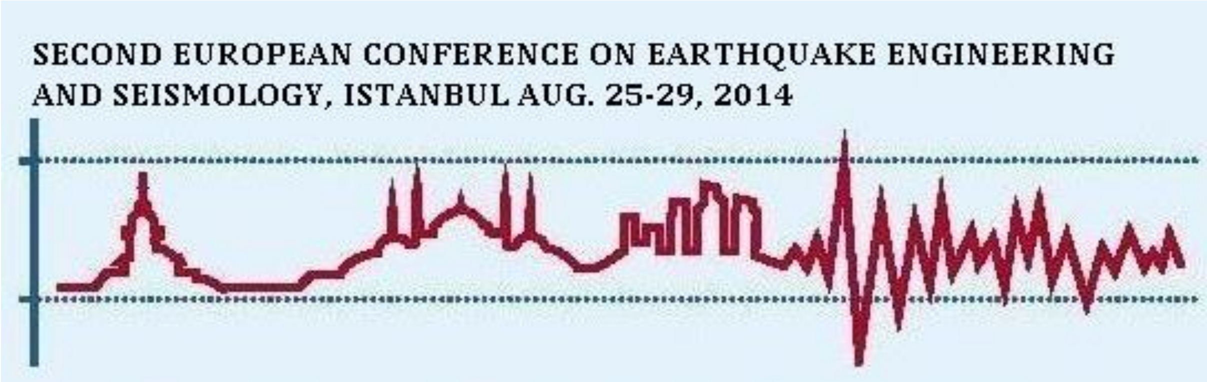

EXPERIMENTAL EVALUATION OF AGING DETERIORATION OF RUBBER BEARINGS IN HIGHWAY BRIDGES

Kunihiro HAYASHI[1], Yukio ADACHI[2], Akira IGARASHI[3] and Ji DANG[4]

ABSTRACT

After served over 10 years for highway bridges, aging deterioration were observed on exterior of some rubber bearings. The concern of these deterioration and their consequence on the performance of whole bridge are one of the most important issue for bridge engineers. In this paper, the loading tests and material tests were carried out to evaluate the remaining performance of the damages lead rubber bearings (LRBs). Quantitative evaluation of the aging deterioration in the change of bearings' characters such as stiffness as well as damping performance was obtained due to these tests.

INTRODUCTION

Since the 1995 Hyogo-ken Nanbu Earthquake (Kobe Earthquake), the rubber bearings (elastomeric bearings) have been extensively used in construction of new bridges or in rehabilitation of existing highway bridges as the replacement of conventional roller type steel bearings with the application of the horizontal seismic force distribution design and the seismic isolation design, so that the seismic performance of bridges can be improved. For the bridges of Hanshin Expressway, seismic retrofitting projects and connecting girders projects involving bearing replacement have been carried out in recent decades. As a result, the proportion of rubber bearings in total 88,000 bearing assets became approximately 32% to date. The in-service rubber bearings are catalogued by serving ages in Figure 1, where it can be seen that most of the rubber bearings have been installed after the Hyogo-ken Nanbu Earthquake and served for 11~20 years, and approximately 10% of them served for more than 20 years.

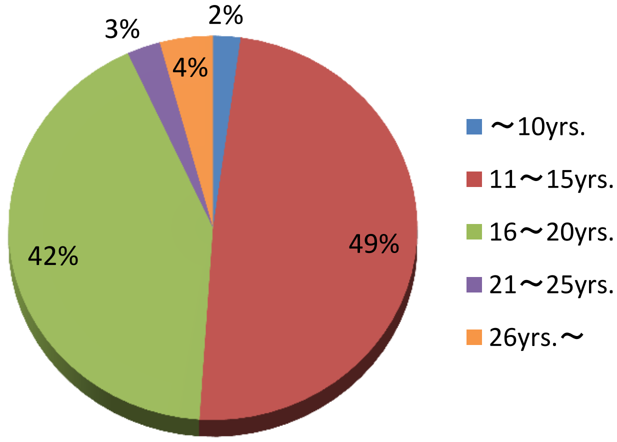

Figure 1. In-service period of the rubber bearings in the bridges in Hanshin Expressway

On the other hand, the natural rubber (NR) bearings are most used than others, though their ozone durability is doubtable. This implies that the performance of the rubber bearings is easy to deteriorate due to aging. Recently, some instances of rubber bearing damage caused by aging

