Transactions, SMiRT-24
BEXCO, Busan, Korea - August 20-25, 2017
Division IX (include assigned division number from I to X)

PERFORMANCE CHARACTERISITCS OF SEISMIC ISOLATION DEVICES FOR NUCLEAR POWER PLANTS ACCORDING TO REAL AND SMALL SCALE MODEL TEST

Min Kyu Kim[1], Jung Han Kim[2]

[1] Principal researcher, Korea Atomic Energy Research Institute, Korea
[1] Senior Researcher, Korea Atomic Energy Research Institute, Korea

ABSTRACT

The behavior expectation of a seismic isolation bearing is one of the most important issues for seismic isolated NPPs. All nuclear power plant structures should be designed to have elastic behavior within a design level earthquake. Otherwise, seismic isolation devices basically behave with nonlinearly from very small earthquake motion. In addition, the main material for a seismic isolation device like a lead rubber bearing is rubber. The behavior characteristics of a rubber material are very difficult to estimate, and it is very difficult to make the same characteristics when compared with other materials.

In this study, for determination of the performance characteristics of lead rubber bearings, characteristic tests were performed for real-scale and small-scale model lead rubber bearings. Twenty small-scale isolation bearings (diameter of 550 mm) and two real-scale isolation bearings (diameter of 1500 mm) were manufactured for the test. The distributions of several mechanical characteristics of LRB were determined. Many dependencies of the mechanical characteristics were also determined. The velocity dependency, input seismic motion dependency, one- and two-dimensional behavior dependencies, and the displacement dependency were considered. Through this test, it can be recognized that in the case of considering a mechanical property test, dynamic and multi-degree loading conditions should be determined. However, these differences should be examined to determine their effect on the global structural behavior.

INTRODUCTION

Seismic isolation is one of the most effective applications for increasing the seismic safety of Nuclear Power Plants. In 2016, the greatest earthquake occurred on the Korean peninsula since instrumental records began. Because of the recent earthquake, many people in Korea are very worried about the seismic safety of Korean Nuclear Power Plants. At this time, seismic isolation is one of the most appropriate solutions for enhancing the seismic safety of NPPs. However, the application of a seismic isolation system for conventional structures and nuclear power plants are totally different. In the case of a conventional structure, the design basis earthquake can be considered for the seismic design but in the case of nuclear power plants, it should be considered for a beyond design base earthquake. In addition, all nuclear power plants should satisfy the safety goal. For verification of the safety goal of nuclear power plants, we should perform a seismic probabilistic safety assessment (SPSA). A seismic fragility assessment is one of the key components while performing a SPSA. For performing a seismic fragility assessment, determination of an ultimate failure capacity is very important. Because of this, in the case of seismic fragility assessment, we should determine the seismic response and capacity of a seismic isolator.

The behavior expectation of a seismic isolation bearing is one of the most important issues for seismic isolated NPPs. All nuclear power plant structures should be designed to have elastic behavior within a design level earthquake. Otherwise, basically seismic isolation devices behave nonlinearly from very small earthquake motion. In addition, the main material for a seismic isolation device like a lead rubber bearing is rubber. The characteristics of rubber material make it very difficult to estimate the behaviour, and also very difficult to make the same characteristics when compared with other materials.

In this study, for the determination of the performance characteristics of lead rubber bearings, characteristic tests were performed for real-scale and small-scale model lead rubber bearings. Twenty small-scale isolation bearings (diameter of 550 mm) and two real-scale isolation bearings (diameter of 1500 mm) were manufactured for the test. The distributions of several mechanical characteristics of LRB were determined. Many dependencies of mechanical characteristics were also determined. The velocity dependency, input seismic motion dependency, one- and two-dimensional behavior dependencies, and displacement dependency were considered. Through this test, it can be recognized that when considering a mechanical property test, dynamic and multi-degree loading conditions should be determined. However, these differences should be examined to determine how much they affect the global structural behavior.

PERFORMANCE CRITERIA OF BASE ISOLATION SYSTEM

The design level criteria of a rubber type bearing used to be no damage and support of a vertical load for a horizontal design displacement. For important facilities, the isolation system needs to maintain its function over the design level earthquake shaking. The performance-based guidelines of the base isolation system for nuclear power plants suggest that the failure probability by the extended design basis earthquake should be less than 10%, as summarized in Table 1 [USNRC, 2012]. This requires a prototype test of the isolators to the horizontal displacement in accordance with the 90th percentile of the extended design basis earthquake level response. In this performance criteria, the extended design basis earthquake response needs to be increased to three times the design basis earthquake displacement response conservatively [Huang et al., 2009]. The performance-based design suggests that the isolation system should maintain its major function under the extended design basis earthquake. Therefore, the bidirectional load that can occur by an extreme earthquake should be considered in the performance test.

