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EXPERIMENTAL STUDY ON BASIC CHARACTERISTICS AND FATIGUE PROPERTIES OF LEAD DAMPER FOR SEISMIC ISOLATION SYSTEM

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Abstract

In order to protect people, buildings and other important facilities from damage caused by earthquakes, seismic isolation systems have been developed. In Japan, many buildings are protected using seismic isolation with supplemental damping, including U-shaped lead dampers. Lead is used as the energy dissipation component of these dampers, because pure lead has the characteristics of low yield stress and very high ductility with minimal strain hardening. The hysteretic behavior of this damper is elasto-plastic, and this allows it to provide high levels of damping performance. However, the formation of fatigue cracks on the surface of the lead caused by small oscillations due to wind or traffic vibration, affects the damping properties of the damper. Although it is known that the fatigue properties of lead can be improved by a vaseline-coating or a grease-coating on the specimen surface, the effect of the coating is not well understood qualitatively and quantitatively. To clarify this effect, we carried out two types of tests: (1) very small deformation cyclic tests under similar actual conditions using a full-size, U-shaped lead damper, and (2) rotating-bending fatigue tests on pure lead round bars. Based on the results of these tests, a grease-coating is identified as an effective method of fatigue life enhancement.

Keywords: Seismic Isolation, Lead, Damper, Fatigue Test

1. Introduction

In order to protect people, buildings and other important facilities from damage caused by earthquakes, seismic isolation systems have been developed. With seismic isolation, the whole structure is set on elastomeric bearings, which function as isolators. The main effect of the isolators is to decouple the structure from the ground and increase the resonant period of the structure to a value outside the range of periods containing the principal earthquake energy. There are two classes of elastomeric isolators. One is an isolator with a built-in damping function such as a lead rubber bearing (LRB), or a high damping rubber bearing (HRB). The other is an isolator without a built-in damping function, such as a natural rubber bearing (NRB). Natural rubber bearings need to be combined with supplemental energy dissipation devices, when installed as a seismic isolation system. In Japan many isolated buildings use isolators in combination with supplemental dampers, and there are many types of dampers. The dampers are connected to the building in a similar manner to the isolators. One end of the damper is fixed to the basement and the other is attached to the superstructure. In this paper, we discuss the properties of U-shaped lead dampers and fatigue phenomenon in lead.

Lead is used as an energy dissipation device for seismic isolation and vibration control systems, because pure lead has the characteristics of low yield stress and very high ductility with minimal strain hardening. The hysteretic behavior of the U-shaped lead damper is elasto-plastic, and this allows it to provide high levels of damping during earthquakes.

But in recent years, it has been reported that cracking takes place on the surface of in-service lead dampers even though they have not experienced a large earthquake. These cracks affect the damping properties of the device. Lead is a fatigue-resistant metal due to the effect of re-crystallization at ambient temperatures. However, fatigue cracks in lead may be generated by small vibrations over a long period of time when exposed to oxygen. These small oscillations may be due to wind, traffic vibrations, small earthquakes, and the like.

The influence of testing environment on the fatigue properties of lead has been reported in the literature [1-8]. For instance, Gough and Sopwith [1] studied the effect of test atmosphere on the fatigue strength of lead, and inferred that the strength in the air was influenced by the interaction between oxygen and cyclic loading. Snowden et al. [2-8] systematically examined the effects of surface condition and surface coatings on the fatigue properties of high purity, polycrystalline lead. It was found that oxygen plays a major role in reducing the fatigue life. Furthermore, it was found that coating the specimen surface with grease, is very effective at improving the fatigue life at atmospheric pressure [7]. Such a coating has the equivalent effect of a 10^{-4} Pa high-vacuum environment. McKeown reported the effects of surface coating including vaseline on the fatigue limit of pure lead and lead alloy [9-10].

Although it is clear from the literature that the fatigue properties of lead can be improved by a vaseline-coating or a grease-coating on the surface, the effect of this coating is not well understood qualitatively and quantitatively. For instance, it is not known whether a grease-coating can prevent the formation of fatigue cracks in a lead damper caused by small oscillations due to wind or traffic vibrations. The objective of this paper is to identify the influence of grease-coating, which provides an environmental shielding effect on the fatigue life and fatigue crack formation in lead dampers.

