Experimental investigation of aging effect on damping ratio of high damping rubber bearing

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In recent years, high damping rubber (HDR) bridge bearings have been widely used because of the excellent ability to provide high damping as well as flexibility. In the previous research, the change of equivalent shear stiffness due to aging has been studied. However, the effect of aging on the damping ratio of HDR bearing has not been investigated before. Lap-shear tests for HDR and cyclic tests of HDR bearings are performed in this study to obtain damping properties of HDR bearing after HDR bearings are subjected to the accelerated thermal oxidation test. Test results show that the equivalent damping ratio of HDR bearing slightly decreases due to aging, but the effect is insignificant when compared to the original damping ratio.

Keywords: high damping rubber bearing, damping ratio, thermal oxidation, aging, long-term performance

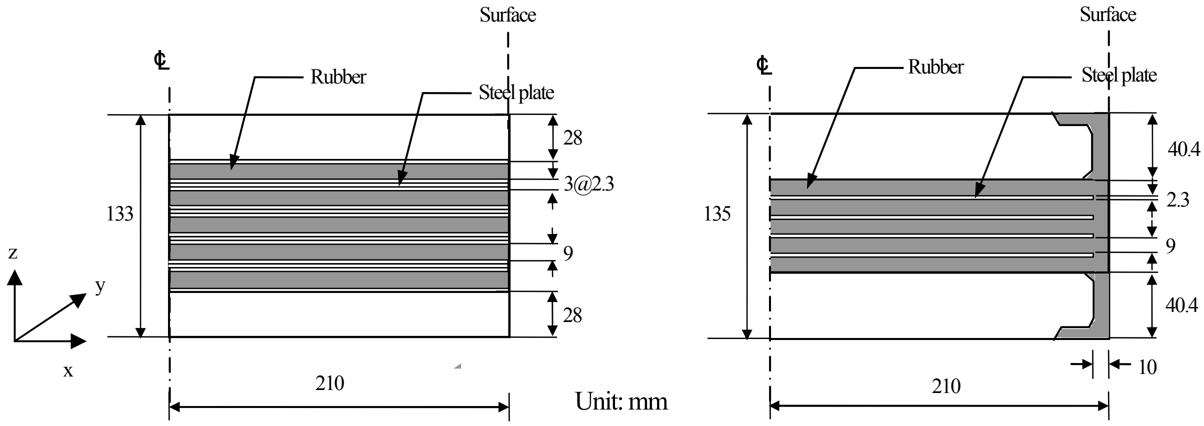
1. INTRODUCTION

After the Hyogo-ken Nanbu earthquake (Kobe earthquake) in 1995, civil engineers have accepted base isolation, which artificially increases both the natural period of vibration and the energy dissipation capacity of structure, as an attractive way to protect structures from earthquakes. Laminated rubber bearings have been widely adopted as isolation bearings in bridges, including natural rubber (NR) bearing, lead rubber bearing (LRB), and high damping rubber (HDR) bearing. Among these bearings, the use of HDR bearing as the seismic isolation device in bridges is increased due to its high damping properties without installing any other damping devices.

The physical properties of rubbers change over time as a result of the degradation process, called aging. Aging on rubbers can be caused by oxygen, ozone, heat, light, dynamic strain, oil, and other liquids, and it causes rubber to stiffen and its tensile strength and elongation at break to decrease. As aging causes shear stiffness of rubber material to increase, rubber bearings also tend to increase their stiffness over time, resulting in the increase of the fundamental frequency of the isolated bridge from its design value. In the current design specifications[1], the property change of rubber bearings due to aging is not considered.

Some studies were carried out to understand the aging of rubber bearing. For example, Morita et al.[2), 3)] experimentally studied the long-term creep of laminated rubber bearing. Nakamura et al.[4)] studied the aging characteristics of natural rubber bearing in an existing base isolated building. Yasui et al.[5)] estimated the deterioration of natural rubber bearings used in the building by using static loading and free vibration tests, and response acceleration data in the earthquake events. Hamaguchi et al.[6)] studied the aging effect on a rubber bearing after 20 years in use. Chou et al.[7)] investigated the effect of cyclic compression and thermal aging on dynamic properties of neoprene rubber bearings. Chou et al.[8)] evaluated the effects of thermal aging on fatigue of carbon black-reinforced EPDM rubber. Kato et al.[9)] evaluated the aging effect on laminated rubber bearing of Pelham Bridge. And Fujita et al.[10)] studied the prediction of the long-term durability of seismic isolation bearings.

A series of tests were performed by Itoh et al.[11), 12), 13), 14)] on various rubber materials, including HDR, to investigate the degradation effects of different environmental factors. It was found that the thermal oxidation is the most predominant



(a) For lap-shear test (b) For bearing cyclic shear test

Fig. 1 HDR bearings used in this study model

degradation factor for HDR use for bridge bearings.

To understand the variation of the material property inside the HDR bearings due to aging, Itoh et al.[15] performed accelerated tests on rubber blocks for the dominant degradation factor, thermal oxidation. Based on the experiment results, a deterioration prediction model for HDR bearings to estimate the property profile in the aged bearing was developed. The time-dependent and temperature-dependent characteristics of the equivalent shear stiffness were quantitatively evaluated for any size of bearing. Using this model, the material property at any temperature and at any aging time can be estimated at any position inside the HDR bearing, and the prediction of long-term performance of HDR bearing in terms of equivalent shear stiffness was proposed. However, aging effect on the equivalent damping ratio was not examined because the effect of aging on the mechanical properties of HDR bearing was determined by uniaxial tension tests of rubber.

In this paper, the aging effect on the equivalent damping ratio of HDR bearing was investigated through the cyclic lap-shear test of HDR and the cyclic shear test of HDR bearing. The accelerated thermal oxidation test was performed to include the effect of aging on the bearing before the cyclic shear tests.

The objective of this study is to investigate the change of damping ratio of HDR bearing due to aging.