Table 1 – Performance criteria of the isolation system for nuclear power plants

Ground Motion Level	Performance Criteria
Design Basis Earthquake	100% confidence of the isolation system surviving without damage
Extended Design Basis Earthquake	90% confidence of the isolation system surviving without loss of gravity-load capacity

SCALE MODEL TEST

Basic Mechanical Property Test

For an evaluation of the variation of mechanical properties for a lead rubber bearing, scale model LRBs were manufactured. Drawings and manufactured LRBs are shown in Figure 1. As shown in Figure 1, the diameter of the LRB is 550 mm. Basic property tests were performed for all 20 specimens. Test results are shown in Figures 2 and 3. As shown in Figures 2 and 3, the mechanical properties of all 20 specimens did not show many differences; however, when comparing the target properties, the variation is not too negligible. This means that the mechanical properties of LRB are not well matched for the target design parameters, but the variations of each parameter of LRB are not very high [Min Kyu Kim et al., 2016].

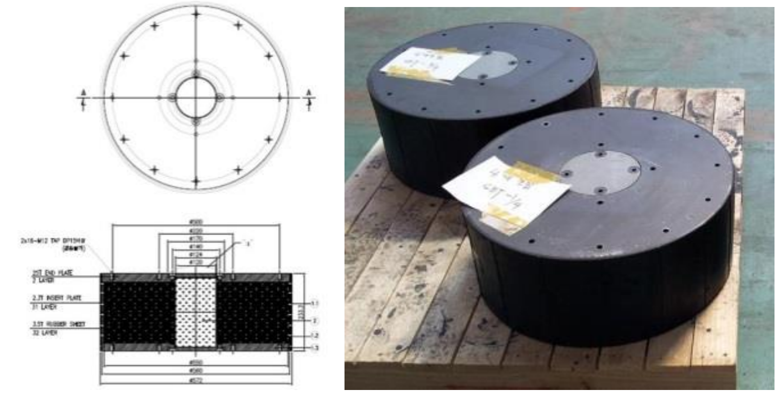


Figure 1. Drawing and LRB for mechanical property test

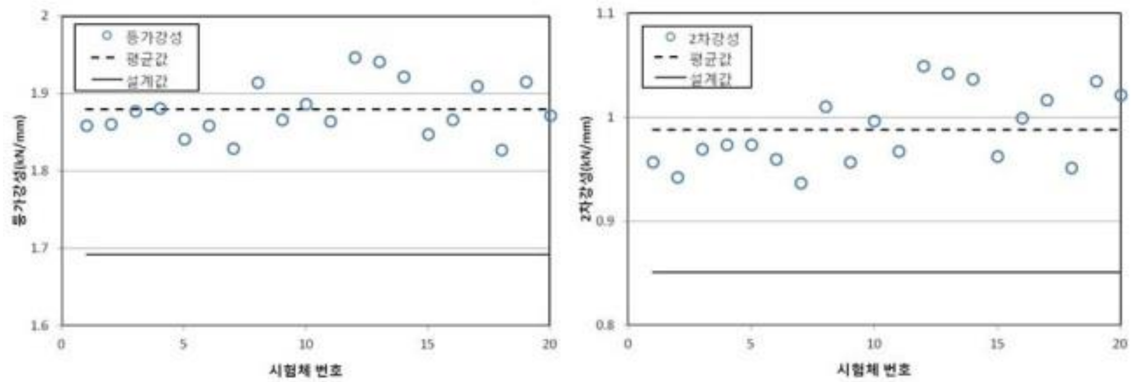


Figure 2. The variation of effective stiffness and secondary stiffness of all LRB specimens

