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DEVELOPMENT OF EVALUATION METHOD FOR SEISMIC ISOLATION SYSTEMS OF NUCLEAR POWER FACILITIES -BREAK TEST OF FULL SCALE LEAD RUBBER BEARINGS FOR NUCLEAR FACILITIES, PART 1 OUTLINE OF BREAK TEST OF LRB OF 1.6M IN DIAMETER -

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ABSTRACT

In Japan, a research and development program for seismically isolated Nuclear Power Plants was launched in 2008 as the national program entitled "Development of next generation LWRs", partially supported by the Japanese Government. Within the program, a feasibility study had been conducted to specify and choose the best seismic isolation devices for reactor buildings. The horizontal maximum acceleration of design earthquake ground motion is 800 cm/s^2. Consequently, a LRB (Lead Rubber Bearing) of 1600mm in diameter with a large lead plug type is chosen as the actual seismic isolation devices. The diameter of 1600 mm is the largest available on the market in Japan.

For the application of the seismic isolation devices to the safety related facilities, it is important that the ultimate properties are adequately understood under beyond design basis earthquakes, and there should be carefully evaluated scale effects on the breaking strain. However, due to the capacity limitation of the test facilities, there was no data reported on the ultimate properties of LRBs of this size, and a large test machine was needed to provide the data to examine the safety margin of the LRBs. For the above reasons, the world's largest test machine had been developed and constructed to verify the breaking strain of the LRBs experimentally.

In 2013 and 2014, break tests had been performed to evaluate the dependence of breaking strain of the LRBs under various conditions using the test machine. This paper summarizes the break test program, test results on the LRBs of 1600mm in diameter and findings. In addition, this paper presents basic properties as the design specification of the LRBs.

INTRODUCTION

"Development of evaluation method for seismic isolation systems of nuclear power facilities" has been carried out since 2008 as the newest Japanese national project. Within the study, two types of reactor buildings, BWR and PWR, are discussed with the application of seismic isolation systems. In this project, a LRB of 1600mm diameter with a large lead plug was newly designed to satisfy the current design requirements for seismically isolated NPPs, and the type of rubber was changed into G4 from G6. The dimension of the LRBs is as large as possible to reduce the number of bearings required while not excessively large from a viewpoint of production.

For the application of seismic base isolation to the safety related buildings, the ultimate properties of LRBs and the seismic performance of isolation devices should be guaranteed beyond Design Basis Earthquake (DBE), and also, more careful evaluation is required in evaluation for the ultimate behavior of isolators by larger-scale experiments, because it is known that the size effect may not be neglected especially in evaluation on the ultimate property of isolators.

To investigate size effect on break strain of the full scale LRBs, the world's largest break test machine was newly constructed, and static break tests were conducted on full-scale LRBs of 1600mm diameter designed in this project.

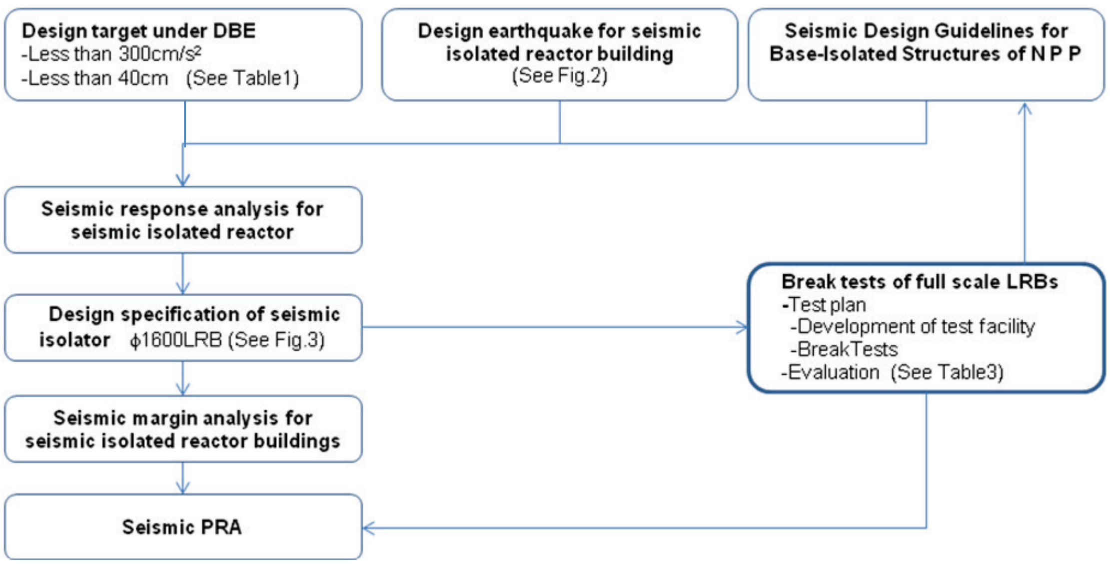


Figure 1. Overview of seismic isolated design and break tests of full scale LRBs in this project

