16th World Conference on Earthquake Engineering, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 3990

Registration Code: S-E1464748038

EXPERIMENTAL STUDY ON THE BIDIRECTIONAL BEHAVIOR OF A LEAD-RUBBER BEARING

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Abstract

There has been an increasing demand for introducing a base isolation system to secure the seismic safety of structures and equipment. Most of the guidelines for the seismically isolated structures require the production test to verify the mechanical properties of isolation devices. When the risk and performance based design concept is applied, the prototype test under the beyond design basis seismic loading also required to make sure that the base isolation system have enough seismic margin. However, the behavior of isolators with elastomeric rubber material under the large displacement is not very well understood. In this study, the full scale lead-rubber bearings which have 1,500 mm diameter of rubber and 320 mm diameter of lead core were tested. The displacement controlled horizontal motions were applied to the specimens with a constant vertical load. These horizontal input motions were determined by the response analysis of an earthquake motion or used as simplified sinusoidal motion. For the input displacement of two orthogonal horizontal directions, the maximum directional response of ground motions was considered. As an experimental results, the behaviors of isolators in the design displacement range and the beyond design displacement ware investigated. The difference between unidirectional and bidirectional force-displacement curve were compared and the fracture test were also accomplished in each cases. Finally, the considerations for the test protocol of isolation devices and the limit state under seismic loading were discussed.

Keywords: base isolation; lead-rubber bearing; bidirectional behavior; maximum directional response

1. Introduction

A seismic base isolation system is introduced in high seismicity regions to secure the seismic safety of important facilities. For the nuclear power plants, the benefit of seismic isolation system is not only for the structural safety but also the equipment installed on the floor of nuclear power plant structures. . It is also required for the seismic design of next generation nuclear power plants. Several guidelines for base isolated nuclear power plants are being developed in many countries.

For the application of nuclear power plants, the behavior of isolation system should be predictable more accurately. It should be analyzable in the range of design load and the isolation system should keep its function over the design level earthquake with a high confidence like any other equipment in nuclear power plants. The seismic response of isolators by the extended design level earthquakes should be controlled not to exceed the ultimate limit state of it.

The type of base isolator appropriate for a nuclear power plant structure is regarded as elastomeric rubber bearings with a lead core. However these are not easy to be predicted because of its high nonlinearity and complex loading condition by an earthquake excitation. In this study, lead-rubber bearings (LRBs) were tested to verify its behavior and performance. There has been many experimental research of the seismic isolation bearing in horizontally unidirectional movement. So, this test was focused on the bidirectional behavior and limit state. The dimension of LRB was full scale model which is expected to be used in nuclear power plants. The displacement controlled horizontal displacements were applied to the specimens with a constant vertical load in a test. This full scale model was tested to understand various characteristics of the bidirectional behavior on the two-dimensional horizontal plane. As an experimental result, the difference between unidirectional and bidirectional behaviors and the limit state were investigated. The considerations for the prototype test of isolation devices were discussed.

2. Performance Criteria of Base Isolation System

The design level criteria of a rubber type bearing used to be no damage and supporting vertical load at the design horizontal displacement. For the important facilities, the isolation system needs to maintain its function over the design level earthquake shaking. The performance-based guideline 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 [1]. It requires the prototype test of isolators to the horizontal displacement in accordance with the 90th%ile of the extended design basis earthquake level response. In this performance criteria, the extended design basis earthquake response need to be increased as 3 times of design basis earthquake displacement response conservatively [2]. The performance-based design suggest that the isolation system should maintain its major function under the extended design basis earthquake. Therefore, the bidirectional load which can be occurred by the extreme earthquake should be considered in performance test.

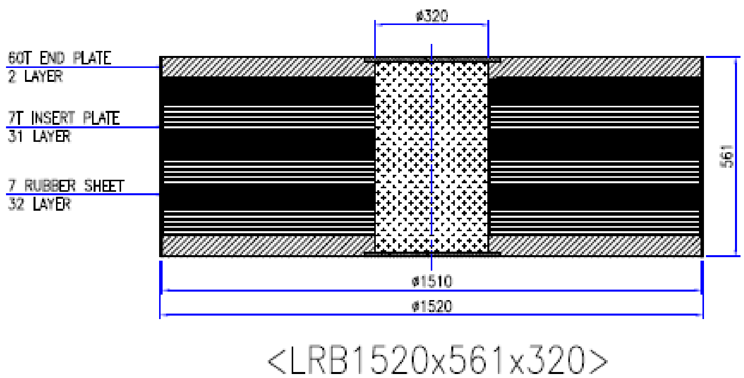
Table 1 – Performance criteria of the isolation system for nuclear power plants

