# RECENT RESEARCHES ON PROPERTIES OF LAMINATED ELASTOMERIC RUBBER BEARINGS UNDER CYCLIC LOADING

Jun-ichi Hoshikuma[1], Masatsugu Shinohara[2] and Takao Okada[3]


## Abstract

Laminated elastomeric rubber bearings designed with a large-scale earthquake have been widely employed in bridges since the 1995 Kobe Earthquake. However, some of such laminated elastomeric rubber bearings suffered severe damage including rupture or deep cracking into rubber due to the 2011 Great East Japan Earthquake. The seismic design specifications for highway bridges were revised in 2012 based on lessons learned from the 2011 Great East Japan Earthquake. Some additional technical requirements for the laminated elastomeric rubber bearings have been described in the specifications, so that those bearings could work adequately under a cyclic loading. This paper introduces recent PWRI research projects on verification of the mechanical properties of the laminated elastomeric rubber bearings and the effect of the seismic damage on the mechanical and material properties. More than 100 laminated rubber bearings manufactured recently in Japan were tested under the cyclic loading to examine the capacity of the shear strain, the stiffness and the property of damping. Furthermore, some laminated rubber bearings damaged with crack due to the earthquake and removed from a bridge were also tested, so that the effect of the cracking on the mechanical properties of the bearings.


## Introduction

The 2011 Great East Japan earthquake caused the catastrophic damage by the huge tsunami and the strong ground motion in the Tohoku and Kanto regions. Many highway bridges were washed away in the coastal areas due to the tsunami effect, while the structural damage caused by the strong ground motion was relatively less significant (NILIM and PWRI, 2011). This is because the seismic retrofit projects have been performed for highway bridges and the retrofitted bridges performed well under the strong ground excitation. Almost of the damaged bridges were unretrofitted ones designed in accordance with old specifications. (Hoshikuma, 2014)

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[1] Chief Researcher, Center for Advanced Engineering Structural Assessment and Research, PWRI

[2] Senior Researcher, Center for Advanced Engineering Structural Assessment and Research, PWRI

[3] Senior Researcher, Center for Advanced Engineering Structural Assessment and Research, PWRI

**Photo 1** Rupture of Laminated Elastomeric Rubber Bearing

**Photo 2** Crack in Lead Rubber Bearing

In terms of damage of bearings in bridges caused by the 2011 earthquake, unretrofitted steel bearings designed with the pre-1980 design specifications suffered severe damage, which was often observed in the past earthquakes. Failure of side stopper of fixed bearings, failure of side blocks, fracture of set bolts were observed after the event. On the other hand, less significant damage was observed in steel bearings designed with the post-1995 design specifications.

Laminated elastomeric rubber bearings have been widely employed since the 1995 Kobe Earthquake, and severe damage have never been observed before the 2011 Great East Japan Earthquake. However, some of laminated elastomeric rubber bearings, including those designed with the post-1995 design specifications, suffered rupture or deep cracking into rubber due to the 2011 earthquake as shown in Photos 1 and 2 (J. Hoshikuma, 2011). Details and the mechanism of the damage to the laminated elastomeric rubber bearings are discussed in references listed in the end of this paper (T. Hirose, 2012, K. Kawashima, 2013). Based on the discussion, possible contributing factors of the damage are supposed to be: 1) effect of the seismic response of complicate structural girders; 2) effect of creep and shrinkage of PC girder; 3) effect of unexpected dispersion; and 4) effect of an aging change of the mechanical properties.

The seismic design specifications for highway bridges were revised in 2012 based on lessons learned from the 2011 Great East Japan Earthquake (J. Sakai, 2013). The revised specifications have required for bearing supports that 1) the failure mode of the bearing supports under the seismic loading should be clarified and a limit state should be determined to be safety and functionable based on the failure mode; 2) the seismic behavior of the bearing supports should be stable through a service time of bridges; and 3) the bearing supports should be replaceable structure for the maintenance. Therefore, it is important to clarify the test protocol for the bearing supports and the evaluation method of the limit state based on the test.

Furthermore, the effect of the damage due to the seismic loading or the aging deterioration on the mechanical properties of the laminated elastomeric rubber bearings should be studied, because the significant damage was observed in the laminated elastomeric rubber bearings as described above and also this issue is important in terms of the bridge maintenance and management.