2. EXPERIMENTAL PROCEDURES

The aging effect on damping ratio of HDR bearing is examined through the experiments in this paper. HDR bearings of 420 mm × 420 mm × 133 mm and 420 mm × 420 mm × 135 mm produced by Tokai Rubber Industries, Ltd. as shown in Fig. 1 were used. These bearing sizes are the one of typical sizes usually used in bridge applications. As shown in Fig. 1(a), bearings for the lap-shear test were manufactured specially for this study, which have three steel plates with the thickness of 2.3 mm between two adjacent rubber layers. By doing this, specimens containing rubber and steel plates which have the same bonding properties as an actual bearing can be produced. The bearing for the cyclic shear test has a surface rubber of 10 mm thickness. Totally, four bearings were prepared: two for the lap-shear test and two for the bearing cyclic shear test.

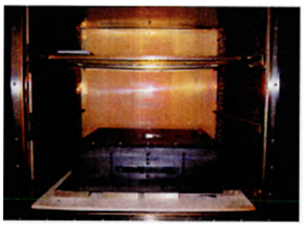
To investigate the aging effect on bearing property change, accelerated thermal oxidation test was firstly performed on rubber bearings for heat oxidation. One bearing for the lap-shear test and one bearing for the bearing cyclic shear test were placed in a thermal aging geer oven (GPHH-200) at temperature of 80˚C for 16 days (384 hours).

Two kinds of experiments were performed. The first test is the four-block cyclic lap-shear test of small rubber blocks which were cut out from the bearing shown in Fig. 1(a). The second test is the cyclic shear test of a whole bearing under a constant vertical loading.

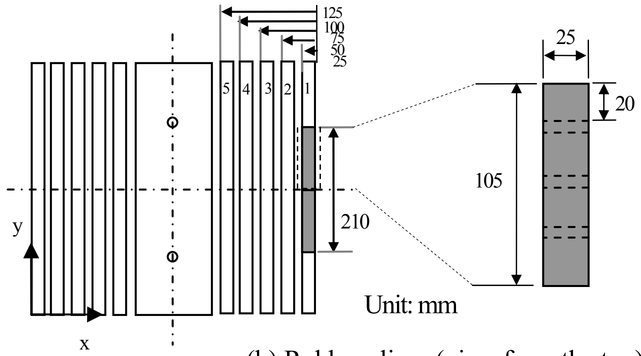
To compare conditions of bearings with and without aging effect, both lap-shear and bearing experiments were performed for bearings with and without heat oxidation. In this paper, "virgin" condition refers to the initial condition, while "aged" condition refers to the condition of bearing after heat oxidation. Test specimens were kept at 23˚C in the temperature-controlled room until the test. The ambient temperature of the experimental room was also about 23˚C.

2.1 Four-Block Lap-Shear Test

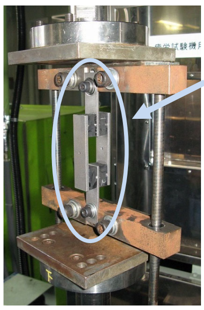
A flow of the lap-shear test for the aged bearing is shown in Fig. 2. First, a bearing was placed inside the thermal aging geer oven for 364 hours. After the bearing was taken out from the oven, rubber in the third layer with a thickness of 9 mm was cut into five strips from surface to the inner part of bearing, and each strip has a width of 25 mm. Each specimen is consisted of four rubber blocks of 9 mm thick and 25 mm length and 20 mm width bonded to steel plates as shown in Fig. 2(d). From a strip



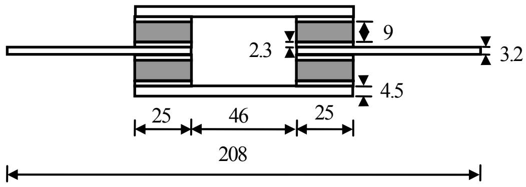
(a) Accelerated test



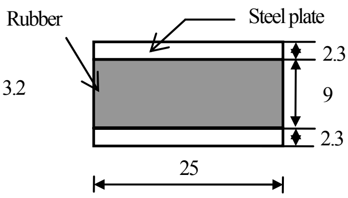
(b) Rubber slices (view from the top)



(e) Lap-shear test



(d) Specimen



(c) Rubber pad

Fig. 2 Lap-shear test flow

(a) Geer oven GPHH-200

(b) Dynamic servo cyclic test machine

(c) Lap-shear test specimen

Fig. 3 Equipments and specimen of lap-shear test

of one position, eight rubber blocks were cut out, and two specimens were built from the one strip as shown in Fig. 2(b). To investigate the damping ratio variation inside the bearing, test specimens were constructed from five different depths from the surface of bearing as shown in Fig. 2(b). Since there are five positions, totally 10 specimens were prepared from one bearing. By taking advantage of symmetry, rubber blocks were cut out only from the half of a bearing.

The specimen was subjected to fully-reversed cyclic shear displacement of a sine wave with an amplitude of 14 mm for 70% shear strain and 35 mm for 175% shear strain and a frequency of 0.5 Hz by using a dynamic servo machine produced by Saginomiya. Each specimen was tested for 70% shear strain conditions first, and then the same specimen was subjected to 175% strain conditions. For the virgin bearing, the same flow as shown in Fig. 2(b) to Fig. 2(e) was applied. Test conditions of lap-shear test are summarized in Table 1, and test specimens are listed in Table 2. Fig. 3 shows the equipment and specimens in the lap-shear test.

