2nd International Conference on Advances in Experimental Structural Engineering
Tongji Univ., Shanghai 200092, China
December 4-6, 2007

Paper No. 07120113

LONG-TERM PERFORMANCE EVALUATION OF HIGH DAMPING RUBBER BEARINGS BY ACCELERATED THERMAL OXIDATION TEST

Paramashanti[1], Yoshito Itoh[2], Yasuo Kitane[3], and Haosheng Gu[4]

[1]*Nagoya University, Japan, parama@civil.nagoya-u.ac.jp*
[2]*Nagoya University, Japan, itoh@civil.nagoya-u.ac.jp*
[3]*Nagoya University, Japan, ykitane@civil.nagoya-u.ac.jp*
[4]*Tongji University, China, guhaosheng@gmail.com*

Abstract

High damping rubber (HDR) bearings are widely accepted as a base isolator in buildings and bridges in the world. It is well known that rubber materials change their properties when exposed to degradation factors including oxygen, ultraviolet, ozone, temperature, acid, and humidity. Among them, thermal oxidation is the predominant degradation factor for HDR in the built environments. In this study, based on the deterioration characteristics resulted from accelerated thermal oxidation tests of HDR bearings, a simple formula is derived to predict the variation of the equivalent shear stiffness of an HDR bearing. The long-term seismic performance of a base-isolated continuous steel bridge is evaluated by considering aging of HDR bearings. Using the simple formula, the equivalent stiffness and equivalent damping ratio of HDR bearings is calculated based on the size of bearing, an average temperature of the construction site, and various aging times up to 100 years. The results show that the equivalent shear stiffness of HDR bearing increases due to aging, which will cause the seismic force on the bridge to increase. The maximum stiffness change found in this study is about 14% of the initial stiffness. However, the most part of the change occurs soon after bearing installation.

Keywords: High damping rubber bearing, long-term performance, accelerated exposure test, aging, base-isolation

1. Introduction

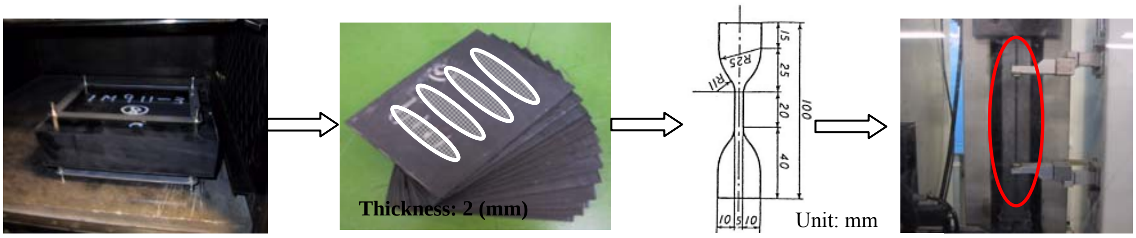
High damping rubber (HDR) bearings are now widely used as isolation bearings in the bridge. HDR material possesses both flexibility and high damping properties, so that bridge bearings made of HDR can not only extend the natural period of the bridge, but also dissipate seismic energy. Therefore, additional damping devices are not unnecessary for HDR bearings. In the manufacturing process of HDR, natural rubber is vulcanized together with carbon black, plasticizer, oil, and so on. Consequently HDR possesses peculiar characteristics such as maximum strain dependency of stress evolution, energy absorbing properties, and hardening properties.

A series of accelerated exposure tests were performed by Itoh et al. [1], [2] 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 degradation factor for the HDR material. Itoh et al. [3] also performed the accelerated thermal oxidation tests on HDR blocks to study deterioration characteristics of HDR bridge bearings. Their long-term mechanical performance was investigated by taking the site environment into consideration. A deterioration prediction model was developed to estimate property profiles. Then, carrying out finite element analyses (FEA) with deteriorated material properties, the effect of aging on the mechanical properties of an HDR bridge bearing was examined. The time-dependent and temperature-dependent characteristics of the equivalent shear stiffness and the equivalent damping ratio were quantitatively evaluated as well as the size effect.