[1] Chief Engineer, Hanshin Expressway Co., Ltd., Osaka, JAPAN, kunihiro-hayashi@hanshin-exp.co.jp
[2] Manager, Hanshin Expressway Co., Ltd., Osaka, JAPAN, yukio-adachi@hanshin-exp.co.jp
[3] Professor, Kyoto University, Kyoto, JAPAN, igarashi.akira.7m@kyoto-u.ac.jp
[4] Asistant Professor, Saitama University, Saitama, JAPAN, dangji@mail.saitama-u.ac.jp

deterioration have been found requiring repair as shown in Figure 2. However, the remaining performance of rubber bearings with deterioration damage is not clear. Moreover, since there is no efficient repair method, most of the damaged bearings are being used with continuing observation.

Figure 2. Damage examples of rubber bearing (Left : Crack, Right : Lead extrusion)

At the time of the Great East Japan Earthquake on March 11, 2011, several severe damage of rubber bearings including rubber rupture have been reported. These are also motivating the experimental investigation of the performance of in-service deteriorated rubber bearings.

In this study, several real bearings showing rubber crack or lead protrusion were unloaded from their serving highway bridge. The remaining performance of the rubber bearings with aging deterioration was evaluated by monotonic and the cyclic loading tests as well as the material tests.

DAMAGES OF RUBBER BEARINGS

Totally 811 damage observations of the rubber bearings, which supposed to be repaired, have been reported from 2006 to 2012. Figure 3 shows the category of observed damages.

The damages of "Rubber Crack", "Rubber Broken" and "Lead Extrusion" due to the rubber aging deterioration are approximately 5% of the total. These damages are assumed to increase with time. The right photo in Figure 2 shows a lead extrusion from the upper side of bearing found in the past inspection. This bearing has been already replaced, but the similar damages are reported repeatedly and most of them are waiting to be changed.

In this study, the authors focused on the damage of rubber crack or lead extrusion, and evaluate the remaining performance of deformation and energy dissipation.

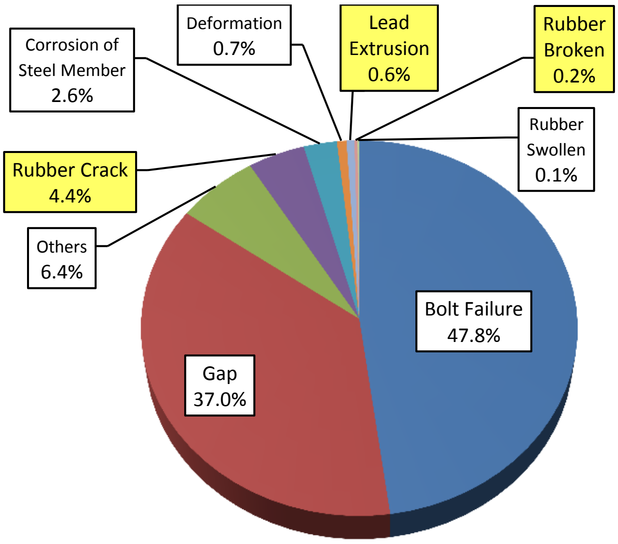

Figure 3. Damages of rubber bearings

TERGET BEARINGS FOR RESIDUAL PERFORMANCE TESTS

In this study, experimental verification was conducted for LRBs with lead plug damages. These bearings were installed in 1995 to replace the old steel roller bearing in order to distribute the horizontal seismic force and improve the bridges' seismic performance. The bearings are composed by

5 layers of the natural rubber strengthened by steel plate, as shown in Figure 4. The main parameters of this LRB are as follows;

- Plan scale of rubber : 350mm × 550mm
- Total thickness : 70mm (=@14mm × 5 layers)
- Shape coefficient : S_1=6.87, S_2=4.71
- Lead plug : 4 plugs (D=55mm) assigned in the diamond shape

