Excitation Test Response Characteristics and Simulations of a Seismically Isolated Test Structure

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ABSTRACT

The seismic excitation test results of a seismically isolated test structure subjected to an artificial time history excitation are summarized. The analytical structural models of the isolated test structure and isolation bearings are built based on the actual dynamic behaviors and the excitation responses of the test structure. Seismic response simulations with linear and bilinear structural models for isolators are performed and the analysis results are compared with those of the seismic tests. The simulation results are in well agreement with the test responses in the range of large shear strain of isolators.

KEY WORDS: seismic isolation, lead rubber bearing, isolator, bilinear model, response spectrum, isolation frequency, shaking table test, time history analysis, shear stiffness, hysteresis curve, shear strain, yield load value

INTRODUCTION

Seismically isolated test structure of 23 tons in Fig. 1 was fabricated in order to simulate liquid metal reactor (LMR) building. Two series of seismic excitation tests are performed with shaking table of 30 tons capacity in 1997 and 1998. The first test is about the two types of test structure with high damping rubber bearings, the excitation motions are EL Centro 1940 NS, Mexico 1985, and artificial time history (ATH). The total number of tests is 230 with different seismic excitation intensity. The second test was performed for a modified test structure with four kinds of lead laminated rubber bearings (LLRB) with different lead plug size, and also 3D isolators.

The isolated test structure shown in Fig. 1 consists of the lower slab, upper slab, and beam structure supporting the upper slab. The isolators installed at four corners between the test structure and the shaking table are 1/8 scale with the diameter of 150 mm. The test structure has a target isolation frequency of 1.41 Hz to keep the similarity with LMR building of 0.5Hz isolation frequency [1].

In this study, a simple beam model with lumped-mass for the seismically isolated test structure is used to calculate the excitation responses by numerical method[2]. Shear deformation and force behavior characteristics of isolators are summarized with the performance test data of the lead rubber bearings. The linear and bilinear structural models for the isolators are built by the isolator test data and the excitation responses of the test structure. Using the simple beam model, the seismic responses of the test structure are calculated for artificial time history acceleration with a time interval of 0.007sec and 15second duration. The calculated results are compared with actual shaking table test results for the same acceleration excitation.

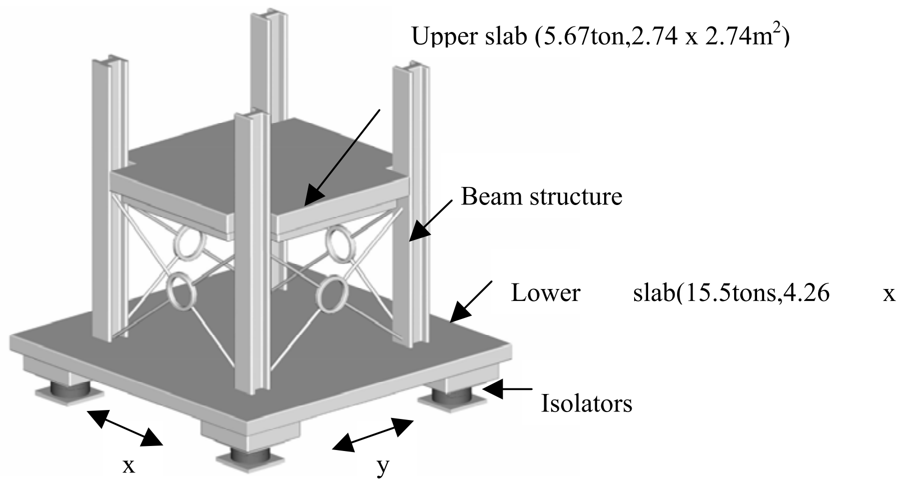


Fig. 1 Concept drawing of isolated test structure

RESPONSES OF TEST STRUCTURE FOR ARTIFICIAL TIME HISTORY EXCITATION

For the horizontal ATH excitation by about 0.3g (actually measured level of 0.4g), the horizontal displacements measured by LVDT and the maximum shear deformations of isolators are represented in Table 1. The lead plug diameters of the three isolators are 27mm(LLRB1), 37mm(LLRB2), and 48mm(LLRB3), respectively. The measured maximum excitation displacement of the shaking table records about 8mm amplitude.