2. Basic Properties of U-shaped Lead Damper

2.1 Specimen and Experimental Method

The tests were performed on two different sized U-shaped dampers: U180 and U2426. Fig. 1 shows a diagram of the lead damper, Table 1 summarizes the dimensions for each damper tested, and Fig. 2 shows a photograph of the testing machine. U-shaped lead dampers are made of high purity lead, and Table 2 shows the chemical composition. The U-shaped lead damper has a cylindrical-shaped flexible part and a reinforced part that connects to the flange plate. The reinforced part is welded to the steel flange plate by homogeneous welding. The flexible part has an internal kink like U-shape, which decreases the axial tension forces that could be developed through geometrical nonlinearity combined with large horizontal deformation. The diameter of the flexible part is D, the height is H and the length along the column is L. The direction parallel to the kink is referred to as the P-direction (Parallel direction), and the direction normal to this is referred to as the O-direction (Orthogonal direction). There are no significant differences due to the loading direction, so it is assumed that there is no directionality in performance.

The specimens are actual size dampers that are used in seismic isolated buildings. The top and bottom flanges of the specimen are fixed to the testing machine, and a dynamic, displacement-controlled, horizontal, sinusoidal deformation is applied to the top flange by the loading beam of the testing machine, which is connected to an actuator.

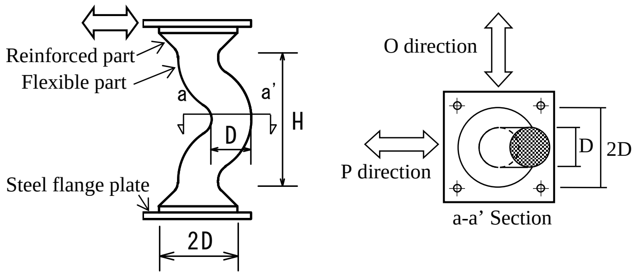


Figure 1. U-shaped lead damper

Figure 2. Testing machine

Table 1. Summary of U-shaped lead damper

	Diameter (mm)	**H**eight (mm)	**L**ength (mm)
U180	180	560	660
U2426	260 (Partially 240)	560	660

Table 2. Chemical composition of lead in wt. %.

Pb	**Ag**	**Cu**	**Bi**
Rest	0.00002	0.00003	0.0003

2.2 Hysteresis Loop

Figs. 3 and 4 show basic hysteresis loops of the U2426 and U180 damper. The shape of the hysteresis loop is rectangular, and the dependence on velocity and temperature is small, so lead dampers are frequently modeled with an elastic-perfectly plastic model. The U2426 damper has a larger diameter than the U180 damper, so the shear force is larger. The yielding of lead dampers occurs at smaller forces compared to steel dampers, and it is possible to exhibit damping performance at comparatively small deformations. Fig. 4 (b) shows a hysteresis loop of the damper to a 550mm dynamically imposed lateral deformation and a 700mm statically imposed lateral deformation. The tendency of a gradual hardening phenomenon at lateral deformations exceeding 150 mm is indicated, because the influence of the axial deformation gradually appears.