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

3. Test Setup

3.1 Test specimen

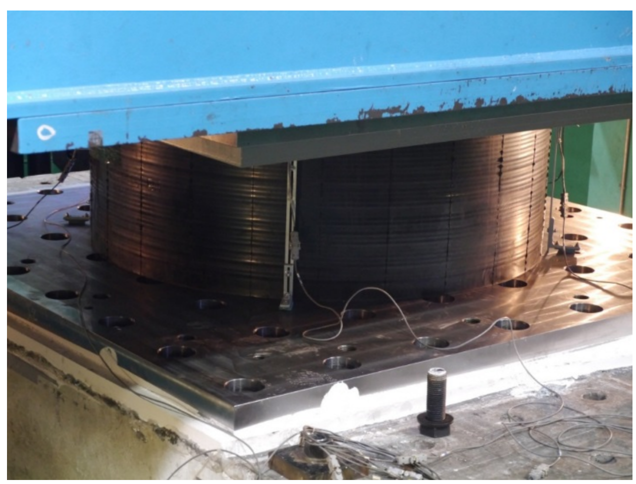
The LRBs used in the full scale experiment have 1,500 mm diameter and the total height of rubber is 224 mm by 32 layers with 7 mm height as shown in Fig 1. The diameter of lead core is 320 mm. The shear modulus of rubber material is 4 MPa. The secondary stiffness in the horizontal direction was estimated to be 3.12 kN/mm, and the stiffness in the vertical direction was 6,621 kN/mm. The characteristic strength determined by lead core was estimated to be 670 kN.



bFig. 1 – Dimension of the LRB specimen

Fig. 2 (a) shows the test specimen of LRB. The upper and lower plates have several holes for bolt fastening. The cover rubber was wrapped side of LRB. Test specimen was installed with upper and lower zig plate to be fixed to test machine as shown in Fig. 2(b). The test machine applied vertical force constantly during the horizontal loading. The vertical load, Pd, iss design axial force which is correspond to the axial stress of 13 MPa on the rubber area and it was calculated as 22,000 kN. The horizontal loading was applied by displacement control motions in two-dimensional horizontal plane.

