

# LONG-TERM DETERIORATION OF HIGH DAMPING RUBBER BRIDGE BEARING

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In recent years, high damping rubber (HDR) bridge bearings have become widely used because of the excellent ability to provide high damping as well as flexibility. However, there are few systematic studies on the deterioration problems of HDRs during their service life, and usually the long-term performance was not considered in the design stage. In this research, through accelerated thermal oxidation tests on HDR blocks, the property variations inside the HDR bridge bearing are examined. A deterioration prediction model is developed to estimate the property profiles. Then using a constitutive model and carrying out FEM analysis, the behavior of a HDR bridge bearing during its lifespan is clarified. A design procedure is proposed that takes the long-term performance in the site environment into consideration.

**Key Words:** *high damping rubber bearing, thermal oxidation, deterioration, long-term performance*

## 1. INTRODUCTION

Since Hyogoken-Nanbu earthquake that occurred on January 17th, 1995, bridge bearings have been widely adopted in Japan as an effective means to weaken the severe damage of steel and concrete piers due to an earthquake<sup>1), 2)</sup>. Rubber is frequently applied in bridge bearings because of its special properties such as high elasticity and large elongation at failure. However, natural rubber cannot afford sufficient damping which is indispensable to a seismic isolation system. Usually rubber bearing is used together with steel bars, lead plugs, or other types of damping devices. In order to add energy dissipation to the flexibility existing in laminated rubber bearings, in the early 1980's, the development in rubber technology led to new rubber compounds, which were termed high damping rubber (HDR). HDR material possesses both flexibility and high damping properties. The bridge bearings made of HDR can not only extend the natural period of the bridge, but also

reduce the displacement response of structures<sup>3)</sup>. Moreover, because of the inherent high damping characteristics of HDR, there is no need of additional devices to achieve the required levels of protection from earthquakes for most applications, so that the seismic isolation system becomes more compact.

In the manufacture process of HDR, natural rubber is vulcanized together with carbon black, plasticizer, oil and so on. Consequently HDR possesses specific characteristics such as maximum strain-dependency of stress evolution, energy absorbing properties and hardening properties. Yuan et al.<sup>4)</sup> experimentally studied the dynamic behaviors of HDR bearing. Yoshida et al.<sup>5), 6)</sup> developed a mathematical model of HDR materials and proposed a three-dimensional finite element modeling methodology to simulate the behaviors of a HDR bearing numerically. Besides, a series of accelerated exposure tests were performed by Itoh et al.<sup>7), 8)</sup> on various rubber materials including HDR to investigate the degradation effects of different environmental fac-

tors. It was found that the thermal oxidation is the most predominant degradation factor affecting the HDR material. Since oxygen is able to permeate into the interior of a thick rubber, in this research the deterioration of HDR bridge bearings is assumed to be mainly caused by the thermal oxidation. For the purpose of clarifying the deterioration characteristics of bridge rubber bearings during their lifespan, some bearings practically in use were recalled and their mechanical properties were tested<sup>9)~11)</sup>. However, because of their scatter nature and the lack of data, the long-term performance of HDR is not very clear. During the design process, usually the behaviors of deteriorated bridge rubber bearings during their lifespan are not considered.

In the previous research, Itoh et al.<sup>12), 13)</sup> studied the long-term performance of natural rubber (NR) bridge bearings. Through accelerated thermal oxidation tests carried out on NR blocks, the deterioration characteristics of both the outer and the interior regions were examined. Based on the test results, a prediction model was established to estimate the property profiles of the deteriorated NR bridge bearing. Then using the constitutive law proposed by Yoshida<sup>5)</sup>, finite element model was built and the analysis was performed, which enabled the long-term performance of NR bridge bearing to be predicted. The relations among property variation, temperature, aging time and bearing size were also investigated.

In this research, through the similar accelerated thermal oxidation tests on HDR blocks, the deterioration characteristics of HDR bridge bearings are studied, and their long-term mechanical performance is investigated by taking the site environment taken into consideration. The HDR specimens are provided by Tokai Rubber Industries, Ltd. It is possible that when suffered by aging, the HDR from other companies may behave differently due to the difference of chemical compound. The deterioration characteristics of the HDR material with other compounding ingredients and additives will be discussed in the future study.

## 2. ACCELERATED THERMAL OXIDATION TESTS

Among different degradation factors such as oxidation, ultraviolet radiation, ozone, temperature, acid and humidity, it is found that thermal oxidation changes the HDR properties more greatly than other factors<sup>5)</sup>, resulting in an increase of HDR's stiffness and a decreases of elongation at break as well as tensile strength. Besides, for thick rubbers, it is obvious that the surface is more easily affected by deterioration factors than the interior because of the

diffusion-limited oxidation effect<sup>14), 15)</sup>. In order to understand the variation of the material properties inside HDR bearings, accelerated tests were performed using rubber blocks focusing on the most significant degradation factor, thermal oxidation. The test method and results are described as follows.

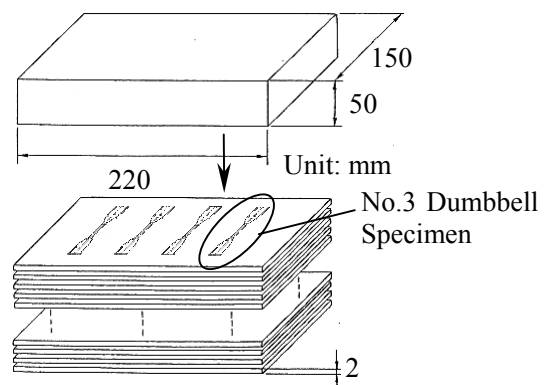
### (1) Accelerated thermal oxidation test method

Fifteen HDR blocks were tested. The dimension is  $220 \times 150 \times 50$ mm (length  $\times$  width  $\times$  thickness). The specimens were kept in a Thermal Aging Geer Oven. The acceleration test conditions are listed in **Table 1**. The temperatures were kept at three elevated temperatures, 60°C, 70°C, and 80°C in the oven. For the test at each temperature, the experiment duration were set as 5 stages, with the maximum of 300 days. The similar tests have already been performed on NR<sup>10)</sup>. When the aging test was finished, HDR blocks were sliced into pieces with a thickness of 2mm. From each slice, four specimens with No.3 dumbbell shape were cut out<sup>16)</sup>, as shown in **Fig.1**. The number of the specimens was 1,500 in total. Then through the tensile tests on these dumbbell specimens, the stress-strain curves were obtained, which represented the rubber properties at the corresponding position.

