EFFECT OF RUBBER BEARING AGEING ON SEISMIC RESPONSE OF BASE-ISOLATED STEEL BRIDGES

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ABSTRACT

This paper focuses on the aged rubber bearing's influence on the seismic response of base-isolated steel piers. The long-term properties of the natural rubber material are investigated through a series of accelerated exposure tests. Based on the test results, the aged rubber bearing is modeled considering the ageing degree in the outer regions, and the performances are predicted precisely using the finite element method. It shows that the shear stiffness of the rubber bearing increases over time. Then, the study on the seismic response of steel piers equipped with aged rubber bearings is carried out. The results prove that the ageing of the rubber bearing has large effects on the seismic response of the isolated bridges. Generally, the damage degree of the steel pier upgrades to a higher level if the shear stiffness of the bearing increases by 20%, which is crucial from the design point of view.

KEYWORDS

rubber bearing, ageing, seismic response, steel bridge, accelerated exposure test, deterioration

1. INTRODUCTION

Elastomeric bridge bearings have now been widely used in Japan for the reason that rubber is an ideal material to withstand large deformation and absorb energy because of its high elasticity, high damping and large elongation at failure. Many research projects have been carried out on the dynamic performance of rubber bearings [2] or on the seismic response of the steel piers installed with rubber bearings [6]. Also, many efforts have been made to develop more precise models reflecting the highly nonlinear characteristics of rubber materials [8]. Meanwhile, the ageing problems have also been studied for many years [1]. However, the effect of rubber ageing on the seismic response of the steel piers are seldom studied, because there are still many unknown issues relating to the long-term behaviors of rubber materials. Even in the present *Design Specifications of Highway Bridges* by Japan Road Association (JRA) [4], the long-term behavior of the rubber bearing is not considered. Without accurate predictions of the future performance of rubber bearings, the safety of the bridge against the earthquake cannot be secured. The objective of this research is to investigate the mechanical performance of aged rubber bearing and its influence on the seismic response of base-isolated bridges.

In this study, using the accelerated exposure tests, the effects of the environmental factors such as oxidation, ozone, temperature, ultraviolet, acid and humidity, etc. are examined. The property change is investigated through uniaxial tension experiment. Then the rubber bearing is modeled precisely using the constitutive model and the finite element method (FEM) considering the ageing progress in the outer regions. The mechanical properties of aged bearings are estimated. Finally, seismic analysis is carried out to evaluate the influence of rubber ageing on the seismic response of the steel piers.