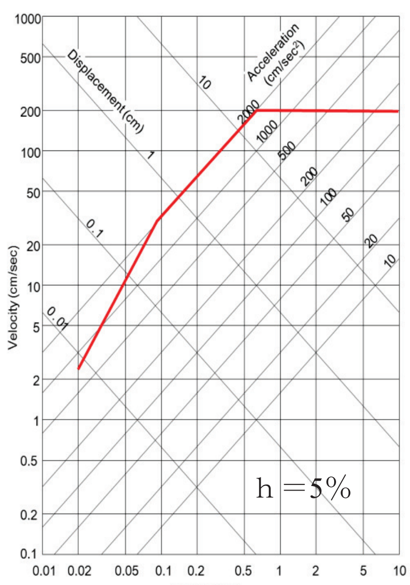


Figure 2. Design earthquake ground motion utilized in the seismic design of reactor buildings with application of seismic isolation system in this project

Table 1 Design target Considered within this project

	Isolated R/B	LRB	
	Response acc. at base mat	Shear deformation	Lateral displacement
Design target	Less than $300 cm/s^2$	Less than δ_e /1.5	Less than 40cm

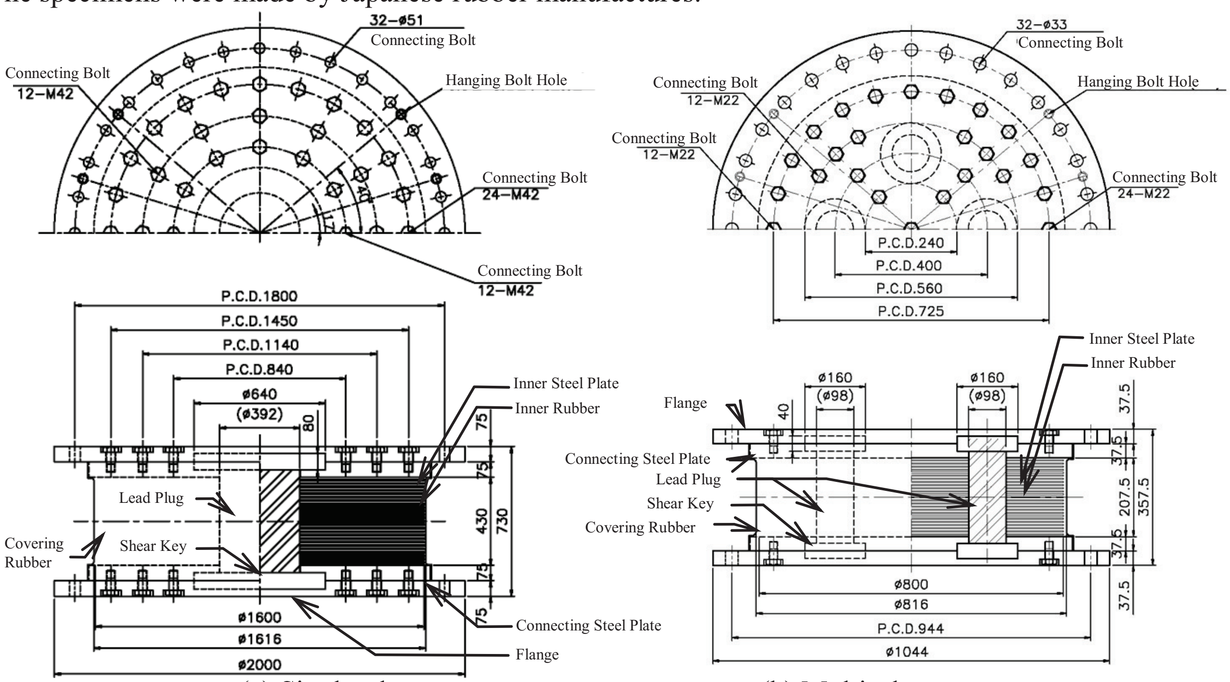
R/B: Reactor Building

δ_e: elastic limit deformation of LRBs

TEST SPECIMENS AND TEST MACHINE

Test Specimens

Two types of LRB of 1600mm in diameter, a large-diameter single-plug type and a multi-plug type with four plugs, are tested, as common seismic isolation systems for both BWR and PWR reactor buildings. Fig-3 shows details of single plug type LRB and multi-plug type LRB. Test specimens have an overall diameter of 1600mm, a total rubber height of 260mm and first shape factor S1 equal to 40.0. There are 26 layers of elastomer, each 10mm thick, alternated with 25 steel plates of 6.8mm thickness. The bearings were fabricated using a compound with a shear modulus G=0.4MPa, and, multi plug type LRBs and single plug type LRBs with shear modulus G=0.6MPa were also manufactured as reference specimens. The specimens were made by Japanese rubber manufactures.