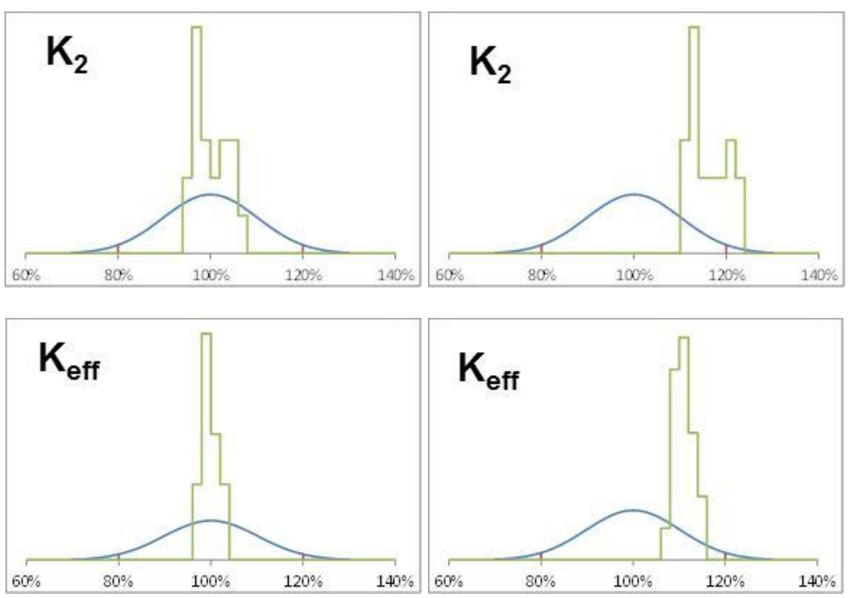


Figure 3. The distribution of mechanical properties for LRB specimens

Dynamic Performance Test

In general, mechanical property tests are performed at a static speed in Korea. This is because the machine for an isolator performance test cannot perform a dynamic property test. However, in the case of an earthquake, the isolation bearing must move dynamically. Thus, the dynamic property should be considered for the performance criteria of an isolation bearing. For performing a dynamic property test, an isolation system that combines 4 LRB specimens, as shown in Figure 4, was prepared.

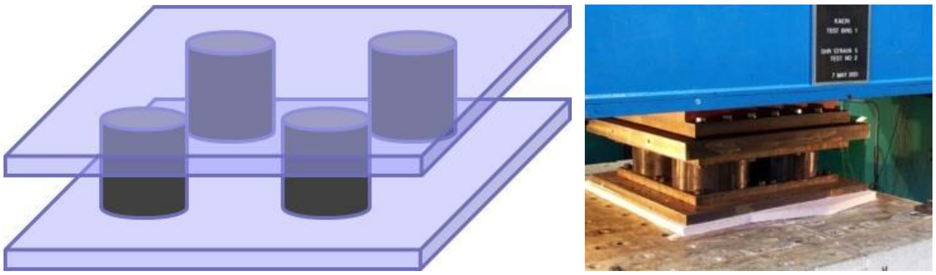


Figure 4. An isolation system for performing a dynamic test

The results of static and dynamic loading cases were compared in Figure 5. As shown in Figure 5, the scragging effect of the dynamic test is bigger than that of static test. However, the hysteresis of over the third loop, static and dynamic cases show similar results.

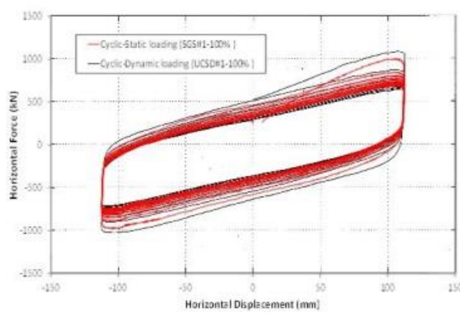
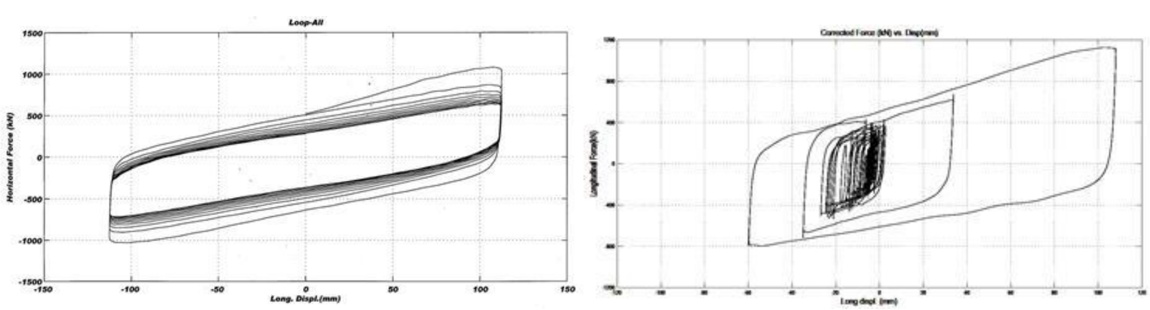


Figure 5. Comparison of the hysteretic results of static and dynamic harmonic loading test

In the case of a 100% shear strain, the harmonic loading case and earthquake loading case were compared, and are shown in Figure 6. As shown in Figure 6, the shape of the displacement-force hysteresis loop was slightly different, and a damping of the earthquake input case is bigger than that of the harmonic loading condition.



