6th International Conference on Advances in Experimental Structural Engineering
11th International Workshop on Advanced Smart Materials and Smart Structures Technology
August 1-2, 2015, University of Illinois, Urbana-Champaign, United States

Experimental Evaluation of Seismic Residual Performance for Deteriorated Rubber Bearings in Highway Bridges

Kunihiro HAYASHI [1], Yukio ADACHI [2], Naota SAKAMOTO [3], Akira IGARASHI [4] and Ji DANG [5]

1 *Chief Engineer, Osaka Business and Maintenance Bureau, Hanshin Expressway Co., Ltd., Osaka, Japan.*
E-mail: kunihiro-hayashi@hanshin-exp.co.jp
2 *Manager, Maintenance and Traffic Management Dept., Hanshin Expressway Co., Ltd., Osaka, Japan.*
E-mail: yukio-adachi@hanshin-exp.co.jp
3 *Chief Engineer, Engineering Dept., Hanshin Expressway Engineering Co., Ltd., Osaka, Japan.*
E-mail: naota-sakamoto@hex-eng.co.jp
4 *Professor, Disaster Prevention Research Institute, Kyoto University, Kyoto, Japan.*
E-mail: akira.igarashi.7m@kyoto-u.ac.jp
5 *Assistant Professor, Dept. of Civil and Environmental Engineering, Saitama University, Saitama, Japan.*
E-mail: dangji@mail.saitama-u.ac.jp

ABSTRACT

Aging deterioration of rubber bearings (elastomeric bearings) in highway bridges is an issue of great significance for bridge management, in view of the influence to the seismic performance and functionality during regular condition of the bridges. In Japan, the use of rubber bearings in the construction of bridges started in early 1980's, and also an extensive number of conventional bearings of existing bridges have been extensively replaced with rubber bearings since 1995. As a consequence of the duration of service exceeding 20 years, a considerable number of surface rubber cracks of rubber bearings due to aging deterioration have been found by inspection of highway bridges.

In this study, seismic residual performance of rubber bearing samples with aging deterioration taken from a highway bridge site was evaluated by shear loading tests and the material tests. The reduction of the load bearing capacity and that of the stiffness obtained by the test are indicative measures of the aging deterioration effect on the rubber bearings. A particular feature of debonding between rubber and steel layers are found in the deteriorated bearings.

KEYWORDS: *Rubber bearing, Aging deterioration, Seismic residual performance*

1. INTRODUCTION

Since the 1995 Kobe Earthquake, rubber bearings (elastomeric bearings) have been extensively used in the construction of new bridges or in the rehabilitation of existing bridges as the replacement of conventional steel bearings to apply the horizontal seismic force distribution design and the seismic isolation design concept to achieve improved seismic performance. The rubber bearings were also applied to continuous connected girders from early 1980's to 1995 as the devices to provide elastic support of the superstructures. As shown in Figure 1.1, most of the rubber bearings were installed after the Kobe Earthquake, and approximately 8% of them have been in service for more than 20 years.

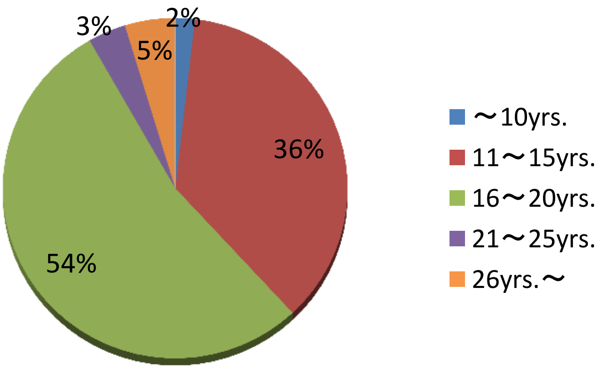

Figure 1.1 In-service periods of rubber bearings in the bridges in Hanshin Expressway

The natural rubber (NR), used in most of the rubber bearings, has the disadvantage of poor ozone durability. This implies that the performance of the rubber bearings is easy to deteriorate due to aging. Recently, some instances of rubber bearing damage caused by aging deterioration requiring repair works have been found. However, seismic residual performance of rubber bearings with deterioration damage is not clearly known. Moreover, no action has been taken to most of the damaged bearings since efficient repair methods for such bearings are not established [1].