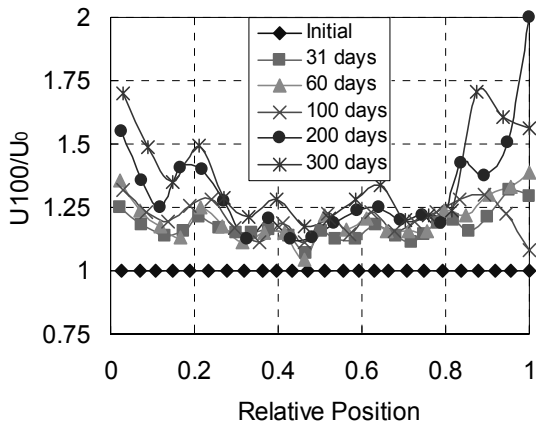
In this research, strain energy was chosen for examination because it can exhibit the effect of thermal oxidation more remarkably than stresses at certain strains. In the following description, U100 stands for the strain energy corresponding to the strain of 100%, UB stands for the strain energy up to the break, and M100 stands for the stress corresponding to the strain of 100%. Similarly, U100

**Table 1** Accelerated thermal oxidation test condition

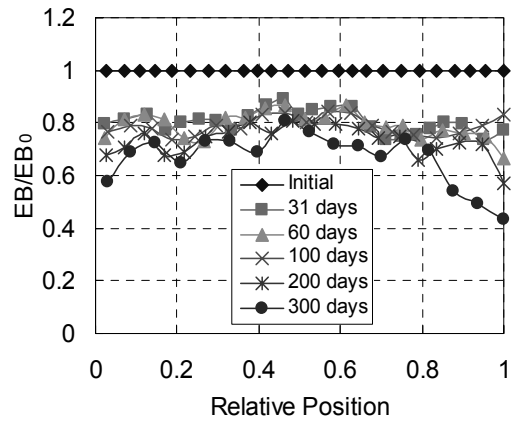
Temperature [°C]	Test Duration [days]
60	31, 60, 100, 200, 300
70	12, 22, 38, 75, 113
80	4, 8, 14, 28, 42



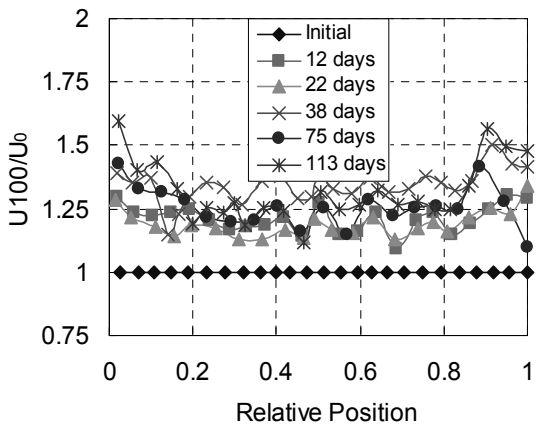
**Fig.1** Slice of HDR block



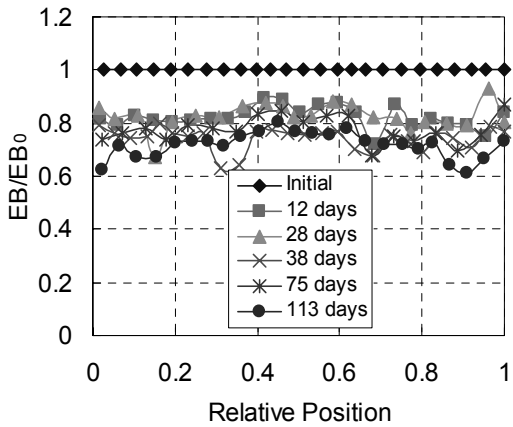
(a) 60°C



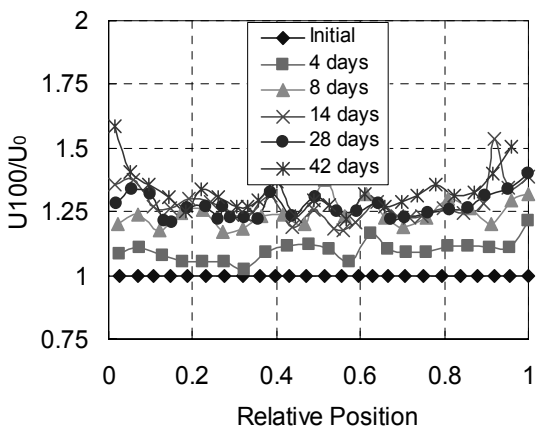
(a) 60°C



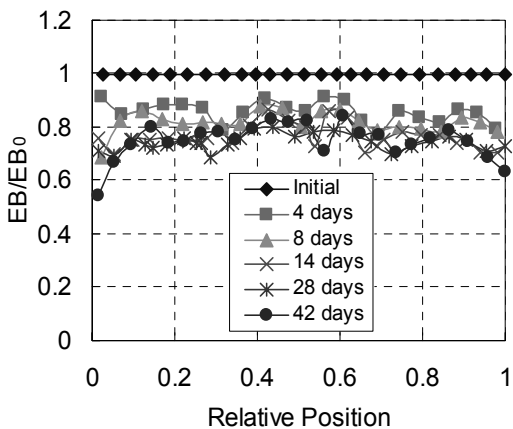
(b) 70°C



(b) 70°C



(c) 80°C



(c) 80°C

Fig.2 U100/U<sub>0</sub> profile

Fig.3 EB/EB<sub>0</sub> profile

profile stands for the distribution of U100 inside HDR blocks, and property profile means the distribution of the mechanical properties such as stresses corresponding to certain strains, elongation at break (EB) and tensile strength (TS). As for the rubber breakage, EB is focused on. In addition, U<sub>0</sub> and EB<sub>0</sub> stand for U100 and EB in the initial state, respectively.

**(2) Test results and examinations**

The profiles of U100/U<sub>0</sub> and EB/EB<sub>0</sub> at every test temperature are illustrated in Fig.2 and Fig.3, respectively. The horizontal axis shows the relative position with regard to the thickness of HDR block. The values 0 and 1 on this axis correspond to the surface of the block. The vertical axis shows the normalized change of U100 with the original value regarded as 1.0 in Fig.2, and shows the normalized