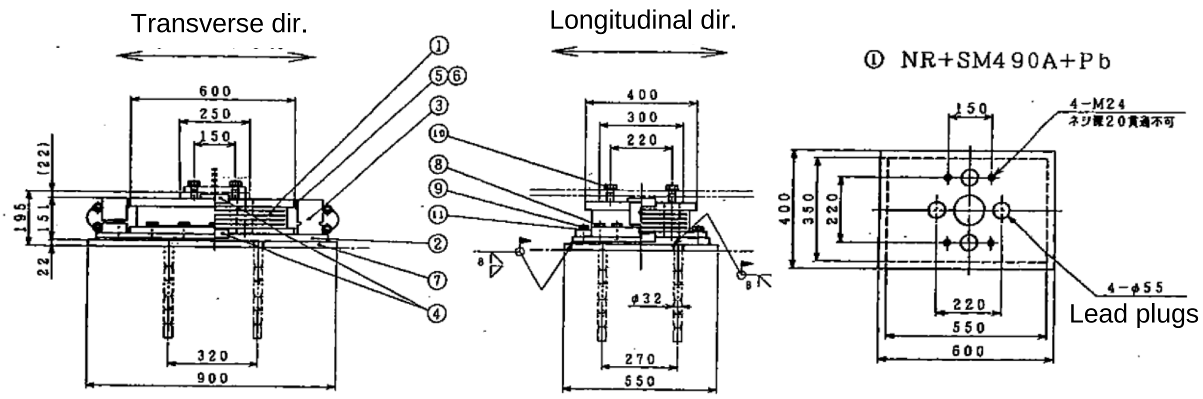

Figure 4. Structure of LRB for tests

These LRBs were designed based on the 1990 version Specifications for Highway Bridges in Japan and the 1991 version Bearing Handbook for Highway Bridges in Japan, the limit seismic shear strain was considered as 150% at that time.

As can be seen in Figure 5, the damaged lead plug partially extruded from the bearings' lateral side in the bridge longitudinal direction. According to the inspection records, the damage were firstly observed as the rubber swollen in 2005 (10 years after installation), and the lead were virtually confirmed from 2008. It is clear that the lead plugs were deformed and finally extruded from the restrain of rubber as a continual progress.

Figure 5. Damage status of lead extrusion

EXPERIMENTAL STUDY FOR RESIDUAL PERFORMANCE

(1) Loading Tests

Seven loading tests were conducted to clarify seismic and service performance of aging deteriorated bearings. The plan of loading tests for this study are listed in Table 1. Four types of loading tests: Deformation Limit 1 (150%) test, Deformation Limit 2 (250%) test, Ultra Deformation test, and Service Capability test, marked as DL1-, DL2-, UD-, and SC-, respectively, in the "Test Code" column of the table, were conducted for the aging deteriorated bearings, marked as –D in Test Code.

Three reference bearing, marked as –R, specimens are newly fabricated following the same sizes of deteriorated bearings and were served to the tests except the Service Capability test.

Table 1. Loading tests plan

No.	Test Code	Loading Type	Specimen	Loading Method	Amplitude	Cyclic Loading	loading Rate
1	DL1-D	Deformation Limit 1 (150%) test	Deteriorated	Quasi-static cyclic loading with constant loading strain amplitude	150%	3 sets × 5 cycles	Static: 2 mm/s
2	DL1-R		Reference				
3	DL2-D	Deformation Limit 2 (250%) test	Deteriorated	Quasi-static cyclic loading with constant loading strain amplitude	250%	1 set × 5 cycles	Slow: 1 mm/s
4	DL2-R		Reference				
5	UD-D	Ultra Deformation test	Deteriorated	Monotonic loading	Until rubber broken	-	Very Slow: 0.5 mm/s
6	UD-R		Reference				
7	SC-D	Service Capability test	Deteriorated	constant loading strain amplitude	70%	50 sets× 50 cycles	

All tests are horizontal shearing loading tests under a constant vertical load corresponding to the gravity of the superstructure. As shown in Figure 6, specimens are clamped under the horizontal-free-vertical-fixed beam and above the vertical-movable-horizontal-fixed table. The loading beam is supported by gravity-simulator reaction frame, and the carrying table is supported by four vertical jacks put totally 570 kN vertical load to the bearings. The vertical load is calculated from the gravity of girder weight and the total number of bearings beneath.