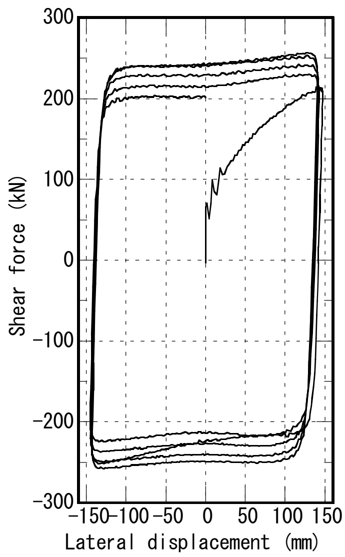
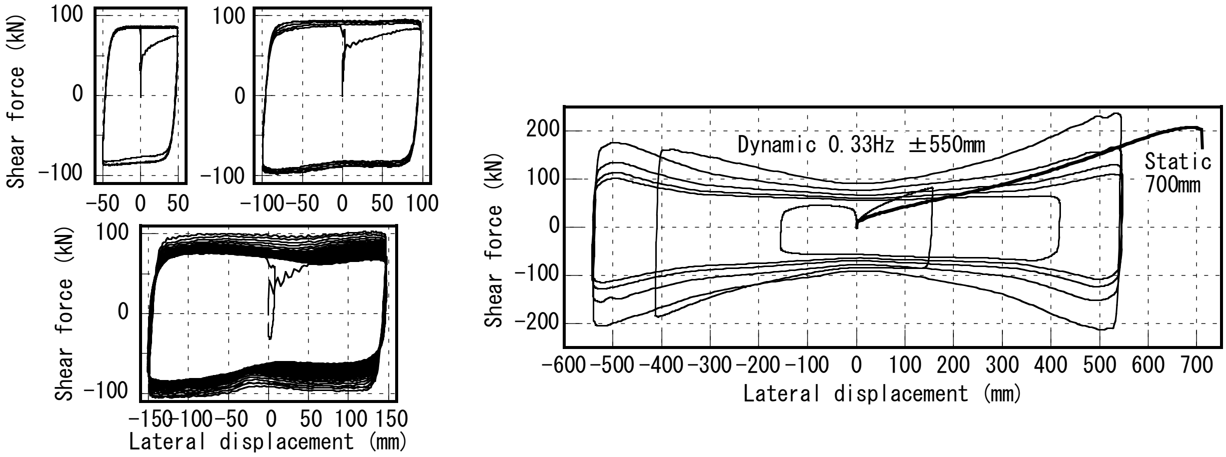


Figure 3. Hysteresis loops of the U2426

(0.33Hz, P-direction)



(a) 0.33Hz

(b) 0.33Hz and Static

Figure 4. Hysteresis loops of the U180 (P-direction)

3. Fatigue Tests

The U-shaped lead damper was designed for energy absorption during an earthquake, so we carried out the cyclic repetition tests within the targeted lateral deformation range from 20mm to 800mm. Since the fatigue phenomenon was caused by small deformation, high-cycle fatigue tests were also conducted. These tests included rotating-bending fatigue tests of lead material samples and cyclic repetition tests of U-shaped lead dampers. The fatigue tests were conducted with and without grease-coating. The grease used was the Li-Complex Grease made by Sumico Lubricant Co., Ltd.

3.1 Rotating-bending Fatigue Test

Rotating-bending fatigue tests were conducted on lead specimens made of the same high purity lead that was used in the U-shaped lead damper. The shape of the specimens is shown in Fig. 5. The fatigue limit of lead was about 2 MPa [11], which is significantly smaller compared to that of commercial steel. The fatigue test was conducted by using a rotating-bending fatigue test machine (Fig. 6) in the high-cycle fatigue mode. The test machine has a structure that gives constant load amplitude and uniform bending moment along the specimen length. The specimens were tested at frequencies from 5Hz to 25Hz. Two types of specimens were tested: a grease-coated specimen and a non-coated specimen (no grease-coating). There is a theoretical value for the stress amplitude below which the material will not fail for any number of cycles, called a fatigue limit or endurance limit. In case of the steel, the fatigue limit is defined as the maximum stress that endured the number of cycles between 10^6 and 10^7. In this test, the fatigue limit occurred at $N>3.0\times10^7$ cycles.

3.1.1 Effect of Grease-coating on Fatigue Life and Fatigue Limit

Fig. 7 shows the S-N curve, a relationship between the stress amplitude and the number of cycles to failure. With respect to non-coated specimens, the fatigue limit is estimated to be 1.6~2.1 MPa. The fatigue limit defined at $N = 10^7$ cycles is about 2.0 MPa [11], which is close to the present experimental data. The fatigue life of the grease-coated specimen was increased 5~10 times compared to that of the non-coated specimen as shown by Fig. 7. For instance, when the stress amplitude was 3.2 MPa, the non-coated specimen fractured at about $N = 4.5 \times 10^6$ cycles, while the grease-coated specimen did not fracture even at $N = 3.0 \times 10^7$ cycles. Accordingly, the present study clearly demonstrates the significant effect of grease-coating on fatigue life. Concerning the fatigue limit of the grease-coated specimen, it is twice as high as that of the non-coated specimen. Further, as the bending stress is decreased, the effect of grease-coating becomes prominent as shown in Fig. 7. Consequently, the grease-coating on the surface of lead has the favorable effect of enhancing the fatigue life and the fatigue limit.

