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Characteristics of Reduced-Scale High Damping, Lead, and 3D Laminated Rubber Bearings for Seismic Isolation for Nuclear Facilities

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1. Introduction

The various seismic isolation systems composed of rubber bearings have been applied for the seismic isolation design and construction of the nuclear facilities [1-2], such as PWRs (Koeberg NPPs, Cruas NPPs), Research Reactor (JHR), fusion reactor (ITER), a Liquid Metal Reactor (KALIMER), Lead Cooled Reactor, and Generation IV reactors to improve the safety and the economic benefit against Design Basis Earthquake and Beyond Design Basis Earthquake.

Through the fabrications and tests of rubber bearings, the stiffness and the damping characteristics of the bearings are key parameters of the seismic isolation systems, which determines design isolation frequencies of the isolated nuclear facilities housing all safety related structures, systems, and components to reduce the seismic acceleration responses, hence to enhance the structural integrity of the whole nuclear facilities subjected to strong earthquakes [3-6].

This paper presents design targets of the isolators (LRBs), static and dynamic shear-compression test results, and evaluation of the characteristics of lead rubber bearings (LLRB) with different lead plug diameters, High Damping Rubber Bearing (HLRB), and 3-D LRB [4,7].

2. Design Targets and Test Setting for LRBs

The key design targets for LRBs are horizontal and vertical stiffness, damping coefficients, and the maximum shear strain under design vertical load, and the design targets of prototype and 1/8 scale LRBs to be tested are as shown in Table 1. Vertical target damping value for 3D-LRB is 10%.

Table 1 Specification and Design Targets for LRB

	Prototype LRB	1/8 Scale LLRB
Design Vertical Load (Ton)	294	4.6
Effective OD(cm) / ID(cm)	120/4	15/(2.7,3.7,4.8)*
Rubber Thick.(mm)Layers	278(9.629)	34.8(1.229)
Steel Thick.(mm) x Layers	3.2 x 28	1.8 x 28
Primary Shape Factor($D/4t_r$)	31.25	31.25
Secondary Shape Factor(D/nt_r)	4.31	4.31
Vertical Stiffness(kgf/cm)	$51.6x10^5$	$6.4x10^5$
Horizontal Stiffness (kgf/cm)	2,846 (5,692)**	356 (711.4)**
Damping Coefficient(%)	12	12
Max. Shear Strain(%)	300	300

* Inner Diameter of Lead Rubber Bearing and Diameter of Lead Plug
** Horizontal Stiffness at Isolation Frequency of 0.5 Hz (0.7Hz)

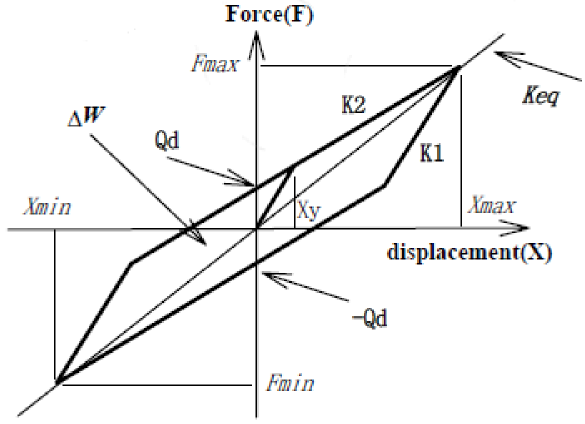


Fig. 1 Schematics of Equivalent Stiffness and Damping from LRB Tests

In Figure 1, Equivalent Stiffness (Keq) and equivalent damping (ζeq) are simply defined as follows;

$$K_{eq} = \frac{F_{max} - F_{min}}{X_{max} - X_{min}}, \qquad \zeta_{eq} = \frac{\triangle W}{2\pi K_{eq}\,\delta_{max}}$$

The hysteretic characteristics of rubber bearings can be obtained by shear-compression bearing tests as shown in Figure 2. The test data are plotted and analyzed to be compared with design target values such as equivalent horizontal stiffness, yield load value, and equivalent damping ratio, specifically including the vertical deformation characteristics for the HLRB, LLRB, and 3-D LRB as shown in Figures 3 & 4.