A simple formula to estimate the future performance of an HDR bridge bearing is derived in this study. In the current design practice, properties of aged bridge rubber bearings are not considered. To examine the effect of aging of HDR bearings on the seismic response of a base-isolated bridge, a case study is conducted in this research. The long-term performance of HDR bearings is first evaluated by the derived simple formula for 20, 40, 60, 80, and 100-year aging times. With the calculated equivalent shear stiffness and damping ratio for aged HDR bearings, dynamic analysis of a base-isolated steel bridge is performed. The aging effect on the seismic performance of the bridge is evaluated by comparing peak responses from the dynamic analysis of different aging times with those for the initial state.

2. Accelerated Thermal Oxidation Test on HDR Blocks

In order to understand the variation of the material property inside the HDR bearings, accelerated tests were performed by Itoh et al. [3] on rubber blocks for the dominant degradation factor, thermal oxidation. Fifteen HDR blocks of 220 mm × 150 mm × 50 mm (length × width × thickness) were used as test specimens. The specimens were placed in a Thermal Aging Geer Oven at three different elevated temperatures, 60˚C, 70˚C, and 80˚C. Five test durations were set at each temperature, with the maximum of 300 days. When a rubber block specimen was taken out from the oven, it was sliced into pieces with a thickness of 2 mm. From each slice, four specimens with a dumbbell shape (JIS K6251 No. 3) were cut out. Finally, through the uniaxial tensile test, the stress-strain relationship of each dumbbell specimen was obtained, which represents the rubber properties at the corresponding position inside the rubber block. Fig. 1 shows the accelerated thermal oxidation test flow.



(a) Accelerated test (b) Rubber slices (c) Dumbbell specimen (d) Tensile test

Figure 1: Accelerated thermal oxidation test flow

The $U100/U_0$ and EB/EB_0 profiles of HDR blocks tested at temperature 60˚C are illustrated in Fig. 2 and Fig. 3, respectively, where $U100$ is the strain energy corresponding to the strain of 100%, and EB is elongation at break. U_0 and EB_0 stand for $U100$ and EB in the initial state, respectively. $U100$ profile and EB profile stand for the distribution of $U100$ and EB inside the rubber block.

As can be observed in Figs. 2 and Fig. 3 in the early stage of the test, the material properties change almost uniformly over the entire region. The property variation of the interior region soon reaches an equilibrium state and becomes stable. However, the properties near the surface continue to change over time. The largest change was found on the surface. From the surface to the interior, the properties vary less and less towards the equilibrium value at the critical depth. The critical depth is a depth beyond which oxidation cannot reach. Degradation characteristics of HDR imply that there are two factors affecting the aging of HDR: spontaneous reaction and oxidation. Since the oxidation cannnot reach beyond the critical depth, the interior region is only affected by spontaneous reaction that is related to temperature and completes in a relatively short time. However, in the outer region from the surface to the critical depth, the spontaneous reaction and oxidation affect HDR simultaneously at first. After the spontaneous reaction reaches a stable state, only the oxidation deterioration continues.

