Effects of Lead Plug in Lead Rubber Bearings on Seismic Responses for an Isolated Test Structure

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ABSTRACT

The effects of lead rubber bearings are investigated by shaking table tests and seismic response analyses for 1/8-scale isolated test structure. A simple analysis model representing the actual dynamic behaviors of the test structure is developed, and the seismic analyses of the simple model are performed for lead rubber bearings with three different diameters of lead plug. The diameter of the lead plug had to be enlarged to increase isolator damping more than 24 % and this causes the isolator stiffness to increase, which results in amplifying the acceleration response of the isolated test structure in the higher frequency ranges with the monotonic reduction of isolator shear displacement.

INTRODUCTION

Much research has been carried out on seismic base isolation to verify the usefulness and to improve the earthquake resistance functions to prevent devastating damages experienced in the last decades. To reduce the seismic responses of both accelerations and relative displacements, the isolation frequency of the structure, which is determined by the stiffness of isolators, should be far away from the dominant frequency range of the earthquake ground accelerations. In parallel, the damping of the isolators implemented by either natural rubber bearings with separate dampers, high damping rubber bearings, or lead plug rubber bearings, should be decided such that it play an important role not to imperil the secondary structures attached to the primary structure of which fundamental frequencies correspond to the dominant frequencies of input motions but to reduce the accelerations and the relative displacements in the whole superstructures. The arguments of damping effects of isolation devices still continued. However there has not been much research that used shaking table tests to evaluate the damping effects of isolation devices in a seismically isolated structure to reduce seismic responses.

This paper reports on the results of shaking table tests performed to verify the damping effects on seismic responses of an isolated test structure with lead laminated rubber bearings (LLRB). The test results are presented to determine the effects on the structure responses according to the size of the lead plug diameter. A simple lumped-mass model is developed based on the modal analysis results from the detail structure model. Time history analyses to simulate test results are performed for the simple model using equivalent viscous damping obtained from the shear and compression tests of the lead rubber bearings. The comparisons between shaking table tests and analyses for the isolated structure are given for an artificial time history excitation in horizontal Y-direction.

The effects of damping and stiffness of the LLRB on the seismic responses of the isolated structure are also discussed with the analysis results.

SHAKING TABLE TEST RESULTS ON LLRBS

The input excitation motions used were Artificial Time Histories(ATH) simulating the acceleration spectrum of US NRC Regulatory Guide 1.60. For the shaking table tests, the artificial time history input motions were reconstructed through the band limited filtering of original data from 0.07Hz to 25Hz. With consideration of the similarity of the 1/8 scaled down system, the time interval of input motions is re-scaled from 0.02 second to 7.07 ms. The isolated test structure is shown in Fig. 1, which is designed to represent the dynamic characteristics of the Korea Advanced Liquid Metal Reactor (KALIMER) building. This model is composed of the rectangular basemat (lower slab,15.5 tons, 4.3m x 4.3m x 0.3m) and four columns (0.5 ton each) supporting the upper slab (5.67 tons). To increase the horizontal stiffness and provide the safety feature to the column structure, X- type crossbars were attached to the columns. The seismic isolators with the diameter of 120mm are 1/8-scaled LRB shown in Fig. 2, and four isolators are installed under the four corners of the basemat. The design isolation frequency is 1.41 Hz at 100% shear strain. The size of the 6 degrees of freedom shaking table used in the test is 4m x 4m, and the shaking capacity is 30 tons [1,2].

Fig. 1 Isolated Test Structure

Fig. 2 Scaled Laminated Rubber Bearings

Characteristic Test Results of LLRB

The hysteretic curves up to 100% shear strain for the LRBs (the natural rubber bearing(NRB) and the LLRB with three different diameters of lead plug) are represented in Fig. 3. The equivalent stiffness and damping for the several strain points are represented in Fig.4.