With these backgrounds, PWRI have initiated two collaboration programs on the laminated elastomeric rubber bearings after the 2011 Great East Japan Earthquake. One is collaborated with 9 manufacturers of the laminated elastomeric rubber bearings for bridges. More than 100 laminated elastomeric rubber bearings were tested in the program and test data were analyzed for discussion of the mechanical properties at the time of producing. The other program is collaborated with 4 expressway companies. Effect of the damage to the laminated elastomeric rubber bearings caused by an earthquake or an aging deterioration has been studied based on some loading tests for uninstalled bearings from bridges. This paper introduces some research findings from the two collaboration programs for the laminated elastomeric rubber bearings.

## Property of Ultimate Shear Strain of Laminated Elastomeric Rubber Bearings

The mechanical properties of the laminated elastomeric rubber bearings under the cyclic loading were examined through a series of shear loading tests for various specimens. In the test program, 48 laminated elastomeric natural rubber bearing (RB), 34 laminated lead rubber bearings (LRB) and 30 laminated high dumping rubber bearings (HDR) were produced by 9 Japanese manufacturers. A range of dimensions and details of the test specimens are listed in Table 1, where the primary shape factor $S_1$ and the secondary shape factor $S_2$ are defined as follows.

$$S_1 = \frac{A_e}{2(a+b)} \qquad S_2 = \frac{\min(a,b)}{\sum t_e}$$

where,

$A_e$ : area of rubber

$a$ : dimension in the longitudinal direction

$b$ : dimension in the transverse direction

$\sum t_e$ : total thickness of rubber layers

**Table 1** Dimensions and properties of test specimen

| Speciation | Number of specimens | Plane dimension | | Rubber layer | | | Lead plug shape | | | | Shape factor | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Longitudinal | Lateral | Layer thickness | Number of layers | Total layer thickness | Lead diameter | Number of Lead plug | Area | Area ratio | Primary | Secondary |
| | | mm | mm | mm | | mm | mm | | Ap | κ(=Ap/Ae) | | |
| RB | 48 | 240～600 | 240～600 | 7～18 | 3～10 | 30～100 | — | — | — | — | 5.455～8.571 | 2.400～8.000 |
| LRB | 34 | 240～1000 | 240～1000 | 7～39 | 4～10 | 35～156 | 34.5～144 | 1～4 | 3739～65144 | 0.067～0.072 | 5.100～10.390 | 3.429～7.059 |
| HDR | 30 | 240～1000 | 240～1000 | 7～32 | 3～10 | 35～203 | — | — | — | — | 5.455～8.621 | 3.125～8.333 |

**Table 2** Series of Loading Sequence of Experimental Verification

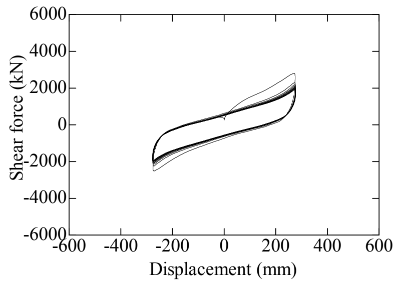
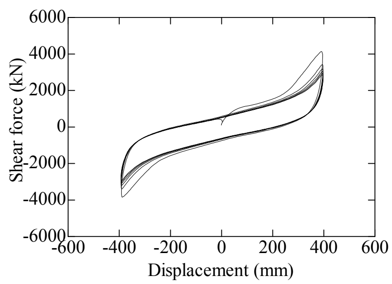
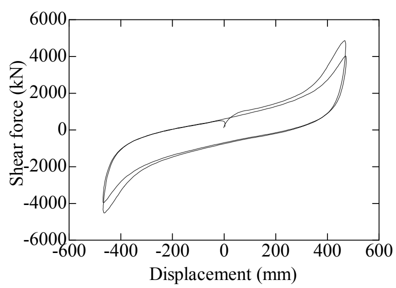
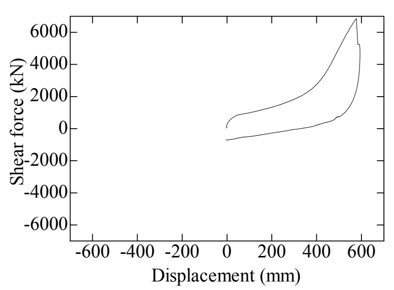
| STEP | Displacement Excursion | Number of cycle | Purpose |
|---|---|---|---|
| 1. | Effective design displacement (0.7×δa) | 11 | Quality control |
| 2. | Design limited displacement (δa) | 6 | Verification of stable behavior |
| 3. | Ultimate limited displacement (1.2×δa) | 2 | Verification of behavior at the ultimate limit state |
| 4. | Rupture displacement | Monotonic loading | Verification of safety margin for failure |

These test specimens were cyclically loaded in the lateral direction with the shear strain of 175%, 250%, 300% and then monotonically loaded up to the shear strain when test specimens finally failed. A loading protocol is summarized as shown in Table 2, where a number of cycles in each loading step are determined based on analytical results of the time-history seismic response developed in the rubber bearings (Shinohara et al., 2013). A constant vertical stress of 6.0 ($N/mm^2$) was also applied to the test specimens during the tests.