The hysteretic curve of each specimen for 11 cycles was obtained from the test. Mechanical properties of rubber were determined by using the data from the second cycle to the 11th

Table 1 Lap-shear test conditions

Accelerated thermal oxidation test	
Bearing size	420 mm x 420 mm 9 mm x 5 layers
Number of bearing models	2
Aging condition	Virgin and aged at 80˚C for 384 hours
Cyclic shear test	
Number of cycles	11
Test frequency	0.5 Hz
Name of lap-shear test specimens	LV (virgin condition)
	LA (aged condition)
Number of lap-shear test specimens	10 for virgin condition
	10 for aged condition
Shear strain	70%
	175%

Table 2 List of test specimens for lap-shear test

Location from the surface (mm)	Test specimen	
	Virgin	Aged
12.5	LV1-1	LA1-1
	LV1-2	LA1-2
37.5	LV2-1	LA2-1
	LV2-2	LA2-2
62.5	LV3-1	LA3-1
	LV3-2	LA3-2
87.5	LV4-1	LA4-1
	LV4-2	LA4-2
112.5	LV5-1	LA5-1
	LV5-2	LA5-2

Table 3 Bearing cyclic shear test conditions

Accelerated thermal oxidation test	
Bearing size	420 mm x 420 mm 9 mm x 5 layers
Number of bearing models	2
Aging condition	Virgin and aged at 80˚C for 384 hours
Cyclic shear test	
Number of cycles	11
Test frequency	0.02 Hz
Name of bearing specimens	BV (virgin condition)
	BA (aged condition)
Number of bearing specimens	1 for virgin condition
	1 for aged condition
Shear strain (shear displacement)	70% (32 mm)
	175% (79 mm)
Vertical force	960 kN

Fig. 4 Cyclic test of HDR bearing for 175% shear strain

cycle. Results for one position were taken as the average of two specimens from the same position.

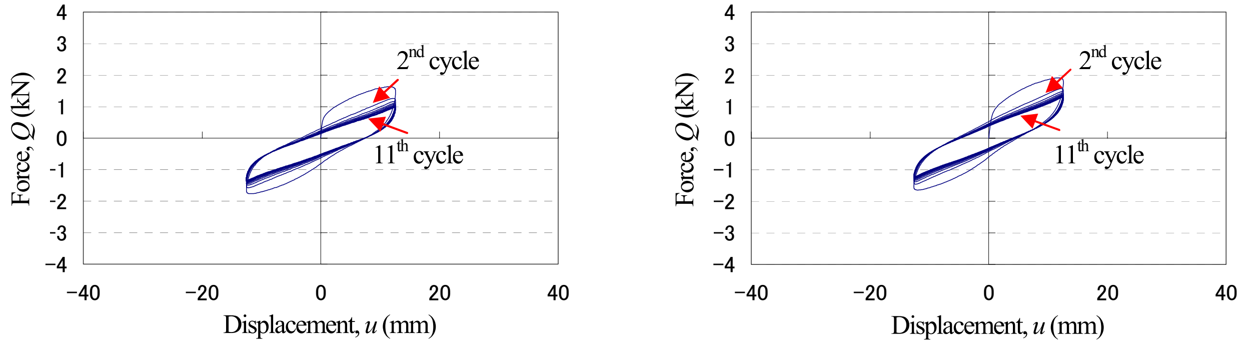
2.2 Cyclic Shear Test of HDR Bearing

Two bearings of 420 x 420 x 135 mm were used in the cyclic shear test of HDR bearings: one bearing aged in the heat oxidation geer oven at 80˚C for 16 days, and one virgin bearing. The full-scale rubber bearing cyclic shear tests were conducted under a constant vertical force of 960 kN, which is equivalent to 6 MPa, while the upper and lower plates were kept horizontal. This loading refers to the Handbook of Highway Bridge Bearing[16], and the loading condition in the bridge application is typically in the range of 3-12 MPa. Horizontal displacement was applied as a sine wave with a frequency of 0.02 Hz and an amplitude of 32 mm and 79 mm for 70% and 175% of shear strain, respectively, as a total rubber thickness of the bearing was 45 mm. Force and displacement data were recorded for 11 cycles, and the data from the second and to the 11th cycle were used to determine bearing properties. The test conditions of HDR bearing cyclic test are shown in Table 3. Fig. 4 shows a picture of a bearing for the condition of 175% shear strain.

No vertical load was subjected to bearings during the accelerated thermal oxidation test. The influence of tensile pre-strain during the accelerated thermal oxidation test on material degradation was studied in the former research by Itoh[11] for four kinds of rubber material. It was found that in most cases, pre-strain has an adverse effect on degradation of rubber although for HDR, the existence of pre-strain results in a reduction of the aging effect on stiffness parameter. However, the effect of compressive pre-strain on the aging is not understood well.

As shown in Table 1, there was no load applied in the perpendicular direction to shear deformation in the lap-shear test. Some researchers investigated the effect of vertical loading on bearing damping ratio. Abe[17] found that vertical load will increase the damping ratio of rubber bearing. However, since it was difficult to apply a constant load perpendicular to shear deformation on the specimen during the lap-shear test, and according to the manufacturer's experiences, the effect of the vertical load on the damping ratio for this specific bearing is expected to be within 1% of the damping ratio, the load was not applied in the lap-shear test.

In the two types of experiment, applied loading frequencies were different. Several studies investigated the dependency of



(a) LV2-1 (virgin condition) (b) LA2-1 (aged condition)

Fig. 5 Hysteretic curves of 2-1 specimen for 70% shear strain experiment

bearing damping ratio on loading frequency. Jain[18] and Igarashi[19] revealed that loading frequency affects the damping ratio of laminated rubber bearing. The higher the frequency, the lower the damping ratio is. If the bearing in this study had been tested with the same frequency as the lap-shear test, the damping ratio would have been slightly larger, probably by about 1% for this specific bearing. Since this study investigates the change of damping ratio due to aging, the effect of loading frequency on the change of damping ratio due to aging is expected to be small.

3. EXPERIMENTAL RESULTS

3.1 Four-Block Lap-Shear Test

(1) 70% Shear Strain Condition

Hysteretic curves from lap-shear test of 70% shear strain for specimens LV2-1 and LA2-1 are shown in Fig. 5. Those specimens refer to the first specimen at the second position inside the bearing as in the Fig. 2(b) for virgin and aged conditions, respectively.