(a) Single-plug type (b) Multi-plug type

Figure 3. Configuration of lead-rubber bearing for seismic isolated reactor building examined in this project

Table 2 Specification of lead rubber bearings for the seismic isolation system examined in this project

Rubber diameter	1,600 mm
Bearing load	9,000 kN
Axial stress	4.8 MPa
Horizontal period T_2	3.41 s (2.90 s*2)
Yield seismic intensity β	0.121
Vertical frequency	16.3 Hz (17.1 Hz*2)
Inner rubber	10.0 mm × 26 layers
Inner steel plate	6.8 mm × 25 layers
Lead plug diameter	392 mm (196 mm*3)
Aspect ratio of lead plug	1.097 (2.19*3)

*1: Single plug-G4 rubber type
*2: G6 rubber type, *3: Multi-plug type

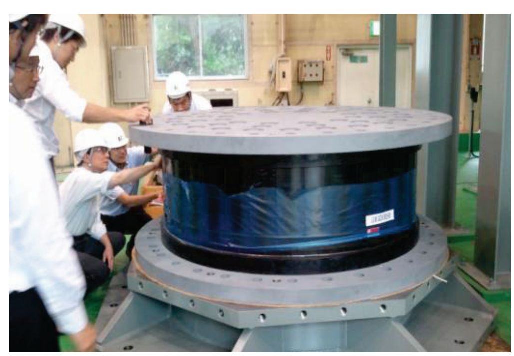


Figure 4. Test specimen
(Lead-rubber bearing of diameter 1600mm)

Test Machine

The test machine consists of an actuator assembly, a reaction frame, a hydraulic power supply and a digital control system. The maximum horizontal capacity is 25MPa with a large stroke. The maximum vertical capacity is 16MPa in compression and 9.5MPa in tension. The break test condition is not only under compression but also under tension. The test machine has a maximum displacement capacity of 0-2,200mm and a maximum loading capacity of 25.1MN in the horizontal direction. Table 3 shows the specification of the test machine, shown in Figure 4.

Table 3 Specification of the test machine

Horizontal direction	Max. load (kN)		25,100
	Max. displacement (mm)		0～2,200 *1*2
Vertical direction	Max. load	Tensile (kN)	9,500
		Compressive (kN)	-16,000
	Max. displacement (mm)		0～1,200 *1
Velocity (cm/s)			0.25

*1 : Monotonous loading
*2 : Alternative loading on 100% shear strain is available.

Figure 4. Photograph of Test machine

The test machine is composed of four vertical and three horizontal actuators as shown in Figure 5. Vertical force is applied by four hydraulic servo control actuators to provide various stress levels. Shear force is applied by three hydraulic servo control actuators to the horizontal slide table. The specimens are placed between the vertical and horizontal slide table. Specimens are bolted with the slide tables. Top and bottom of the specimen are bolted.
Layout of sensors is shown in Figure 6. All the loads are measured by load cells of 10MN, mounted between the end of the pistons and the slide tables. Deformation of the specimen is measured by laser type and gauge type displacement sensors. LRB surface temperature and hydraulic pressure of each actuator of the test machine are measured.