(a) A harmonic loading case (b) An earthquake loading case

Figure 6. Compare the hysteresis loop of harmonic loading and earthquake loading cases

The tests of one- and two-dimensional earthquake loading are compared in Figure 7. As shown in Figure 7, in the case of a two dimensional earthquake input, bi-linear behavior is not very clear compared to one-dimensional loading conditions. All one- and two-dimensional earthquake loading cases according to the shear strain level are shown in Figure 8. As shown in Figure 8, the load-displacement relations are slightly different according to the loading condition. The response results of the dynamic and static loading case and one- and two-dimensional loading conditions are slightly different in this study, and the structural behavior should be examined.

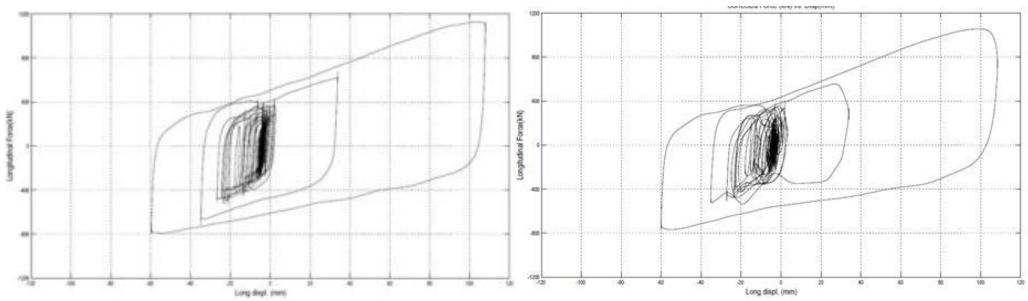


Figure 7. The hysteretic loop of one- and two-dimensional loading cases

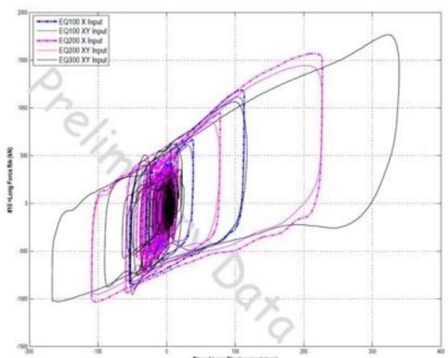


Figure 8. One- and two-dimensional earthquake loading cases according to the shear strain level

REAL SCALE ISOLATOR MODEL TEST

Overview of Test

For an evaluation of the dynamic characteristic test for real-scale isolators, two full-scale isolation devices were manufactured. The diameter, total rubber thickness, and diameter of the lead core are 1500 mm, 224 mm, and 320 mm, respectively. The drawing and figure of the lead rubber bearing are shown in figure 9.

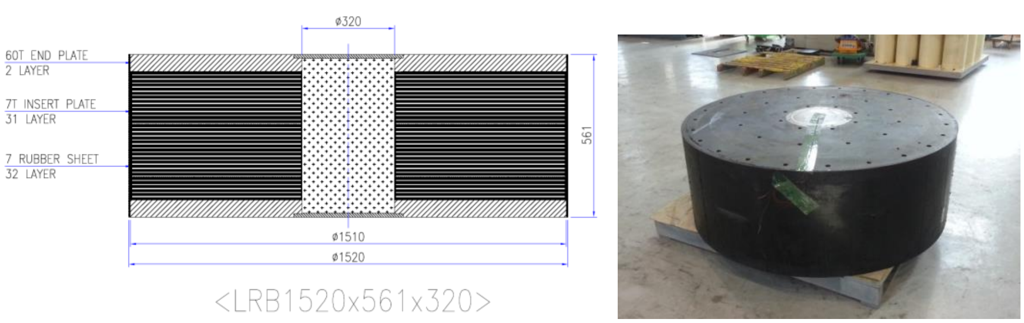


Figure 9. Drawing and LRB for Mechanical property test

For considering the two-dimensional input motion, dynamic input motions were generated. In the case of generating input motion, the capacity of the test machine should be considered. For the 100% and 200% shear strain level tests, seismic input motions were considered, but for the over 300% shear test, only elliptical motions were considered because of the limit displacement of the test machine in UCSD. In particular, in the case of the 500% shear test, special input motion should be considered. For the evaluation of the differences between one-dimensional and two-dimensional input motions, only a one-dimensional test was performed for specimen 1, and a two-dimensional test was performed for specimen 2. The seismic input motion for the 100% and 200% shear strain levels, 300% and 400% elliptical sinusoidal motion, and 500% shear strain level test motion are shown in figures 10, 11, and 12, respectively [Jung Han Kim et al., 2016, 2017].