(a) Manufactured LRB specimen



(b) Under the vertical design loading

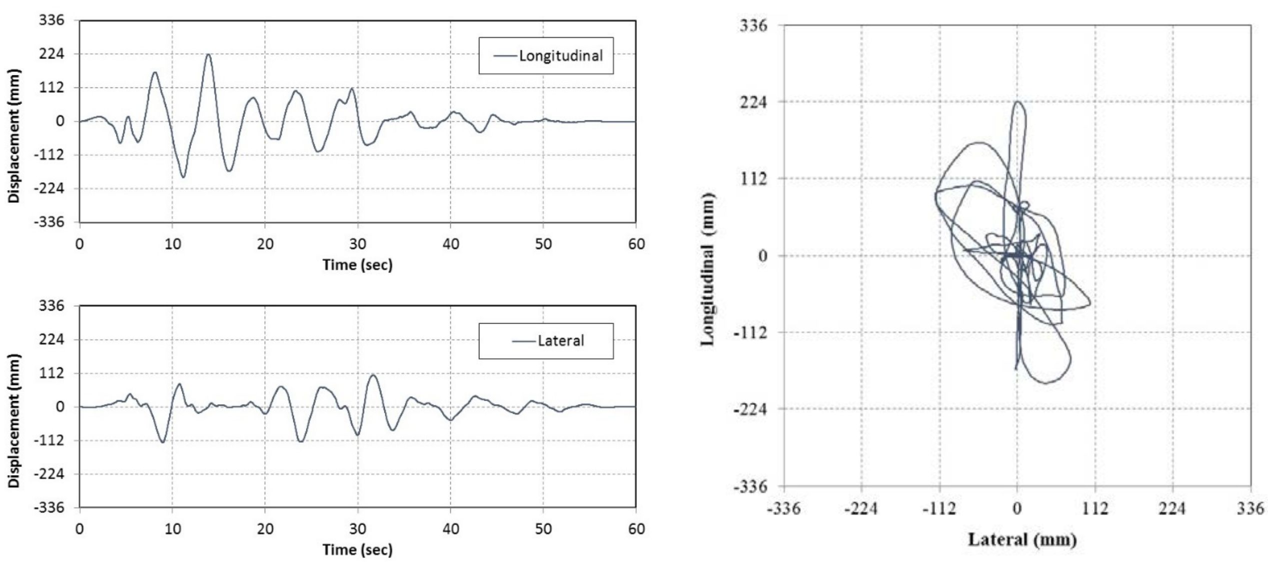
Fig. 2 – View of the LRB specimen

3.2 Input displacement motion

In a seismic design, the structural demand of a seismic load is determined by the design response spectrum. And the directional combination method of resultant forces or displacements of structural elements by two horizontal earthquake input is important. In case of isolation system, isolators usually do not have directionality and the maximum horizontal load can be calculated as a vector sum of two orthogonal horizontal earthquake displacement responses. Therefore, the horizontal movement of base isolated superstructure and its maximum displacement response is important to evaluate the effect of bidirectional behavior.

In this test, the sinusoidal input motion test and the earthquake displacement response input motion test was performed. The earthquake displacement response motion was obtained by numerical analysis of single degree of freedom system with effective isolation frequency and damping ratio. The El-Centro strong ground motion was used as input ground motion. Its displacement response was scaled to have maximum strain of 100%. This earthquake displacement response applied to the test specimens is shown in Fig 3. The 100% strain displacement strain level was determined to be the total rubber height of test specimen, 112 mm.

For the sinusoidal motion, different phase angle was adjusted to have elliptical trace of input displacement motion. The maximum displacement ratio of each direction was determined as 2.0 similar to the earthquake displacement response motion.



(a) Input displacement motion in two orthogonal directions (b) Horizontal trace of input displacement motion

Fig. 3 – View of the LRB specimen

3.3 Test protocol

The test was accomplished by increasing the strain level with 100% interval. Until 200% strain level, earthquake displacement response motion was applied. After that, the elliptical motion was applied to the 500% strain level. Two specimen was tested to compare unidirectional test and bidirectional test. The test until 200% strain level has same test protocol to verify these specimens were almost identical. After that one specimen was tested by one dimensional horizontal motions and the other was tested by two dimensional horizontal motions.

4. Test Result

4.1 Result of design level displacement input test

Fig. 4 shows the strain-force curve by earthquake displacement response scaled by the 100% and 200% strain level. Usually the design strain level is around the 100% strain level in one direction for rubber type base isolation system. Therefore the design displacement in the maximum response direction will be less than 200% strain level.

As shown in Fig 4, the horizontal strain-force curve of 1D-100% strain test can be predicted by bilinear hysteresis model. The second stiffness was almost constant and sharp corner at each unloading chance. In case of 2D-100% strain test, stiffness was slightly decreased when the displacement reached maximum strain level, 200%. It could be a scragging effect by the characteristic of rubber material or because of the increase of temperature by the cumulative hysteretic damping energy. The graph of 2D test shows the strain-force curve to the same direction of 1D test but the displacement input was applied in orthogonal direction simultaneously. The hysteresis curve was much rounded, therefore, it is hard to represent by bilinear curves. This is more likely in small strain level. And the area of hysteresis curve which represent the dissipated energy was reduced in the 2D test. It can cause more large displacement response of isolation system.