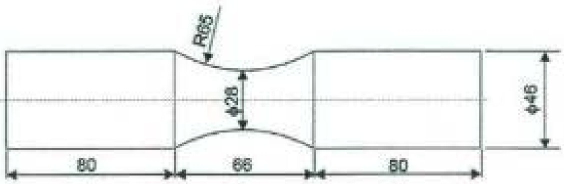


Figure 5. Shape and dimensions of test specimen (mm)

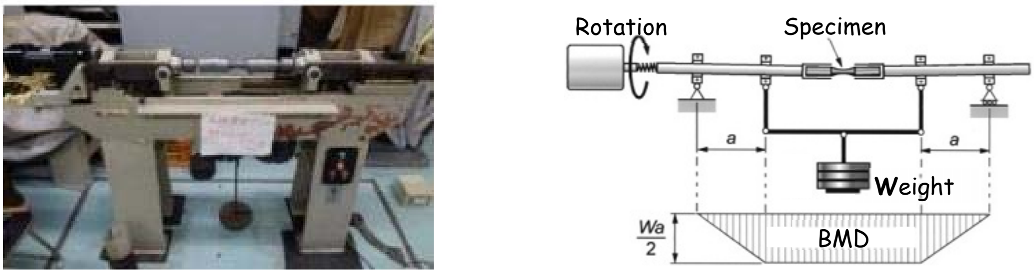


Figure 6. Rotating-bending fatigue test machine

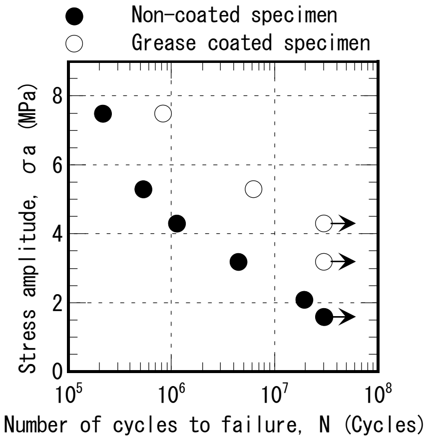


Figure 7. S-N curve

3.1.2 Effect of Grease on Fatigue Crack Propagation Behavior

When the pure lead specimens were tested with and without grease-coating under relatively large bending stress, fatigue cracks were initiated and propagated. It is noted that these fatigue cracks were large enough to be observed with the naked eye.

Fig. 8 shows photographs of the specimen surface after fatigue test. A magnified image of Figs. 8 (e) and (f) respectively are shown in Fig. 9. According to the figures, it is considered that the failure of the as-prepared specimen was caused by the propagation of the main crack; i.e., the fatigue damage was dominated by the main crack, not by some of the fine cracks observed at A (Figs. 8(e) and 9(a)). On the other hand, a number of microscopic cracks were observed at B of the grease-coated specimen (Figs. 8(f) and 9(b)) and the lengths of these cracks were in the range of 1 mm. The surface of the grease-coated specimen was observed at $N = 2.0 \times 10^7$ cycles, and the configuration of the microscopic cracks was very similar to Fig. 9(b) (i.e., further crack propagation in the grease-coated specimen was not observed between $N = 2.0 \times 10^7$ cycles and $N = 3.0 \times 10^7$ cycles). Accordingly, these cracks can be considered as non-propagating. In essence, a certain amount of grease on the specimen surface can penetrate into the material through the cracks. Therefore, this phenomenon of crack arrest associated with grease-coating could be explained by viscous, fluid-induced, crack closure (i.e., the development of crack closure due to hydrodynamic wedging action of grease inside the crack [12]). Though it is easy to imagine that grease on the specimen surface can serve as the shielding agent against the surrounding environment, its significant shielding capability for fatigue crack propagation and fatigue failure is remarkable as demonstrated in Figs. 7 and 9.