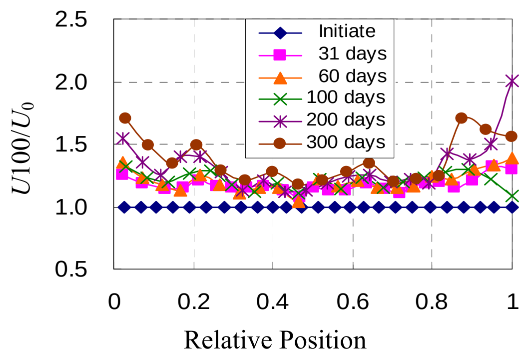


Figure 2: *$U100/U_0$* profile

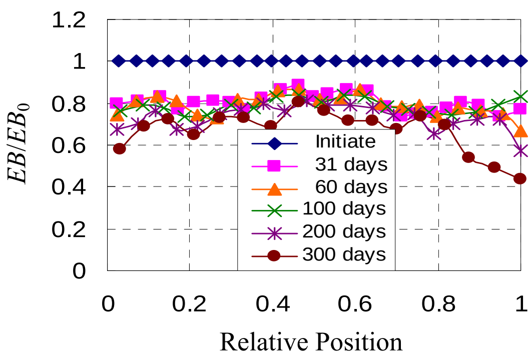


Figure 3: *EB/EB_0* profile

3. Deterioration Model for HDR Bearing

Itoh et al. [3] developed a deterioration prediction model for HDR bearings to estimate the property profile in the aged bearing. The deterioration prediction model was validated with the accelerated thermal oxidation test results and simulations. Using this model, the material property at any temperature and at any aging time can be estimated at any position inside the HDR bearing. In the thermal oxidation test, the temperature is much higher than the temperature in the real environment because high temperature can accelerate the deterioration of materials. Using the Arrhenius methodology, the accelerated aging results could be correlated with aging under service conditions. As the activation energy is used in the Arrhenius methodology, the time-dependency of properties at the surface was used to determine the activation energy of HDR. Performance of aged HDR bearings was evaluated by performing finite element analysis of HDR bearings with deteriorated material properties for 20, 40, 60, 80, and 100-year aging times and temperatures of 5˚C, 10˚C, 15˚C, 20˚C, and 25˚C. From the hysteretic loops obtained from FEA, the equivalent horizontal stiffness and the equivalent damping ratio were determined. The influences of time and termperature on the bearing performance were investigated. It was found that the equivalent horizontal stiffness increases gradually after a rapid increase during the very early period of a service life. At a higher temperature, the increasing rate became faster. However, the analysis results show that aging does not affect the equivalent damping ratio of HDR bearings significantly. The variation was about only ±5%.

4. Long-term Performance Estimation of HDR Bridge Bearing

Based on the study mentioned above, the time-dependent and temperature-dependent characteristics of the equivalent shear stiffness and the equivalent damping ratio were qualitatively evaluated as well as the size effect. In order to predict the future performance of an HDR bridge bearing conveniently, a simple design formula was derived as follows. Because of the limit of uniaxial tension test, the variation of equivalent damping ratio cannot be predicted precisely; therefore here only discussed is the formulation estimating the variation of equivalent shear stiffness. The data obtained from only the uniaxial tension test cannot evaluate the energy absorbing properties required to predict equivalent damping ratio of aged HDR bearings.

According to Reference [5], the equivalent horizontal stiffness K_h of a rubber bearing can be calculated using the following equation:

$$K_h = \frac{GA}{nt_R} \tag{1}$$

where, G is the static shear modulus of the rubber material, A is the effective area supporting the superstructure, n is the number of rubber layers, t_R is the thickness of a rubber layer.

Due to the non-uniform aging effect, the static shear modulus also varies according to the relative position inside the rubber bearing. Therefore, the equivalent shear stiffness of an aged rubber bearing can be expressed by the following equation:

$$K_h = \frac{Q}{nt_R} \tag{2}$$

where,

$$Q = \int G dA = G_0 \int f(x, y) dA \tag{3}$$

and G_0 and G are the static shear moduli before and after aging, respectively. $f(x, y)$ is a function expressing the variation of the shear modulus at any position (x, y). A cross section of a rectangular rubber bearing is shown in Fig. 4 with a side length of a and a width of b. The critical depth is d^*, to which oxidation can reach. A cross section of a bearing can be divided into four regions, A, B, C and D.

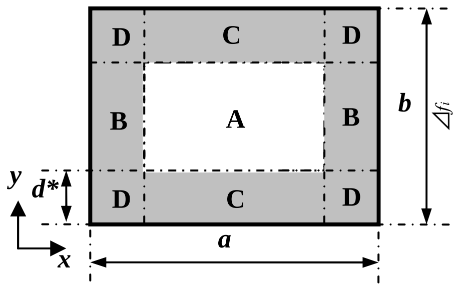


Figure 4: Plan of aged rubber bearing

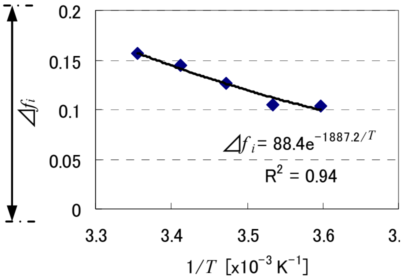


Figure 5: Temperature dependency of Δf_i

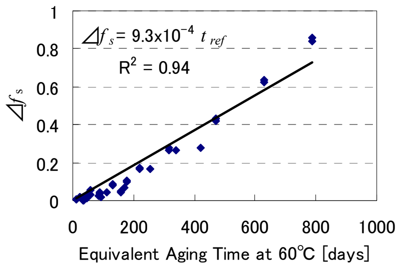


Figure 6: Temperature dependency of Δf_s

In the previous studies, Itoh et al. [6] examined the performance estimation of natural rubber (NR) bearings, and developed simple formulas to calculate a change in the equivalent horizontal stiffness of the NR bearings. The performance estimation of HDR bearings was derived based on the estimation formulas for NR bearings.