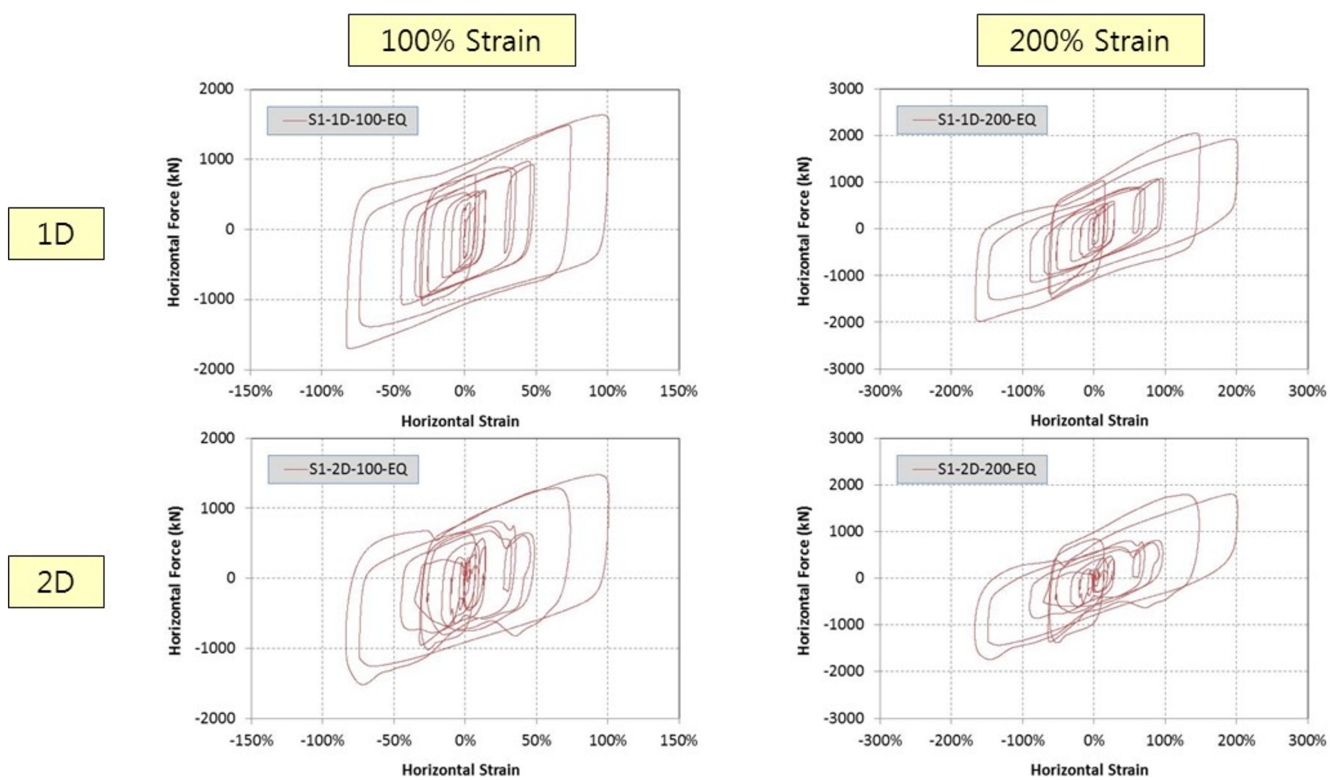


Fig. 4 – Horizontal strain-force curve of unidirectional test and bidirectional test under the displacement response input by earthquake ground motion

4.2 Result of extended design level displacement input test

Fig. 5 shows the strain-force curve by sinusoidal displacement input scaled by the 300% and 400% strain level. The secondary hardening was occurred beyond the 300% strain in all the tests. And the first cycle had high horizontal force compare to the earthquake displacement response tests even in low strain level. It 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 2D tests. The shape of LRB after 2D test is shown in Fig. 6. The body of LRB was distorted with curved side. Nevertheless, the mechanical property of LRB was maintained when 100% strain test was performed again. The distorted shape also recovered to be straight.