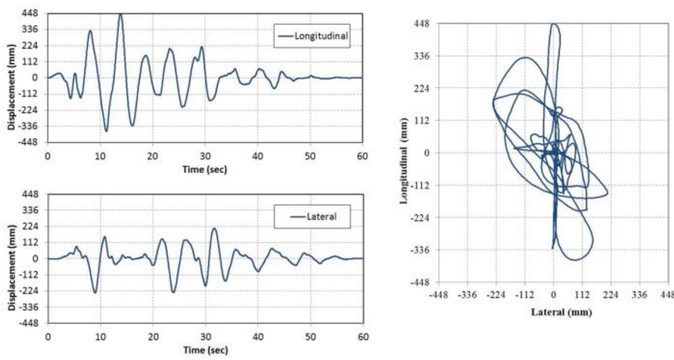


Figure 10. Seismic input motion for 100% and 200% shear tests

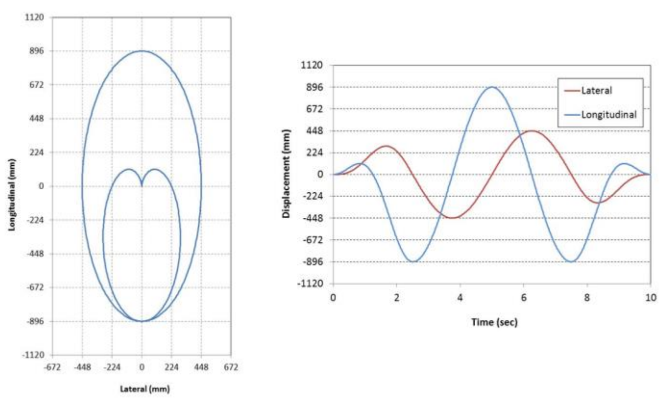


Figure 11. 300%, 400% Elliptical Trace Sinusoidal Motion

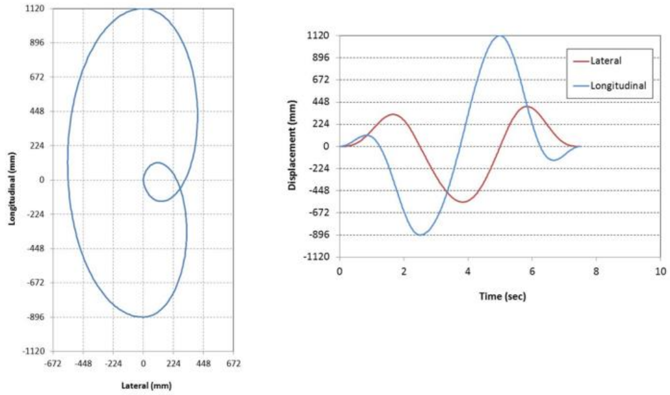


Figure 12. 500% Elliptical Trace Sinusoidal Motion

The test was performed by increasing the strain level at 100% intervals. Earthquake displacement response motions were applied until reaching the 200% strain level. After that, the elliptical motions were applied to the 500% strain level. Two specimens were tested to compare the unidirectional test and bidirectional test. The test until the 200% strain level has same test protocol to verify that these specimens were almost identical. After that, one specimen was tested using one-dimensional horizontal motions, and the other was tested by two-dimensional horizontal motions.

4.1 Result of design level displacement input test

Fig. 13 shows the strain-force relations by the earthquake displacement response based on the 100% and 200% strain level tests. As shown in Fig 13, the horizontal strain-force curve of the 1D-100% strain test can be predicted by a bilinear hysteresis model. The second stiffness was almost constant and a sharp corner appeared in each unloading cases. In the case of the 2D-100% strain test, the stiffness was slightly decreased when the displacement reached the maximum strain level of 200%. This could be a scragging effect by the characteristic of the rubber material or because of the increase in temperature by the cumulative hysteretic damping energy. The graph of the 2D test shows the strain-force curve to the same direction of the 1D test, but the displacement input was applied in the orthogonal direction simultaneously. The hysteresis curve was a little bit rounded, and therefore, it is hard to represent by bilinear curves. This is more likely at a small strain level. In addition, the area of the hysteresis curve which represents the dissipated energy was reduced in the 2D test. This can cause a larger displacement response of the isolation system.

4.2 Result of extended design level displacement input test

Fig. 14 shows the strain-force curve by sinusoidal displacement input scaled by the 300% and 400% strain level tests. The secondary hardening occurred beyond the 300% strain in all tests. In addition, the first cycle had a high horizontal force compared to the earthquake displacement response tests even at a low strain level. This is because this test does not have low level strain cycles before the maximum strain cycle. The force did not decrease abruptly at the unloading moment, and the hysteresis area around the origin was narrow in the 2D tests. The shape of the LRB after the 2D test is shown in Fig. 15. The body of the LRB was distorted with a curved side. Nevertheless, the mechanical property of the LRB was maintained when a 100% strain test was performed again.