The 1/8 scale 3D-LRB composed of integral 2D horizontal synthetic rubber bearing with series of dish springs on top of the 2D LRB connected by rigid surrounding cylindrical container was designed and fabricated. Several kinds of tests are performed to characterize the isolation function of 3D-LRB in two horizontal and vertical directions. The vertical performance tests of 3D-LRB are also carried out with different shear strains.

The variations of the equivalent horizontal stiffness, yield load value, and equivalent damping ratio for the 1/8 scaled high damping, lead, and 3D-LRB are evaluated from test data in range of 25% to 150% of shear strain in horizontal direction.

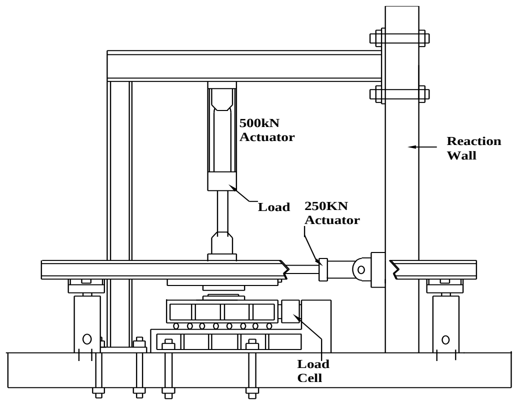


Fig. 2 Shear-Compression Test Setting up for Actuators (V 500KN, H 250KN) and Load Cell

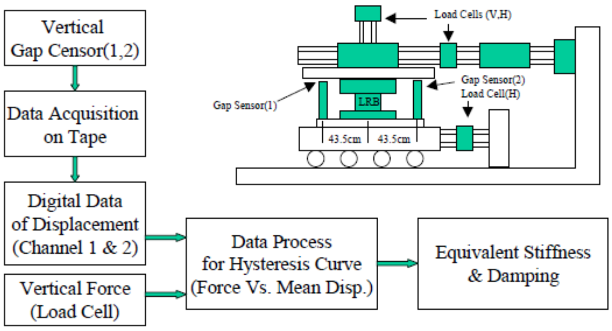


Fig. 3 Test Data Process of Shear-Compression Test for LRBs

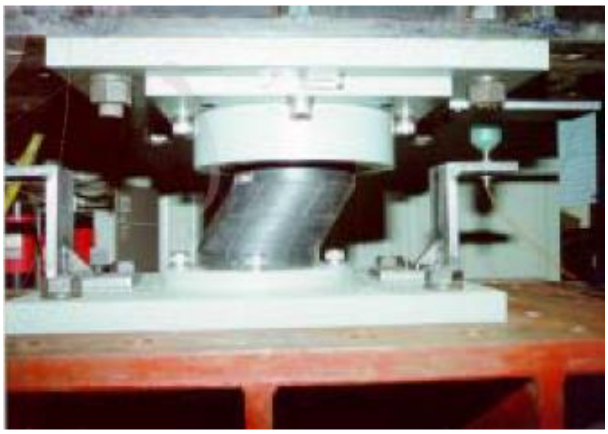


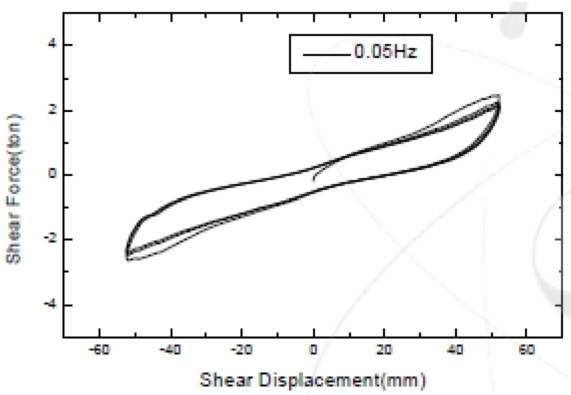
Fig. 4 Shear-Compression Test for 3D-LRB