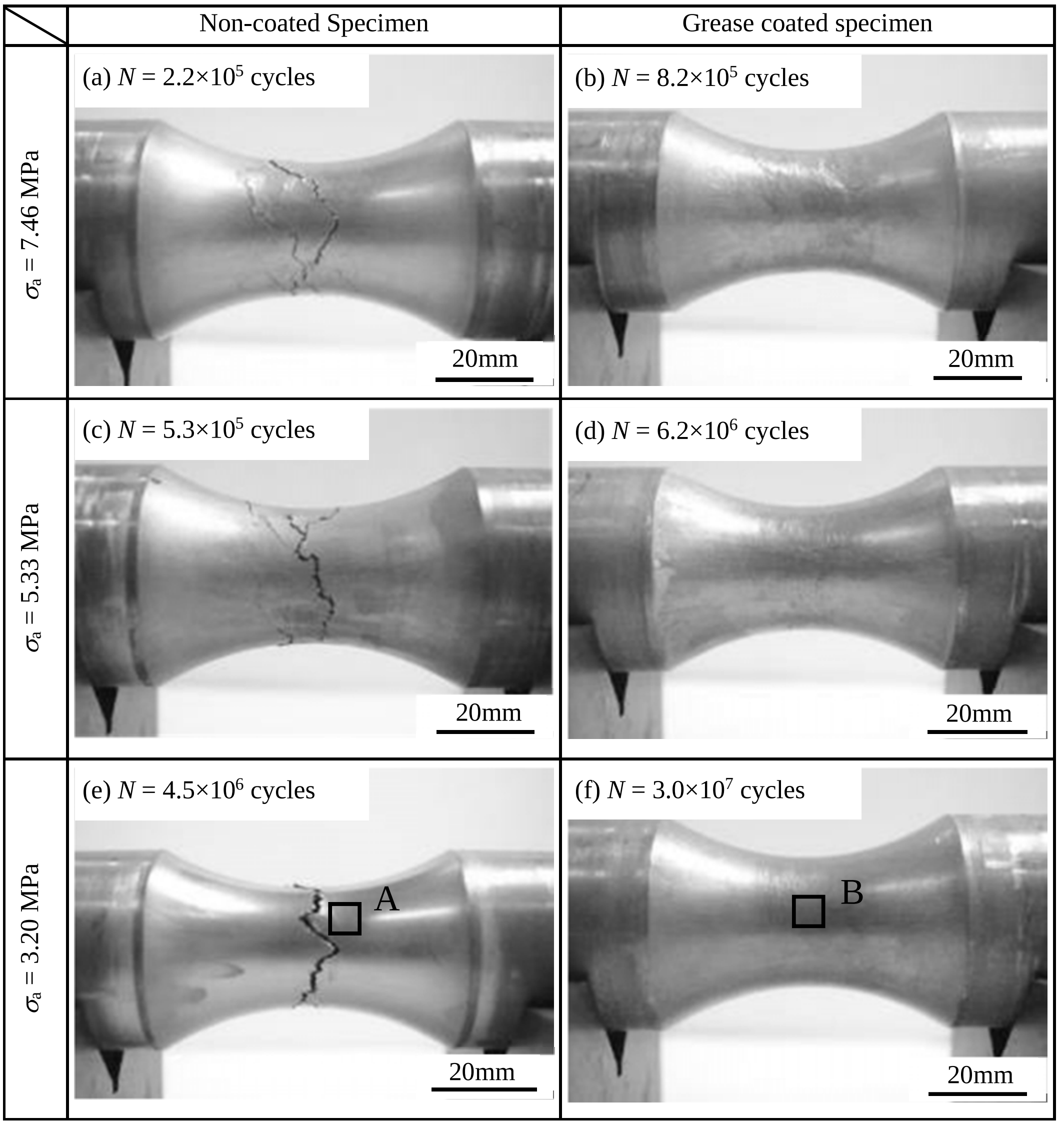
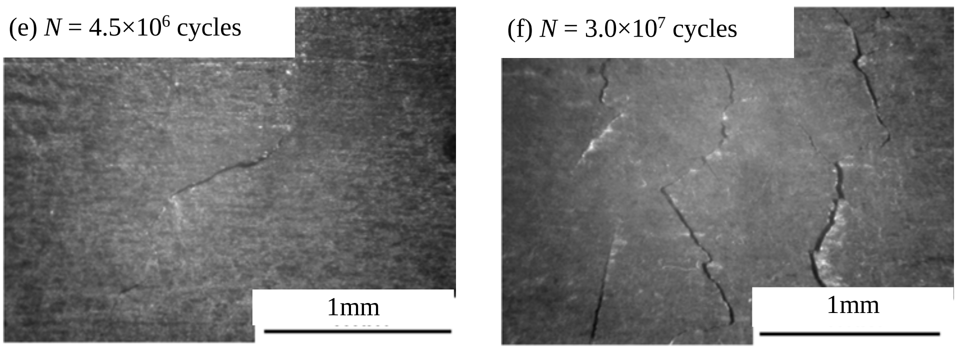