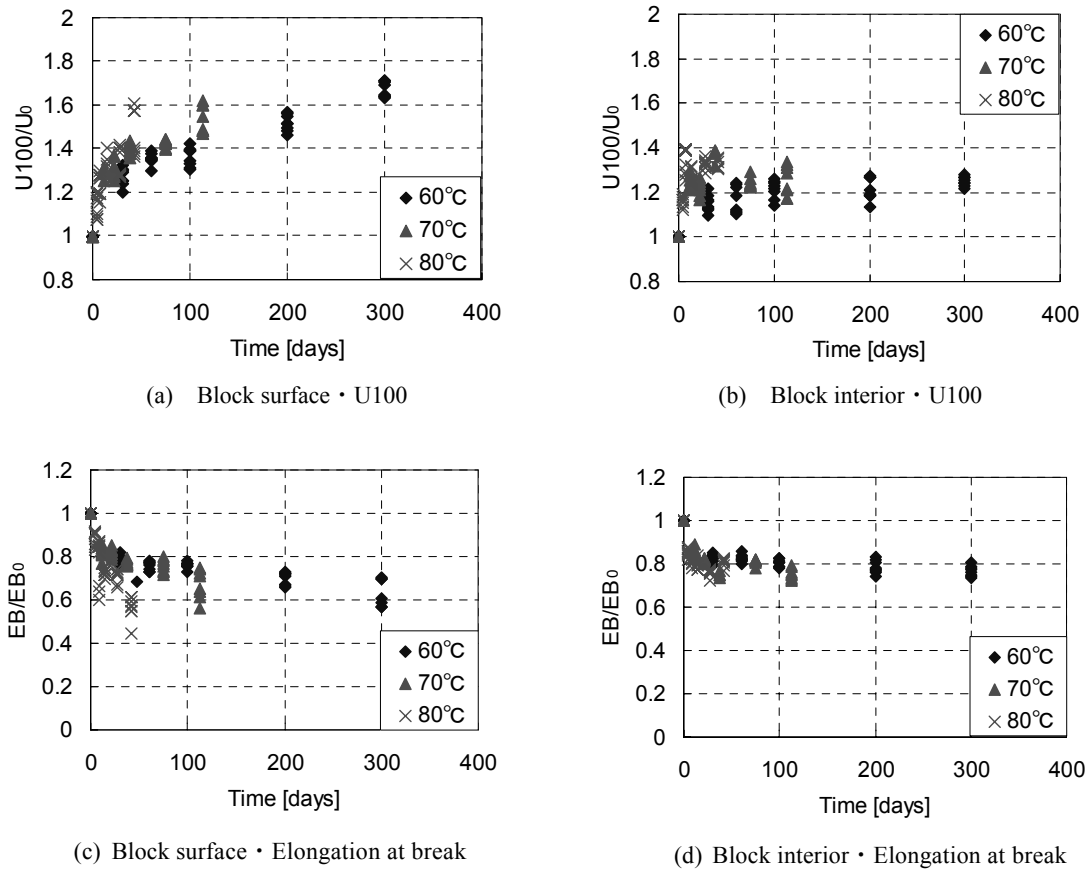


Fig.4 Time-dependency of U100 and elongation at break

change of EB in Fig.3. In these figures, every point represents the mean value of four specimens from the same slice. Because of the scatter nature of rubber materials, at any position four specimens are tested in order to improve the accuracy. Since the oxidized rubber inhibits the ingress of oxygen, and considering the shape of the rubber block, the four specimens are cut out in the area of at least 25mm, a half of the block thickness, away from the around surface. Thus these specimens only reflect the property variations in the thickness direction. The standard deviation of every four-specimen group is quite small and usually less than 5% of the mean value.

From Fig.2 and Fig.3, it can be found that at the earliest stage of the test, the material properties at the outside surface change together with the interior regions. The property variation of the interior region soon reaches the equilibrium state and maintains stable. However, the properties near the surface keep changing over the time, and change most greatly at the surface. From the surface to the interior, the properties vary less and less, until to a certain depth, which is called “critical depth”. The critical depth is about 11.5mm from the block surface at 60°C, 8.5mm at 70°C, and 6mm under 80°C.

From the results of the same tests on NR blocks<sup>12)</sup>, it is found that generally HDR and NR have a similar

tendency of property variation. Both U100 and EB profiles display the features of a diffusion-limited oxidation. Initially the profiles are relatively homogeneous, but strong heterogeneity develops with aging. The properties in the outer region change more than the interior and keep changing over the time. However, unlike the case of NR, the interior region of HDR block experiences a rapid increase and soon reaches the equilibrium state. In contrast, the interior region of NR block does not change at all. In addition, after the same aging time, the property change at the surface of NR block is larger than that of HDR block, which means NR is more vulnerable to thermal oxidation.

Fig.4 shows the time-dependency of U100 and EB at the surface and in the interior of HDR blocks. The horizontal axis shows the deterioration time, and the vertical axis shows the material property variations compared to its initial state. The data of the block surface are taken from the top and the bottom surfaces, while the data of the block interior are taken from two slices close to the middle slice. Therefore, there are 8 points corresponding to every measuring time. From Figs.4(a) and 4(c) it is found that U100 and EB at the block surface change nonlinearly over the time. In Figs.4(b) and 4(d), the properties in the interior region vary in a very short time, and soon

become stable. U100 increases by 20~40% and EB decreases by about 20%.

Besides the accelerated thermal oxidation test, a HDR block was exposed to the environment of Nagoya, where the yearly average temperature is 15.4°C. The properties of each layer was measured and the profiles were obtained after one year. The normalized change of EB profile is shown in Fig.5. It can be seen that EB decreased by nearly 20% after only one year. This figure offers a good proof of the rapid variation speed in the interior of HDR during the earliest stage. Using the deterioration prediction model that is to be introduced in the following section, the simulation of the deterioration after one year is found to be close to the test results.

From the test results, it is clear the deterioration characteristics of HDR block can be observed in two regions, one is in the interior region beyond the critical depth, where the properties only change at the earliest stage, the other is in the outer region from the surface to the critical depth, where the properties continue changing after a rapid initial change. Oxidation cuts the cross-links between chains and accelerates the reformation of molecule structure, however, the latter restricts the ingress of oxygen. It is thought that the equilibrium is reached at the critical depth. The oxidation is a process related to the time, however, the properties in the interior re-

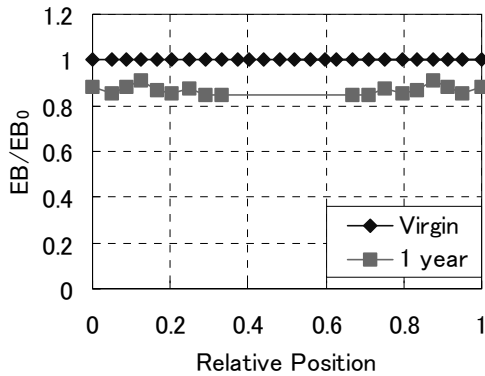


Fig.5 EB/EB<sub>0</sub> profile of HDR block in Nagoya (15.4°C)

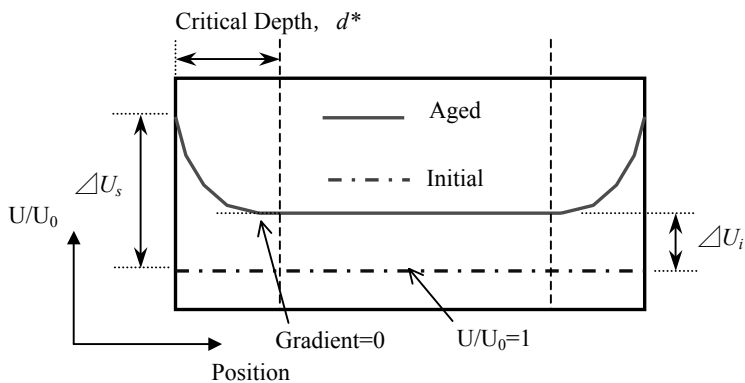


Fig.6 Strain energy profile pattern

gion only vary in a very short time. There should be a factor except for oxidation affecting the interior region of HDR block. Because the property variation in the interior region increases with temperature, it is assumed the reaction is related to temperature. Therefore, it is thought that there are two factors affecting the deterioration of the HDR material, temperature and oxidation. The interior region is mainly affected by temperature, and this reaction finishes in a relatively short time. However, for the outer region near the surface, temperature and oxidation affect HDR simultaneously at first. After the reaction due to temperature reaching the stable state, only the oxidation deterioration continues.