From the hysteretic curve, the equivalent shear stiffness and the equivalent damping ratio can be calculated. In this paper, two methods of calculation of equivalent shear stiffness are presented. In the first method, the equivalent shear stiffness, K_{eq}, is equal to the secant stiffness calculated from the maximum displacement and the corresponding shear forces as depicted in Fig. 6. The calculation of this method follows what is presented in the specifications[1]. Equivalent shear stiffness is calculated by Eq. (1), while the equivalent damping ratio, H_{eq}, is calculated from the dissipated hysteretic energy as in Eq. (2).

$$K_{eq} = \frac{Q_1 - Q_2}{u_{\max} - u_{\min}} \tag{1}$$

$$H_{eq} = \frac{1}{2\pi}\frac{\Delta W}{W} \tag{2}$$

where u_{max} and u_{min} are the maximum and minimum shear displacements, respectively, Q_1 and Q_2 are the corresponding shear forces at maximum and minimum displacement, respectively, ΔW is the total energy absorbed, and W is the elastic energy, which equals to the area of the two triangles shown in Fig. 6.

In the second method, the equivalent shear stiffness is calculated based on the maximum displacement and maximum shear forces as shown in Fig. 7. Equivalent shear stiffness is calculated by Eq. (3), while the equivalent damping ratio, H_{eq}, is calculated by using the same equation as in Eq. (2) with ΔW and W are determined as in Fig. 7.

$$K_{eq} = \frac{Q_{\max} - Q_{\min}}{u_{\max} - u_{\min}} \tag{3}$$

Q_{max} and Q_{min} are the maximum and minimum shear forces, respectively. The second method is presented in the Handbook[16] with the consideration that the hysteresis curve of HDR bearing may have a form in which force at the maximum displacement is smaller than the maximum force and that the equivalent stiffness by Eq. (1) may lead to an underestimation of seismic force on substructure of an isolated bridge. In addition, determining the maximum force is easier than determining the force corresponding to the maximum displacement.

The equivalent stiffness and damping ratio were calculated as the average values of ten cycles. The equivalent shear modulus of rubber G_{eq} was calculated from the equivalent shear stiffness by Eq. (4).

$$G_{eq} = \frac{K_{eq} l_s}{A_s} = \frac{2K_{eq} l_{qs}}{2 l_{ms} l_{ns}} \tag{4}$$

where l_s is the total height of rubber in the specimen, A_s is the area of rubber blocks in a specimen, and l_{qs}, l_{ms}, l_{ns} are the average height, width, and length of rubber blocks, respectively. By using Eq. (4), the equivalent shear modulus is calculated for both virgin and aged conditions.

Fig. 8 shows the equivalent shear modulus and equivalent damping ratio obtained from 70% shear strain tests, both for the first and the second methods. The horizontal axis refers to the

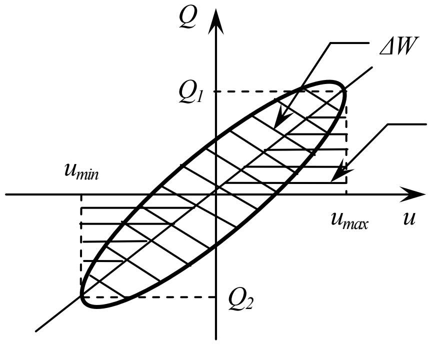


Fig. 6 Equivalent shear stiffness and equivalent damping ratio of bearing based on the maximum displacement

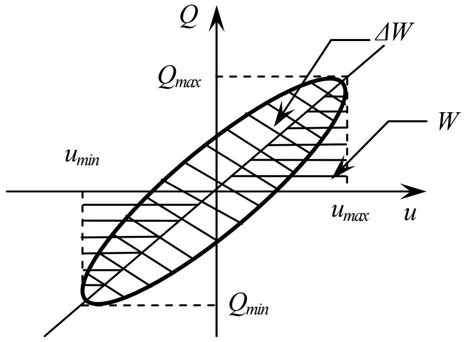


Fig. 7 Equivalent shear stiffness and equivalent damping ratio of bearing based on the maximum force and maximum displacement

position of specimen from the surface as shown in Fig. 2. In Fig. 8(a) and Fig. 8(c), non-filled marker stands for the virgin condition, while black-filled marker stands for the aged condition. In Fig. 8(b) and Fig. 8(d), non-filled marker stands for the first method, while black-filled marker stands for the second method. It can be seen in Fig. 8(a), the equivalent shear modulus increases due to aging of HDR. There is no significant variation on shear modulus of rubber inside the rubber bearing in the virgin condition. In the aged condition, specimens from the position close to the bearing surface have the highest shear modulus. Beyond that position, in the aged condition there is no significant variation either. The change of shear modulus is calculated as a ratio between aged and virgin conditions, G_{eq}/G_{eq0}, where G_{eq0} is the shear modulus of the virgin condition. It can be seen in Fig. 8(b), the maximum shear modulus change occurred at the position closest to the bearing surface, which is 9%. The average equivalent shear modulus increase of all positions is 7%.

As shown in Fig. 8(c) the equivalent damping ratio of rubber slightly decreases due to aging of rubber. Both in virgin and aged conditions, it tends to be uniform inside the rubber bearing. The change of damping ratio due to aging of rubber is provided as the absolute difference between the aged and virgin conditions. In Fig. 8(d), it can be seen that damping ratio shows a small change due to aging of rubber. The maximum absolute difference between the aged and virgin conditions among five positions is 1.4%, and the average of five positions is 1.3%.

It is assumed that the initial properties of aged bearings are the same as those of virgin bearings. Even rubber is the kind of material that has a relatively large variation of material properties, rubber bearings used in this study were produced under the same conditions at the same time to reduce the property variation. Judging from the manufacturer's experiences, a difference in the initial parameters among bearings in the same production lot is expected to be within +3%.

When the total absorbed energy, ΔW, is examined, the aged condition shows a larger value than the virgin condition. However, the elastic energy, W, for the aged condition is also larger than that of the virgin condition, resulting from an increase of the equivalent stiffness due to aging. As a result, the equivalent damping ratio calculated by Eq. (2) does not change significantly between the virgin and aged conditions.