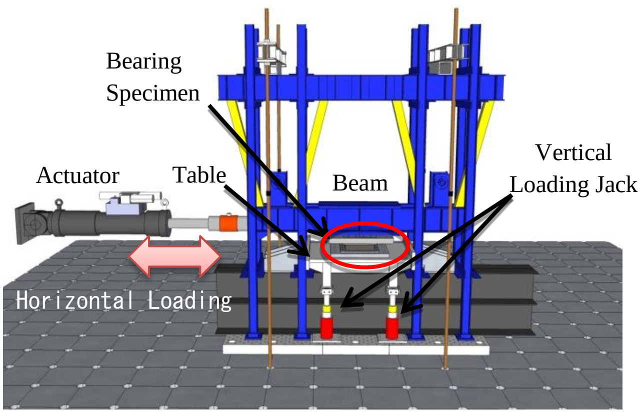

Figure 6. Loading system

a) Deformation Limit 1(DL1) Test

In Japanese design specification, the deformation limit for rubber bearing under Level 1 Earthquake (Design Basis Earthquake) is defined as shearing strain

$$\gamma < 150\% \qquad (1)$$

where shearing γ strain is the rate of horizontal shearing displacement u versus the total thickness t_r of all rubber lamination layers.

$$\gamma = u/t_r \qquad (2)$$

In the DL1 tests, specimens were cyclicaly loaded to a constant amplitude corresponding to the 150% rubber shearing strain. To confirm whether the bearings could perform reliably, 3 sets of 5 cycles, totall 15 times' cyclic loadings were subjected to specimens. This loading path implies that there would be less than 5 major response peak for structures in a Level 1 Earthquake event (DBE). And in the whole service life of a bearing, there may be multiple earthquake events. The 3 sets of L1 Earthquake level loading present the multiple-earthquake-experience. To make sure that the increased inner temperature due to the self-heating effect would not compromise the hysteresis curves, the specimens were hold to cool down by at least 30 minutes after each set of loading. The loading actuator was controlled to load under 2 mm/s for DL1 tests.

As a test result, the deteriorated bearing subjected to the DL1 test survived all the three sets of loading without any sign of hysteresis deterioration nor crack growing. The hysteresis curves obtained from the tests of the deteriorated bearing and the reference bearing were shown in Figure 7. It can be seen that the Deteriorated bearing dissipated less hysteresis energy than the Reference bearing. This could be contributed by the lost of the lead plugs, which were partially extruded from the rubber.

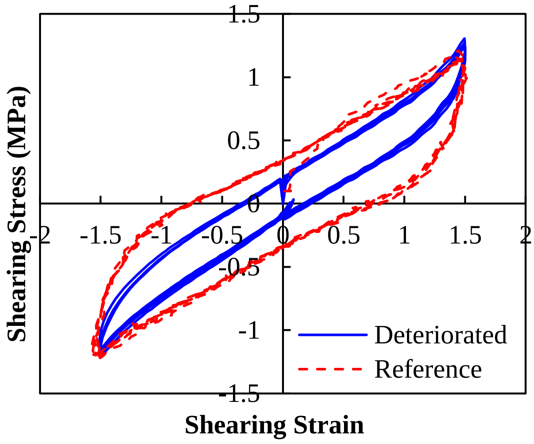

Figure 7. Deformation Limit 1 (150%) tests results

b) Deformation Limit 2 (DL2) Tests

The Deformation Limit 2 for rubber bearing were defined as following equation to assure the bearing can serve as isolator for bridge structures under rare but large magnitude earthquakes (Level 2 Earthquake or MCE).

$$\gamma < 250\% \quad (3)$$

In the DL2 tests, bearings were slowly loaded to 5 cycles with amplitude of 250% shearing strain. Damaged bearing also cleared this test without broken. As can be seen from the hysteresis curves in Figure 8, the damaged bearing showed stronger hardening effect and less hysteresis damping than the new bearing. The obvious stiffness hardening in large deformation domain of damaged bearing may due to the age hardening of rubber. By slitting the new bearing open after its DL2 test, the inner lead plugs, as shown in Figure 9, were observed being fragmented.