### 3. DETERIORATION PREDICTION MODEL FOR HDR BRIDGE BEARING

#### (1) Quantification of deterioration characteristics

To predict the long-term deterioration of HDR bridge bearing, it is necessary to quantify the deterioration characteristics. From the accelerated thermal oxidation test results, the deterioration pattern of the HDR block can be schematically expressed by Fig.6. The vertical axis  $U/U_0$  means the relative property variation, which is the ratio of the current material property  $U$  comparing to the original value  $U_0$ . The horizontal axis shows the relative position inside the HDR block. The interior region beyond the critical depth  $d^*$  is mainly affected by temperature, and the relative property variation is  $\Delta U_i$ . The outer region from surface to the critical depth  $d^*$  is influenced by both temperature and oxidation, and the property changes most greatly near the block surface. The relative property variation at the bearing surface is represented by the symbol of  $\Delta U_s$ . When proceeding into the block, because of the decrease in the amount of oxygen, the oxidation effect becomes weaker, and the property variation also declines. Once exceeding the critical depth, the gradient of the property profile becomes zero.

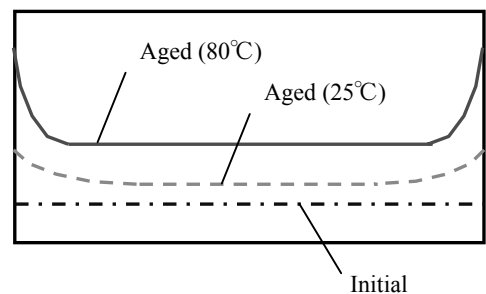


Fig.7 Schematic profile patterns



Moreover, from the test results shown in Figs.2 ~ 5, it can be said that at the lower temperatures, the critical depth becomes larger, however the property variation rate in both the inner and the outer region becomes slower. Hence the property profiles of aged HDR block at different temperatures are expected to be similar to the one shown in Fig.7.

**a) Critical depth**

Muramatsu and Nishikawa<sup>17)</sup> discovered that the critical depth can be expressed as the exponential function of the reciprocal of the absolute temperature, and the following formula was proposed to express the relationship between the critical depth and the temperature.

$$d^* = \alpha \exp\left(\frac{\beta}{T}\right) \tag{1}$$

where,  $d^*$  is the critical depth,  $T$  is the absolute temperature, and the symbols  $\alpha$  and  $\beta$  are coefficients determined by the aging test.

The exponential relationship between the critical depth and the temperature is shown in Fig.8. In this figure it is found that for HDR,  $\alpha=0.00012\text{mm}$ ,  $\beta=3.82 \times 10^{-3}$ .

**b) Property variation of interior region**

The accelerated thermal oxidation test results show that the interior region changes in a relatively

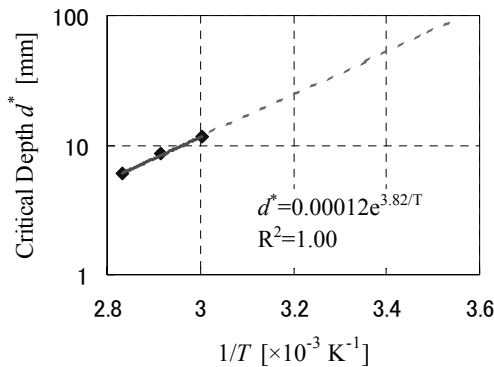


Fig.8 Relations between critical depth and temperature

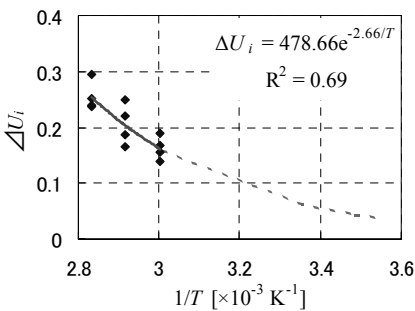
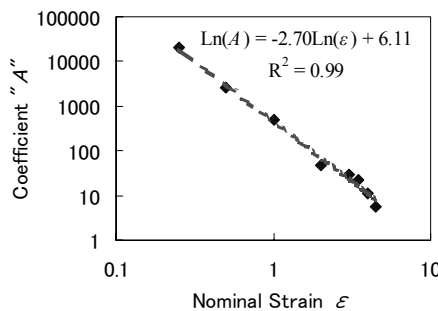
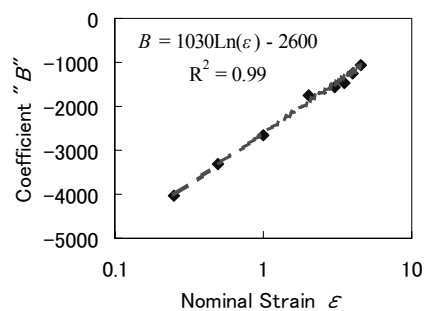


Fig.9 Relations between inner U100 change and temperature



(a) Coefficient "A"



(b) Coefficient "B"

Fig.10 Relations between coefficient "A", "B" and nominal strain ε

very short time, and then keeps stable. The properties change so rapidly that the time-dependency may be neglected. The EB decreases by about 20% and showing no dependency on the temperature. However, the equilibrium state of strain energy is correlated with temperature, as shown in Fig.9. The exact tendency is not clear because of the lack of tests at lower temperatures. In this study, the change of the relative strain energy in the interior region is assumed to be an exponential function of the reciprocal of the absolute temperature as follows:

$$\Delta U_i = A \exp\left(\frac{B}{T}\right) \tag{2}$$

where,  $\Delta U_i$  is the normalized strain energy variation of the interior region,  $T$  is the absolute temperature, and the symbols  $A$  and  $B$  are coefficients.

The symbols  $A$  and  $B$  in Eq.(2) are found to be related to the nominal strain. The strain-dependency of the both coefficients is shown in Fig.10. In this figure, the coefficients  $A$  and  $B$  versus the strain between 25% and 500% are illustrated. Hence they can be correlated approximately using the following equations.

$$\ln A = b_1 \ln \varepsilon + b_2 \tag{3a}$$

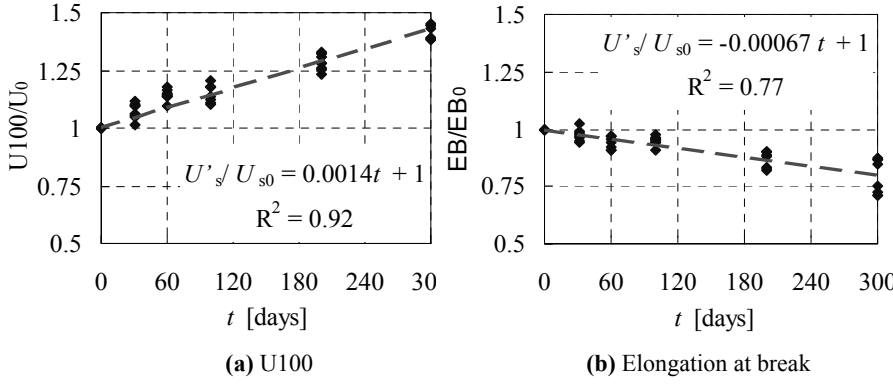
$$B = c_1 \ln \varepsilon + c_2 \tag{3b}$$

where,  $\varepsilon$  is the nominal strain, the symbols  $b_1$ ,  $b_2$ ,  $c_1$ , and  $c_2$  are the factors determined by the aging test.