Thus the performance assessment of deteriorated rubber bearings has emerged as an important research issue. Attention to this problem is also raised by several cases of severe damage to rubber bearings including rubber rupture found after the 2011 Great East Japan Earthquake [2][3]. In the preceding study by the authors, deteriorated elastomeric bearings with natural rubber (ring plate type laminated elastomeric bearings, also known as “ring bearings”) were taken out from an actual highway bridge site, and a series of shear loading tests were conducted. As the results, quantitative evaluation of the aging deterioration in the reduction of load bearing capacity as well as the change of their stiffness is obtained [4].

In this paper, results of several detailed tests of the deteriorated ring bearings to identify the cause of seismic performance degradation are described. Based on the test results, influence of the damage to the ring bearings due to aging deterioration on the performance is discussed.

2. BEARING SAMPLES FOR RESIDUAL PERFORMANCE TESTS

The elastomeric bearings for the experimental performance evaluation in this study were installed in 1986 and designed as seismic isolators to distribute the horizontal seismic force. Energy dissipation during seismic response is not expected in the design. The elastomeric bearings consist of four NR layers and steel ring plates, as shown in Figure 2.1. The plan dimensions are 400mm×450mm, the total thickness is 107mm with four rubber layers of 17mm thickness and three ring plates of 13mm thickness. The shape factors are S_1=5.93 and S_2=3.55. The elastic share modulus of the natural rubber material is 1.05N/mm^2 (G10.5).

The bearings had been used in service for 27 years. As can be seen in Figure 2.2, surface cracks appear on the bearings because of aging deterioration of the rubber material over time. Moreover, the bottom plate suffered partial corrosion due to water leaked through the expansion joint.

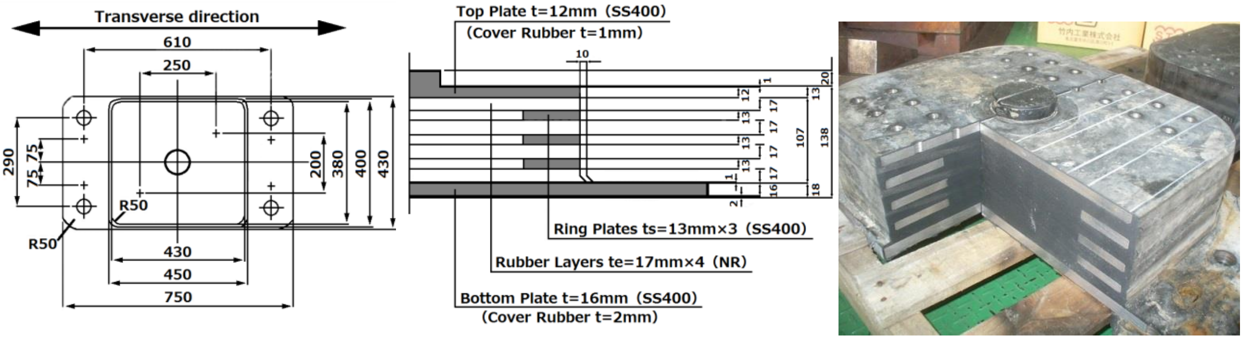

Figure 2.1 Dimensions of ring bearing samples

Figure 2.2 Damage status and cracks of ring bearings

3. TEST METHODS AND RESULTS

Five deteriorated bearings taken out from the actual highway bridge, denoted by G1, G2, G5, G7 and G9, respectively, and the four newly fabricated bearings denoted by N0, N1, N2 and N3, respectively, were used in six detailed loading tests. The newly fabricated bearings are intended to be used as the reference samples. The test plan for this study is listed in Table 3.1.

Table 3.1 List of test plan

No.	**Test Contents**	**Evaluation Object**	**Specimen**	**Criteria**
1	Ultimate Deformation (UD) Loading Test	Maximum shear load, displacement	G1, G2, G5, G7 N1, N2, N3	-
2	Image Analysis of Loading Tests (No.1)	Process of bearing rupture	G1, G2, G5, G7 N1, N2, N3	-
3	Visual Observation	Fracture surface	G1, G2, G5, G7 N0, N1, N2, N3	-
4	Tensile Tests	Tensile strength	G2, G5, G9, N0	$>15\mathrm{N/mm^2}$
		Breaking elongation		>550%
5	Adhesion Debonding Tests	Adhesion performance	G1, G5, G7, N0	>7N/mm
6	Lap Shear Tests	Fracture stress	5type×3	-