Figure 8. Photographs of the specimen surface after fatigue test



(a) Magnified image at A

(b) Magnified image at B

Figure 9. Magnified image at A (Figure 8 (e)) and B (Figure 8 (f))

3.2 U-shaped Lead Damper Fatigue Test

3.2.1 Results of U-shaped Lead Damper Fatigue Test

Fatigue tests were carried out on actual size U-shaped lead dampers, using the testing machine shown in Fig 2. The tests were carried out under displacement control, as described earlier. Table 3 shows a summary of test conditions and results. Crack depth was measured during the fatigue tests. The U2426 non-coated specimen was close to failure, so it was judged to have failed.

Fig. 10 shows a relationship between the amplitude of tests and the number of cycles, including the results reported previously [11]. The results include high-cycle fatigue test and low-cycle fatigue test. In the range of cycles from 10 to 10^6, the relation between amplitude and number of cycles for non-coated U-shaped lead dampers may be expressed as follows:

$$N = 1.39 \times 10^{6} \times A^{-1.82} \quad (1)$$

$$N_c = 4.81 \times 10^{4} \times A^{-1.87} \quad (2)$$

where N is the number of cycles to failure, N_c is the number of cycles to crack occurrence and A is the displacement amplitude (mm). From these formulas, the number of cycles to failure is shown to be 30-40 times greater than the number of cycles to crack occurrence. When the amplitude is 1mm or 2mm for grease-coated dampers, the cycles to failure is increased 3-5 times compared to that of non-coated dampers. On the other hand, when the amplitude was 10mm for grease-coated dampers, the results were close to the regression curves for non-coated specimen. In the case of 10mm amplitude, concentrated parts of crack of the lead damper fell into plastic range. It means the amplitude is low-cycle fatigue test range for the lead damper. So the grease did not work effectively.

Table 3. Summary of test conditions and results (P-direction)

	Damper Type	Amplitude (mm)	Frequency (Hz)	Time of grease coating	Cycles of crack occurrence	Cycles to failure
Non-coated	U180	0.25	10	-	774,000 cycles	Not failure: 2,916,000 cycles (Crack depth 30mm)
		1.0	5	-	30,000	1,512,000 cycles
		2.5	5	-	12,000	Not failure: 54,000 cycles (Crack depth 12.5mm)
		2.5	5	-	6,800	Not failure: 120,000 cycles (Crack depth 27mm)
		2.5	5	-	9,000	378,000 cycles
		5.0	2	-	2,500	64,800 cycles
	U2426	2.5	5	-	9,000	Close to failure: 270,000 cycles (Crack depth 108mm)
Grease coated	U180	10.0	1	before test	830	14,500 cycles
		2.0	5	before test	61,200	1,026,000 cycles
		1.0	10	before test	274,000	4,409,000 cycles
		1.0	10	after crack depth 10mm, 199,000 cycles	52,000	3,943,000 cycles