3. Results and Discussion

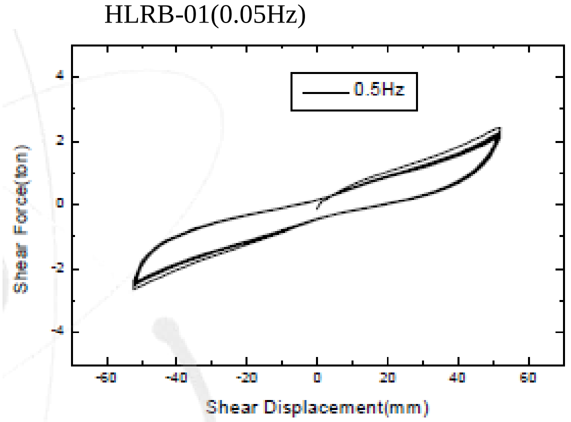
3.1. HLRB Tests

Two HLRBs are tested to obtain the equivalent stiffness and damping values depending on its shear strains from 25% to 150% with varying horizontal actuator frequencies simulating static test by 0.05Hz and dynamic test by 0.5Hz, separately.

Figure 5 shows, for example, the hysteretic curves of HLRB-01 at 150% shear strain for static test with 0.05HZ and dynamic test with 0.5Hz.



a) Hysteretic Curve of 150% Shear-Strain of HLRB-01(0.05Hz)



b) Hysteretic Curve of 150% Shear-Strain of HLRB-01(0.5Hz)

Fig. 5 Horizontal Hysteretic Curves of 150% Shear-Strain of HLRB-01 (a) 0.05Hz, b) 0.5Hz)

In comparison of equivalent stiffness and damping values of HLRB-01 between static tests with 0.05Hz and dynamic tests with 0.5Hz, both properties are reduced from 0.0576 ton/mm to 0.0426 ton/mm, and from 16.52% to 12.5% for static test, and from 0.07 ton/mm to 0.0444 ton/mm, and 14.0% to 10.56%, for dynamic tests, respectively, as shear strain are increasing from 25% to 150%, as shown in Table 2.

Average stiffness in static and dynamic tests are similar, but average damping value of 12.68% in dynamic tests is smaller than that of 14.56% in static tests.

Equivalent damping values of 13.8% and 12.64% of the HLRBs with 100% shear strain in both static and dynamic tests meet the design target value of 12%.

Table 2 Test Results of HLRB-01 (Equivalent Stiffness and Damping Values depending on Shear Strain)

		Stiffness(ton/mm)	Eqdam	displacement(mm) (max/min)
static	25	0.05762	0.1652	8.754/-8.740
	50	0.05962	0.1538	17.47/-17.47
	100	0.04642	0.1382	34.97/-34.98
	150	0.04264	0.1250	52.41/-52.41
dynamic	25	0.07003	0.1401	8.712/-8.694
	50	0.05501	0.1354	17.42/-17.46
	100	0.04412	0.1264	34.87/-34.87
	150	0.04447	0.1056	52.21/-52.27

3.2. LLRB Tests

Four 1/8-scaled LLRBs with effective Outer Diameter of 15 cm are made of natural rubber bearing (NRB) with 4 different diameters of lead plug, 0.0, 27.0 (= 0.18OD), 37.0 (= 0.247OD), and 48.0 (= 0.32OD) mm, and test results are as shown in Figures 6 & 7.

As increasing the lead plug diameter, the values of equivalent stiffness are reduced asymptotically to zero plug diameter NRB as shear strain is increasing to 150% in both static and dynamic tests, while average equivalent damping values are increased from 5, 8, 22.0, to 31.0% in static tests, and from 2.5, 6.0, 20.0, to 29.0 % in dynamic tests, respectively.

Average equivalent damping values of 20.0-31.0% of the LLRBs with above 37 mm lead plug at 100% shear strain in both static and dynamic tests meet the design target value of 12%.