3.1. LOADING TESTS

The test equipment used in the loading tests is shown in Figure 3.1. All tests are horizontal shearing loading tests under a constant vertical load corresponding to the dead load of the superstructure. The specimen is connected to a 200tf horizontal hydraulic actuator through a load beam constrained by the link mechanism attached to a rigid steel frame so as movement only in the horizontal direction is allowed during shear loading. At the same time, a constant vertical load of 563kN equivalent to the dead load reaction force was applied to the specimen using four 500kN vertical loading jacks and a bottom loading table constrained in the horizontal direction with stoppers.

In the Ultimate Deformation (UD) tests, the specimens were monotonically loaded until the rupture of the rubber layer, or failure due to evident loss of strength. The ultimate deformation capacity evaluated by this test is expected to represent the safety and capacity margin against extreme earthquake events exceeding the level of seismic action corresponding to Level 1 Earthquake (Design Basis Earthquake in Japan).

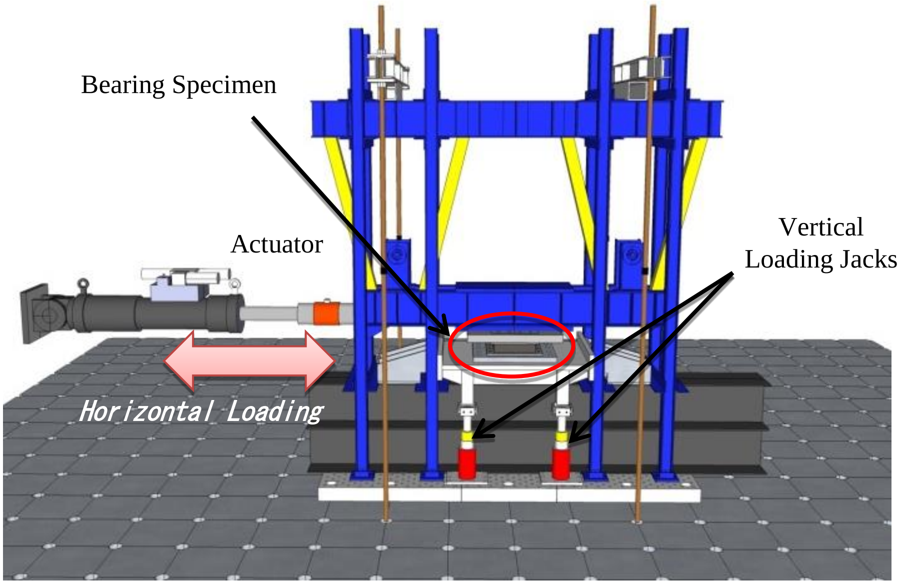

Figure 3.1 Loading test equipment

The restoring force curves obtained by the UD tests are shown in Figure 3.2. The reference sample bearings failed at 240% strain on average, satisfying the allowable shear strain requirement of 150%, although G7 failed at 131% strain. On the other hand, the failure of G1, G2 and G5 took place at shear strains exceeding 150%. Possible reasons for the variation in the failure strain among the samples include the difference in the progress of aging deterioration caused by environmental conditions in service period, manufacturing process or interaction between those factors.

Furthermore, the maximum restoring force of the four deteriorated bearings was 40% less than that of the reference bearing. Since the most influential factor to the load capacity degradation was inferred to be the aging deterioration, several supplemental tests had been conducted in order to evaluate the influence of the deterioration.