Table 3 exemplifies a hysteresis loop of the relation between the shear force and the lateral displacement given to a test specimen of LRB and photographs taken at peak shear strain in each loading step. The final failure of this test specimen was caused by rupture of rubber at the shear strain of 370%. It is, however, noted for a few other specimens that the rupture was observed around an adhesive section between the inside steel plate and the rubber.

The ultimate shear strain is a key parameter to determine the design limit for the rubber bearings, because it varies widely from 160% to 450%. Therefore, based on test results, the properties of the ultimate shear strain are discussed here. Fig. 1 shows an effect of the size of the specimens on the ultimate shear strain. It can be mentioned from Fig. 1 that a significant trend is not observed in the relation between the size and the ultimate shear strain. A relation between the secondary shape factor of the rubber bearings and the ultimate shear strain is shown in Fig. 2, where it can be found that the ultimate shear strain is decreased as the secondary shape factor becomes small. Because the secondary shape factor of the rubber bearings for bridges is recommended to be larger than 4.0, the ultimate shear strain can be evaluated as around 300%. However it should be remarked that one specimen with the secondary shape facto of larger than 4.0 exhibited the ultimate shear strain of less than 300%. More studies will be needed for the contributing factors of the ultimate shear strain of the rubber bearings.

**Table 3** Shear Force Versus Displacement Relation at Each Displacement

<table>
<tr><th>Loading Step</th><th>Force versus displacement relation</th><th>Photo at peak displacement</th></tr>
<tr><td>Step 1<br><br>Effective design displacement 175%<br>11times</td><td>
</td><td></td></tr>
<tr><td>Step 2<br><br>Design limit displacement 250%<br>6times</td><td>
</td><td></td></tr>
<tr><td>Step 3<br><br>Ultimate limit displacement 300%<br>2times</td><td>
</td><td></td></tr>
<tr><td>Step 4<br><br>Rupture Displacement 370%<br>Monotonic loading</td><td>
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</table>