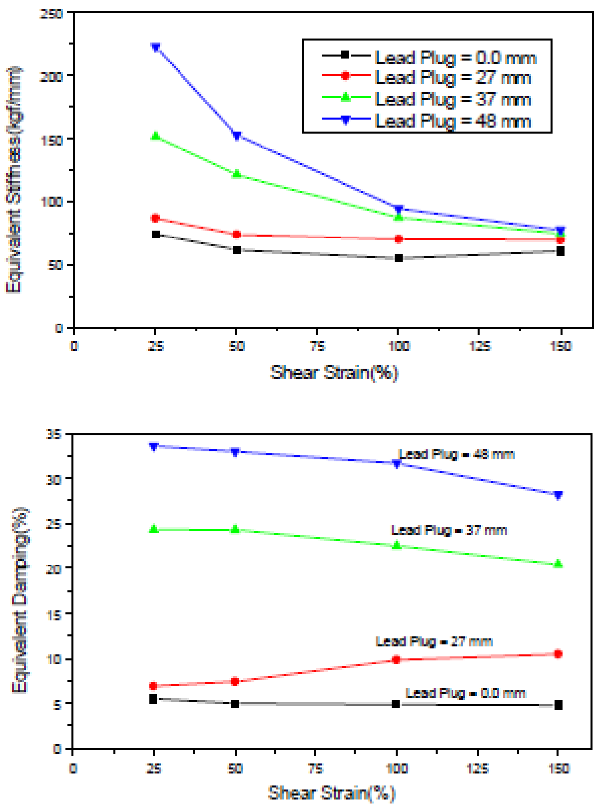


Fig.6 Shear Stiffness and Damping of LLRB-03 (0.05Hz)

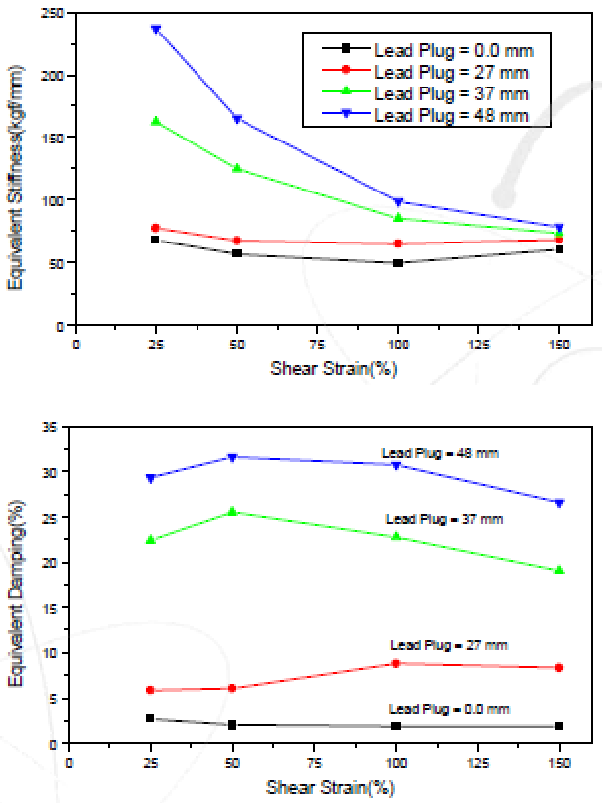
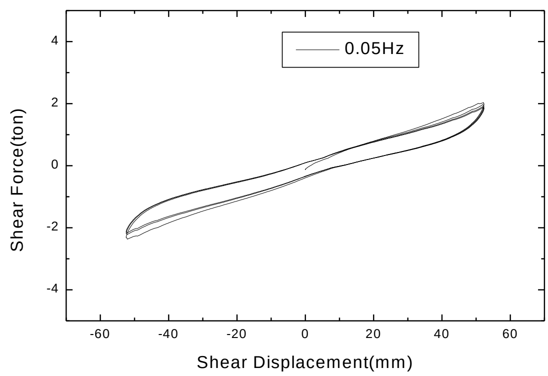