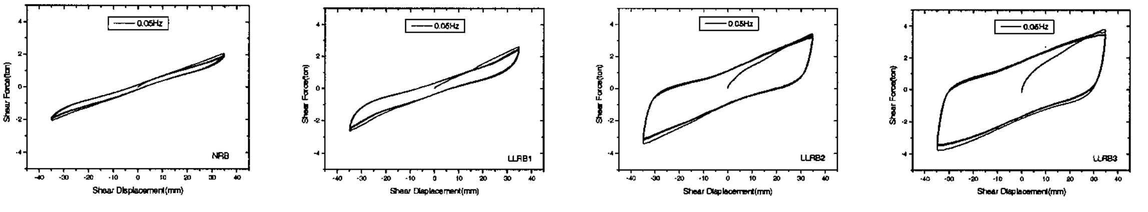

Fig. 3 Shear Strain Hysteresis of 100% Shear Strain for NRB and LLRB (0.05Hz)

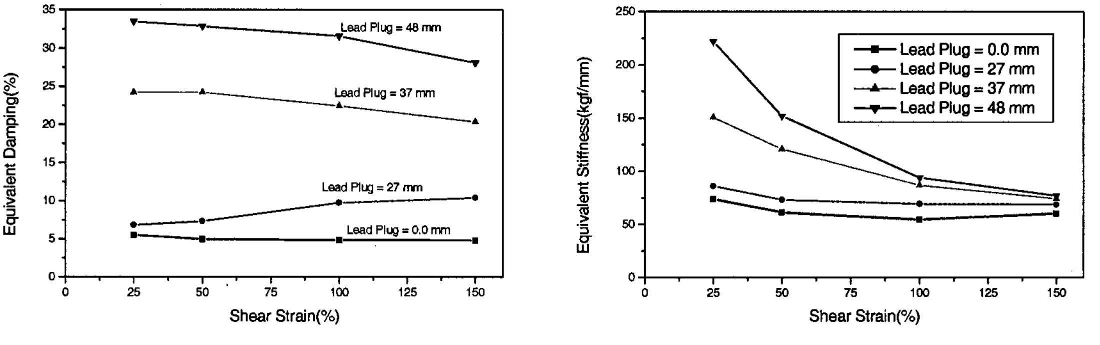

Fig. 4 Equivalent Shear Stiffness and Equivalent Damping of NRB and LLRB (0.05Hz)

Shaking Table Test Results

One of the input excitation motions is shown in Fig. 5. For the excitation levels of 0.372g to 0.439g, the shear displacement time histories normalized with a 0.412g are represented in Fig. 6. The maximum shear displacement is reduced to 10.4mm from 27mm as the lead plug diameter increase from 0.0 to 48mm. The accelerations on the structure and the shear displacements of lead rubber bearings for the input excitation are affected by the stiffness and damping depending on lead plug diameter of LLRB.

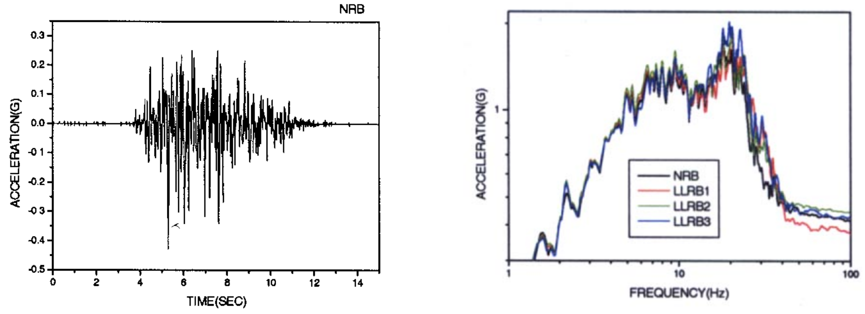

Fig. 5 Acceleration Time History and Response Spectra at Excitation Bed (2% damping)

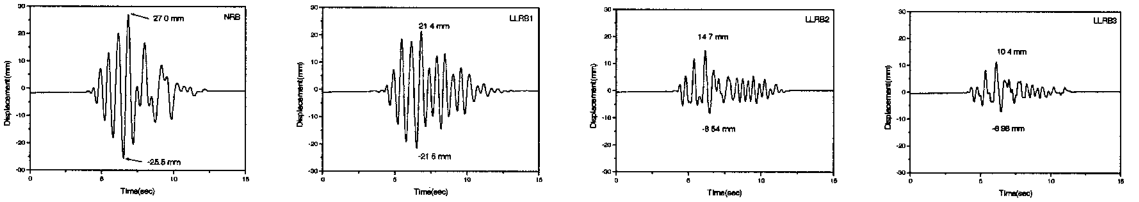

Fig. 6 Time Histories of Isolator Deformation for Input Excitations (ATH, Y-dir, 0.412g)

The equivalent stiffness and damping at the maximum shear displacements obtained from the test are given in Table 1[3]. The reduction in shear displacements for the LLRB is caused by the increases in the stiffness and damping values as the diameter of lead plug increases.