As in the first method, in the second method it can also be seen that the equivalent shear modulus increases due to aging of HDR. Since the shear force in the second method is greater than the first method, the equivalent shear modulus of the second method is also greater than the first one. The averages of equivalent shear modulus from all positions for the virgin condition are 1.73 and 1.80 MPa for the first and second methods, respectively, and they are 1.85 and 1.91 MPa for the aged condition. Although the equivalent shear modulus of this method is higher than that of equivalent shear modulus from the first method, the ratio of initial conditions and aged conditions almost equal to that generated from the first method. The maximum modulus increase also occurred at the position closest to the bearing surface, which is 8%, and the average equivalent shear modulus increase of all positions is 6%. The averages of equivalent damping ratios from all positions for the initial condition are 17.7% and 17.1% for the first and second methods, respectively, and they are 16.0% and 16.4% for the aged bearing condition. There is only a small change in the damping ratio due to aging of rubber. The maximum absolute difference of damping ratio between the aged and virgin conditions among five positions is 1.2%, and the average of five positions is 1.0%.

(2) 175% Shear Strain Condition

Hysteretic curves from the lap-shear test of 175% shear strain are shown in Fig. 9 for specimens LV2-1 and LA2-1. A summary of results for 175% shear strain is shown in Fig. 10, both for the first and the second methods. The averages of the equivalent shear modulus from all positions for the virgin condition are 1.11 and 1.15 MPa for the first and second methods, respectively, and they are 1.24 and 1.28 MPa for the aged condition. The maximum increase in the equivalent shear modulus due to aging is 14% of the virgin rubber, and the