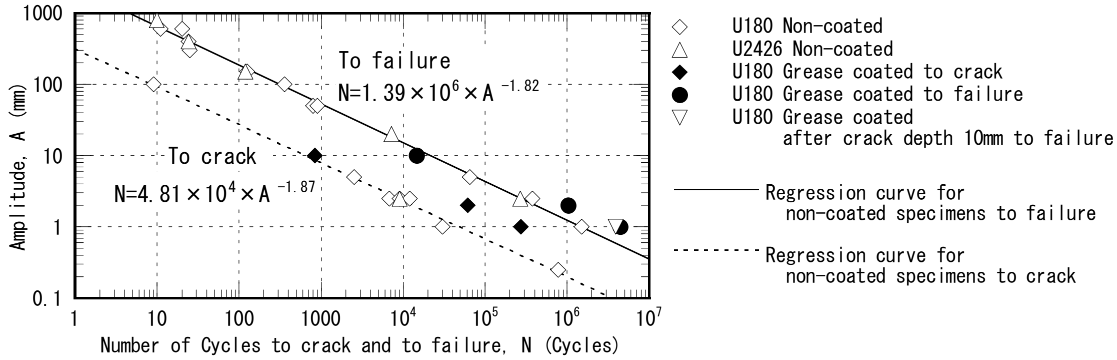


Figure 10. Relationship between amplitude and number of cycles

Fig. 11 shows a relationship between the number of cycles and crack depth. Cracks only initiate from the surface, and every time deformation repeats, they deepen as repeat count increases. A grease-coated specimen shows a slower growth in its crack compared to a crack on a non-coated specimen. Also, cracks grow at almost the same speed in a specimen that already has a grease-coating compared to another specimen where grease-coating was applied after cracks of 10mm in depth initiated. In other words, the grease is effective even if it is applied after cracks initiate.

Fig. 12 shows a relationship between amplitude and crack propagation speed. A regression curve for non-coated specimens can be found by using the following formula.

$$V_c = 8.39 \times 10^{-5} \times A^{1.72} \qquad (3)$$

where V_c is crack propagation speed (mm/cycle) and A is amplitude (mm). The crack growth speed for a grease-coated specimen is less than 1/3 of the crack growth speed for a non-coated specimen when the amplitude is small. However the result for a grease-coated specimen of 10mm amplitude is on the regression curve for non-coated specimens.

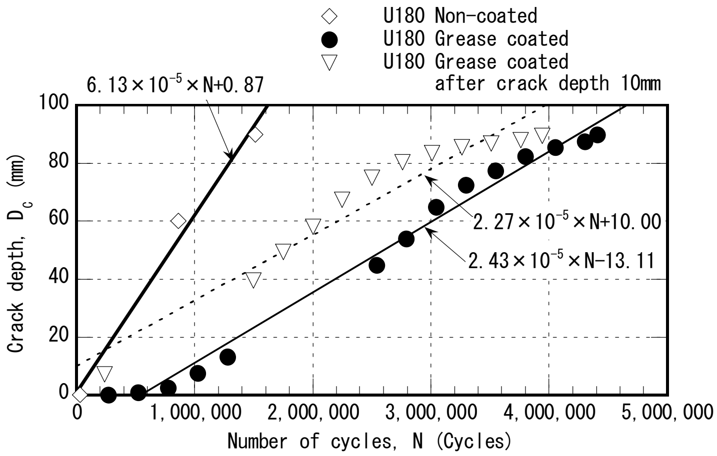


Figure 11. Relationship between crack depth and number of cycles

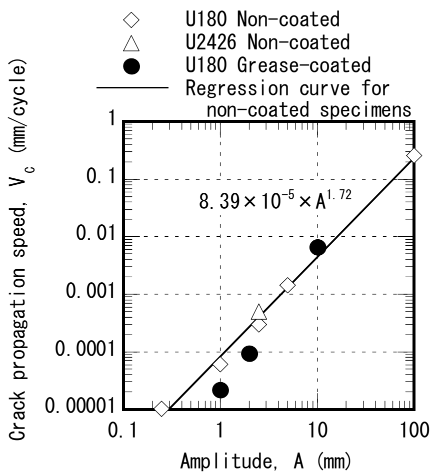


Figure 12. Relationship between crack propagation speed and amplitude

3.2.2 Fracture Surface of a Lead Damper

An electron microscope was used to observe cracks on a fracture surface of a lead damper. Fig. 13 shows a scanning electron microscope image of a fracture surface. Banded patterns, called striations, are seen on the surface which are typical characteristics of fracture due to metal fatigue.