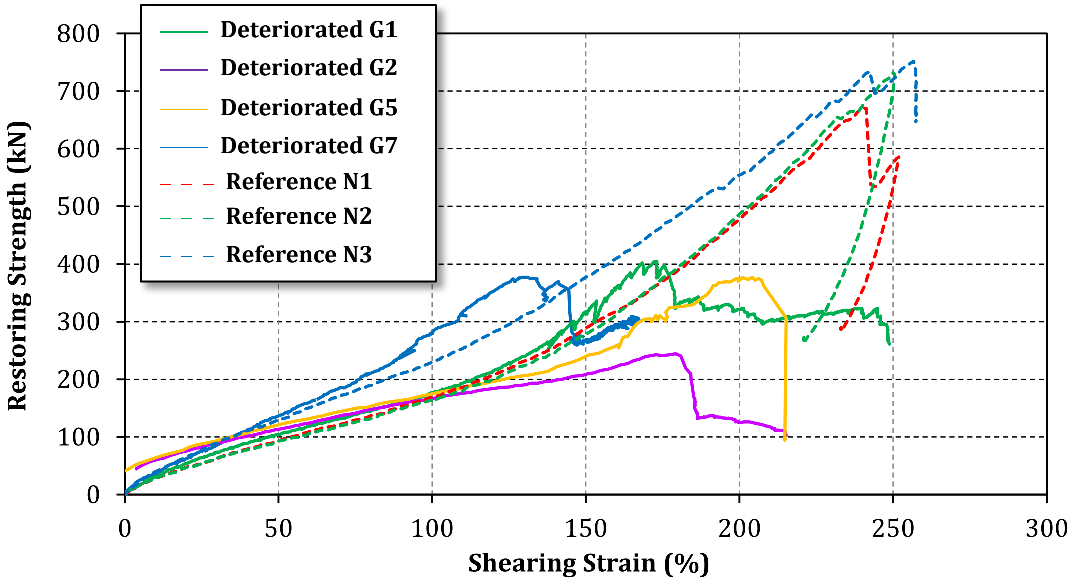

Figure 3.2 Result of UD tests

3.2. IMAGE ANALYSIS OF LOADING TESTS

The onset of fracture and its progress were analyzed by the video image of the UD tests. The images of the G7 test are shown in Figure 3.3. Debonding began from the ring plate, followed by a gradual progress of cracking extended to the bearing surface, and then the ultimate state was reached. The fracture was induced along the boundary between the bottom plate and rubber. The process of fracture forming is identical for all the deteriorated bearing samples. On the other hand, the fracture forming in the reference bearings is different from this description. The fracture was induced within the rubber layer between lower ring plates as commonly assumed in the design of bearings.

Although many ozone cracks are generated in ring bearings during the regular service, any extension and growth of these cracks that cause fracture of rubber layers were not observed in the tests. Therefore, ozone cracks on the surface of the bearings are not considered to be a critical factor that affects the seismic performance or bearing fracture process.

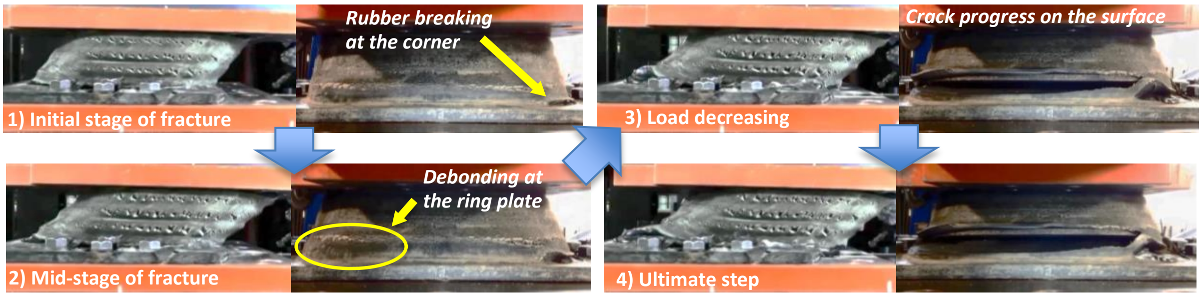

Figure 3.3 Video capture of UD test in G7

3.3. VISUAL OBSERVATION

The fracture surfaces after the UD test were observed using microscope to explore the fracture mechanism. In general, several fracture patterns corresponding to the fracture mechanism of rubber are known, and the periodic striations associated with shear failure are typically observed. Figure 3.4 shows the fracture surface of the bearing sample G7 formed between the bottom plate and rubber layer. The image G7-1 was obtained on the outer edge of bearing involving rusted spots, image G7-2 was taken on the rubber side of the ring plate showing an almost flat fracture surface, and image G7-3 was observed on the surface of bottom plate having emerged due to the debonding between the bottom plate and rubber. The striation pattern is not found in those fracture surface images, including the other deteriorated bearing samples. This observation strongly suggests that the fracture in deteriorated bearings takes place on the area of adhesion between the steel plate and rubber.