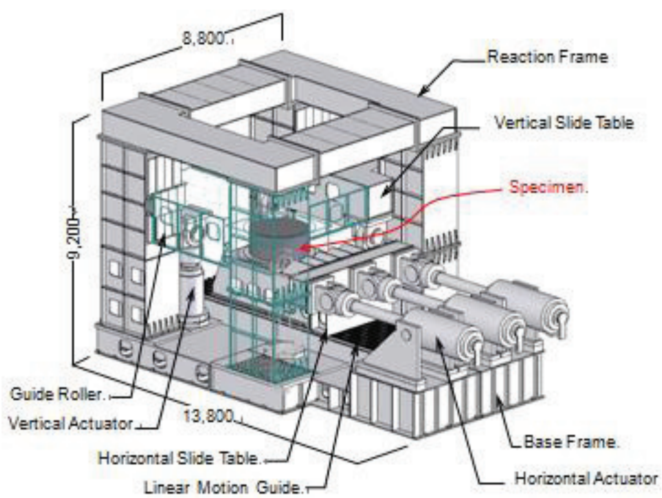


Figure 5. Schematic view of the test machine

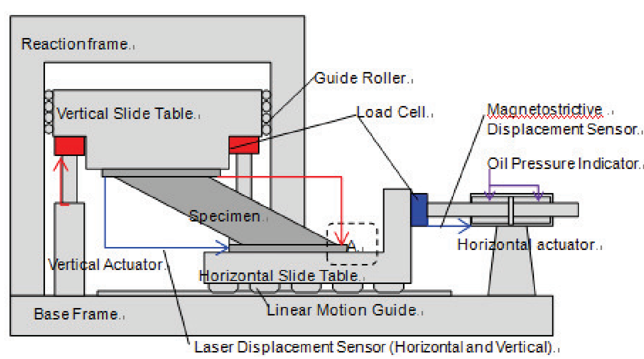


Figure 6. Layout of sensors

TEST PARAMETERS

Basic Property Test

Static loading is repeated four times horizontally by use of a triangular wave at a loading rate of 2.5 mm/s and a displacement amplitude of ±260 mm (shear strain: 100 %) under design contact pressure (-5MPa) so as to evaluate horizontal stiffness (Kd), shear force (Qd) at 0% shear strain and equivalent damping constant (Heq) as the basic characteristics of the LRBs in the horizontal direction. To evaluate vertical stiffness (Kv), static loading is repeated four times vertically by use of a triangular wave under a variable contact pressure of ±30 % of design contact pressure under load control.

Break Tests

(1) Shear Break Tests
A series of shear break tests was conducted by applying horizontal force at six vertical stresses as shown in Table 4. Due to the capacity limitation of the test machine, shear breaking tests under the compression pressure at -15MPa and -30MPa are performed using a couple of 1/2 scale models. These tests are performed by controlling vertical forces.

Table4 Test parameters for shear break tests of full-scale LRB

	Axial Stress (MPa) *1					
	-30	-15	-8	-5	0	1
φ1600-G4-single plug type	-	-	○	○	○	○
φ800-G4-single plug type	○	○	-	○	-	-
φ1600-G4-multi-plug	-	-	-	○	-	-
φ1600-G6-single plug type	-	-	-	○	-	-
φ1600-G4-single plug type *2	-	-	-	○	-	-

*1 : negative, compression *2 : manufactured by other maker with same specs

(2) Tensile Break Tests under offset shear strain
A series of tensile break tests was conducted by applying vertical force at five off-set shear strains of 0, 100, 200, 300, and 400% under the pressure of -5MPa as shown in Table 5. During the tensile breaking test, the machine kept the off-set shear strain. These tests were performed by applying vertical force under the horizontally off-set displacements.

Table 5 Test parameters for tensile break tests of full-scale LRB

	Offset Shear Strain				
	0 [%]	100 [%]	200 [%]	300 [%]	400 [%]
φ1600-G4-single-plug type	○	○	○	○	○
φ1600-G4-multi-plug type		-	-	○	-
φ1600-G6-single-plug type		-	-	○	-
φ1600-G4-single-plug type ＊		-	-	○	-

＊ : manufactured by other maker with same specs.

TEST RESULTS

Tests cases for break tests of full-scale LRB (G4) are given in Table 6. It was found that breaking axial strains with offset shear strain 200% and 300% were smaller than those evaluated by small models in the previous study. In order to obtain more test result data, additional tensile break tests on full scale LRBs with the same large offset shear strains were carried out. The loading patterns and test number are shown in Figure 8.

Table 6 Test conditions for break tests of full-scale LRBs (Rubber: G4)

Test No.	Break tests	Axial Stress [MPa]	Offset Strain [%]	Test specimen		Surface Temp. (℃)
				Diameter [mm]	Plug type	
1	shear break test	-5	-	1600	Single	25.8
2	tensile break test	-	0	1600	Single	20.0
3	shear break test	-8	-	1600	Single	15.5
4	shear break test	0	-	1600	Single	15.3
5	tensile break test	-	100	1600	Single	14.4
6	tensile break test	-	200	1600	Single	12.4
7	tensile break test	-	300	1600	Single	10.3
8	tensile break test	-	400	1600	Single	9.3
9	shear break test	-5	-	800	Single	8.6
10	shear break test	-15	-	800	Single	8.1
11	shear break test	-30	-	800	Single	9.9
12	shear break test *3	-5	-	1600	Multi	8.8
13	shear break test	1	-	1600	Single	6.6
14	tensile break test *1	-	400	1600	Single	26.2
15	shear break test *4	-5	-	1600	Multi	27.8
16	tensile break test *1	-	200	1600	Single	24.2
17	tensile break test *1	-	300	1600	Single	23.8
18	tensile break test *4	-	300	1600	Multi	22.4
19	shear break test *2	-5	-	1600	Single	19.6
20	shear break test *2	-5	-	1600	Single	19.6