As shown in Table 1, the maximum shear deformation of isolators is 25.8mm for NRB, and the LLRB1and LLRB2 are 17.7mm and 10.3mm, respectively, and for the LLRB3 is reduced by 4.5mm. These displacements are equivalent to the shear strain range of 74% to 11.5%. The isolation frequencies are obtained by the shear deformation histories and response spectra represented in Figs. 2 and 3. The isolation frequencies are changed from 1.55 Hz to 3.2 Hz according to the lead plug diameter. The horizontal shear stiffness of isolators has strong dependency on the lead plug diameter size and the maximum shear deformation magnitude.

Table 1. Test response displacements of isolated test structure (ATH, Y-dir, 0.3g)

Name of isolator	Lead plug diameter	Lower slab disp. (A, mm)		Shaking table disp.(B, mm)		Isolator shear disp. (A-B, mm)		Max. shear strain (%)	Isolation freq.(Hz)	Table input(g)
		Max.	Min.	Max.	Min.	Max.	Min.			
NRB	No lead	26.97	-25.5	8.73	-7.63	25.8	-22.26	74.1	1.55	0.413
LLRB1	27 mm	19.30	-19.39	8.54	-7.45	17.7	-15.5	50.9	1.7	0.383
LLRB2	37 mm	15.73	-8.89	8.73	-7.63	10.3	-5.0	29.6	2.9	0.451
LLRB3	48 mm	11.2	-7.2	8.48	-7.39	4.5	-2.25	11.5	3.2	0.433
HLRB	No lead	15.4	-15.74	8.60	-9.40	11.97	-12.53	36.0	1.5/2.2	0.395