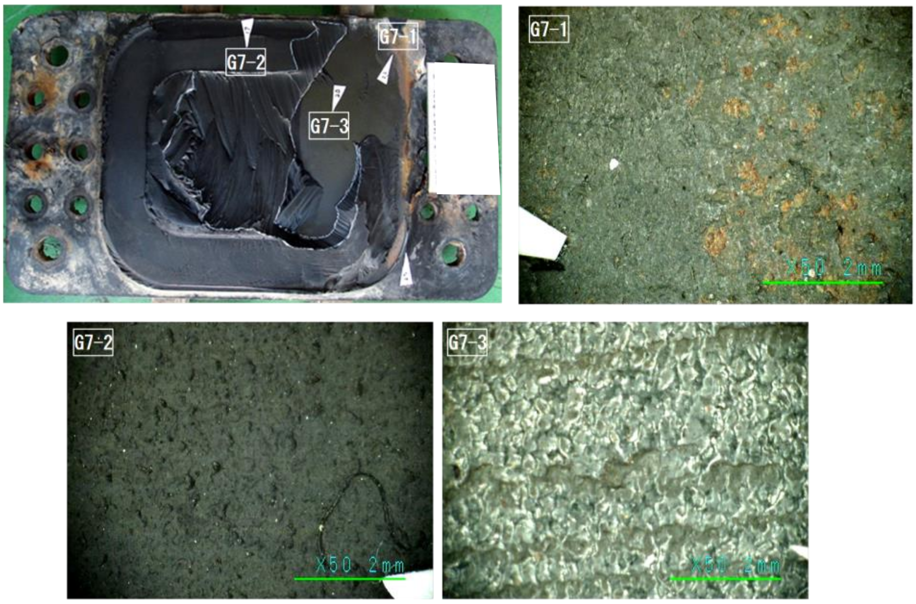

Figure 3.4 Fracture surface of G7

3.4. TENSILE TESTS

To evaluate the mechanical strength of the rubber, the tensile strength and the ultimate elongation capacity were measured by tensile tests. The tensile strength is defined as the maximum tensile force divided by the section area of the rubber specimen, and the ultimate elongation capacity is defined as the ratio of the ultimate deformation to the original length. Nine specimens were obtained from different layers of the deteriorated bearings and three specimens were sampled from the reference bearing. The obtained data of tensile strength and the ultimate elongation capacity are shown in Figure 3.5.

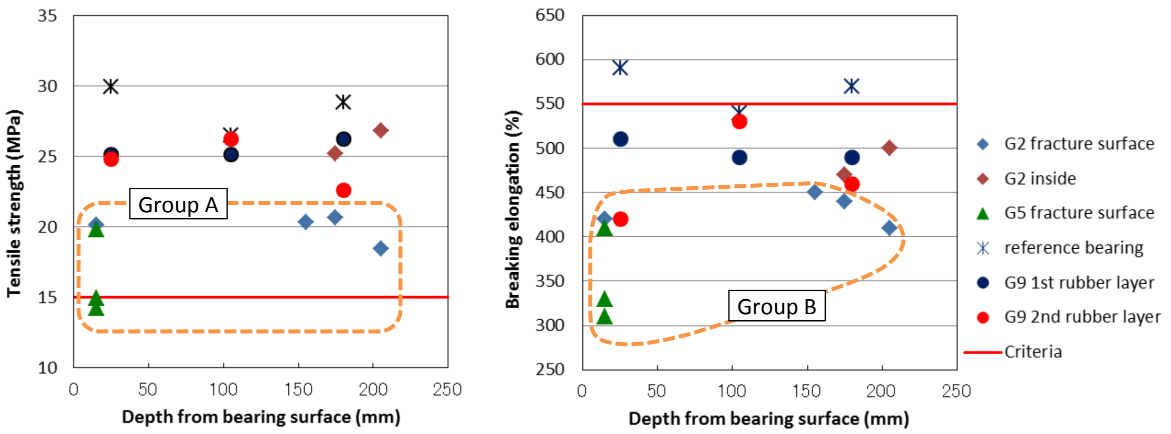

Figure 3.5 Results of tensile tests

The test result indicates that the strength and deformation capacity of the deteriorated bearings are lower than that of the reference bearings. It should be noted that the ultimate elongation capacity of the deteriorated bearings does not reach the criterion of 550%, implying that the degradation of the rubber is evident. Groups A and B in these plots correspond to the specimens taken from the fracture surfaces between the bottom plate and rubber, and the values of these groups consistently lower than the values of the other samples taken from different locations. In particular, since the samples of G5 were taken near the area where rust was seen, this result suggests that water or other external factors may contribute the deterioration process of rubber.