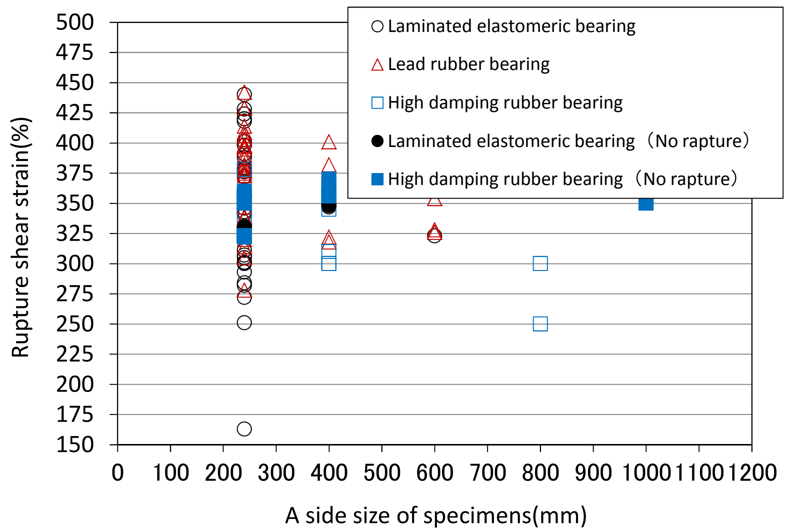



**Fig.1** Relation between rupture shear strain and a side size

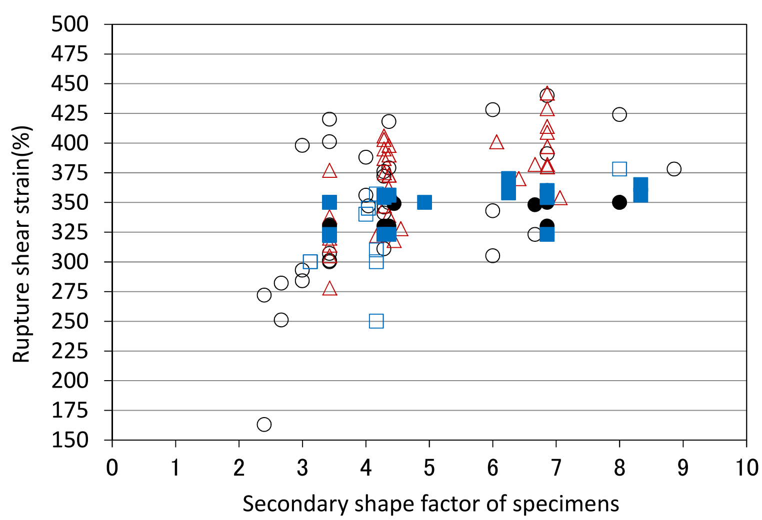



**Fig.2** Relation between rupture shear strain and secondary shape factor

## Effect of Crack in Rubber on Ultimate Shear Strain

Asahi viaduct is a base-isolated bridge with 18 spans of the PC box girder. The bridge is located at the eastern coast area in Hitachi City, Ibaraki, and designed in accordance with the 1996 seismic design specifications. Lead rubber bearings are employed for isolators in the bridge. Significant cracks were developed at the isolators due to the 2011 Great East Japan Earthquake as shown in Fig. 3. These isolators damaged with cracks were replaced with new ones after the earthquake. Since PWRI was provided the isolators removed from Asahi viaduct by the administrator of the bridge, 3 isolators

(As1-G2, P1-G1, P8-G2) were tested to examine the ultimate shear strain, and one isolator (As1-G1) was broken up to investigate the crack propagation inside the rubber and the material properties of rubber.

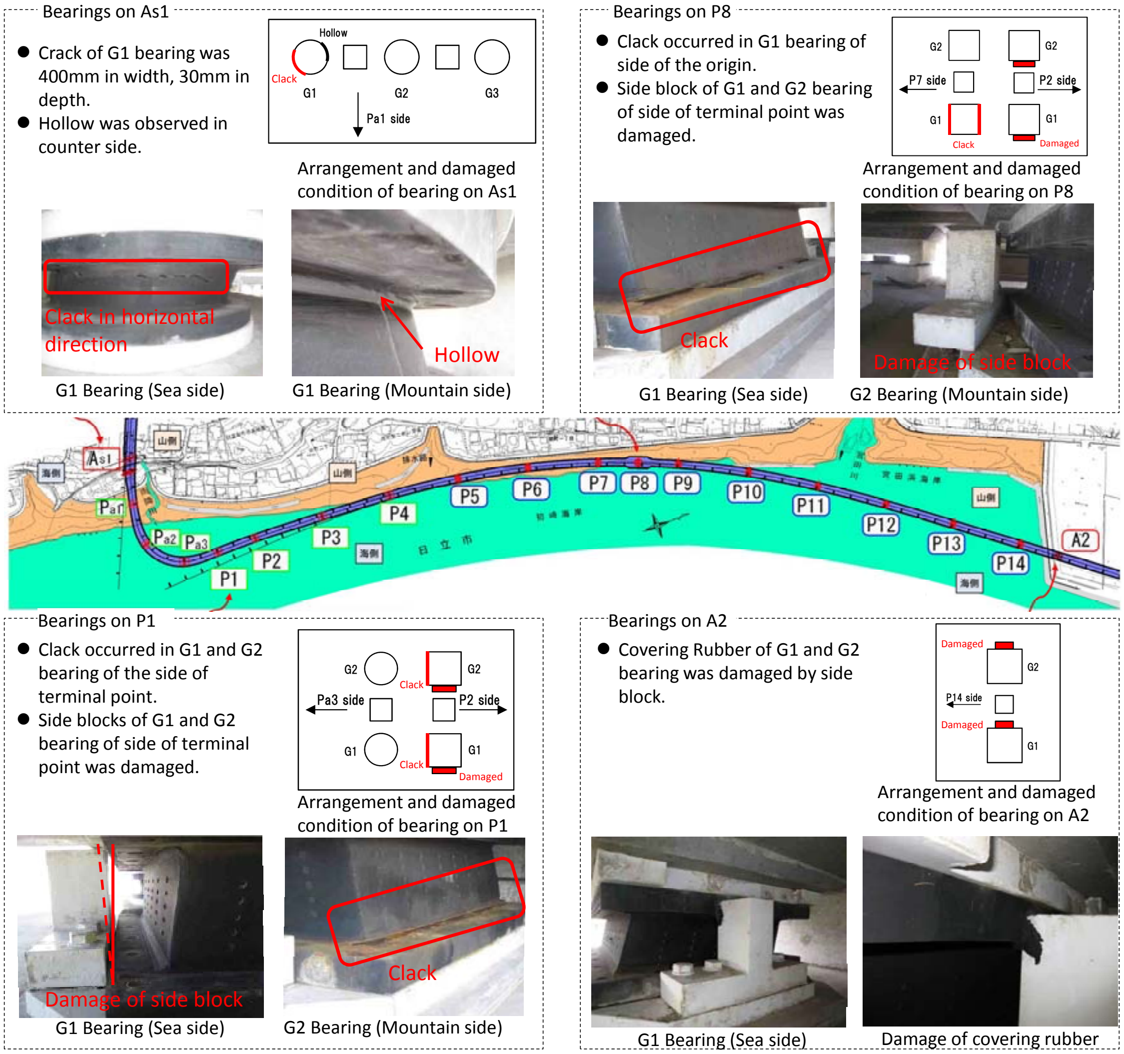
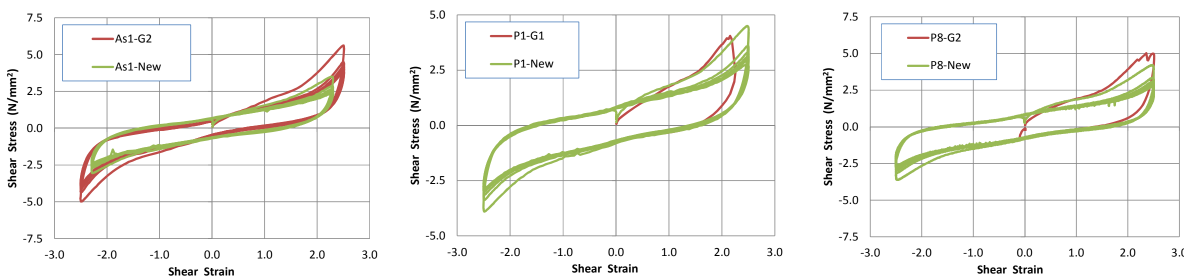