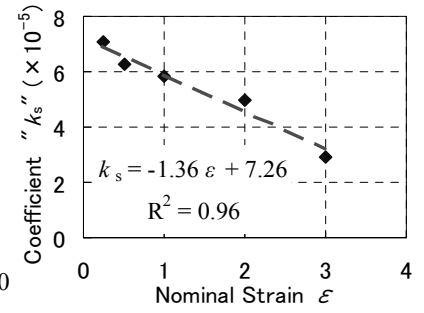
**c) Property variation at block surface**

The property variation at the block surface can be deemed as the combined effect of temperature and oxidation. Temperature not only causes the change in HDR properties, but also accelerates the oxidation reaction.

Figs.11 (a) and 11(b) show the relative change of U100 and EB at the bearing surface with the property variations due to the temperature eliminated.



**Fig.11** Time-dependency of properties at block surface (60°C)



**Fig.12** Relations between strain and coefficient "k<sub>s</sub>" (60°C)

At a certain temperature, the property of HDR exposed to the air depends on time. It is found that the increase of U100 and the decrease of EB are linear with the aging time. For other material properties, the similar relationship is proved. The time-dependency can be expressed by the following equation:

$$U'_s / U_{s0} = k_s \cdot t + 1 \quad (4a)$$

where,  $U'_s / U_{s0}$  is the relative variation of strain energy at the surface of the rubber bearing due to the oxidation only,  $k_s$  is coefficient and  $t$  is the deterioration time.

The relative property variation at the bearing surface also depends on strain. The relationship between the coefficient  $k_s$  and the nominal strain  $\varepsilon$  is shown in **Fig.12**, and the following equation can be obtained.

$$k_s = a_1 \cdot \varepsilon + a_2 \quad (4b)$$

where,  $a_1$  and  $a_2$  are the factors determined by the test.

Since the normalized property variation at the bearing surface  $\Delta U_s$  is affected by the deterioration effects due to both temperature and oxidation, the following equation is obtained.

$$\Delta U_s = (1 + k_s \cdot t) \cdot (1 + \Delta U_i) - 1 \quad (4c)$$

#### d) Shape model of property profile

A simple equation is necessary to express the property variation in the region from the rubber bearing surface to the critical depth. The property variation  $U(t)/U_0$  should be the function of the position  $x$ . The boundary conditions are:

$$U(t)/U_0 = 1 + \Delta U_s \quad (x=0 \text{ or } l) \quad (5a)$$

$$U(t)/U_0 = 1 + \Delta U_i \quad (d^* \leq x \leq l - d^*) \quad (5b)$$

$$dU(t)/dx = 0 \quad (x=d^*) \quad (5c)$$

where,  $U(t)$  and  $U_0$  are the HDR properties at time  $t$  and initial state, respectively.  $\Delta U_i$  and  $\Delta U_s$  are the relative property changes of the interior region and the bearing surface, respectively.  $l$  is the width of the HDR bearing.

If the property variation  $U(t)/U_0$  is assumed to be a square relation of the position  $x$ , the function can be expressed as follows:

$$U(t)/U_0 = g_1 x^2 + g_2 x + g_3 \quad (6)$$

Considering the boundary conditions Eq.(6) can be written as:

$$\frac{U(t)}{U_0} = 1 + [w \Delta U_s + (1-w) \Delta U_i] \quad (7)$$

$$w = \begin{cases} \left( \frac{x-d^*}{d^*} \right)^2 & (0 \leq x \leq d^*) \\ 0 & (d^* \leq x \leq l-d^*) \\ \left( \frac{x-(l-d^*)}{d^*} \right)^2 & (l-d^* \leq x \leq l) \end{cases} \quad (8)$$

where,  $w$  is the coefficient correlated with the position  $x$ , the critical depth  $d^*$  and the width  $l$  of the HDR bearing.

Next, if the relationship between  $U(t)/U_0$  and  $x$  is a 3-order equation, it is expressed by:

$$U(t)/U_0 = g_1 x^3 + g_2 x^2 + g_3 x + g_4 \quad (9)$$

Eq.(9) is resolved using the boundary conditions, the following equation is obtained.

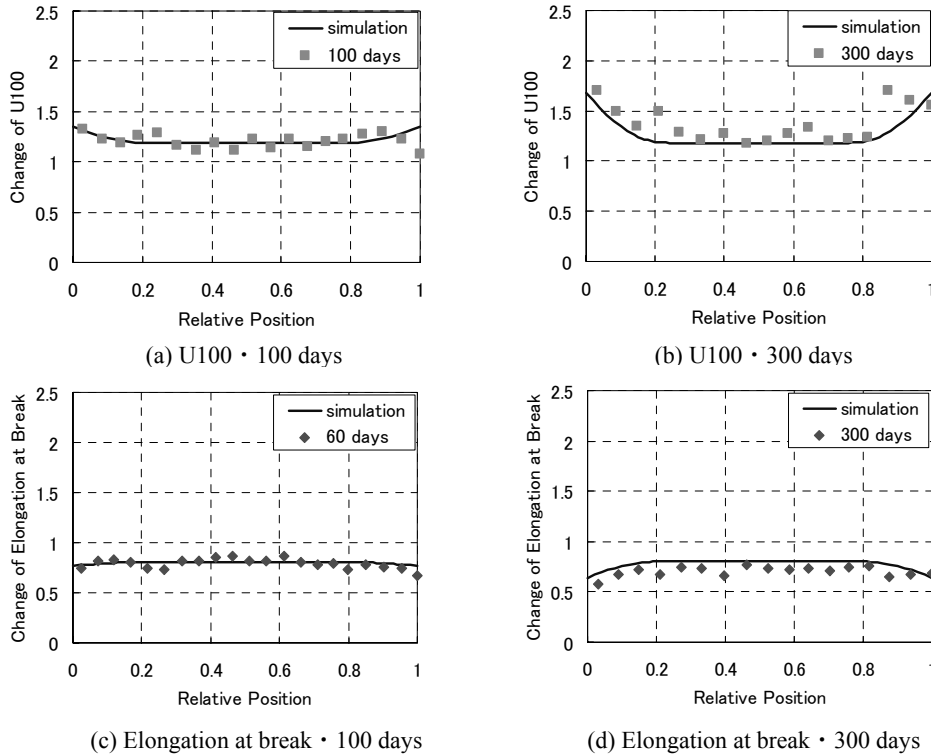
$$\frac{U(t)}{U_0} = g_1 x(x-d^*) + \{1 + [w \Delta U_s + (1-w) \Delta U_i]\} \quad (10)$$

**Table 2** Parameters of HDR deterioration prediction model

$\alpha$ [ $10^{-4}$ mm]	$\beta$ [ $10^{-3}$ K $^{-1}$ ]	$a_1$ [ $10^{-5}$ ]	$a_2$ [ $10^{-5}$ ]	$b_1$	$b_2$	$c_1$ [ $10^3$ ]	$c_2$ [ $10^3$ ]	$k_{bs}$ * [ $10^{-5}$ ]	$\Delta EB_i$ **
1.21	3.82	-1.36	7.26	-2.70	6.11	1.03	-2.60	-2.79	-0.20

\* $k_{bs}$ : Change rate of elongation at break at block surface

\*\* $\Delta EB_i$ : Change of elongation at break in the interior



**Fig. 13** Comparison between test results and prediction model (60°C)

From the test results, it is found that the influence of the first part of Eq.(10) is only about 0.01%~10% of  $U(t)/U_0$ . For simplicity, in this study the square relation as Eq.(7) is adopted.