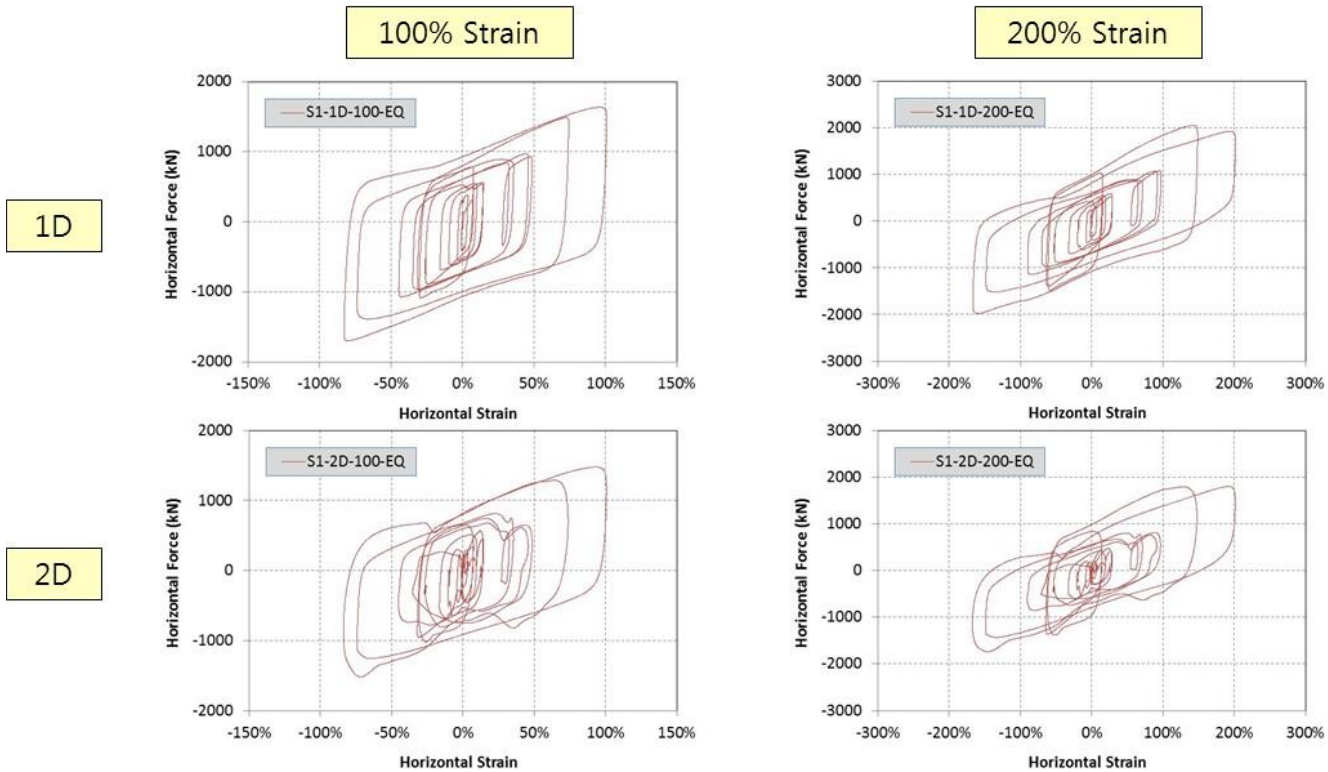


Figure 13. Horizontal strain-force curve of unidirectional test and bidirectional test under the displacement response input by earthquake ground motion