Fig.7 Shear Stiffness and Damping of LLRB-03 (0.5Hz)

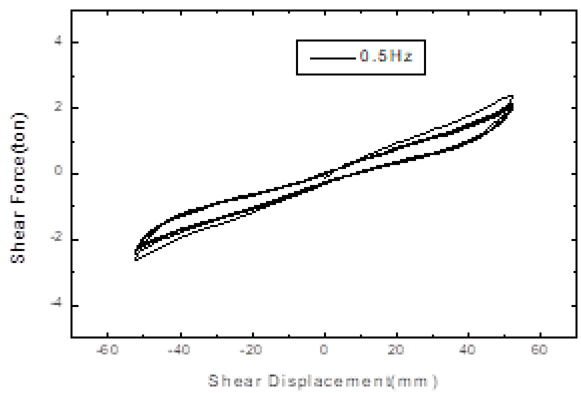
3.3. 3D-LRB Test

Five 3D-LRBs show a good horizontal and vertical performance during shear-compression tests, and the hysteretic curves for 3D-LRB-01 are as shown in Figures 8-10.

Average horizontal equivalent damping values for five 3D-LRBs made of natural rubber are 8.2% in static tests, and 6.64% in dynamic tests, which are less than the design target of 12%. To increase horizontal damping horizontal part of the 3D-LRB should be LLRB or HLRB instead of synthetic NRB.



a) Horizontal Hysteretic Curve of 150% Shear Strain with 0.05 Hz

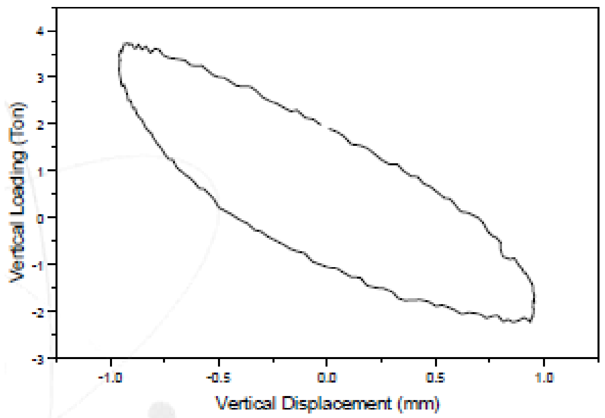


b) Horizontal Hysteretic Curve of 150% Shear Strain with 0.5 Hz

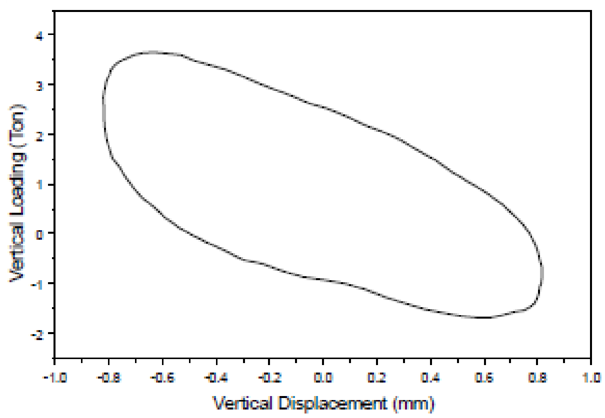
Fig. 8 Horizontal Hysteretic Curves of 150% Shear Strain of 3D-LRB-01 with 3V(4.5ton+-3ton) (0.05Hz and 0.5 Hz)

The vertical hysteretic curves for 3D-LRB-01 are as shown in Figure 9, and vertical deformation tests for five 3D-LRBs are as shown in Figure 10 and Table 3. The vertical equivalent stiffness values for five 3D-LRBs made of serial dish springs vary from 2.17 to 4.4ton/mm, which are larger than the design target of 1.25ton/mm. The larger vertical stiffness would cause to increase the vertical isolation frequency.