**(2) Comparison with test results**

Using Eqs.(1)~(6), the property profiles of the deteriorated HDR blocks can be estimated. Based on the test results, the coefficients in these equations are obtained and listed in **Table 2**. Through the comparisons between test results and simulations shown in **Fig.13**, it is found that the simulations of the critical depth, the property variations on the block surface and in the interior region are in good agreement with the test results. Thus the feasibility of the deterioration prediction method is verified. Using this model, the material property can be predicted at any position inside the HDR bearing, at any temperature and at any aging time.

**(3) Activation energy**

In the thermal oxidation test the temperature applied is much higher than the real environment. This is because high temperature can accelerate the deterioration<sup>18)</sup>. The Arrhenius methodology<sup>3)</sup> is commonly used to correlate the accelerated aging results with the aging under service conditions. Generally the thermal oxidation is assumed to be the 1<sup>st</sup> order chemical reaction for rubber materials<sup>3)</sup>. Then the aging time in the accelerated exposure tests can be converted into the real time under the service conditions through the following formula:

$$\ln\left(\frac{t_r}{t}\right) = \frac{E_a}{R} \left(\frac{1}{T_r} - \frac{1}{T}\right) \tag{11}$$

where,  $E_a$  is the activation energy of the rubber,  $R$  is the gaseous constant (=8.314[J/mol· K]),  $T_r$  indicates the absolute temperature under the service condition, and  $T$  is the absolute temperature in the thermal



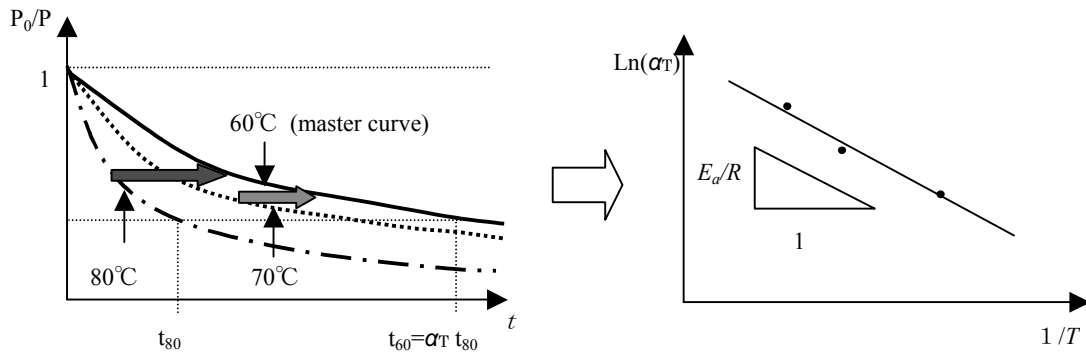


Fig. 14 Principle of time/temperature superposition to obtain activation energy

Table 3 Activation energy of HDR

HDR Property	$E_a$ (J/mol)
U25	$8.97 \times 10^4$
U50	$8.90 \times 10^4$
U100	$8.84 \times 10^4$
U200	$8.23 \times 10^4$
U300	$7.61 \times 10^4$
UB	$9.93 \times 10^4$
EB	$1.08 \times 10^5$
Average	$9.04 \times 10^4$

UB: Strain energy at break  
 EB: Elongation at break

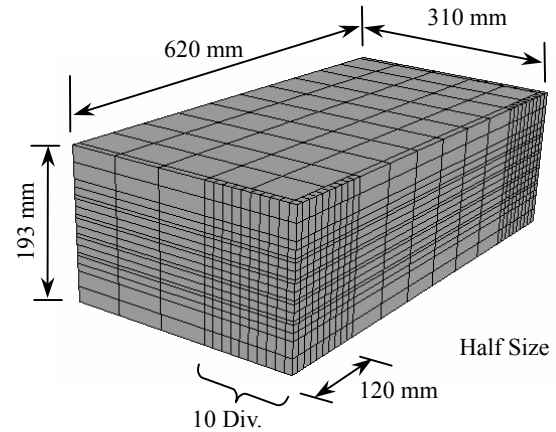


Fig. 15 FEM model of HDR bearing

Table 4 Parameters of FEM model

Bearing size [mm]	600 × 600
Thickness of rubber layer [mm]	19
Thickness of steel plate [mm]	4.5
Thickness of coating rubber [mm]	10.0
Number of rubber layers	5
Number of steel plates	4
The 1 <sup>st</sup> shape factor	7.89
Number of Nodes	10,650
Number of Elements	4,080

oxidation test. The symbols  $t_r$  and  $t$  are the real time and test time, respectively.

Since the rubber surface contacts with the air, the surface is thought completely oxidized. Therefore, the time-dependency of the properties at the surface are used to determine the activation energy, for example, the data in Fig.4(a) and Fig.4(c). The principle of time/temperature superposition by shifting the raw data to a selected reference temperature  $T_{ref}$  is employed<sup>19)</sup>. This principle is shown in Fig.14. The reference temperature is chosen as 60°C so that the curve at 60°C is the master curve. The shift factors  $a_T$  are chosen to give the best superposition of the data. If the data adhere to an Arrhenius relation, the set of the shift factors  $a_T$  will be related to the Arrhenius activation energy  $E_a$  by the following expression:

$$a_T = \exp \frac{E_a}{R} \left( \frac{1}{T_{ref}} - \frac{1}{T} \right) \quad (12)$$

The activation energy is calculated and listed in Table 3. The average value of  $E_a$  is about  $9.04 \times 10^4$  [J/mol]. Then using the Arrhenius methodology,

the property variations of HDR under any service condition may be predicted based on the accelerated thermal oxidation test results.

#### 4. PERFORMANCE PREDICTION OF AGED HDR BRIDGE BEARING

##### (1) FEM modeling and analytical conditions

Using the constitutive model of HDR materials proposed by Yoshida et al.<sup>5)</sup>, HDR bridge bearings are modeled with a three-dimensional finite elements methodology (FEM)<sup>6), 13)</sup>, as shown in Fig.15. The basic information of the FEM model is presented in

**Table 4.** The coating rubber is 10mm, which is manufactured together with the main body during the molding process. Thus, the coating rubber also contributes to the shear force. The critical depth is calculated from the surface of the coating rubber.

Firstly the deterioration prediction model gives the property profiles of aged HDR bridge bearings. Then, the parameters of the constitutive model are determined by the predicted properties using the Genetic Algorithm (GA). These parameters are used to define the HDR elements at the corresponding position in the FEM model<sup>20)</sup>. Since it was estimated that the change in material properties between the surface and the critical depth would be more outstanding than that in other regions, this region is meshed finely. In Japan, the yearly average temperature varies from 5.4°C to 24°C, and the maximum critical depth is nearly 120mm according to Eq.(1). Therefore, the periphery with a thickness of 120mm is finely meshed.

It is known if the model is meshed more finely, the result will be more accurate. However, the time required for computing will be much longer. In order to get enough precise resolution within reasonable time, the influence of the mesh size is investigated, as shown in Fig.16. The outer region is divided into 5, 10 and 20 layers. It can be seen that the discrepancy between 10 and 20 dividing is only about 1%. Therefore, 10 dividing of the outer region are thought to be able to yield good accuracy.