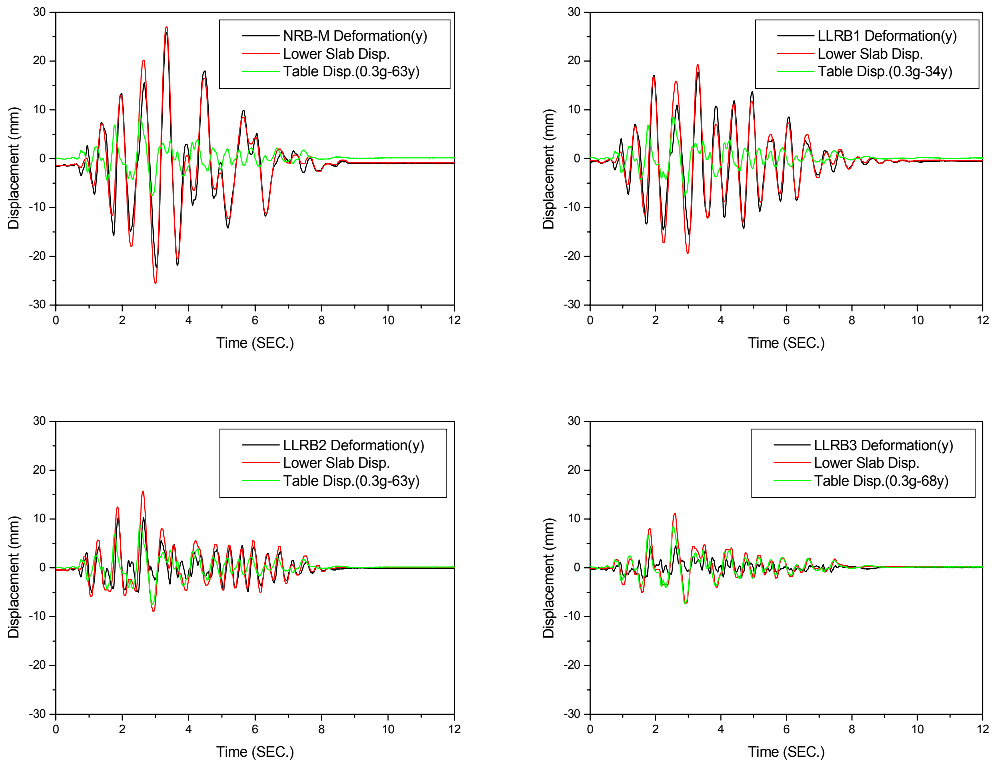


Fig. 2 Shear displacement time histories of isolated test structure(ATH, Y-dir, 0.3g)

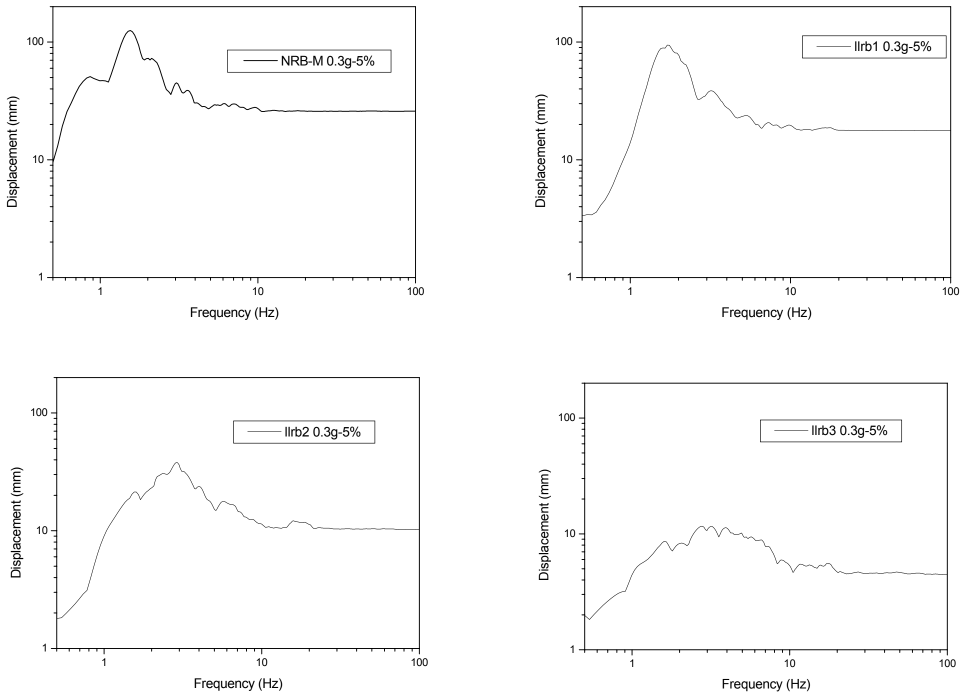


Fig. 3 Shear displacement response spectra of isolators (ATH, Y-dir, 0.3g)

PERFORMANCE CHARACTERISTICS OF ISOLATORS

For the analytical approach to get excitation responses of the seismically isolated test structure, two structural models are required. The one is for the isolated test structure, the other is for the isolators. As for the structural model of four kind of isolator, the shear hysteresis curves of four LLRBs in Fig.4 are investigated to get the structural modeling parameters of isolator behaviors. These are the shear deformation curves of 25%, 50%, 100% and 150% with a performance test frequency of 0.5Hz[3]. The outer diameter and total rubber thickness of LLRB are 150mm and 34.8mm with 29 layers, respectively. The lead plug diameters of the three isolators are 27mm(LLRB1), 37mm(LLRB2), 48mm(LLRB3), and the ratios of the lead plug diameters to the bearing ones are 0.18, 0.25, and 0.32, the ratios of lead plug area to the LLRB1 one are given as 1.0, 1.88, 3.16, respectively.