**Fig.3** Damage of Lead Rubber Bearings in Asahi viaduct

The cyclic shear loading tests for the isolators of As1-G2, P1-G1 and P8-G2 were conducted to evaluate the effect of the crack in the rubber on the mechanical properties for the shear force. The bearings of As1-G2 and P8-G2 were undamaged due to the earthquake, while a bearing of p1-G1 was damaged with the visible crack. Replica bearings of those isolators were also manufactured and tested for a comparison. Fig. 4 shows hysteresis loops of the relation between shear stress and shear strain in the loading step of 250% (design limit of shear strain for a large earthquake). It should be noted that the bearing of

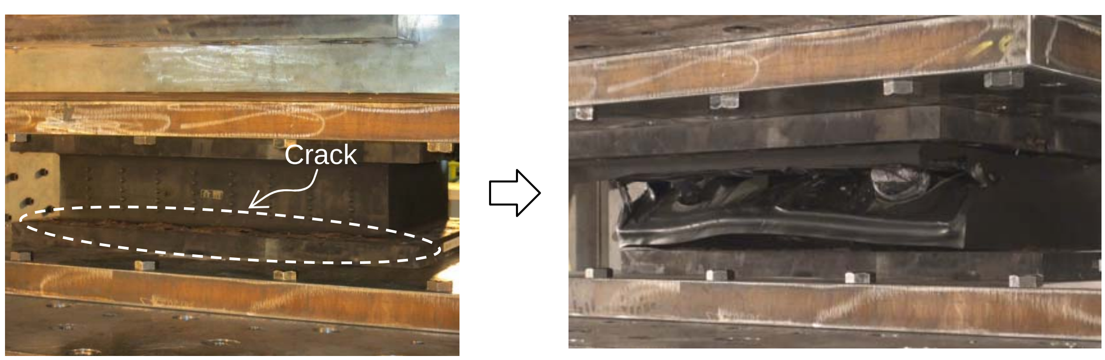
P1-G1 exhibited rupture of the rubber at the shear strain of less that 250% as shown in Photo 3, while the replica of P1-G1 behaved stably in the cyclic loading step of 250%. On the other hand, the bearings of As1-G2 and P8-G2 without the crack exhibited similar hysteresis loops with their replicas up to the cyclic loading step of 250%, which indicated that the crack developed in the rubber due to an earthquake might affect the mechanical properties of the rubber bearings.