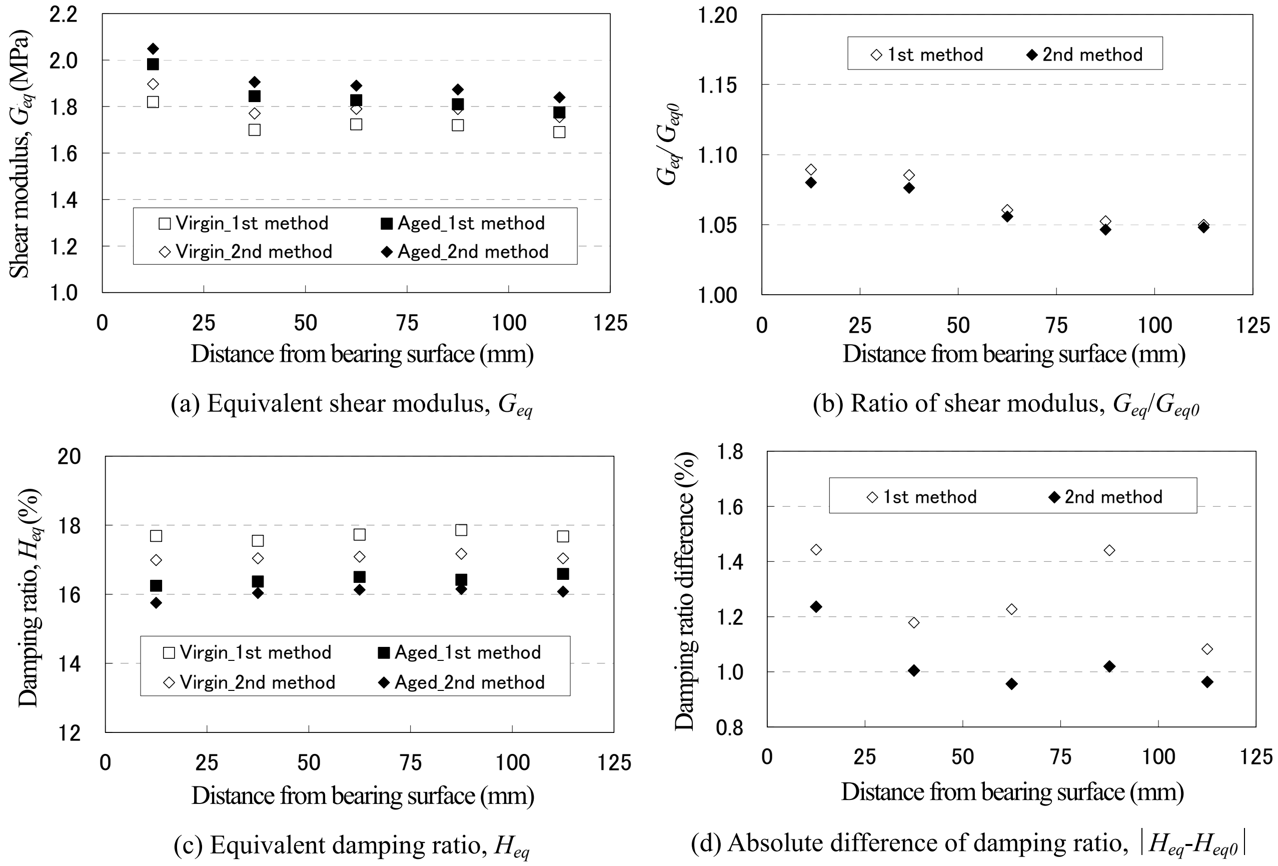


Fig. 8 Lap-shear test results of specimen for 70% shear strain condition

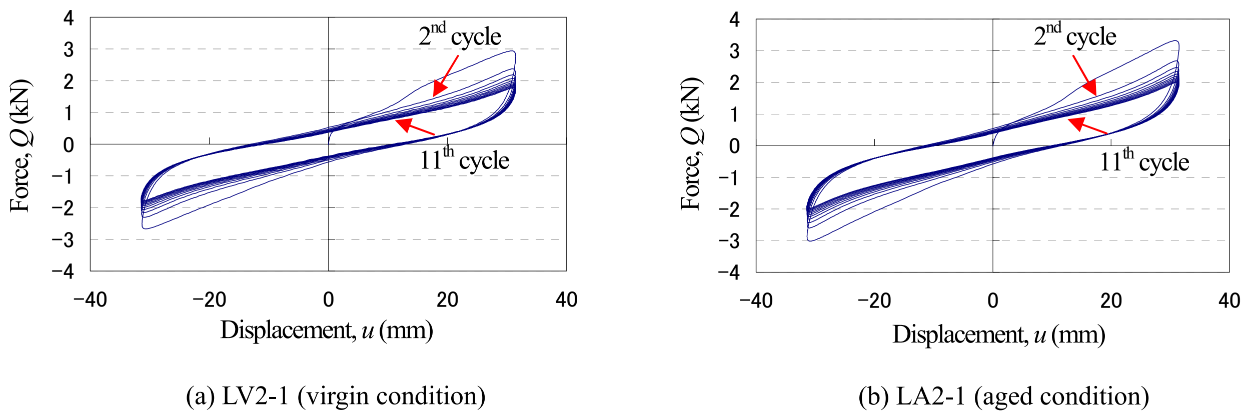
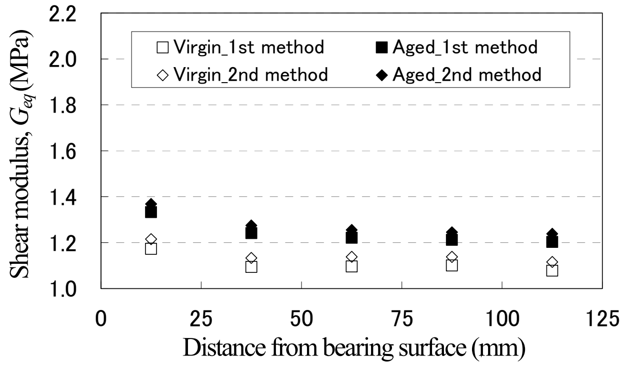


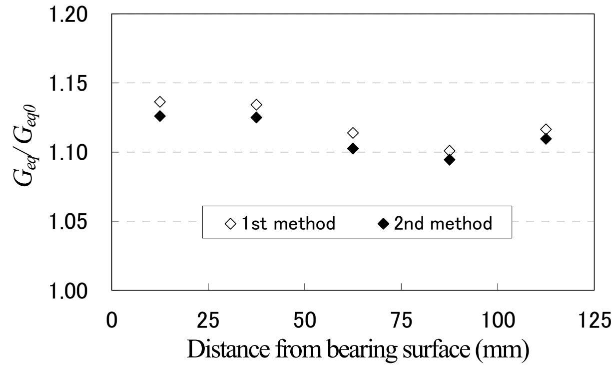
Fig. 9 Hysteretic curves of 2-1 specimen for 175% shear strain experiment

average equivalent shear modulus change of all positions is 12% when it is calculated based on the first method, while they are 13% and 11% when it is calculated by the second method. Beyond the position closest to the surface, the variation due to the position inside the bearing is found to be small.

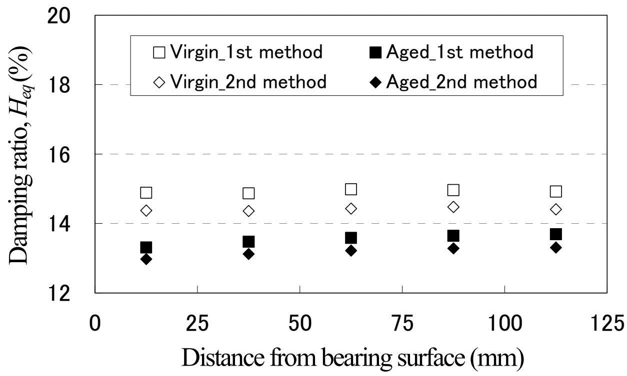
The averages of equivalent damping ratio from all positions for the virgin condition are 14.9% and 14.4% for the first and second methods, respectively, and they are 13.5% and 13.2% for the aged condition. The maximum absolute difference of the equivalent damping ratio between the virgin and aged conditions is only 1.6% and 1.4% from first and second methods, respectively, and the average of the five positions is about 1.4% and 1.2% from first and second methods, respectively. This small change of damping ratio is not expected to affect the overall seismic performance of a base-isolated bridge. As in the case of the 70% shear strain test, there is almost no difference in the equivalent damping ratio among the five positions for the 175% shear strain.



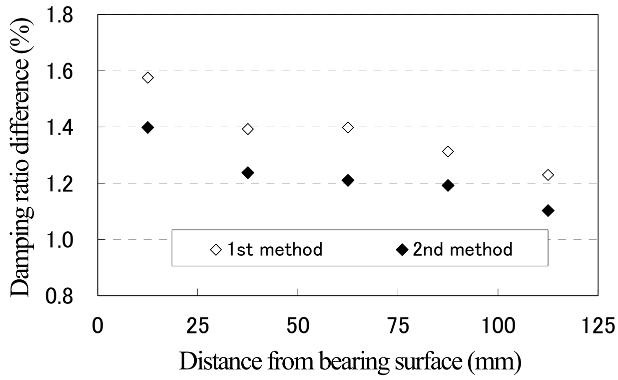
(a) Equivalent shear modulus, G_{eq}



(b) Ratio of shear modulus, G_{eq}/G_{eq0}

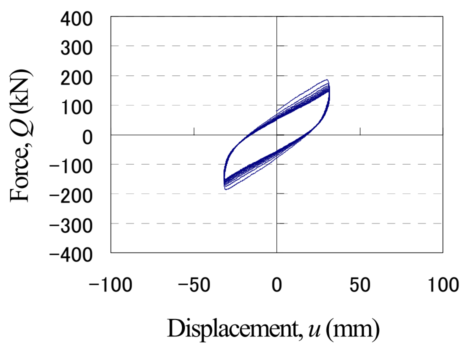


(c) Equivalent damping ratio, H_{eq}

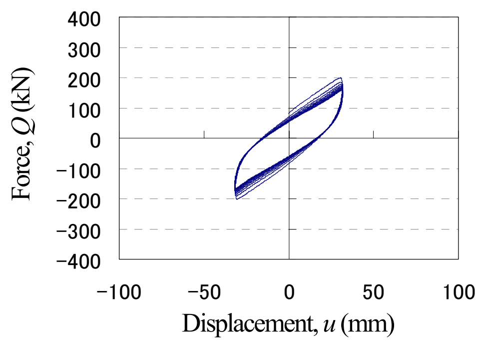


(d) Absolute difference of damping ratio, $|H_{eq}-H_{eq0}|$

Fig. 10 Lap-shear test results of specimen for 175% shear strain condition



(a) BV (virgin condition)