2. ACCELERATED EXPOSURE TESTS

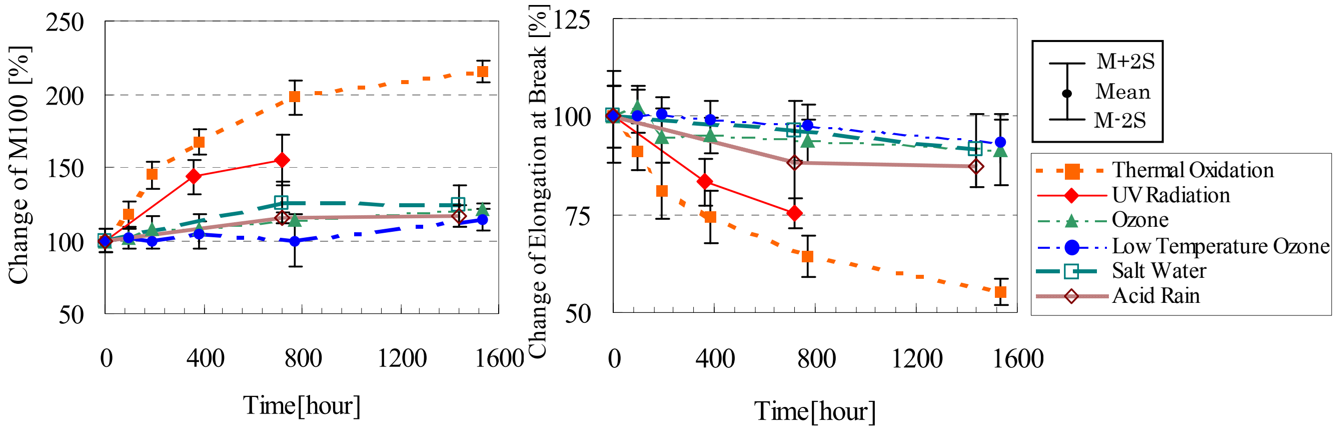
The accelerated exposure tests simulate six kinds of environmental conditions [3]. They are thermal oxidation, ozone, low temperature ozone, ultraviolet radiation, salt water and acid rain corrosion tests, as shown in Table 1. The JIS No.3 dumbbell specimens made of natural rubber (NR) with a thickness of 2mm are used. Because the bridge bearing is subjected to the compressive load of the superstructure, the brim of the rubber layer blooms outwards and is in the tensile state. In order to find out the influence of this tensile strain on the ageing process, the specimens are elongated to the strains of 0%, 20% and 40% and kept the pre-strains throughout the accelerated exposure tests. After each extraction, the mechanical properties like stresses at 25%, 50%, 100%, 200% and 300% strain, i.e. M25, M50, M100, M200 and M300, elongation at break and tensile strength are tested through uniaxial tension experiment. The test conditions and examination methods conform to the quality inspection method specified by the Japan Highway Public Corporation as well as the Japanese Industrial Standards.

It is well known that ageing usually increases the stiffness of rubbers while decreasing the elongation at break and the tensile strength. From Fig. 1 it can be seen that thermal oxidation affects the rubber properties much greater than other factors. After 1536 hours, the stiffness increases by over 100%, and the elongation at break decreases to near 50% of the original value.

TABLE 1

CONDITIONS OF ACCELERATED EXPOSURE TESTS

Degradation Factor	Test Environment	Time (hours)
Thermal Oxidation	70℃	96, 192, 384, 768, 1536, 3072, 6144
Ozone	Ozone=0.5ppm, 40℃	96, 192, 384, 768, 1536
Low Temperature Ozone	Ozone=0.5ppm, -30℃	96, 192, 384, 768, 1536
Ultraviolet (UV) Radiation	Radiation+Water spray	360, 720, 1440
Salt Water Spray	Wetting and drying cycle	360, 720, 1440
Acid Rain Spray	Wetting and drying cycle	360, 720, 1440



(a) M100 (b) Elongation at break

Figure 1: Relative change of natural rubber (NR) properties (pre-strain ε_p=40%)

In order to reveal the property variations from the surface to the interior of rubber, a thermal oxidation test is performed on natural rubber blocks. Fig. 2 shows a NR block (220×150×50) in the oven. The temperature in the oven is controlled as 60℃, 70℃, 80℃ and the duration of the test is set as 300 days. After taken out the rubber blocks are sliced into pieces with a thickness of 2mm. From these slices the JIS No.3 dumbbell specimens are made and performed tensile test, as shown in Fig. 3.