The vertical equivalent damping values for five 3D-LRBs made of serial dish springs vary 7.88~54.26%, and average vertical equivalent damping values are 23.9% in static tests, and 25.7% in dynamic tests, which are larger than the design target of 10%.



a) Third cycle, 2.746 ton/mm, 28.8% Damping (0.05Hz)



b) Third cycle, 2.17 ton/mm, 54.26% Damping (0.5Hz)

Fig. 9 Vertical Hysteretic Curve of 3D-LRB-01 Isolator

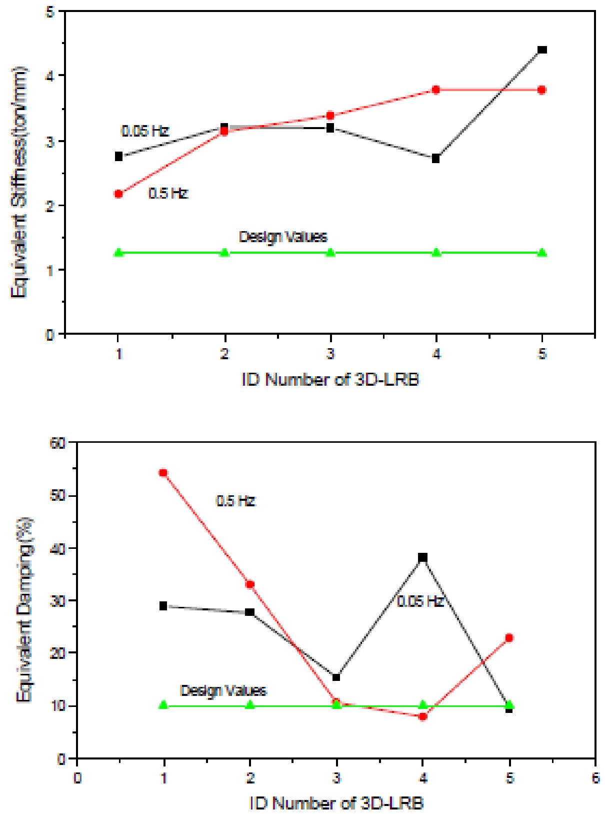


Fig. 10 Vertical Stiffness and Damping of 3D-LRBs (green: design value, black: 0.05Hz, red: 0.5Hz)

Table 3 Vertical Equivalent Stiffness and Damping of 3D-LRBs

	Test Speed	3D LRB-01	3D LRB-02	3D LRB-03	3D LRB-04	3D LRB-05
Equivalent Stiffness (Ton/mm)	0.05Hz	2.746	3.210	3.196	2.719	4.415
	0.5Hz	2.170	3.136	3.387	3.786	3.784
Equivalent Damping (%)	0.05Hz	28.88	27.65	15.40	38.10	9.54
	0.5Hz	54.26	33.00	10.60	7.88	22.82

4. Conclusion

This paper evaluates the characteristics of the HLRB, LLRBs with 3 different lead plug diameters, 3D-LRB obtained by shear-compression tests with 2 different shear frequencies of 0.05Hz (static) and 0.5Hz (dynamic), respectively. Test results are compared with the design target values to provide with the equivalent stiffness and damping values for the seismic base isolation system designs for the nuclear facilities.

The conclusions of the evaluation of the LRB tests are as follows;

1) In HLRBs, the average equivalent stiffness is smaller than the design target, but the average equivalent damping values meets the target of 12%.

2) In LLRB with 3 different lead plug diameters, as increasing the lead plug diameter, the values of yield load, equivalent stiffness are asymptotically reduced to that of zero lead plug diameter, while equivalent damping values are increased to 34%.

3) All five 3D-LRB shows a good mechanical performance in horizontal and vertical directions. Average horizontal equivalent damping values for five 3D-LRBs are less than the design target of 10% due to NRB are used for 3D-LRBs. Average vertical equivalent damping values for five 3D-LRBs made of serial dish springs are larger than the design target of 10%.

Followings further studies are recommended;

1) The effective vertical isolator design and tests, especially design of dish springs with in series as well as in parallel, and damping values due to friction between dish springs
2) 3D seismic isolation tests including reactor building, reactor, and its reactor internal structures.

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