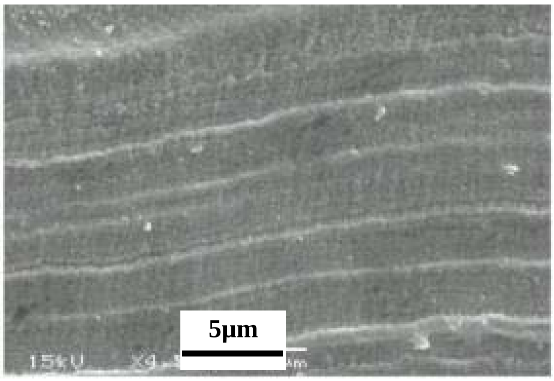


Figure 13. Fracture surface of a lead damper (4,500 magnifications)

3.2.3 Oxide Layer Thickness after Fatigue Test

After the fatigue test, the oxide layer thickness was measured on parts with and without the grease-coating. Inspections were carried out after cross sections were cut off in a way that the thickness of the oxide layers could be measured from the damper surface. They were then implanted in epoxy resin and polished. Fig. 14 shows the cross section of a part with grease-coating, whereas Fig. 15 shows the cross section of a part without grease-coating. The thickness of the oxide layer without grease-coating is more than 0.1mm, whereas the layer with grease-coating is 2µm thick. Based on the thickness of the oxide layers, the oxidation of the surface is confirmed to be suppressed due to the environment shielding effects of coating.

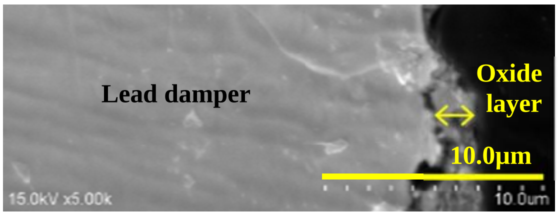


Figure 14. Grease coated specimen

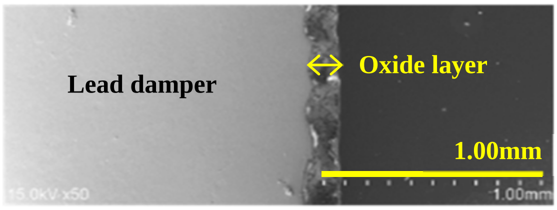


Figure 15. Non-coated specimen

4. Conclusions

In this paper, we introduced the basic property of the U-shaped lead damper, the results of fatigue tests and the effect of grease-coating on enhancing fatigue life and fatigue limit. The conclusions, based on the test results, are as follows:

1. Lead is used as an energy dissipation device in seismic isolation and vibration control systems, because pure lead has the characteristics of low yield stress and very high ductility with minimal strain hardening. The hysteretic behavior of the U-shaped lead damper is elasto-plastic, and this allows it to provide high levels of damping for a wide range of excitations from small vibrations to large earthquakes.
2. Lead is fatigue-resistant due to the effect of re-crystallization at ambient temperature. However, fatigue cracks may be generated under sustained small vibrations and exposure to oxygen. But, as shown in previous studies, this phenomenon can be improved by applying the grease to the surface of the lead damper.

3. The fatigue life of a grease-coated lead specimen is increased compared to a non-coated specimen. For the rotating-bending fatigue test, the fatigue life increased 5-10 times. And in the U-shaped lead damper fatigue test, the fatigue life increased 3-5 times.
4. It was found that the grease-coating significantly affects fatigue propagation behavior. The crack closure mechanism induced by the coating is very effective, and can arrest the fatigue crack propagation even when a number of macro cracks were already present on the surface of the specimen.

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