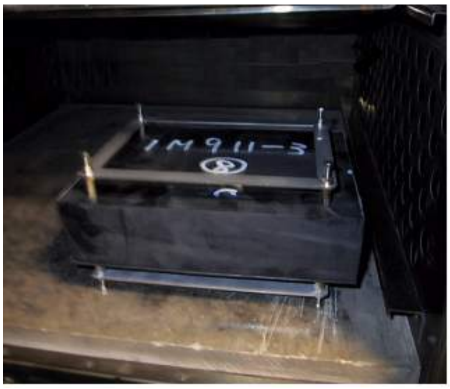


Figure 2: Rubber block in the oven

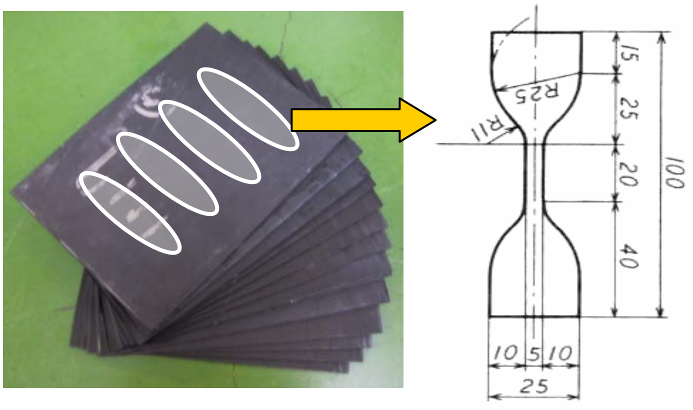


Figure 3: Rubber slice and JIS No.3 specimen

The molecule structure variations are reflected by the internal strain energy, which can be calculated by the area enclosed by the stress-strain relationship curve. Here, the internal strain energy corresponding to the strain of 100% (U100) is chosen as the representative. Figure. 4 shows the profile of U100 inside the rubber block under the test temperature of 70℃. As for NR, it can be found that the deterioration only concentrates near the surface of the rubber block. The properties of the interior region do not change at all.

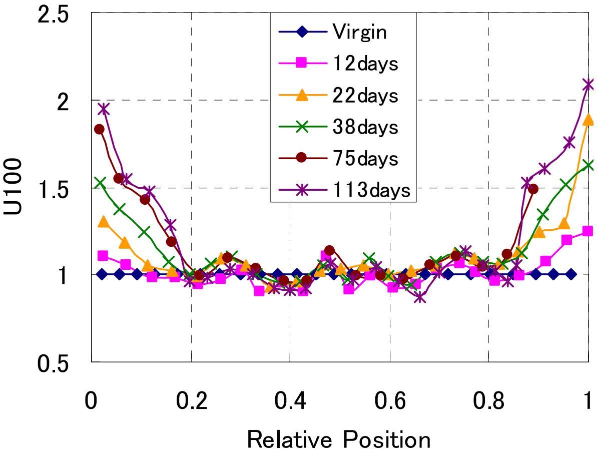


Figure 4: Property profile inside NR block

Generally, it is assumed that for rubber materials the thermal oxidation is the 1st chemical reaction. Thus, the accelerated deterioration can be converted into the real environmental conditions by using the Arrhenius formula [7].

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

where, E_a is the activation energy (=9.94×10^4J/mol for NR), R is gaseous constant (=8.314[J/mol· K]), T_r indicates the absolute temperature in the real environment, and T is the absolute temperature in the thermal oxidation test. The symbols t_r and t are the real time and test time, respectively. For example, 60 years in real environment of 25℃ corresponds to 113 days in the thermal oxidation test.

3. FEM MODELING OF THE RUBBER BEARING

Based on the results from the uniaxial tension experiments on deteriorated rubber specimens, the material characteristics can be defined by a constitutive model proposed by J. Yoshida [8]. A FEM model is built considering the relationship between the deterioration degree and the depth from the rubber surface. Parameters of the rubber bearing model are presented in Table 2.

TABLE 2

PARAMETERS OF THE FEM MODEL

Number of steel plates	Thickness of steel plate [mm]	Number of rubber layers	Thickness of rubber layer [mm]	Primary shape factor S_1	Secondary shape factor S_2
4	4.5	5	19.0	7.9	6.3

TABLE 3

PARAMETERS OF THE FEM MODEL

Evaluation Criteria	Virgin	Deteriorated
Maximum Shear Force [kN]	865	1045 (+20.8%)
Horizontal Stiffness [kN/mm]	5.20	6.29 (+20.8%)
Equivalent Damping Ratio	0.068	0.059 (-13.2%)

The FEM analysis results about the relationship between shear force and horizontal displacement are shown in Fig. 5. And Table 3 compares the related evaluation criteria. It is found that the maximum shear force and the horizontal stiffness increase by about 20.8% after 80 years in the real environmental with a mean yearly temperature of 25℃.

