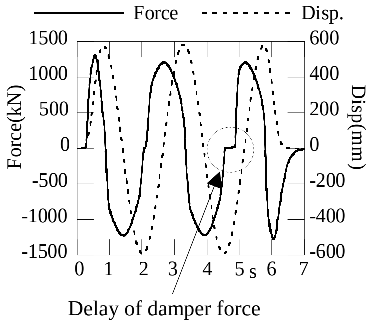


Figure 5.6. Damper force and displacement (Case Osv4)

As for the elastic sliding bearing, coefficients of friction were evaluated for multi-cyclic sinusoidal excitations of which the cumulative displacement exceeded 100 m. It was found necessary to consider not only the accumulated absorbed energy but also its dissipation in order to model the observed variations in coefficient of friction.

Regarding the oil damper, the main body of the damper was connected to the shaking table and exposed to the table excitations such that its seismic response is similar to that of dampers installed in actual base-isolated buildings. (In an ordinary test for an oil damper before shipping, the piston is excited in a test machine, while the main body of the damper is not subjected to excitations.) The cumulative displacement reached 102.4 m in this test and the temperature of oil increased to 108°C in the multi-cyclic sinusoidal excitations. It is clarified that there is little change in maximum damper force and absorbed energy with temperature.

Large displacement and velocity excitations were also conducted; two cycles of sinusoidal waves were applied and some delay in damper force was observed in the second cycle of excitation when the damper velocity was more than 125 cm/s. The results demonstrate that the proposed excitation method is both necessary and effective as a means of confirming the performance of an oil damper.

The results obtained in this study will contribute to the safety evaluation of base isolation devices in future.

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