Since the rubber samples taken from within the rubber layers of G9 are not subjected to significant aging deterioration, the load capacity degradation observed in the UD test cannot be elucidated by the hypothesis of aging deterioration of rubber material alone. On the other hand, the surface rubber of the bearing is more susceptible to aging deterioration due to exposure to water or air. It implies that cracks are easily induced in the surface rubber and the intrusion of water through the cracks may introduce corrosive action on the boundary between the bottom steel plate surface and neighboring rubber layer.

3.5. ADHESION DEBONDING TESTS

The adhesion debonding tests were conducted using the samples taken from the deteriorated and the reference bearings. All measurement results on the debonding strength are shown in Figure 3.6 indicating the difference of the debonding properties depending on the location. While the debonding strengths at the bottom plate and ring plate satisfy the requirement of 7N/mm specified in the manufacturing criteria, that at the outer bottom plate is not always sufficient. Figure 3.7 shows the photos of adhesion debonding tests at outside of the bottom plate of the deteriorated bearing G7 and reference bearing N0. In contrast to the smooth debonding surface of G7, a striation pattern is observed for the case of N0. These results suggest that the debonding strength of the bonding area in the deteriorated bearings is lowered by a loss of adhesive action.

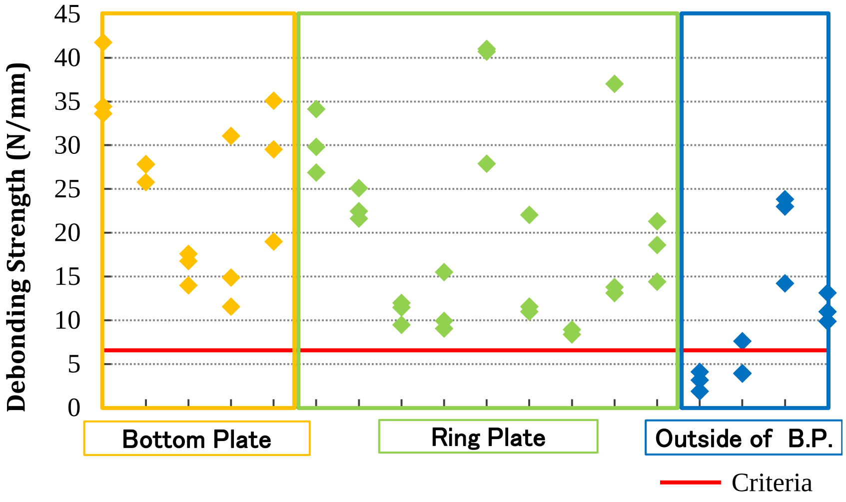

Figure 3.6 Results of adhesion debonding tests

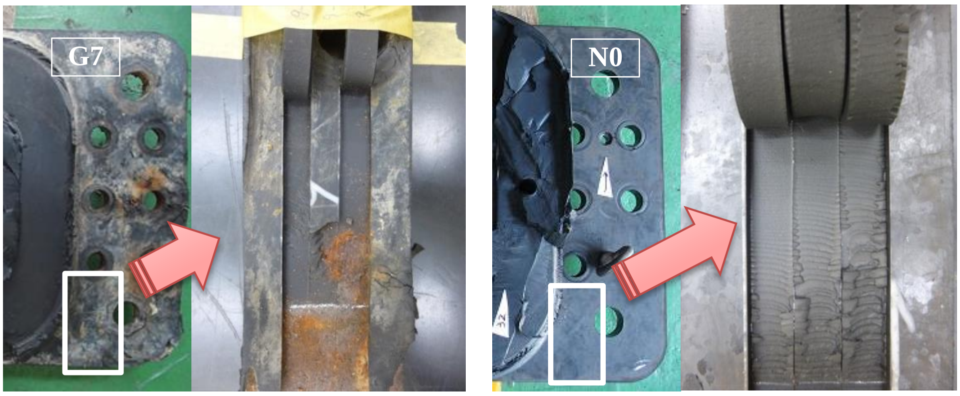

Figure 3.7 Appearance of outside of bottom plate in adhesion debonding test (Left: G7, Right: N0)

3.6. LAP SHEAR TESTS

The lap shear tests were carried out to evaluate the influence of rubber surface cracks and debonding between the steel plate and rubber on the seismic performance of the bearing. As shown in Figure 3.8, five types of specimen (A~E) taken from differed distances from the bonding area and shape were prepared, and the failure strength in shearing direction were measured. The test results are shown in Figure 3.9.