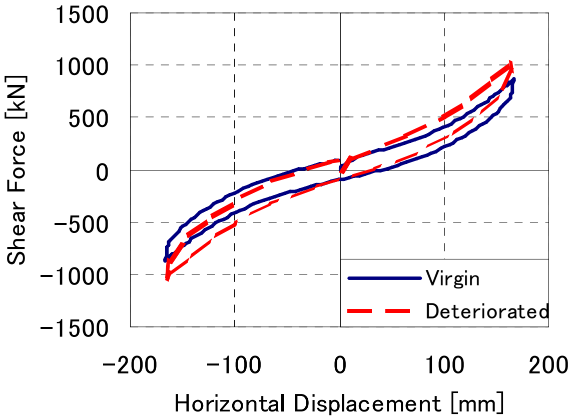


Figure 5: FEM analysis results

4. SEISMIC ANALYSIS OF BASE-ISOLATED STEEL PIERS

The current *Design Specification of Highway Bridges* of JRA suggests that dynamic analysis should be carried out to check that maximum displacement and residual displacement do not exceed structural capacity in order to secure that highway bridges can resume normal function as quickly as possible after a major earthquake. In this study, allowable maximum displacement is chosen as δ_{95}, which is the displacement value corresponding to the cyclic strength dropping to 95% of the peak cyclic strength, and it can be calculated using Eqn. 2. As to allowable residual displacement, the damage degree of steel piers is divided into five ranks based on residual displacement δ_R and the corresponding time needed for repair, as shown in Table 4 [5]. The residual displacement can be achieved from the maximum displacement δ_{max} through Eqn. 3.

$$\frac{\delta_{95}}{\delta_y} = \frac{0.0147}{\left\{\left(1+P/P_y\right)R_f\sqrt{\bar{\lambda}}\right\}^{3.5}} + 4.20 \tag{2}$$

$$\frac{\delta_R}{h} = \frac{1}{200}\left(\frac{\delta_{\max}}{\delta_y}\right)^{0.75} - \frac{3}{400} \tag{3}$$

$$R_f = \frac{b}{t}\sqrt{\frac{\sigma_y}{E}\frac{12(1-\nu^2)}{4\pi^2 n^2}}\ , \quad \bar{\lambda} = \frac{2h}{r}\frac{1}{\pi}\sqrt{\frac{\sigma_y}{E}} \tag{4}$$

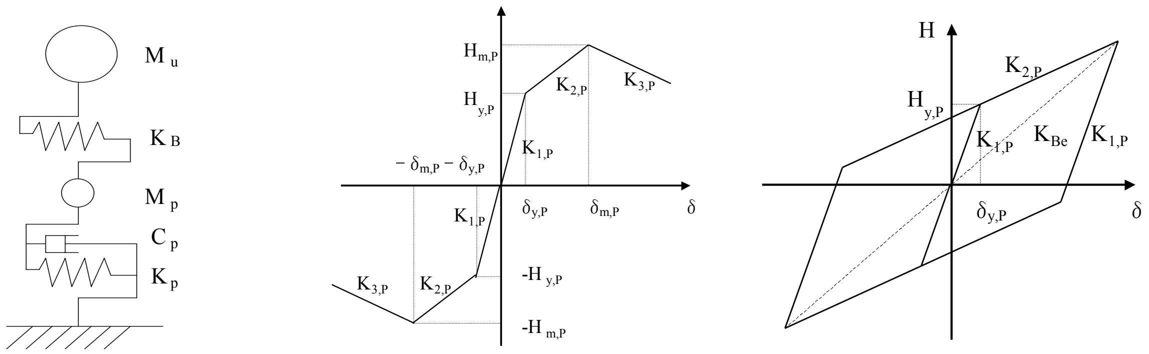
where, δ_y=yield displacement, R_f=width-thickness ratio parameter, $\bar{\lambda}$=slenderness ratio parameter, P/P_y=axial load ratio, E=Young's modulus (205GPa), υ=Poisson's ratio (0.3), σ_y=yield stress (315MPa), t=thickness (20mm), b=width of flange, n=number of sub-panels, r=radius of gyration of cross-section and h=pier height.