*1 : Additional tests to confirm tensile break strain with large offset strain,200%, 300%, and 400%
*2 : Reproducibility under design contact pressure
*3 : four plugs type with 0 degree loading
*4 : four plugs type with 45 degree loading

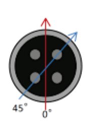


Figure 7. Loading directions for multi plug

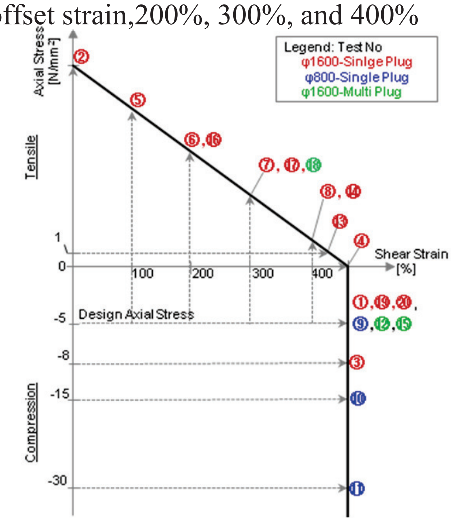


Figure 8. Loading patterns and Test No.

Break Tests for Ultimate Property Diagram of Φ1600 LRBs

(1) Shear Break Tests
Shear break tests were monotonically conducted on eight full scale LRBs (φ1600-G4) and three half-scale LRBs under large axial stresses. Figure 11 shows tests results for the breaking conditions. All the LRBs exhibited good horizontal ductility capacity approximately corresponding to 450% shear strain, as evaluated by scale models in the previous studies. Under the tensile stress of 1MPa, shear strain at break point is 394%. Figure 9 shows the full-scale LRB and Figure 10 shows the LRB during test.

(2) Tensile Break Tests
Monotonic tensile break tests were performed on nine full scale LRBs (φ1600-G4) to evaluate effect of the offset shear strain on the tensile capacity. Figure 12 shows offset shear strain-axial strain relationship of tensile break tests on full-scale LRBs. Breaking axial strains with offset shear strain 200%, 300% and 400% were small with 141% or less compared with those of full-scale LRBs with offset shear strain 0% and 100%. From the results of tensile break tests, it was confirmed that breaking axial strains of all full-scale LRBs on tensile break tests were more than 11% .

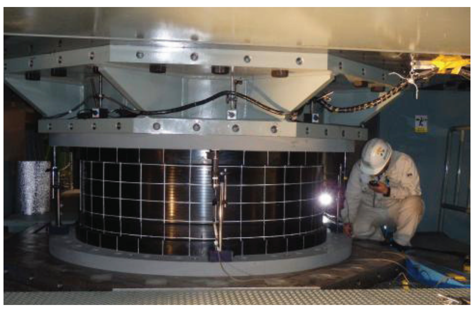


Figure 9. Photograph of full-scale LRB

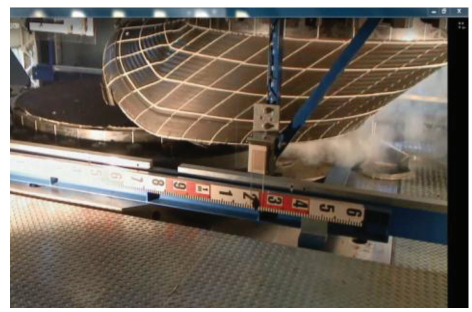


Figure 10. Photograph of full-scale LRB during test

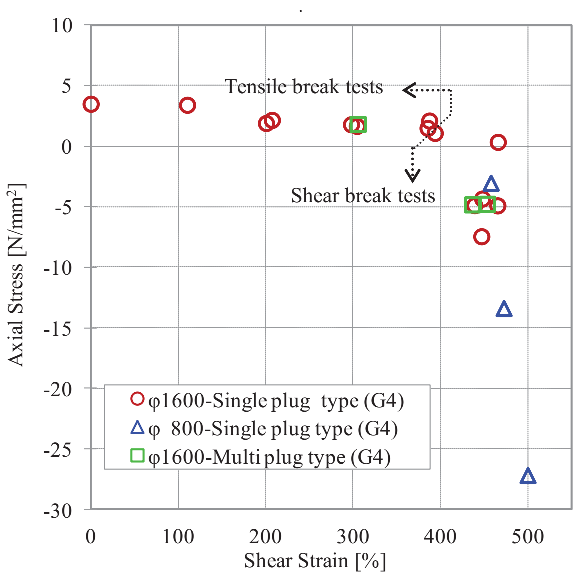


Figure 11. Breaking conditions in shear strain-axial stress plane
(ϕ 1600LRB, G4)