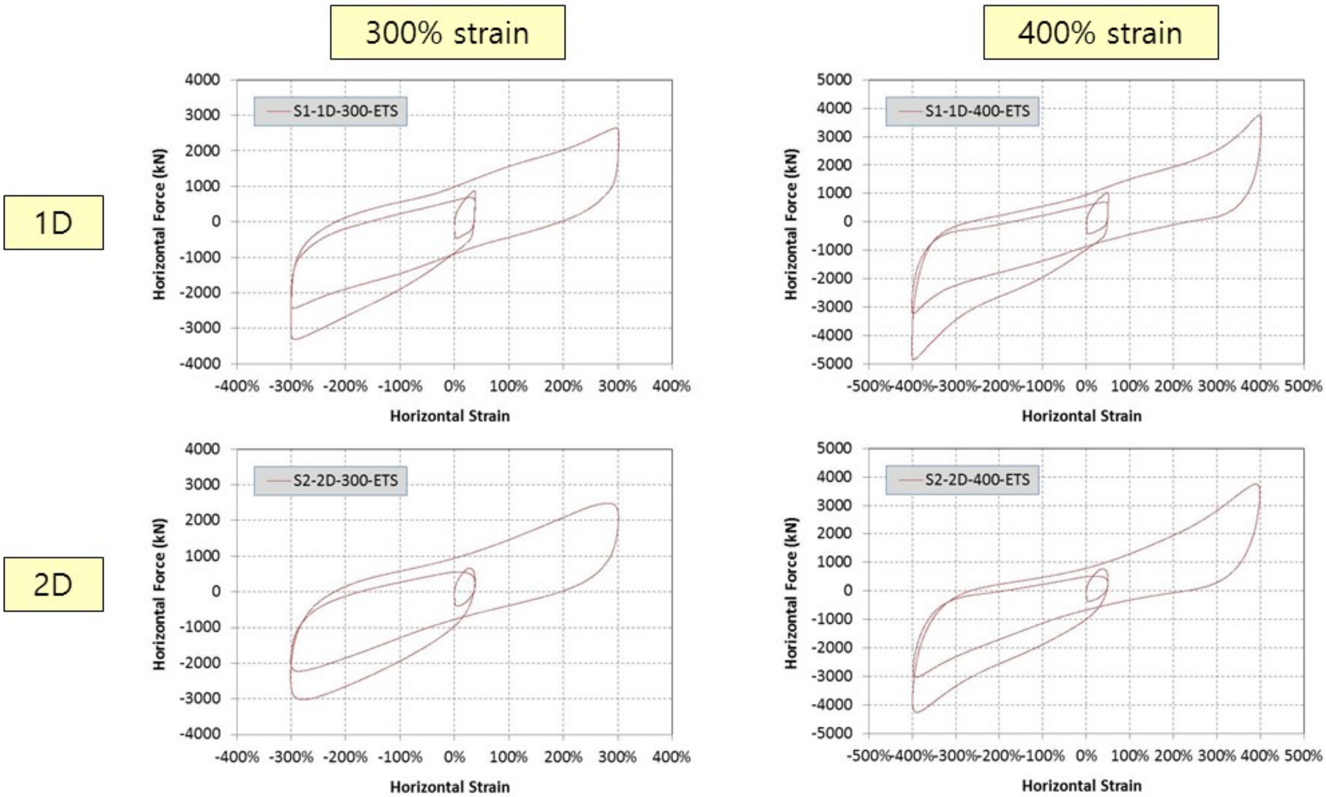


Fig. 5 – Horizontal strain-force curve of unidirectional test and bidirectional test under the sinusoidal displacement input

Fig. 6 – Distortion of LRB after 2D-400% strain test

4.3 Result of extreme displacement input test

As mentioned above, the displacement of extended design basis earthquakes is 3 times of the design basis earthquakes. Therefore around 400% strain level could be performance limit when design strain level is about 100% strain in one direction. In this test, the failure test was performed to examine the bidirectional effect in failure criteria. Fig. 7 shows the different behavior between 1D and 2D input displacements. For the 2D input motion, the input motion in the orthogonal direction has the half amplitude 1D input motion with 90 degree difference of phase angle. In the 1D test, the failure did not occur at the 500% strain level. After this test, the shear fracture was occurred around the 510% shear strain level by monotonically increasing displacement. However in the 2D test, the failure occurred slightly over the 400% strain level. This shows that the horizontal limit state should be estimated to be 20% lower when 1D experiment was applied. After shear fracture of rubber layer, the LRB was severely deformed as shown in Fig. 8. However it still carried the design vertical load. The gap of shear fracture can be seen after the vertical load was removed.

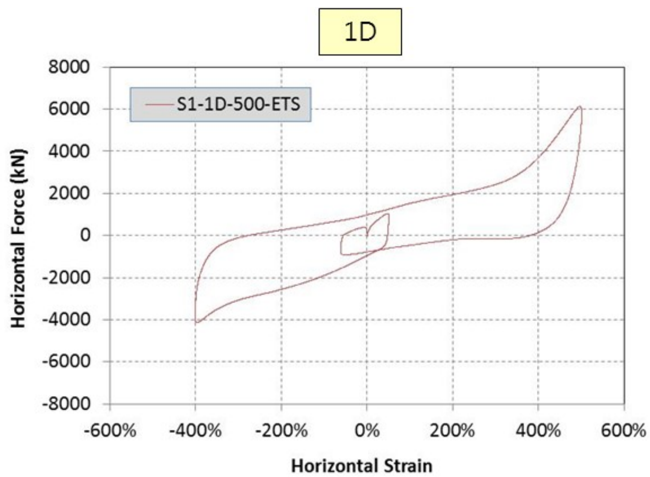


Fig. 7 – Horizontal strain-force curve of unidirectional test and bidirectional test under the extreme displacement input

Fig. 8 – View of test specimens after failure test

5. Conclusion

In this research, various strain level test of LRB were performed and the effect of bidirectional behavior and the ultimate behavior was discussed. For the unidirectional behavior below the design strain level shows predictable behavior represented by bilinear hysteresis curve. However, in can be complex when strain level increases and bidirectional motions are applied. The point to be more emphasized is that the failure limit is reduced when bidirectional movement occurs. The test protocol need to be considered this effect. These results can be applied to the performance test criteria of the LRB for nuclear power plants.

6. Acknowledgements

This work was supported by the Nuclear Power Core Technology Development Program of the Korea Institute of Energy Technology Evaluation and Planning (KETEP), granted financial resource from the Ministry of Trade, Industry & Energy, Republic of Korea. (No. 2014151010170C).

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