TABLE 4

RANKING OF DAMAGE DEGREE

Rank	Residual Displacement	Damage Degree
A_s (collapse)	$h/100 \leq \delta_R$	Collapsed
A (Large Damage)	$h/150 \leq \delta_R < h/100$	Not collapsed, but have lost function. More than two months are required for restoring.
B (Medium Damage)	$h/300 \leq \delta_R < h/150$	Only emergency vehicles can run. Two weeks~ two months are required for restoring.
C (Small Damage)	$h/1000 \leq \delta_R < h/300$	Several days are required for restoring, or ordinary vehicles can pass while being repaired.
D (No Damage)	$\delta_R < h/1000$	Almost no damage.

Note: δ_R — residual displacement; h — pier height.

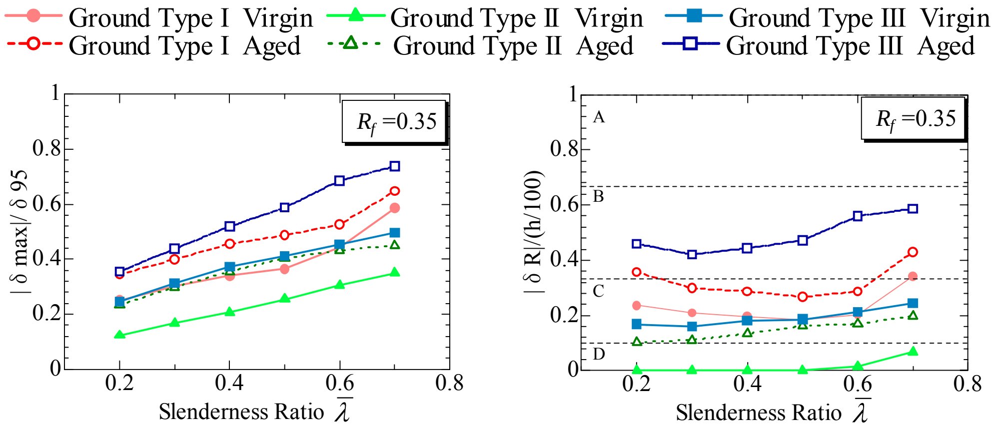


(a) Base-isolated pier model (b) 2-parameter model of the pier (c) Bilinear model of rubber bearing

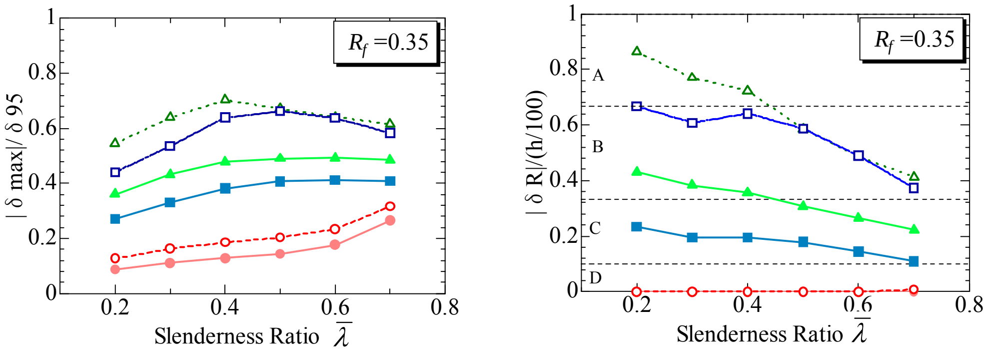
Figure 6: Analysis model of the pier with base-isolated rubber bearing