(b) BA (aged condition of 80˚C, 16 days)

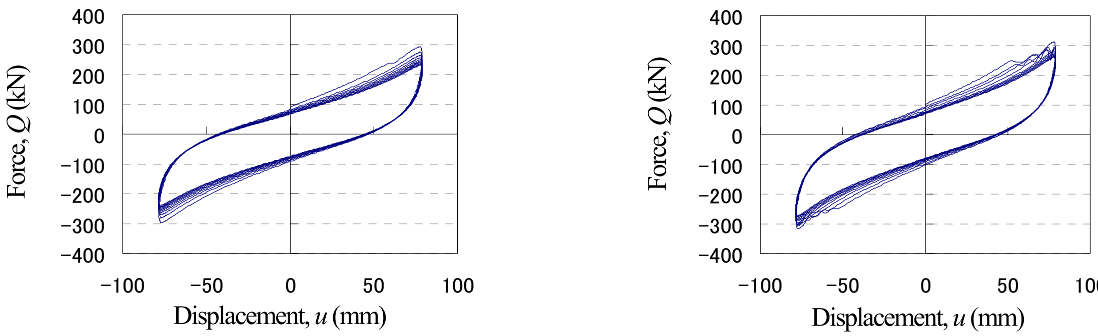
Fig. 11 Hysteretic curve of cyclic shear test of bearing (70% shear strain)

From the results above, it can also be concluded that the first and second methods evaluates the aging effect in a very similar manner.

3.2 Cyclic Shear Test of HDR Bearing

The hysteretic curves from cyclic shear test of HDR bearing for 70% and 175% shear strain conditions are shown in Fig. 11 and Fig. 12, respectively. A summary of equivalent shear stiffness and equivalent damping ratio calculated as the average value of the 2nd cycle to the 11th cycle is shown in Fig. 13 and Table 4. In this test results, damping ratios are calculated by using the second method. In Table 4, the change of equivalent shear stiffness is calculated as the ratio of stiffnesses between the aged and virgin bearings. However, the change of damping ratio is calculated as a damping ratio difference between the aged and virgin bearings.

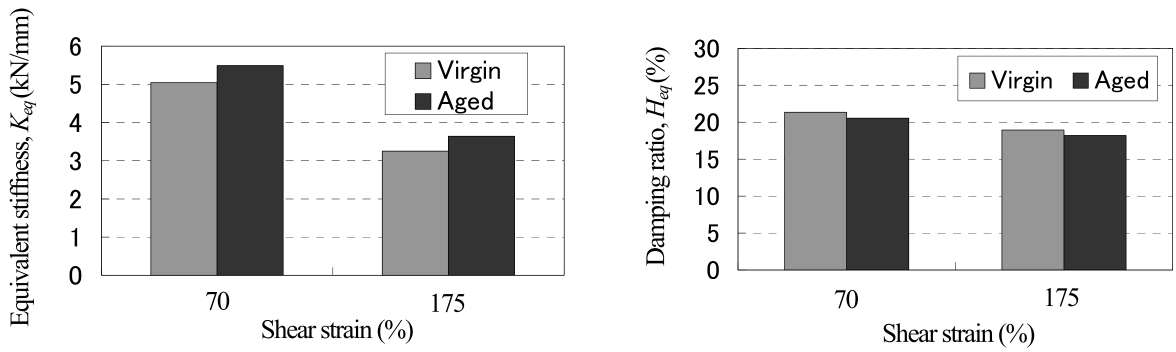
The equivalent shear stiffness of bearing increases due to aging of the HDR. The changes are 9% and 12% for 70% and 175% shear strain tests, respectively. As with the case of the lap-shear test, the equivalent damping ratio from the cyclic shear



(a) BV (virgin condition)

(b) BA (aged condition of 80˚C, 16 days)

Fig. 12 Hysteretic curve of cyclic shear test of bearing (175% shear strain)



(a) Equivalent shear stiffness

(b) Equivalent damping ratio

Fig. 13 Experimental results of cyclic shear test of HDR bearing

Table 4 Equivalent shear stiffness and damping ratio of HDR bearing from the bearing cyclic shear test

Property	Shear strain	Virgin	Aged	Ratio Aged/virgin	Difference Aged-virgin
Equivalent stiffness (kN/mm)	70%	5.05	5.49	1.09	-
	175%	3.25	3.64	1.12	-
Equivalent damping ratio (%)	70%	21.4	20.5	-	-0.82
	175%	19.0	18.2	-	-0.75

test of the bearing decreased due to aging. The absolute difference between conditions with and without heat oxidation for both 70% and 175% shear strains are only less than 1%.

From both the lap-shear test and the bearing cyclic shear test, it can be concluded that the effect of aging on damping ratio of HDR bearing is not significant.

4. EFFECT OF DAMPING RATIO CHANGE ON SEISMIC RESPONSE OF BASE-ISOLATED BRIDGE

Based on the results from the lap-shear test of HDR blocks and the cyclic shear test of HDR bearings, the absolute difference of the equivalent damping ratio between the virgin and the aged at 80˚C for 16 days is about 1%. The Arrhenius equation, Eq. (5), is commonly used to correlate the accelerated aging test results with the aging under service condition

$$\ln\left(\frac{t_{ref}}{t}\right)=\frac{E_a}{R}\left(\frac{1}{T_{ref}}-\frac{1}{T}\right) \tag{5}$$

E_a is the activation energy of HDR, R is the gaseous constant (=8.314 J/mol/K), T is the absolute temperature in the service condition, T_{ref} is the reference temperature used in the accelerated test, t is the real aging time, and t_{ref} is the equivalent aging time in the accelerated test.