Table 1. Equivalent Damping and Stiffness for LRB Types according to Seismic Excitation

LRB Type	Excitation Input (g)	Diameter of Lead Plug(mm)	Shear Displ. (mm)	Equivalent Damping (%)	Equivalent Stiffness(Kgf/cm)
NRB	0.412	No Lead	27.0 (27.0)*	4.5	600
LLRB1	0.372	27	19.4 (21.5)*	8.0	750
LLRB2	0.439	37	15.7 (14.7)*	24.0	1250
LLRB3	0.426	48	10.8 (10.4)*	33.0	2000

()* : Scaled Values with Input Level of 0.412g

The zero period accelerations(ZPA) on the upper and lower slabs of the isolated test structure for the acceleration level from 0.367g to 0.439g are given in Table 2. The test acceleration response spectra at the upper and lower slabs normalized with 0.412g are represented in Fig. 7. In the test results, the isolation frequency is increased as the lead plug diameter increases; the accelerations in the high frequency content are amplified; and the ZPAs are also increased; but the shear displacement of LRB is greatly decreased from 27.0mm to 10.8mm.

Table 2. Test Response ZPA at Lower and Upper Slab for Input Excitations

LRB Type	Excitation Input (g)	ZPA at Lower Slab (g)	ZPA at Upper Slab (g)
NRB	0.412	0.236 (0.236)*	0.259 (0.259)*
LLRB1	0.372	0.232 (0.257)*	0.256 (0.284)*
LLRB2	0.439	0.280 (0.263)*	0.317 (0.297)*
LLRB3	0.426	0.237 (0.233)*	0.373 (0.361)*

()* : Scaled Values with the Input Level of 0.412g

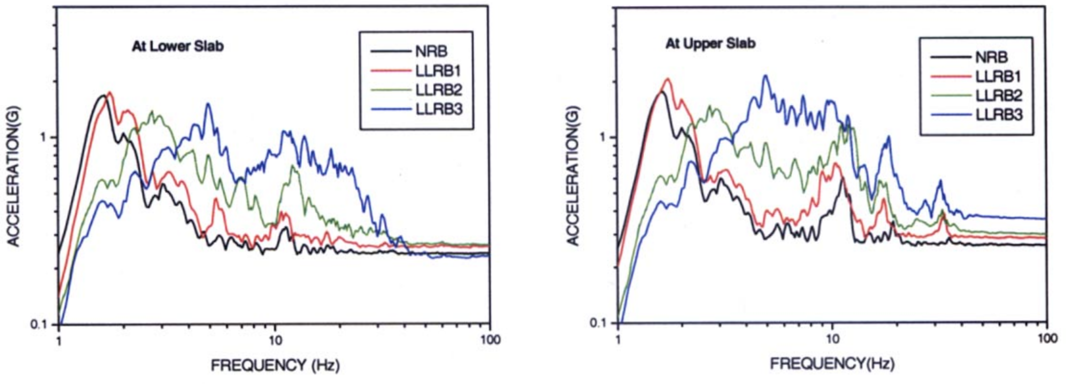

Fig. 7 Test Acceleration Response Spectra(2% Damping) of Isolated Structure (ATH, Y-dir, 0.412g)

SIMPLE ANALYSIS MODEL

To evaluate the influence of isolator damping on the structure responses, a simple analysis model (Fig.8) is developed based on the modal analysis results from the detail analysis model (Fig.9). The detail model accurately represents the dynamic characteristics of the isolated test structure with low viscous damping of about 2%, which is equivalent to no lead plug in LRB. The sample model has 16 nodes and 14 elements for reducing the computation time.

The isolators are modeled by linear spring and dashpot elements. The values for horizontal stiffness and damping are obtained from the shear and compression test results of 495.6Kg$_f$/cm and 2% viscous damping at 100% shear strain.