In order to get the shear stiffness of HDR bridge bearing, the FEM model is analyzed in simulation following the conditions shown in Fig.17. The loading conditions conform to the *Manual of Highway Bridge Bearing* (JRA)<sup>21)</sup>. A constant vertical force is loaded to the upper plane of the bearing while keeping the upper and lower planes horizontal. The nodal displacements are constrained to  $\pm 166.3\text{mm}$ , which corresponds to  $\pm 175\%$  of shear strain. Two cycles of sine wave are inputted at 0.5Hz.

Considering the yearly average temperature in Japan and the common bridge lifespan, the following cases are analyzed. The temperatures are assumed to be 5°C, 10°C, 15°C, 20°C and 25°C. The deterioration time considered is from 0 year to 100 years with an interval of 20 years. Including the case in the initial state, totally there are totally 26 deterioration cases analyzed.

## (2) FEM analysis results

From the hysteretic loops obtained from FEM analysis, the equivalent horizontal stiffness and the equivalent hysteretic damping ratio can be obtained<sup>22)</sup>. The influences of time and temperature are investigated.

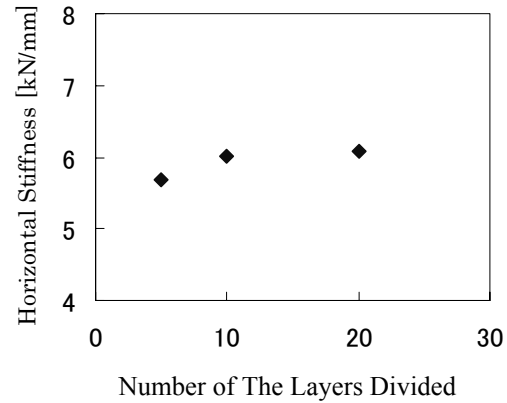


Fig. 16 Influence of mesh size

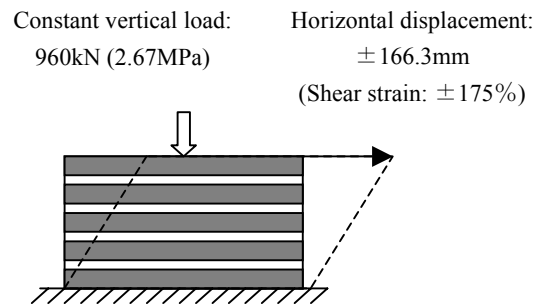


Fig. 17 Loading condition of FEM analysis

Fig.18 shows the time-dependency of the equivalent horizontal stiffness and the equivalent damping ratio of a 600 mm square HDR bridge bearing. The values are normalized by taking the initial properties as 1.0. In Fig.18(a), generally the equivalent horizontal stiffness increases over the time, and it increases much faster during the earliest stage of application. After that, the increasing speed slows down. After 100 years, the equivalent horizontal stiffness increases more than 20% at 25°C. However, at 5°C and 10°C, it only increases by about 10%. In this figure, the irregularity of the tendency is the result of the errors during the definition of parameters in the constitutive model, which accumulated and behaved themselves in the FEM results. Moreover, in this study only the uniaxial test is performed, it is difficult to precisely predict the equivalent damping ratio for hyperelastic HDR material, but the variation tendency can be at least obtained. From Fig.18(b), it is found the equivalent damping ratios show a small increment soon after the HDR bearing is applied, then decrease over the time. After 100 years the equivalent damping ratio is not estimated to change much, and remains within the range of  $\pm 5\%$ .

Fig.19 shows the temperature-dependency of the equivalent horizontal stiffness and the equivalent damping ratio. It is clear that the equivalent horizontal stiffness increases more greatly at a higher

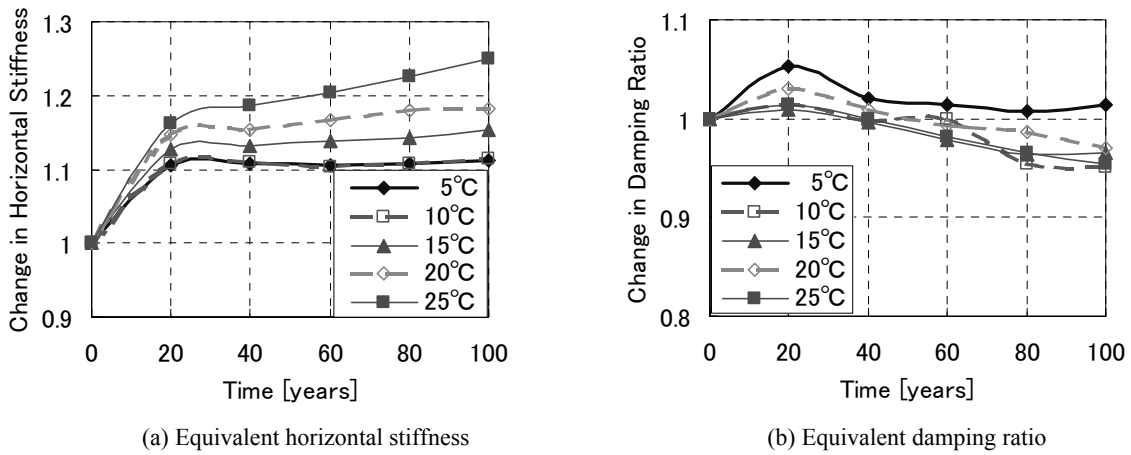


Fig. 18 Time-dependency of the performance of HDR bridge bearing (600×600 mm)

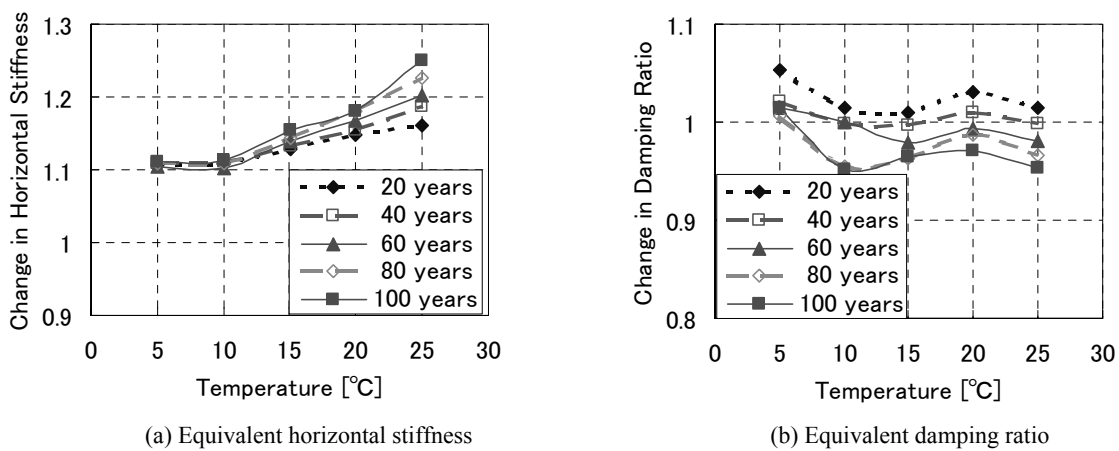


Fig. 19 Temperature-dependency of the performance of HDR bridge bearing (600×600 mm)

temperature. However, the effect of temperature is small when below 10°C. After 60 years, the increase of the equivalent horizontal stiffness at 25°C is estimated to be twice as high as that at 5°C or 10°C. On the other hand, there seems no apparent correlation between the equivalent damping ratio and the temperature, and the variations among different analyzed temperatures are very small and remains within 5%.