As discussed in Section 3, the spontaneous reaction occurs in the very early stage of aging and the material properties of the HDR bearing change uniformuly in the bearing in a short time. Moreover, the degree of this spontaneous reaction was found to be dependent on temperature. Therefore, equations for calculating Q of aged HDR bearings and a variation of the equivalent stiffness can be expressed as follows:

$$Q = G_0 \Big[(a - 2d^*)(b - 2d^*) + 2d^*(a + b - 4d^*)(1 + \Delta f_s/3) + 4d^{*2}(1 + \Delta f_s/2) \Big] \cdot (1 + \Delta f_i) \tag{4}$$

$$K_h / K_{h0} = Q / G_0 ab = (1 + k_s \Delta f_s)(1 + \Delta f_i) \tag{5}$$

$$k_s = 2d^*(a + b - d^*)/3ab \tag{6}$$

where, Δf_i is a variation of the static shear modulus in the whole HDR bearing due to the spontaneous reaction and Δf_s is a variation of the static shear modulus in the whole HDR bearing due to the oxidation as a fraction of the initial static shear modulus.

Since the degree of aging due to the spontaneous reaction is only dependent on temperature, the relationship between Δf_i and temperature is drawn in Fig. 5. Data in Fig. 5 are from FEA discussed in Section 3. It was found that Δf_i is an exponential function of a reciprocal of the absolute temperature. Δf_s was found to be a linear function of an equivalent aging time at a reference temperature as shown in Fig. 6. The corresponding time to Δf_s at any temperature was converted to the equivalent aging time at the reference temperature using the Arrhenius methodology as defined in Eq. (9). As discussed in Section 3, the temperature in the accelerated thermal oxidation test is much higher than the temperature in the real environment because high temperature can accelerate the deterioration of materials. Using the Arrhenius methodology, the equivalent aging time and the reference temperature at the accelerated thermal oxidation test could be converted to real aging time and temperature under service conditions. In this research, the reference temperature is assumed to be 60˚C. Therefore, the variation of the static shear modulus resulting from both the spontaneous reaction and the oxidation can be expressed by the following equations.

$$\Delta f_i = 88.4 \exp\left(\frac{-1887.2}{T}\right) \quad (7)$$

$$\Delta f_s = 0.93 \times 10^{-4} \cdot t_{ref} \quad (8)$$

$$\ln\left(\frac{t_{ref}}{t}\right) = \frac{E_a}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right) \quad (9)$$

where, E_a is the activation energy of HDR, R is the gaseous constant, T is the absolute temperature in the service condition, T_{ref} is the reference temperature, t is the real aging time, and t_{ref} is the equivalent aging time at the reference temperature. The parameters used in this study to estimate the variation of the equivalent shear stiffness are listed in Table 1.

Table 1. Parameters used for aging property estimation

	α [10^{-4}mm]	β [10^3K^{-1}]	E_a [10^4J/mol]	R [J/mol/K]	T_{ref} [K]
HDR	1.20	3.82	9.04	8.31	343

5. Seismic Performance of Base-Isolated Multi-Span Continuous Bridge with Aged HDR Bearings

To examine the effect of aging of HDR bearings on the seismic response of a base-isolated bridge, dynamic analysis was performed for one of benchmark bridges presented in Reference [7]. Fig. 7 shows a three-span continuous highway bridge. HDR bearings for this bridge were designed in this study following the procedures specified in Reference [5]. HDR bearings resulted from the design have dimensions of 500 x 500 x 250 mm.