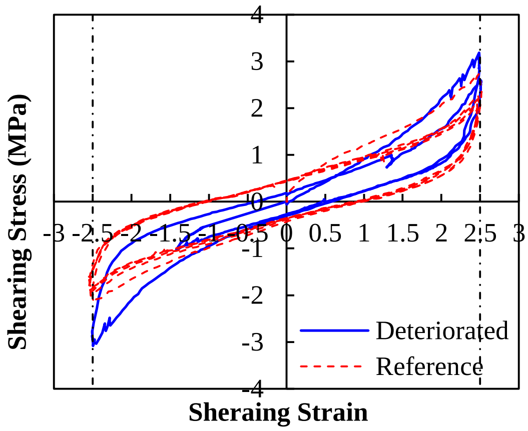

Figure 8. Deformation Limit 2 (250%) tests results

Figure 9. Fragmented lead plugs after DL2 test

c) Ultra Deformation (UD) Tests

To find out the ultra deformation ability of deteriorated bearings, comparing monotonic loading tests were conducted as show in Table 1. The LRB specimens were monotonically loaded until broken. The hysteresis curves obtained from the Ultra Deformation (UD) tests for damaged and new bearings are shown in Figure 10. As can be seen from the figure, although ultra deformation of damage bearing is less than that of new bearing, its deformation ability is still over 250% and nearing 300%. Generally, the experimental deformation ability asked for new bearing is over 300%, the deformation ability of nearly 20 years used bearing can be considered as acceptable. On the other hand, the force hardening helped the damaged bearing response even larger force, which means the seismic response of bearing part may be smaller than new bearings. Though the buden may trasfered to the capacity of the sub-structure.

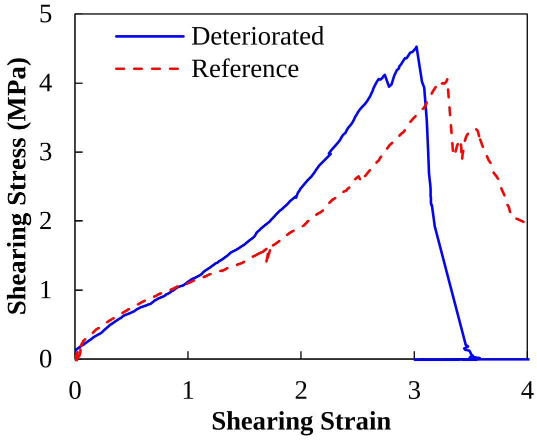

Figure 10. Ultra Deformation tests results

d) Service Capability (SC) Tests

To understand how the seismic performance of LRB deteriorate with time and how these damaged bearing would deteriorate with time without further care or exchange, Service Capability tests was conducted. The temperature deformation of girder was considered as the major reason caused the damage of lead plug. The temperature deformation due to complex climate chance was simplified as that the total cumulative deformation per year equals 50 cycles of 70% cyclic shearing loading. Service capability of 50 years was investigated by subjecting 50 sets of 50 cycles 70% loading to the damaged bearing. The equivalent stiffness k_{eq} and equivalent damping ratio h_{eq} obtained from each set are plotted in Figure 11.

It can be seen that both equivalent stiffness and equivalent damping were dropping with loadings. As loading were conducted in very short term (two sets per day) than the real case, so that the rubber hardening effect with time of rubber is not counted in the test. However, it can be seen clearly that the dropping of damping is converged to a constant value 0.08. It implies that, even with further deterioration without any care or exchange, the lead plug may continually be damaged, hysteresis damping droping may be stoped some how at 0.08.

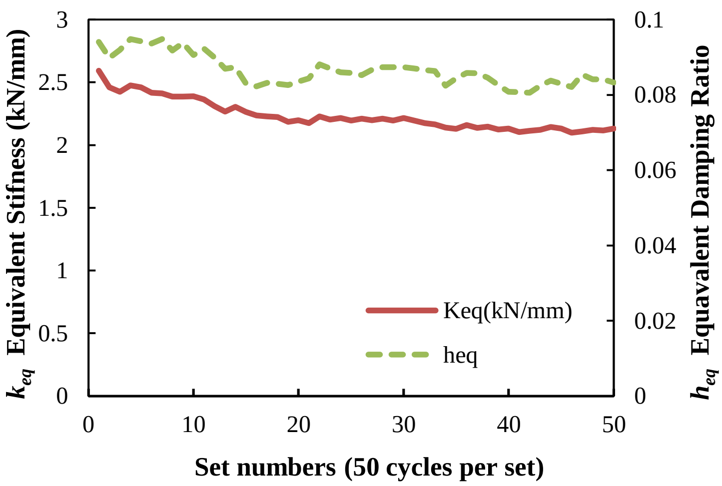

Figure 11. Service Capability tests results

(2) Material Tests

The material tests for the aging deteriorated bearings were carried out to evaluate the physical residual performance of rubber. Table 2 shows the plan of material tests and these contents were based on the Bearing Handbook for Highway Bridges in Japan.