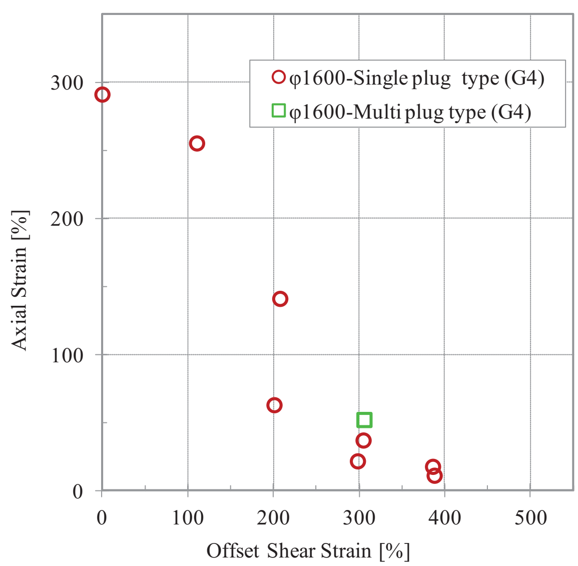
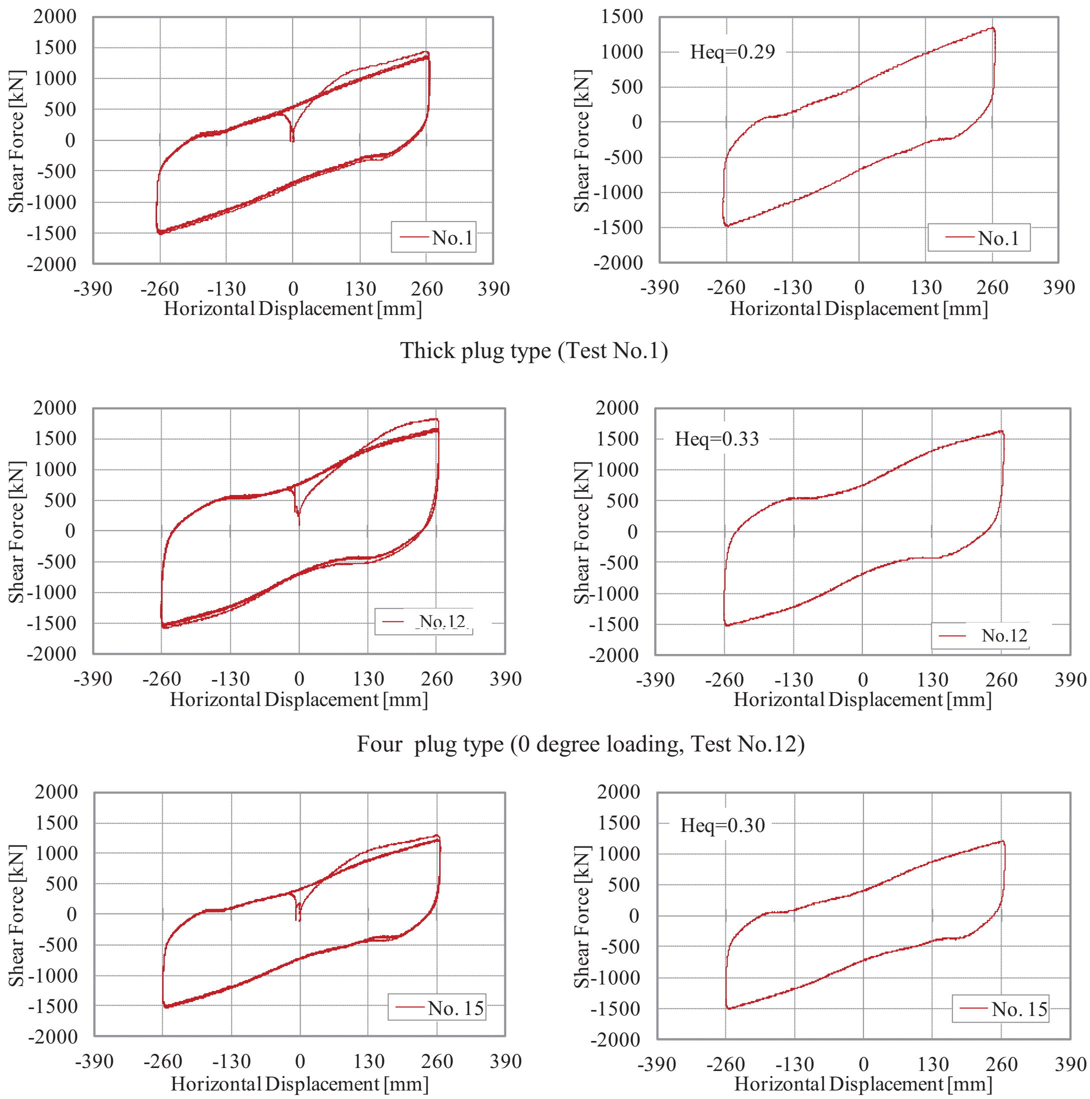