5.1 Long-Term Performance of HDR Bearing

By using the simple formula discussed in Section 4, the equivalent stiffness of HDR bearings was calculated for an average temperature of Nagoya City (15.4˚C) and various aging times up to 100 years, and variations in the equivalent stiffness due to aging are shown in Fig. 8. In the figure, a ratio of the equivalent shear stiffness at a certain aging time to the initial stiffness, K_{Be}/K_{Be0}, is plotted. As can be seen from the figure, the maximum stiffness change is about 14%. The results indicate that the equivalent stiffness increases rapidly in the very early period of the bearing service life and the increase in stiffness slows down. At the time of writing this paper, it is not fully understood when the spontaneous reaction reaches the equilibrium state. The minimum accelerated thermal oxidation test duration was 31 days, which corresponds to 13 years for the service temperature of 15.4˚C Judging from the test results, the spontaneous reaction already reached an euilibrium state within the test duration of 31 days as can be seen in Figs. 2 and 3. Therefore, in this study, it is assumed that it reaches the equilibrium state in 20 years. In fact the equilibrium state may be reached in much less than 20 years. Because there are not sufficient data on the aging behavior during the first 20 years, the graph between 0 year and 20 years is drawn as a dashed line. Further study on the spontaneous reaction will be conducted in the near future.

The increase in the bearing equivalent stiffness leads to a decrease in the global natural period of the bridge. In this case, the decrease in the global natural period turned out to be about 4% of the initial natural period after 100 years.

5.2 Finite Element Model and Analysis Conditions

Dynamic analysis of the bridge was performed by using the general purpose FEA program, ABAQUS. HDR bearings were modeled as truss elements with a bilinear force-displacement relationship as shown in Fig. 9. The piers and the girder were modeled as beam elements. Steel used in piers is the SM490 steel, 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 Young's modulus after yield $E'=E/100$. Level 2 Type II earthquake record specifined in Reference [8] for Soil type I was used as an input motion in this study. The ground acceleration time history is shown in Fig. 10.