Photo 4 shows a cut section of the inside of an isolator As1-G1 which was cracked due to the earthquake. This isolator was broken up without conducting the cyclic shear loading test as described above. It is interestingly noted that the crack developed toward the inside steel plate with a zigzag shape and the inside steel plate was unbounded with rubber. It is also found that the inside steel plates deformed near the set-up hole employed in the manufacturing process, however the mechanism of the deformation of the inside steel plate is unclear.



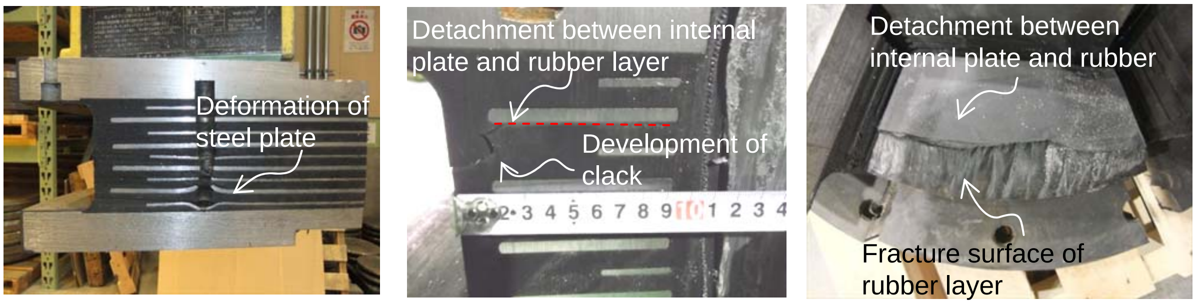

(a)As1-G2 (b)P1-G1 (c)P8-G2

**Fig.4** Relation between Shear Stress and Shear Strain at Design Limit Displacement




(a) Before loading (b) Condition when bearing ruptured

**Photo 3** Shear Loading at Design Limit Displacement (P1-G1)




(a) Deformation of Inside Steel Plate

(b) Crack toward Inside Steel Plate

(c) Fracture Surface of Rubber Layer

**Photo 4** Cut Section of As1-G1 Bearing

## Concluding Remarks

This paper introduces recent PWRI research projects on the mechanical properties of the laminated elastomeric rubber bearings and the effect of the seismic damage on the mechanical properties. More than 100 laminated rubber bearings manufactured recently in Japan were tested under the cyclic loading. It is found that the ultimate shear strain varies widely from 160% to 450% with dependence on the secondary shape factor of the rubber bearings. An effect of rupture mode in the rubber bearing on the ultimate shear strain should be also studied, to improve the reliability of the design shear strain limit.

Furthermore, some laminated rubber bearings damaged with crack due to the earthquake were also tested for the cyclic shear force. It should be remarked that the rubber bearings with significant crack caused by the earthquake affect the mechanical properties for the shear force.

PWRI has also researched on the aging effect of the rubber bearings on the mechanical properties with expressway companies. The rubber bearings will be cracked due to not only the seismic effect but the aging deterioration such as the ozone attack. A mechanism of the aging deterioration and the effect of it on the seismic behavior of the bridges are now studied based on various experimental works for used rubber bearings with the aging deterioration.

## Acknowledgments

The mechanical properties of the laminated elastomeric rubber bearings under the cyclic loading were tested in collaboration with 9 manufacturers, namely, Oiles Corporation, Kawakin Core-Tech Co., Ltd., Tokai Rubber Industries, Ltd., Tokyo Fabric Industry Co., Ltd, Nitta Corporation, Nippon Chuzo Co., Ltd., BBM Co., ltd., Bridgestone

Corporation and The Yokohama Rubber Co., LTD. The effect of crack in the rubber caused by the earthquake on the ultimate shear strain was discussed in collaboration with 4 expressway companies, namely, Nippon Expressway Research Institute Co., Ltd., Metropolitan Expressway Co., Ltd., Hanshin Expressway Co., Ltd. and Nagoya Expressway Public Corporation.

Special appreciation is extended to Hitachi River and National highway Office, Kanto Regional Development Bureau, MLIT for providing isolators employed in Asahi viaduct.

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