Figure 12. Breaking conditions in shear strain-tensile strain plane (ϕ 1600LRB, G4)

Hysteresis loops of Φ1600 LRBs

Prior to break tests, the basic property test for the LRB specimens was performed to investigate the basic performance of the specimens in horizontal and vertical directions. Figure 13 shows the results of static loading test in the horizontal direction under a contact pressure of -5MPa and a shear strain of 100 %. The basic property is evaluated by use of the third of four loops of repetitive loading-displacement relations. Figure 13 (a) shows all hysteresis curves (for 4 loops) of the horizontal basic property test of the full-scale seismic isolators as a sample. The third loop is shown in Figure 13 (b). The hysteresis loops with two different plug types are stable, and the equivalent damping coefficient is around 0.3, although the volume of the plug is 1.5 times that of standard LRBs in the market.



Thick plug type (Test No.1)

Four plug type (0 degree loading, Test No.12)

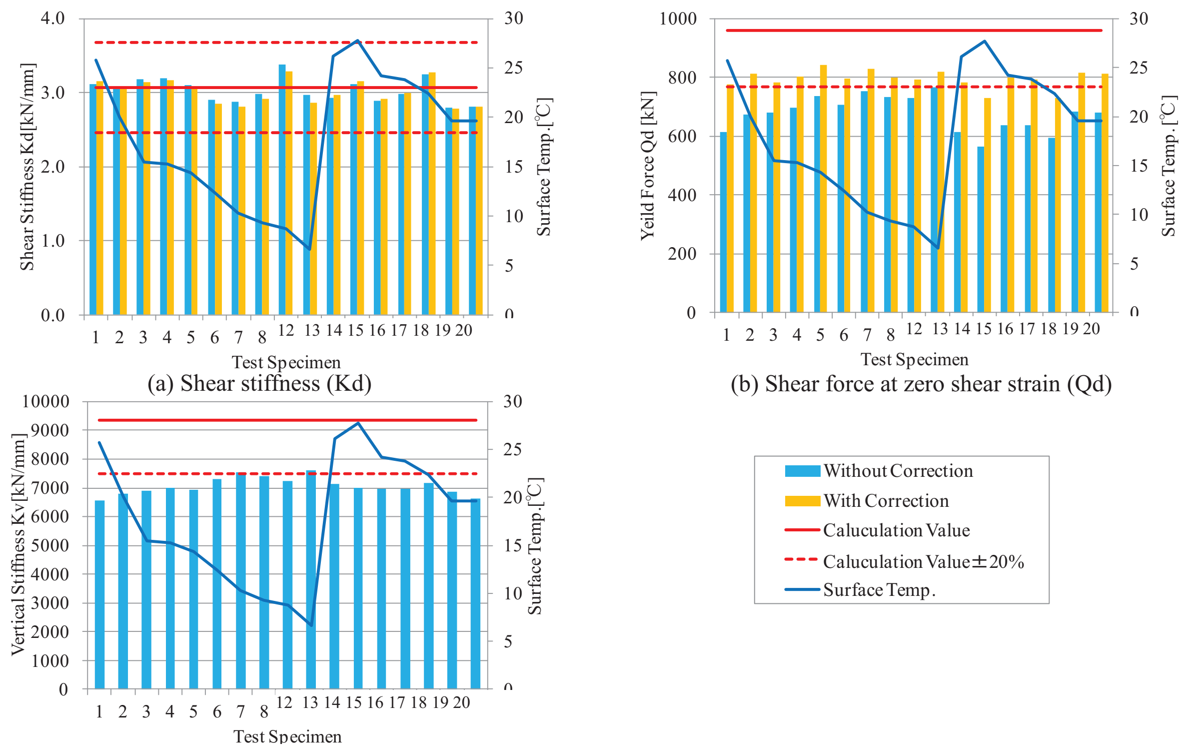
Four plug type (45 degree loading, Test No.15)

(a) For four loop (b) third loop

Figure 13. Load-displacement relationship of LRBs (ϕ 1600, G4)

Basic Properties of Φ1600 LRB

Figure 14 shows the results of the basic properties, (Kd, Qd and Kv) and the design specification. The design specification line in Fig.14 are evaluated by size and physical property of rubber and lead of the LRB at 20 ℃. The shear stiffness given here refers to the values with and without temperature correction, and the shear force at 0% shear strain shows with and without temperature correction of 20 ℃ and loading rate correction because Qd is influenced by lead temperature and strain rate.
The shear stiffness is almost the same as the design specification utilized in the seismic response analysis in this study. The yield force and vertical stiffness remain within 20 % of the design specification as shown Figure 14(b) and (c).