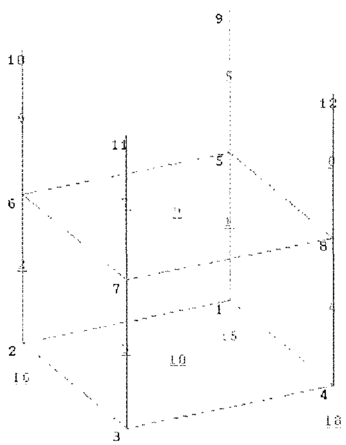

Fig. 8 Simple Analysis Model of Isolated Structure

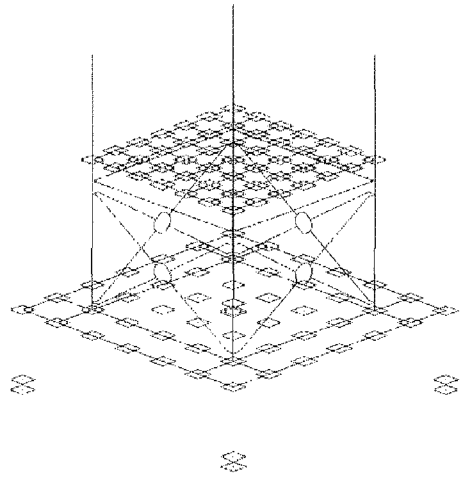

Fig. 9 Detail Analysis Model of Isolated Structure

The frequencies of the isolated test structure were calculated by the ABAQUS program and are represented in Table 3. The almost effective mass is concentrated at the isolation frequency, but the effective mass of each structural mode is very small. The simple analysis model is compatible with the detail one. The first frequency of the simple model in Y-direction is 11.5Hz is very close to 11.3 Hz of the detail model.

Table 3. Frequency Analysis Results of Isolated Structure Models

	Detail Analysis Model			Simple Analysis Model		
Mode	Frequency (Hz)	Effective Mass (kg)	Participation Factor	Frequency (Hz)	Effective Mass (kg)	Participation Factor
Isolation (X,Y)	**1.51**	21,613	1.05	**1.49**	22,317	1.018
Isolation (Z-Rot)	3.20			7.47		
1st (X1)	10.9	2.98	0.058	10.9	2.70	0.0227
2nd (Y1)	**11.3**	2.69	0.044	**11.5**	2.26	0.0186
5-th(X2)	**25.0**	0.008	0.0067	**28.8**	0.12	0.0006
Cross-bar	9.85	0.028	0.028			

SEISMIC RESPONSE ANALYSES USING SIMPLE ANALYSIS MODEL

Time history analyses were performed using the simple analysis model subjected to the artificial time history earthquake with a time interval of 0.007sec and 15second duration. The structural damping in analysis was assumed to be 2%. Fig.10 and Table 4 show the results of the floor response spectra at the slabs. The analyses results agree well with the test results both spectrum contents and peak accelerations. The calculated ZPA of 0.197g, 0.235g and 0.233g at lower slab with LLRBs are compatible with test results of 0.232, 0.280g and 0.237g. The calculated maximum shear deflections of the LLRBs were in the range of 5.04mm to 27.2mm, which are lower than those of test results for large lead plugs.

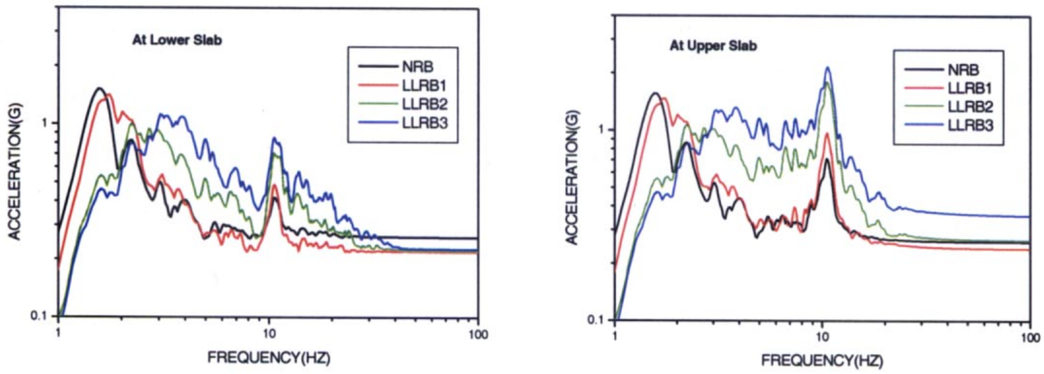

Fig. 10 Analysis Acceleration Response Spectra(2%) of Isolated Structure (ATH, Y-dir, 0.412g)