The test specimens were cut out from the rubber layers of the aging deteriorated bearings and the reference bearing, respectively. Specimens were taken from different loactions from surface to core on the rubber layers. The sampling loacations are shown in Figure 12. Moreover, the specimens were obtained from several layers of the aging deteriorated bearing in order to evaluate differences between each layer of the laminated rubber.

Table 2. Material tests plan

No.	Test Case	Measuring Object	Criteria
1	Tensile test	Tensile strength	≧15N/mm²
		Breaking elongation	≧550%
2	Share Deformation test	Static elastic modulus	≧0.8 N/mm²
3	Hardness test	Durometer hardness	50±5

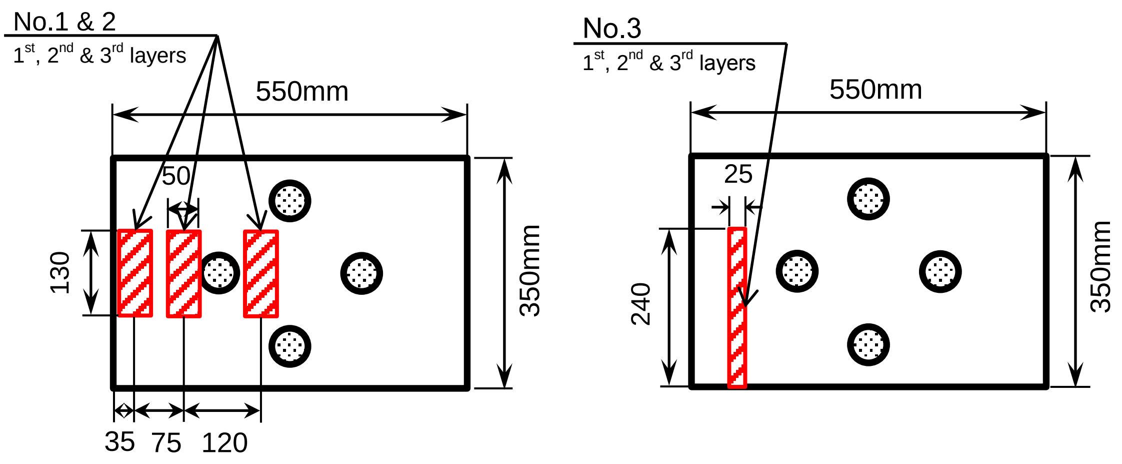

Figure 12. Sampling locations of specimens (from aging deteriorated bearing)

a) Tensile Tests

To verify the mechanical strength of rubber, the tensile strength and the ultra elongation were measured. Here, the tensile strength is defined as the value that the tensile capacity force divided by the section area of rubber specimen, and the ultra elongation is defined as the percentage of ultra deformation to original length. Nine specimens were obtained from the aging deteriorated bearing of different layers and three specimens were from the reference bearing.

The results of the tensile strength are shown in Figure 13 and the results of the ultra elongation are shown in Figure 14. The tensile strength is confirmed more than 15N/mm^2 that is the value of standard, and the aging deteriorated bearing are dropped by 7~16% compared to the reference bearing. On the other hand, the ultra elongation results of the reference bearing are satisfied the criteria 550%, but those of the aging deteriorated bearing are almost under the criteria. The ultra elongation at the fabrication was 570%, so it was reduced by 2~16%.