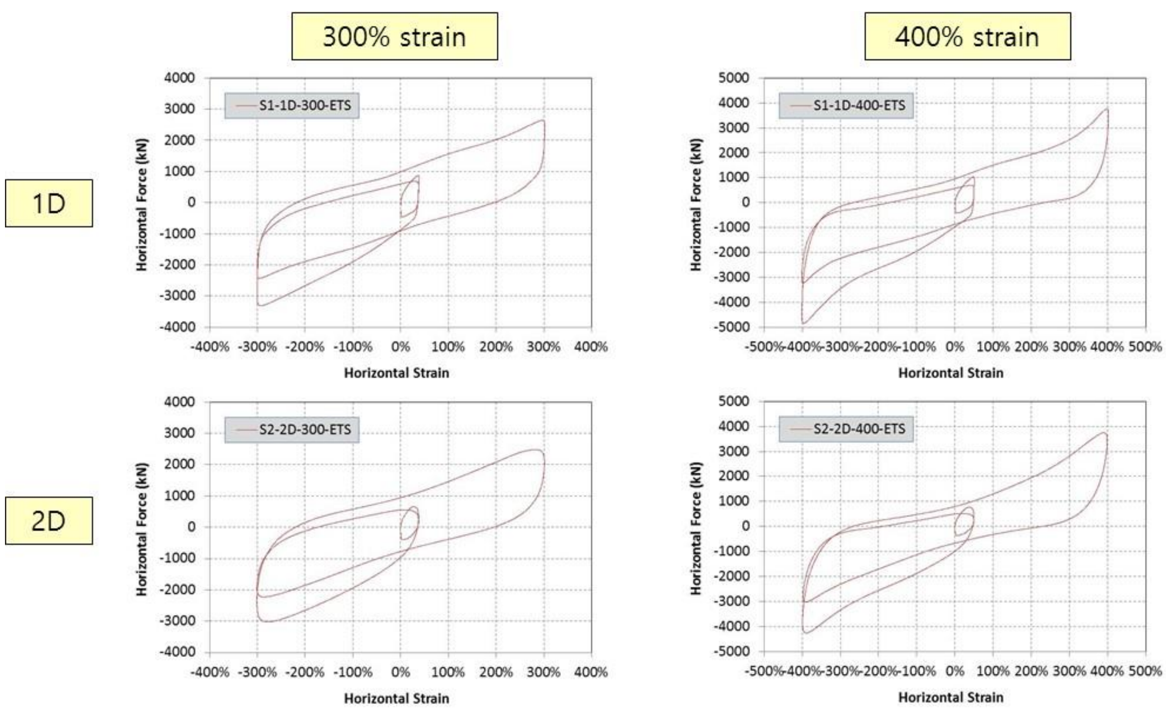


Figure 14. Horizontal strain-force curve of unidirectional test and bidirectional test under the sinusoidal displacement input

Figure 15. Distortion of LRB after 2D-400% strain test [Min Kyu Kim 2015]

4.3 Result of extreme displacement input test

As mentioned above, the displacement of extended design basis earthquakes is three-times the design basis earthquakes. Therefore, around a 400% strain level could be the performance limit when the design strain level is about 100% in one direction. In this test, the failure test was performed to examine the bidirectional effect in the failure criteria. Fig. 16 shows the different behaviors between the 1D and 2D input displacements. For the 2D input motion, the input motion in the orthogonal direction has half the amplitude 1D input motion with a 90 degree difference in phase angle. In the 1D test, the failure did not occur in the 500% strain level test. After this test, a shear fracture occurred at around the 510% shear strain level by monotonically increasing the displacement. However, in the 2D test, the failure occurred at slightly over the 400% strain level. This shows that the horizontal limit state should be estimated to be 20% lower when the 1D experiment was applied. After a shear fracture of the rubber layer, the LRB was severely deformed, as shown in Fig. 17. However, it still carried the designed vertical load. The gap of the shear fracture can be seen after the vertical load was removed.

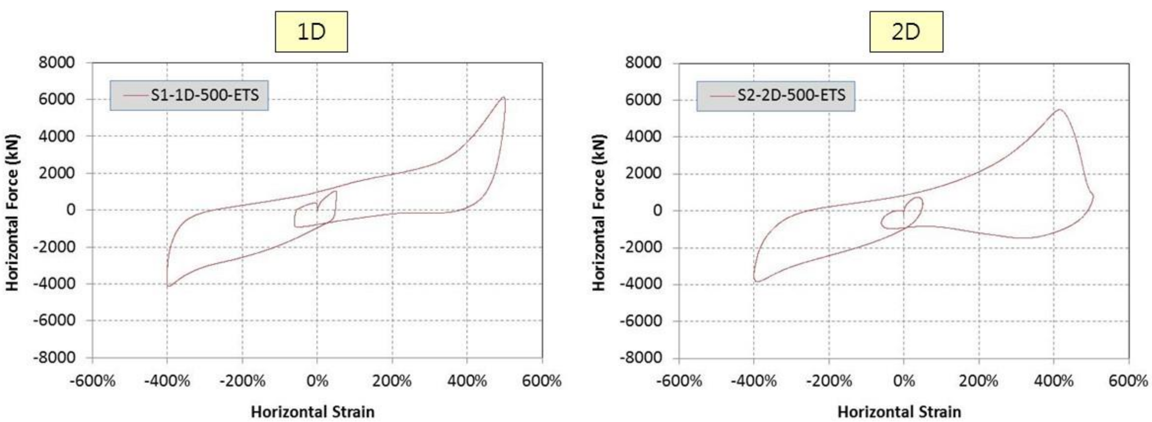
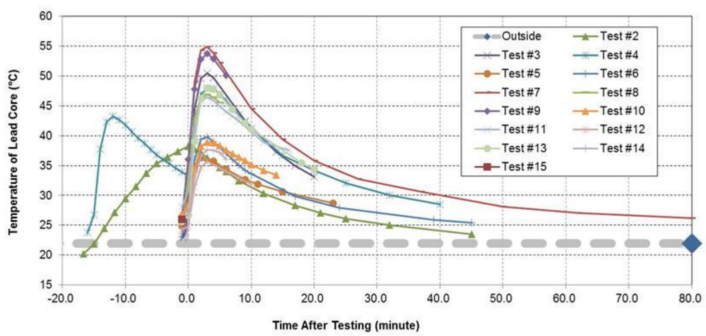