By using Eq. (5) with E_a of 9.04x10^4 J/mol for HDR[15], accelerated aging test conditions performed in this study correspond to the real aging time of 43.5 years in Nagoya with a yearly average temperature of 15.4˚C. Therefore, it can be said

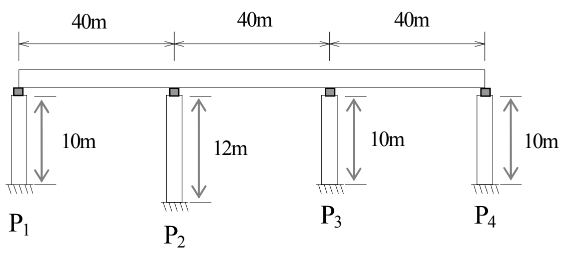


Fig. 14 Base-isolated multi-span continuous bridge example

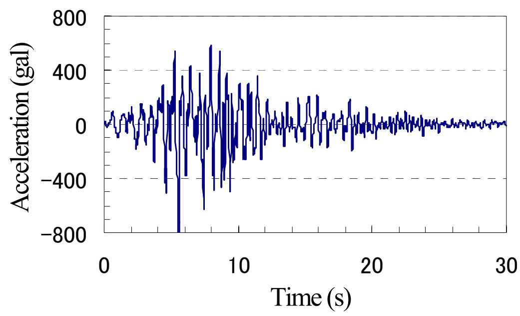


Fig. 15 Input earthquake motion

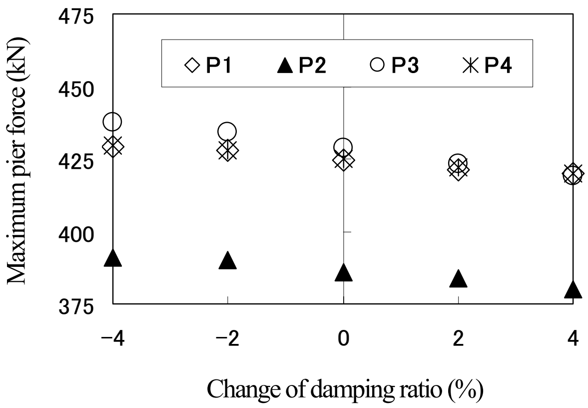


Fig. 16 Maximum restoring pier force

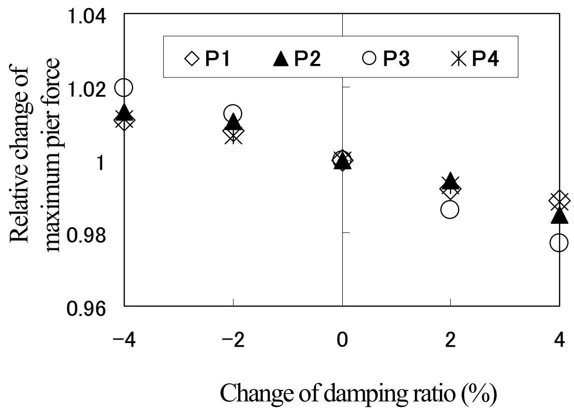


Fig. 17 Change of maximum pier force

that an HDR bearing installed in Nagoya will decrease its damping ratio by only about 1% for 43.5 years. The change of damping ratio by 1% is expected to have a small effect on the overall seismic response of a base-isolated bridge.

To examine the effect of the damping ratio change caused by aging on the seismic response of a base-isolated bridge, dynamic analysis was performed for one of benchmark bridges presented in Ref 20). The bridge is a three-span continuous highway bridge as shown in Fig. 14. HDR bearings for this bridge were designed in this study following the procedures specified in the handbook of bridge bearings[16]. HDR bearings resulted from the design have dimensions of 500 x 500 x 250 mm. Based on the design displacement, a damping ratio of HDR bearing in the initial condition is calculated as 18%.

Dynamic analysis of the bridge was performed by using the general purpose FEA program, ABAQUS. HDR bearings were modeled by truss elements with a bilinear force-displacement relationship as specified in the handbook of bridge bearings[16]. The piers and the girder were modeled by beam elements. Steel used in piers is SM490, represented by a bilinear model with Young's modulus E=206 GPa, yield stress σ_y=314 MPa, Poisson's ratio μ=0.3, and modulus after yield E'=E/100. Level 2 Type II earthquake record specified in the Specifications[1] for Soil type I was used as an input motion in this study. The ground acceleration time history is shown in Fig. 15.

The effect of damping ratio change on bridge response is investigated by changing the damping ratio by -4%, -2%, 2%, and 4% from the initial damping ratio.

Results from the dynamic analysis of the bridge are shown in Figs. 16 and 17, for the maximum restoring force of the pier and the change of maximum restoring force, respectively. The change of maximum restoring force is defined as the ratio between the maximum restoring force at the condition of the initial damping ratio and the maximum force after the damping ratio changes. It can be seen in Fig. 16 and Fig. 17 that the change of bearing damping ratio in this analysis has an insignificant effect on the maximum pier force. When the change of bearing damping ratio is ±4%, the maximum pier force changes by only about 2%. Since from the lap-shear test and the cyclic shear test of HDR bearings, the change of damping ratio due to aging equivalent to 43.5 years in Nagoya is only 1%, it can be concluded that the effect of aging on the equivalent damping ratio of HDR bearing is insignificant and that the damping ratio can be assumed as a constant value in the long-term performance evaluation of a base-isolated bridge.

5. SUMMARY AND CONCLUSIONS

In this research, based on the results from accelerated thermal oxidation tests of HDR bearings followed by the lap-shear test of small rubber blocks and the cyclic shear test of HDR bearings, the effect of aging of HDR on the equivalent damping ratio of

HDR bearing is investigated. Conclusions from this study are summarized as follows:

1) Two types of test performed in this study to obtain damping characteristics of HDR bearing, i.e., four-block lap-shear test and cyclic shear test of HDR bearings, provide good agreement in terms of aging effect on the euiqvalent damping ratio of HDR bearing.
2) The effect of aging on the equivalent damping ratio of HDR bearing is insignificant. The aging at 80˚C for 16 days (384 hours) in the accelerated thermal oxidation test, which corresponds to an aging time of 43.5 years in Nagoya where the yearly average temperature is 15.4˚C, causes the equivalent damping ratio to decrease by only about 1% from the initial condition.
3) The aging effect on the equivalent damping ratio can be neglected in evaluating long-term seismic performance of a base-isolated bridge with HDR bearings.

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