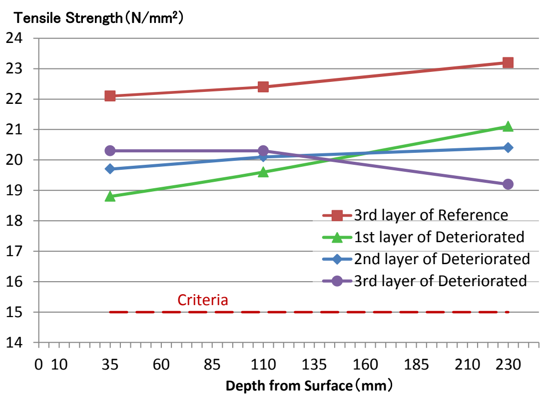

Figure 13. Tensile strength test results

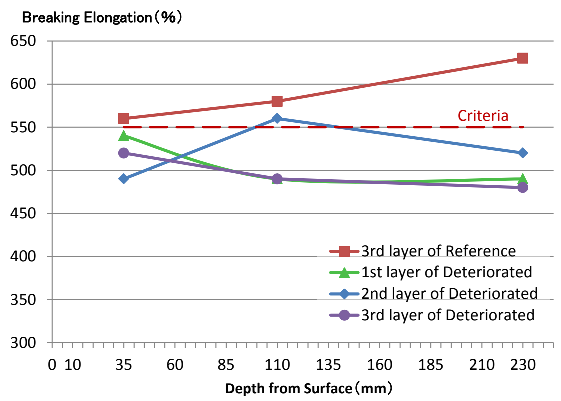

Figure 14. Breaking elongation test results

b) Share Deformation Tests

To evaluate the rubber properties of stress-strain, the static elastic modulus was measured. The position and number of specimen are the same as the tensile tests.

As shown in Figure 15, the static elastic moduli of the aging deteriorated bearing were higher than that of the reference bearing. The criterion of these rubber bearings is 0.8N/mm^2, the reference bearing was close to the criteria and the aging deteriorated bearing was approximately 20% larger on average. So the rubber hardening was verified.

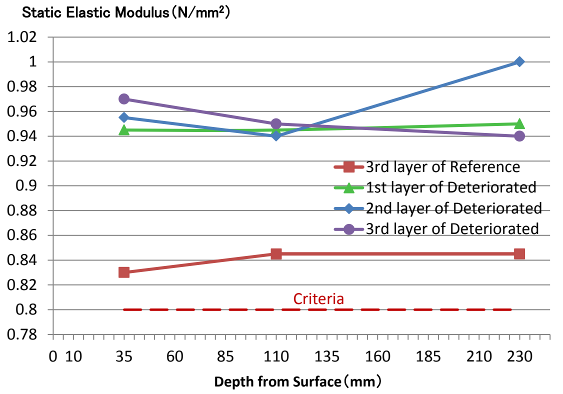

Figure 15. Static elastic modulus test results

c) Hardness Tests

The rubber hardness was measured using durometer and evaluated in value of 0 to 100, where 100 presents high hardness. The specimen size was 25mm × 240mm, as shown in Figure 12, and nine points with 20mm interval were sampled from edge to core rubber.

The test values had some diversity, but it was found to remain within the criteria. Meanwhile, the specimens of the aging deteriorated bearing show a trend of increase in hardness compared to that of the reference. This result was agree with the rubber hardness due to aging deterioration.

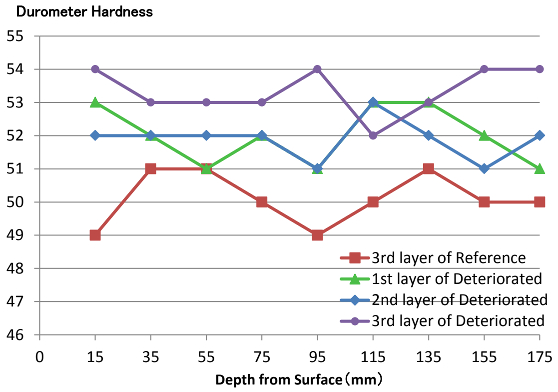

Figure 16. Durometer hardness test results

CONCLUSIONS

The residual performance of aging deteriorated LRBs that had lead extrusion damages was evaluated to conduct the loading tests and material tests and verified to compare with the newly products, what called "reference bearings". The knowledge obtain from these experiments was as follows;

- The stiffness of LRBs was increased due to rubber hardening with time.
- The energy dissipation of aging deteriorated bearings showed the clear tendency of declined. The main reason was considered as the damage of the lead plugs.
- From the results of the ultra deformation tests, the deformation ability of nearly 20-year-used bearing is still over 250%.

The residual seismic performance of these aging deteriorated bearings should be further evaluated by the seismic response analysis. Additionally, the lead plugs after the loading tests were fragmented. It is very important to clarify the mechanism and reason of this kind of deterioration.

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