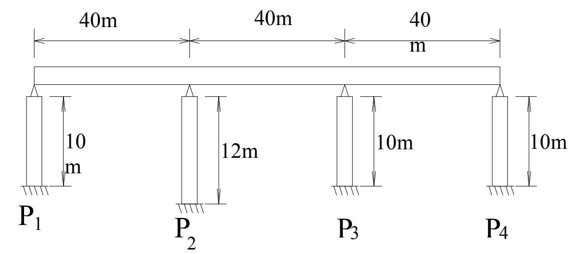


Figure 7: Base-isolated multi-span continuous bridge example

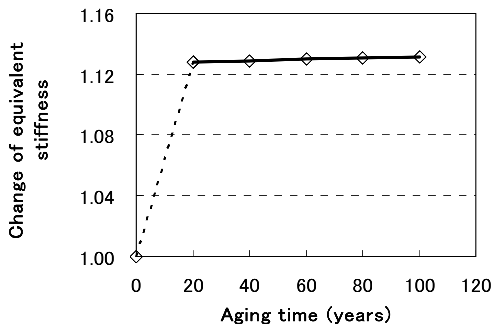


Figure 8: Change of equivalent shear stiffness

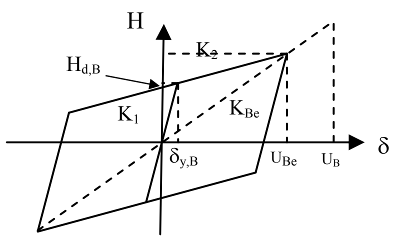


Figure 9: Bilinear force-displacement relationship of HDR bearing stiffness

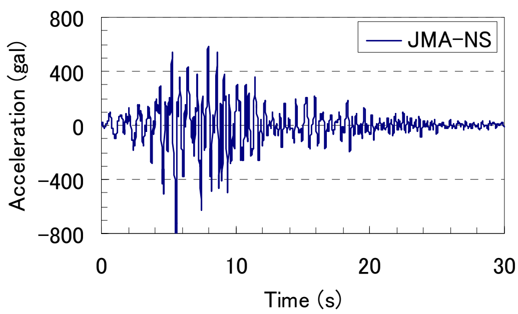


Figure 10: JMA-NS-M earthquake

For a bilinear model of an HDR bearing as shown in Fig. 9, the initial stiffness K_1 and the secondary stiffness K_2 are required. The equivalent stiffness of an aged HDR bearing can be calculated by Eq. (5). As discussed in Section 4, since there is no sufficient data available to determine aging characteristics of the equivalent damping ratio, and Itoh et al. [3] found that the change of the equivalent damping ratio of HDR bearing is not significant due to aging, it is assumed in this study that the equivalent damping ratio of HDR bearings does not change due to aging. In addition to the equivalent stiffness and the equivalent damping ratio, another equation is required to determine K_1 and K_2 for the bilinear model. In this study, a ratio between K_1 and K_2 was used. The ratio was obtained based on the recommended bilinear model specified for the bearing design process in Reference [5]. Two bearing sizes (500 x 500 x 120mm and 600 x 600 x 200mm) with three different cases for static shear modulus *G* (0.8 MPa, 1.0 MPa, 1.2 MPa) were examined. The summary of the result can be seen in Table 2. Results show that all cases have the value of 9.0 for the ratio between K_1 and K_2 of the bearings. Therefore, it is assumed that the aged HDR bearings also have a ratio of 9.0 between K_1 and K_2.

5.3 Analysis Results

Results from the dynamic analysis of the bridge are shown in Figs. 11 through 13. Fig. 11 shows hysteretic curves obtained at the bearings on Pier 2 for the initial state (the condition of new bridge) and the states after 20 and 100-year aging times. It can be seen from the figure that the aging of a rubber bearing results in an increase in the bearing stiffness and in the horizontal force. Since the increase of the bearing equivalent stiffness causes the global natural period to decrease, acceleration responses of the base-isolated bridge increase, and, consequently, seismic forces on the piers increase. The hysteretic curve of 20-year aging is almost the same as that for 100-year aging. At Pier 2, the maximum force increased by 4% after 100 years while the maximum displacement decreased by 7%.

Table 2. Ratio between K_1 and K_2

Size of Bearing (mm)	Static Shear Modulus (N/mm^2)	Ratio K_1/K_2
500 x 500 x 120mm & 600 x 600 x 200mm	0.8	9.0
	1.0	9.0
	1.2	9.0

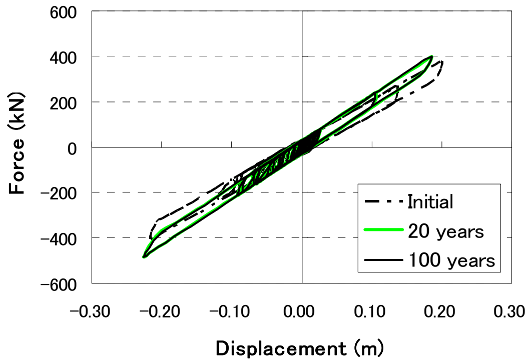


Figure 11: Hysteretic curve of bearing on Pier 2

In this paper, the seismic performance of piers is discussed in terms of maximum displacements and maximum forces. Fig. 12 shows the change of the maximum displacement of each pier for different aging times. The legend in the figure shows the maximum displacements for the initial state in the parentheses. As can be seen in Fig. 12, the pier maximum displacements tend to increase with the aging time. After 100 years, the maximum change increased by 7% at Pier 3, while the largest value is 0.08 m occurred at Pier 2. Fig. 13 shows the change of maximum force of each pier for different aging times. As can be seen in Fig. 13, the pier maximum forces tend to increase with the aging time. After 100 years, the maximum change increased by 8% at Pier 2, while the largest value was 430 kN at Pier 3. From Figs. 12 and 13, it can be seen that the maximum force and maximum displacement of the piers increase rapidly during the initial part of the bridge service life.