The difference of the failure stresses between the specimens is not significant. It is also noteworthy that the results of the specimen E are in the same range in spite of possible high stress concentration in the specimen E due to partly cutout. When a good bonding condition is ensured, the boding between the steel plate and rubber is not regarded as a critical factor for the cause of rupture and failure of the bearing.

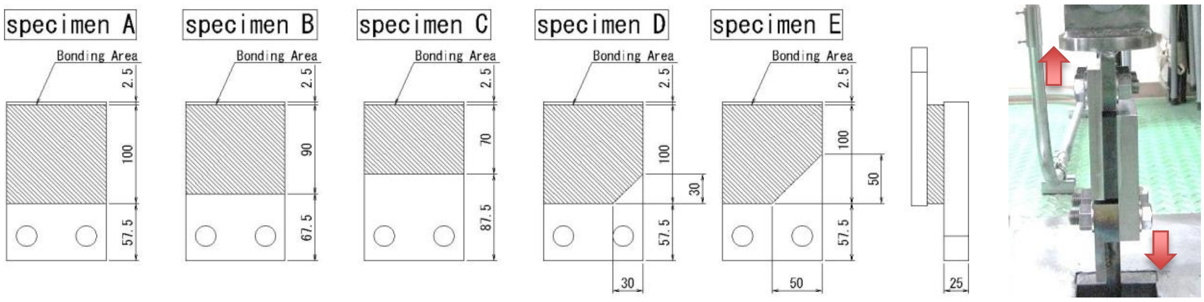

Figure 3.8 Specimens of lap shear tests

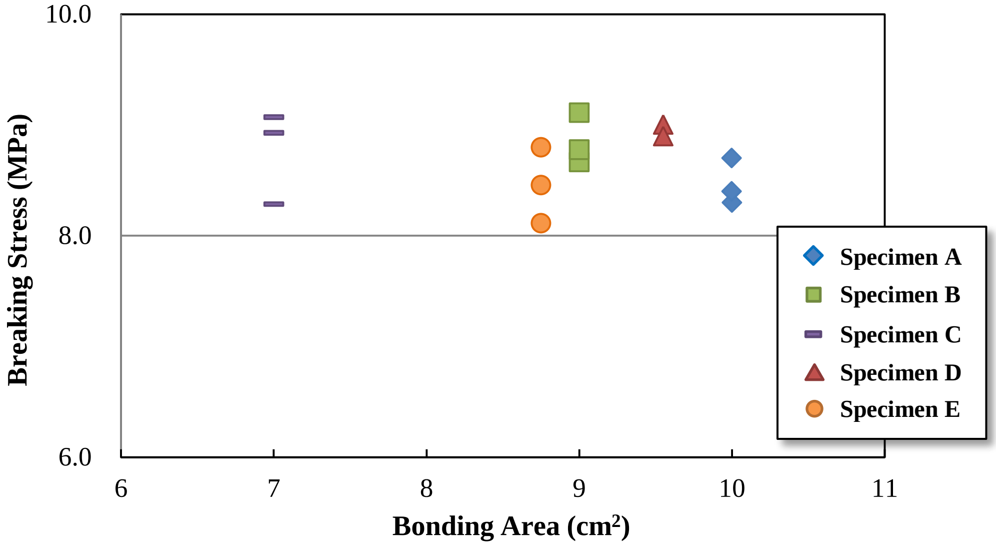

Figure 3.9 Results of lap shear tests

4. EVALUATION OF SEISEMIC RESIDUAL PERFORMANCE

Influence of the reduction of the ultimate strength of the deteriorated bearings on the seismic performance required by the design code is discussed in this section. Table 4.1 shows the design requirements for the bearing specified for the Level-1 earthquake.