Figure 16. Horizontal strain-force curve of unidirectional test and bidirectional test under extreme displacement input

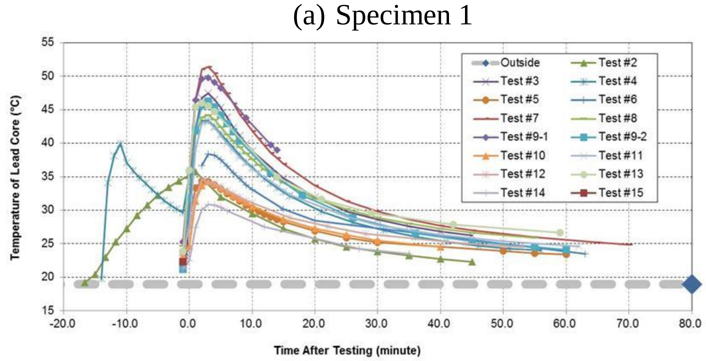
Figure 17 – View of test specimens after failure test

Temperature effects according to the performance test

The temperature of the lead core of the LRB during a performance test was measured for an evaluation of the temperature increase and performance of the LRB. At first, three thermometers were installed inside the lead core, but only one thermometer was alive for measuring the temperature. The temperature variations during the performance tests are shown in Figure 18. As shown in Figure 18, the slopes of the temperature increase and decrease are almost similar. Temperature changes and the total travel of the LRB during the performance test are compared in Figure 19. As shown in Figure 19, the relation of the temperature increase and the total travel distance is linearly matched. However, there are two points that are not well matched in specimen 2. The two points are the results of the 2-dimensional performance test. That means, even with the same travel distance, the 2-dimensional performance tests can create a greater temperature increase in the LRB specimen.



(a) Specimen 1



(b) Specimen 2

Figure 18. Temperature variations during performance test

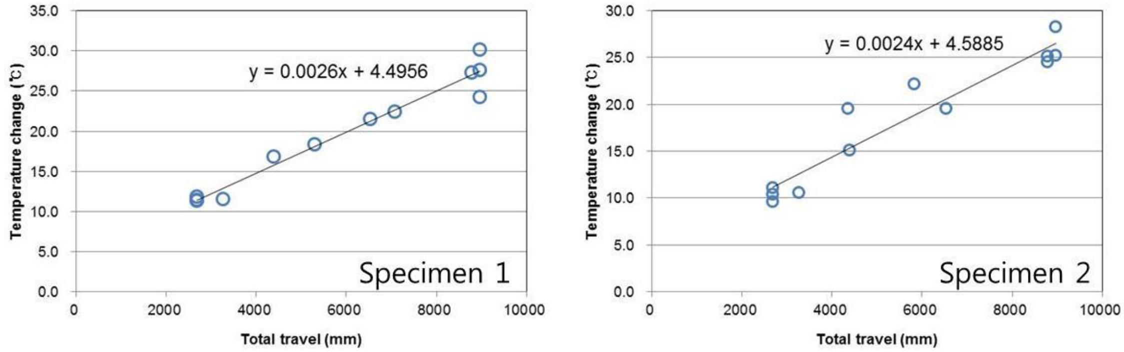


Figure 19. View of test specimens after failure test

Proposal for Performance Test of Lead Rubber Bearing

Based on a previous scaled isolator model and real-scale model test, considerations for the performance test of lead rubber bearings can be suggested. Even though it is very difficult to identify in the case of a scaled model test, the test velocity should be considered for the performance test. A low velocity test can overestimate the effective stiffness of an LRB. In the case of the performance test, sinusoidal motion but not real seismic motion can be performed. In the case of the test direction, the LRB characteristics are similar, but the shear strain levels of a failure are different. Thus, if we want to determine the failure capacity of a LRB, a 2-dimensional dynamic test should be needed. If a 2-dimensional test is not possible, 1-dimensional test results should be modified.

CONCLUSIONS

In this study, seismic isolation device tests were performed for an evaluation of the performance criteria of the isolation system. Through this test, it can be recognized that in the case of considering a mechanical property test, dynamic and multi degrees of loading conditions should be determined. However, these differences should be examined to determine how much they affect the global structural behavior.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (No. 2017M2A8A4014829)

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