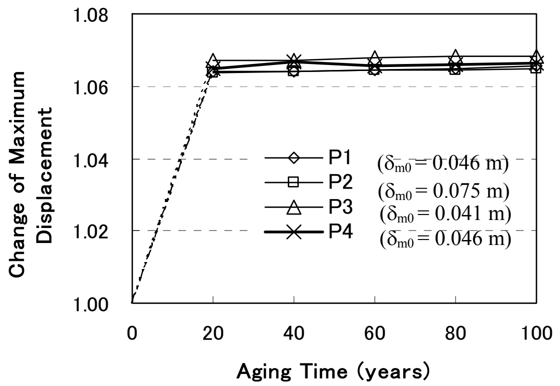


Figure 12: Change of maximum pier displacement

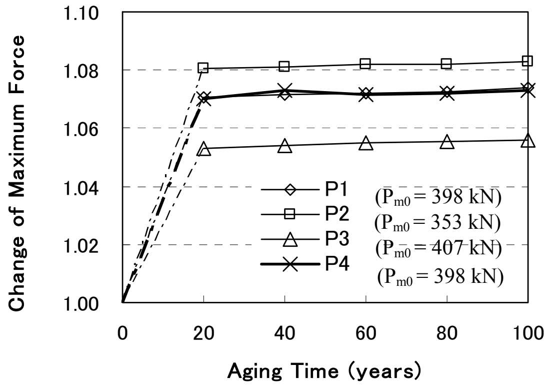


Figure 13: Change of maximum pier force

6. Conclusions

In this research, based on the result from accelerated thermal oxidation tests of HDR blocks, a simple design formula to estimate the long-term performance estimation of HDR bridge bearings has been proposed. By perfoming dynamic analysis, the long-term seismic performance of a base-isolated continuous steel bridge has been evaluated by considering aging of HDR bearings. The conclusions are summarized as follows:

1) The deterioration of HDR block can be divided into two regions; one is in the interior region beyond the critical depth, the other is in the outer region from the surface to the critical depth. In the interior region, the property variation soon reaches an equilibrium state and become stable, while in the region near the surface the properties continue to change over time. The change is most significant on the surface.
2) There are two factors affecting the deterioration of HDR due to aging, spontaneous reaction and oxidation. The interior region is only affected by spontaneous reaction that is dependent on temperature and completes in a relatively short time. In the outer region, the spontaneous reaction and oxidation affect HDR simultaneously at first, and after the spontaneous reaction reaches a stable state, only the oxidation deterioration continues.
3) The equivalent stiffness of HDR bearings increases due to aging, which causes the seismic force on the bridge to increase. The stiffness increases rapidly during the early stage of the bearing service life, and after the spontaneous reaction in HDR reaches the equilibrium state, the increasing rate reduces.

It is important to evaluate future seismic performance of a base-isolated bridge including the aging effect of rubber bearings so that an appropriate maintenance strategy for a life span of the bridge can be determined at the initial planning phase. To obtain more information about the deterioration of HDR bearings due to aging, the experiment is currently underway. Based on the results, the estimation method proposed in this paper will be reevaluated.

7. References

[1] Itoh, Y., Yazawa, A., Satoh, K., Gu, H.S., Kutsuna, Y. and Yamamoto, Y.: Study on environmental deterioration of rubber material for bridge bearings, *Journal of Structural Mechanics and Earthquake Engineering, JSCE*, No.794/I-72, pp.253-266, 2005 (in Japanese).

[2] Itoh, Y., Gu, H. S., Satoh, K. and Kutsuna, Y.: Experimental investigation on aging behaviors of rubbers used for bridge bearings, *Journal of Structural Mechanics and Earthquake Engineering, JSCE*, No.808/I-74, pp.17-32, 2006.

[3] Itoh, Y., Gu, H. S., Satoh, K., and Yamamoto, Y.: Long-term deterioration of high damping rubber bridge bearing, *Journal of Structural Mechanics and Earthquake Engineering, JSCE*, Vol.62, No.3, 2006.

[4] Yoshida, J., Abe, M. and Fujino, Y.: Constitutive model of high-damping rubber materials, *Journal of Engineering Mechanics, ASCE*, Vol. 130, No. 2, pp. 129-141, 2004.

[5] Japan Road Association: Handbook of Highway Bridge Bearings, *Japan Road Association*, 2004a (in Japan ese).

[6] Itoh, Y., Satoh, K., Gu, H. S. and Yamamoto, Y.: Study on the deterioration characteristics of natural rubber bearings, *Journal of Structural Mechanics and Earthquake Engineering, JSCE*, Vol.62, No.2, pp.255-266, 2006.
[7] JSCE & JSSC: Benchmark for seismic analysis on steel structures and advances in seismic design method, *JSCE & JSSC, 2000* (in Japanese).
[8] Japan Road Association, *Design Specifications of Highway Bridges*, V, 2002 (in Japanese).