Table 4. ABAQUS Analysis Response ZPA at Lower and Upper Slabs for Input Excitations

LRB Type	Excitation Input ZPA (g)	Shear Displacement (mm)	ZPA at Lower Slab (g)	ZPA at Upper Slab (g)
NRB	0.412	27.2 (27.2)*	0.259 (0.259)*	0.260 (0.260)*
LLRB1	0.372	15.7 (17.4)*	0.197 (0.218)*	0.216 (0.238)*
LLRB2	0.439	6.84 (6.42)*	0.235 (0.220)*	0.281 (0.264)*
LLRB3	0.426	5.04 (4.96)*	0.233 (0.226)*	0.367 (0.355)*

()* : Scaled Values with the Input Level of 0.412g

The contributions to the acceleration response from the damping and the stiffness of lead plugs are not distinguished. Two parametric studies were performed: one to study the effects of damping and the other to study effects of stiffness of the LRB. The analysis results are represented in Fig. 11.

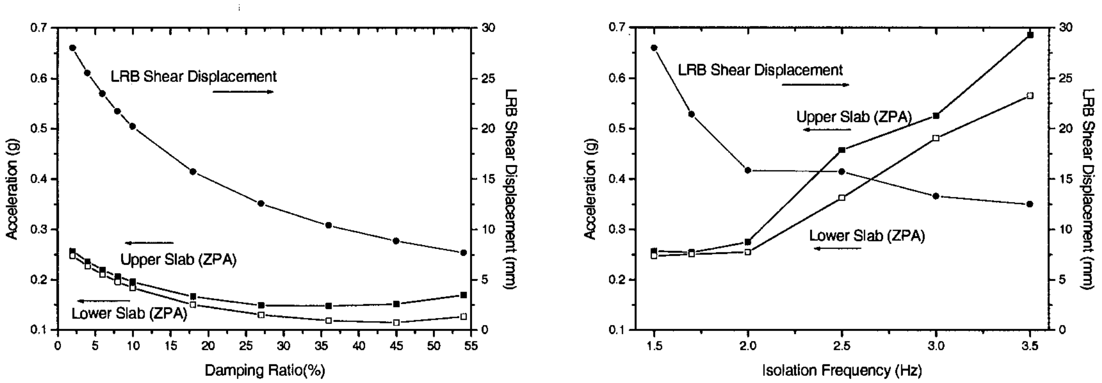

Fig. 11 Accelerations & LRB Deformations According to Damping and Isolation Frequency Variations

When the viscous damping is increased while the stiffness of the LRB is fixed, the ZPA of structure and the shear deformation of the LRB monotonically decrease until to the damping level of about 35 %. However the ZPA of upper structure increases as increasing the damping more than 35% for upper slab of test structure. When the stiffness is increased while the damping of the LRB is fixed at 2% viscous damping, the response acceleration is increased rapidly, but the shear deformation of LRB is decreased for both cases. When the LLRB are used to reduce the seismic acceleration responses of structures, the diameter of lead plug is a key parameter because it simultaneously impacts on the structural accelerations through two points. One is the acceleration amplification of increased isolation frequency by the increase of stiffness, and the other is the acceleration reduction by the increased damping up to about 35%.

CONCLUSIONS

Test results show that increasing the lead plug diameter results in (1) amplifying the acceleration responses of the isolated test structure in the higher frequency ranges, and (2) rapidly reducing the shear displacement in the isolators.

When LLRBs are adopted to reduce the seismic acceleration response of structure, the diameter of the lead plug simultaneously affects the structural acceleration through two points, one is the acceleration amplification of increased isolation frequency by the increase of stiffness, and the other is the ZPA reduction by the increased damping up to about 35%.

Based upon tests and analyses of the isolated structures, the increased diameter of lead plug above 37mm in the isolator could give an adversary effects on the secondary systems and components attached to the primary structure because the acceleration amplification in high frequency content of the primary structure is notified.

Acknowledgement

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