(a) Shear stiffness (Kd)

(b) Shear force at zero shear strain (Qd)

(c) Vertical stiffness (Kv)

Figure.14. Results of basic property tests (ϕ 1600 LRB (G4))

CONCLUSION

Break tests were conducted in order to investigate ultimate properties of LRBs of 1600 mm in diameter with a large lead plug. The results obtained herein are summarized as follows:

(1) Under the compressive load, breaking shear strains are approximately 450%, as evaluated by scale models in the previous studies. Also, under the tensile load of 1.0 MPa, breaking shear strains are approximately 400%. Tests results indicate almost no scale effect on the break strains.
(2) Tensile break strains of LRBs of 1600 mm in diameter were more than 11% under large offset shear strains. Break strains were basically less affected by scale of specimens in the vertical direction, although tensile break strains with large off-set shear strains were slightly small.
(3) It was confirmed that the hysteresis loops with two different plug types are stable, and the equivalent damping coefficient is approximately 0.3, although the volume of the plug is 1.5 times that of standard LRBs on the market.

We will apply the findings obtained in this project to updating the JEAG4614-2013.

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REFERENCES

Nuclear Safety Commission of Japan (2006), "Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities."

Japan Electric Association (2013), "Technical Guidelines on Seismic Base Isolated System for Structural Safety and Design of Nuclear Power Plants (JEAG4614-2013) .".

Matsuoka, S. et al.(2013), "Development an Evaluation Method for Seismic Isolation System (Part 1) Design of Seismic Isolation Systems for Nuclear Power Plant," Proc. of 13th World Conference on Seismic Isolation, Energy Dissipation and Active Vibration Control of Structures.

Takeuchi, Y. et al.(2013), "Development an Evaluation Method for Seismic Isolation System (Part 2) The Basic Characteristics Test of a Seismic Isolation System for Nuclear Power Plant," Proc. of 13th World Conference on Seismic Isolation, Energy Dissipation and Active Vibration Control of Structures.

Suzuki, Y. et al.(2014), "Development of an Evaluation Method for Seismic Isolation Systems of Nuclear Power Facilities (Part 1), The Work Schedule of Project and a Seismic Design of Crossover Piping System," ASME PVP2014-29035.

Kosugi, S. et al.(2014), "Development of an Evaluation Method for Seismic Isolation Systems of Nuclear Power Facilities (Part 7), Breaking Test Plan and Development of Test Machine for Full-Scale Lead Rubber Bearings," ASME PVP2014-29009.

Sato, N. et al.(2014), "Development of an Evaluation Method for Seismic Isolation Systems of Nuclear Power Facilities (Part8), Fundamental Properties of Full-Scale Lead Rubber Bearings Based on Breaking Test," ASME PVP2014-29006.

Hiraki, T. et al.(2014), "Development of an Evaluation Method for Seismic Isolation Systems of Nuclear Power Facilities (Part9), Ultimate properties of full-scale lead rubber bearings based on breaking test," ASME PVP2014-29001.

Nakayama, T. et al.(2015), "Development of Evaluation Method for Seismic Isolation Systems of Nuclear Power Facilities, -Break Test of Full Scale Lead Rubber Bearings for Nuclear Facilities, Part 2," Trans of the twenty-third Structural Mechanics in Reactor Technology (SMiRT-23), Manchester, UK .

Mori, T. et al.(2015), "Development of Evaluation Method for Seismic Isolation Systems of Nuclear Power Facilities, -Break Test of Full Scale Lead Rubber Bearings for Nuclear Facilities, Part 3," Trans of the twenty-third Structural Mechanics in Reactor Technology (SMiRT-23), Manchester, UK .

Kanazawa, T. et al.(2015), "Development of Evaluation Method for Seismic Isolation Systems of Nuclear Power Facilities, -Break Test of Full Scale Lead Rubber Bearings for Nuclear Facilities, Part 4," Trans of the twenty-third Structural Mechanics in Reactor Technology (SMiRT-23), Manchester, UK .