Table 4.1 Design condition of bearing

Items	Design value
Shear deformation	100.4mm
Shear strain	93.8%
Strength	169kN

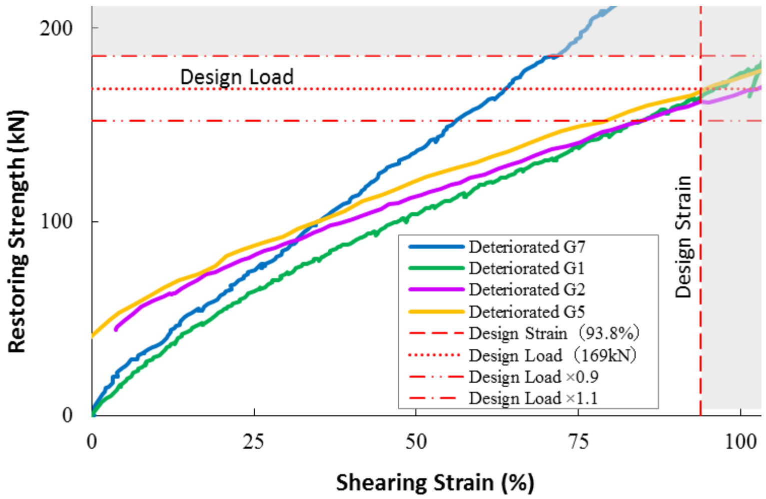

Figure 4.1 Design values and result of UD tests

Figure 4.1 shows the result of the UD tests in comparison with the design values. The strength of all deteriorated bearings exceeded the design load of 169kN, and the restoring forces at the design strain (93.8%) are found to be almost equivalent to the design load with a factor between 0.9 and 1.1, with the exception of G7. Therefore, the seismic residual performance of the deteriorated bearings is almost satisfactory with respect to the requirement for the Level 1 Earthquake. However, requirements for the Level 2 Earthquake (MCE) in the current seismic design specificationsare yet to be investigated.

5. CONCLUSIONS

The findings obtained in this study can be summarized as follows;

- The fracture process observed in the UD tests suggests that the onset of fracture takes place in the bonding layer between the bottom plate and rubber due to a reduction of bonding strength of the adhesive action.
- In the UD tests, ozone cracks on the bearing surface rubber did not extend, and is not the origin of fracture. Therefore, ozone cracks on the surface of the bearings are not considered to be a critical factor that affects the seismic performance or bearing fracture process.
- From the result of the tensile tests and adhesion debonding tests, material degradation of rubber was not significant except for surface, suggesting that the load capacity degradation observed in the UD test cannot be elucidated by the hypothesis of aging deterioration of rubber material alone. On the other hand, the surface rubber of the bearing is more susceptible to aging deterioration due to exposure to water or air, possibly introducing corrosive action on the boundary between the bottom steel plate surface and rubber.
- From the result of the lap shear tests, it is found that a good boding between the steel plate and rubber is not regarded as a critical factor for the cause of rupture and failure of the bearing.

The test results in this study suggest that the degradation of adhesion can greatly influence the seismic performance of the bearing. The seismic residual performance of the aging bearings should be further investigated by the analysis of adhesion degradation mechanism and change of adhesion properties.

REFERENCES

1. Hayashi, K., Adachi, Y., Igarashi, A. and Dang J. (2014). Experimental Evaluation of Aging Deterioration of Rubber Bearings in Highway Bridge. *The 2nd European Conference on Earthquake Engineering and Seismology*. Istanbul, Turkey.
2. Hirose, T. and Yamada, K. (2012). Investigation into Causes of Ruptures of Elastomeric Bearings due to the Great East Japan Earthquake. *28th US-Japan Bridge Engineering Workshop*. Portland, OR, USA.
3. Takahashi, Y. (2012). Damage of Rubber Bearings and Dampers of Bridges in 2011 Great East Japan Earthquake. *Proceedings of the International Symposium on Engineering Lessons Learned from the 2011 Great East Japan Earthquake*. 1333-1342.
4. Hamano, M., Igarashi, A., Hayashi, K., Adachi, Y. and Dang J. (2014). Experimental Evaluation of Remaining Performance and Aging Deterioration of Elastomeric Bridge Bearings with Natural Rubber. *The 27th KKHTCNN Symposium on Civil Engineering*. Shanghai, China.