It can be concluded that the equivalent horizontal stiffness increases rapidly during the earliest service stage until the reaction due to the temperature reaches the equilibrium state, and then the increase speed slows down. In the second stage it increases faster at higher temperatures. After 100 years the equivalent horizontal stiffness of a 600 mm square HDR bridge bearing is estimated to increase by about 10~25%. As to the equivalent damping ratio, it declines slowly after a small increment during the earliest stage. After 100 years it is estimated to change within ±5% and shows no relations with temperature.

Following the aforementioned procedure, the property profiles of a HDR bearing with any size can be estimated using the deterioration prediction

model, and the performance can be obtained through the similar FEM analysis. Since in a larger HDR bearing, the proportion of the outer region, where the property changes more greatly, to the whole area is less, the equivalent horizontal stiffness will change less than a smaller HDR bearing. However, because the temperature affects the whole HDR bearing, the material properties change evenly in the earliest stage before the aging due to the oxidation behaving itself, and the varied value is only related to the temperature. Therefore, the initial variation of the equivalent horizontal stiffness does not make any difference for any size at a certain temperature.

### 5. DESIGN PROCEDURE OF HDR BRIDGE BEARING CONSIDERING LONG-TERM PERFORMANCE

According to the current design manual of highway bridge bearings<sup>21), 22)</sup>, the deterioration of rubber bridge bearing is not considered in the design. From the analysis results mentioned in the previous sections, it is found by simulation that for a 600 mm

square HDR bridge bearings, the equivalent horizontal stiffness increases by about 10~25%, and the equivalent damping ratio changes about  $\pm 5\%$  after 100 years, as shown in Fig.18. The performance variation rates are different due to the local temperature. In this research, a modified design procedure of the HDR bridge bearing is proposed to take its long-term performance into consideration, as shown in Fig.20.

#### Step 1: Design of HDR bridge bearing

Based on the basic design concepts such as bridge loads, shape, ground type, importance, and bearing type, etc., the HDR bridge bearing can be designed referring to the design manual. However, it should be noted that temperature causes an increment of the equivalent horizontal stiffness in a relatively short time. Therefore, it is suggested when designing the HDR bridge bearing, it is significant to take this early increment into consideration.

#### Step 2: Prediction of long-term performance

The information on the average yearly temperature is available depending on the construction site. The lifespan of the HDR bridge bearing is firstly assumed, and then using the proposed prediction model, the property profiles corresponding to the desired service life can be estimated. Subsequently, through FEM analysis, the equivalent horizontal stiffness and the equivalent damping ratio in the future are obtained.

#### Step 3: Seismic analysis

Seismic analysis on the bridge pier with the aged HDR bearing is performed using the predicted results. Usually the increase in the equivalent horizontal stiffness or the decrease of the equivalent damping ratio results in the enlargement of the pier response, thus it is necessary to check the future response of the pier. If the response exceeds the limit, for example the residual displacement limit,  $\delta_{R, \text{lim}}$ , which is specified by the required performance, the lifespan should be reassumed. However, if the lifespan is too short and even less than the beforehand determined lifespan limitation,  $t_{\text{lim}}$ , the HDR bridge bearing should be redesigned.

## 6. CONCLUSIONS

In this research, in order to clarify the long-term performance of high damping rubber bridge bearings, accelerated thermal oxidation tests are performed on HDR blocks provided by Tokai Rubber Industries, Ltd., and the deterioration characteristics are studied. Based on the test results, a deterioration prediction model is proposed. Then, the long-term performance of the HDR bridge bearing is investi-

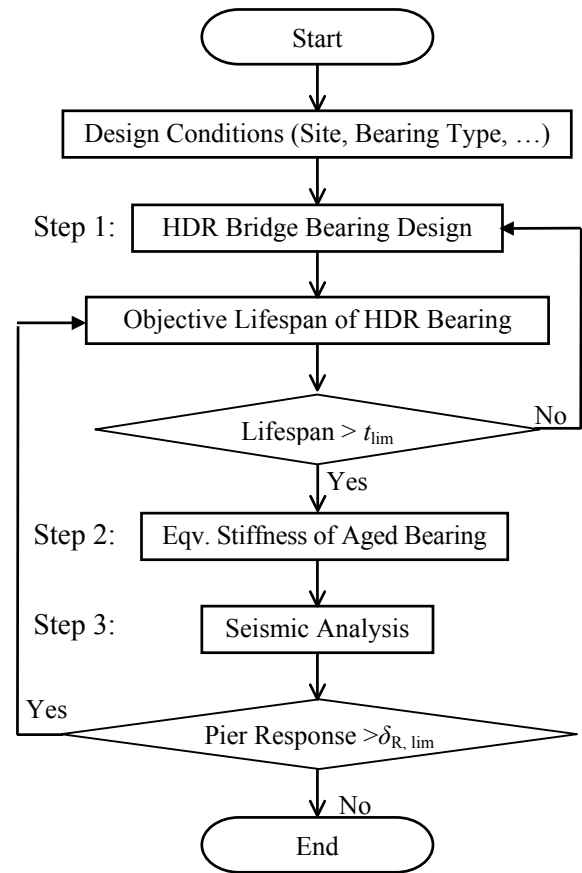


Fig. 20 Design procedure of HDR bridge bearing

gated through FEM analysis by estimating the future property profiles using the proposed deterioration prediction model. Moreover, a modified design procedure of a HDR bridge bearing is suggested, which takes the long-term performance of the bearing and the local temperature into consideration. The major findings and conclusions are summarized as follows:

- 1) In the long run, the outer surface of the HDR block is affected by the combination of temperature and oxidation. It changes most greatly and keeps changing over the time. Because of the diffusion-limited oxidation effect, the influence of oxidation becomes less and less from the surface to the critical depth. On the other hand, unlike the invariable interior region of NR, the interior region of HDR shows a rapid change soon after the bearing is installed, which is deemed as the effect of temperature.
- 2) Based on the test results, the relationships among the property change, the temperature, the position, and the nominal strain are quantified. A deterioration prediction model is proposed, which can estimate the property profiles of aged HDR bridge bearings. The simulations well agree with the test results. Combined with the



Arrhenius methodology, the deterioration characteristics under the service condition can be predicted.

- 3) Through FEM analysis of a 600 mm square HDR bridge bearing, it is found that the equivalent horizontal stiffness increases gradually after a rapid increment during the earliest service stage. After 100 years it is estimated to increase by about 10~25%. At a higher temperature, the increase speed becomes faster. However, the equivalent damping ratio decreases over the time, and seems to have no correlation with the temperature. The variation is only about only  $\pm 5\%$ .
- 4) A modified design procedure of HDR bridge bearings is proposed considering the long-term performance at the local temperature of the construction site of the bridge.

Through uniaxial tension test using the specimens taken from the sliced aged HDR blocks, the progress of the oxidation inside HDR blocks has been made clear. However, it is difficult for this test alone to well behave materials with high damping. In the future it is necessary to perform other tests such as biaxial tension test, shear test, etc. to predict the performance of HDR bearings more precisely.

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