In this research, isolated thin-walled stiffened box piers are studied and a two-degree-freedom model is adopted as shown in Fig. 6(a). The mass of the superstructure is M_u and the mass on the top of the pier M_p is taken as 30% of the mass of the whole pier. Fig. 6(b) and Fig. 6(c) illustrate the resilience models of the steel pier and the rubber bearing, respectively. The linear acceleration method is used to resolve the elastoplastic seismic response problem. According to the previous research [6], the damping factor of the steel pier is ξ_P=0.05 and the damping factor of the rubber bearing is ignored. The time interval is set as Δt=0.001s. For dynamic analysis the JRA code prescribes three Type Ⅰ acceleraograms and three Type Ⅱ accelerograms for each ground type (Ⅰ , Ⅱ and Ⅲ), and suggests the average responses of the three accelerograms in each group be taken as the final analysis results. Steel piers with R_f=0.35 and R_f=0.45, $\overline{\lambda}$ =0.20, 0.30, 0.40, 0.50, 0.60 and 0.70 are designed according to Eqn. 4. For each pier, rubber bearing is designed with the target natural period T=2.0s. It is assumed that the maximum shear force of the deteriorated rubber bearing increases by about 20% while the most agreeable yielding load $H_{d,B}$ not change. So the equivalent stiffness K_{Be} will also increase by 20% and the primary stiffness $K_{1,B}$ and the secondary stiffness $K_{2,B}$ will change correspondingly.

The seismic responses of the piers with R_f=0.35 are shown in Fig. 7. It is found that, compared with the virgin state, in most cases the maximum and the residual displacements increase greatly after deterioration. Except for the case of Ground Type I the damage degree will upgrade to a more dangerous rank when the horizontal stiffness of the rubber bearing increases by 20% due to deterioration. This is because when the horizontal stiffness of the rubber bearing increases, the natural period of the base-isolated pier will decrease, resulting in an increase of the energy absorbed by the pier. Therefore, the seismic response of the steel pier will increase. This phenomenon should be paid attention to during the design stage.



(a) Level 2, Type I, R_f=0.35



(b) Level 2, Type II, R_f=0.35

Figure 7: Response of base-isolated thin-walled stiffened box piers

5. CONCLUSIONS

The long-term characteristics of natural rubber are clarified through accelerated exposure tests. Based on the test results, a FEM model is made, which predicts an increase of 20.8% of shear stiffness after 80 years in 25℃. It is discovered that the deterioration of the rubber bearing can affect the seismic response of the steel pier greatly, with a damage degree upgrade for Ground Type II and III.

References

1. Celia M., Wise J., Ottesen D.K., Gillen K.T. and Clough R.L. (2000). Correlation of chemical and mechanical property changes during oxidative degradation of neoprene. *Polymer Degradation and Stability*. Vol.68, 171-184.
2. Derham C.J., Thomas A.G. and Kelly J.M. (1978). A rubber bearing system for seismic protection of structures. *Proceedings*, Conference on Engineering Design for Earthquake Environments, The Institution of Mechanical Engineers, United Kingdom.
3. Itoh Y., Yazawa A., Kitagawa T., Kainuma S., Yamamoto Y., and Kutsuna Y. (2002). Study on environmental durability of rubber bearing for bridges. *IABSE Symposium Melbourne*, 268-269.
4. Japan Road Association (2002). Design specifications of highway bridges V.
5. JSCE (1996). Interim guideline and new technology for seismic design of steel highway bridges.
6. Kobayashi M., Usami T. and Kasai A. (1999). Seismic performance evaluation of steel bridge piers with and without seismic isolator. *J. Struct. Mech. And Earth. Eng. JSCE*. No.619/I-47, 177-192. (in Japanese).
7. Satoh K., Itoh Y., Yazawa A. and Yamamoto Y. (2004). Study on heat deterioration characteristics of rubber bearing for bridges. *IABSE Symposium Shanghai*, 412-413.
8. Yoshida J., Abe M. and Fujino Y. (2002). Constitutive model of high damping rubber materials. *J. Struct. Mech. And Earth. Eng. JSCE*. No.710/I-60, 209-224. (in Japanese).