From the shear displacement time histories of the isolated test structure in Fig. 2, the maximum shear deformations of isolators are obtained. The equivalent stiffness and viscous damping related to the maximum shear deformation are calculated by the characteristic test data of isolators as shown in Fig. 4. The equivalent stiffness and viscous damping corresponding to the reference shear strains are represented in Table 2. The reference shear strain for LLRB3 is not the maximum shear strain of 11.5% that the isolator has experienced in shaking table excitation test, the shear strain of 25% is used because the isolator performance test data is not available in the small strain region.

Table 2. Calculated characteristic values of isolators for linear model

	NRB	LLRB1	LLRB2	LLRB3
Reference shear strain	75%	50%	30%	25%
Equivalent stiffness (kg_f/mm)	52.4	67.1	147.3	236.8
Equivalent damping(ζ,%)	1.92	6.31	23.6	29.3
Frequency (f_n)	1.53	1.72	2.56	3.24

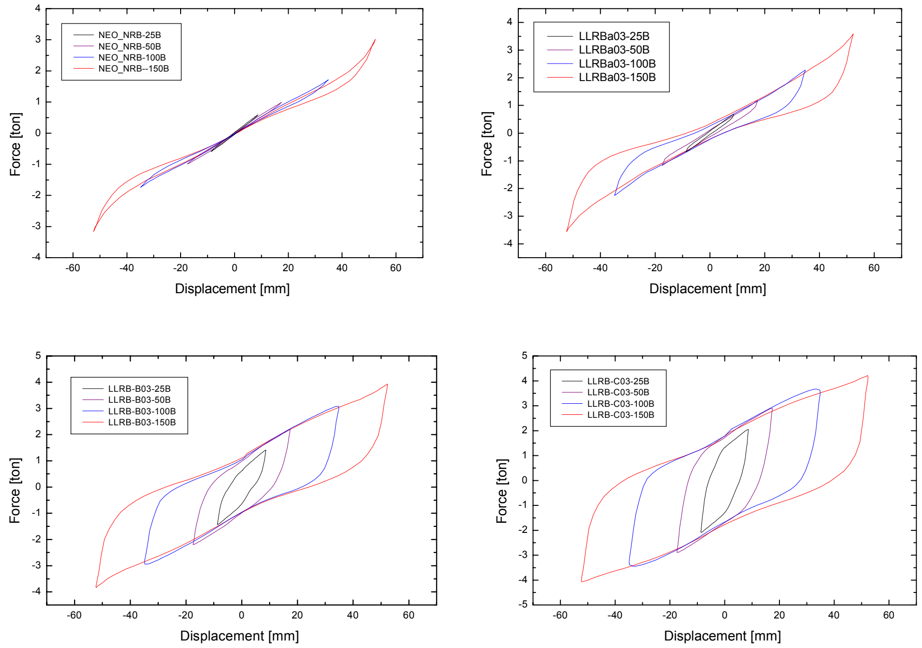


Fig. 4 Characteristic curves of lead rubber bearings (0.5Hz)

STRUCTURE MODELING OF ISOLATORS

Several structural models for simulating the shear behavior of isolators are reported such as Linear, Bilinear, Multilinear, Rate and Ramberg-Osgood model[4,5,6,7]. These models have been developed to simulate the actual behavior of isolators based on the relation between shear force and shear strain obtained from isolator-performance tests.

The equivalent stiffness(K_{eq}) and the equivalent damping(ζ_{eq}) used in modeling of the equivalent linear model are obtained by the hysteresis curve represented with shear force(F) and shear deformation(X) of isolator

$$K_{eq} = \frac{F_{\max} - F_{\min}}{X_{\max} - X_{\min}}, \quad \zeta_{eq} = \frac{\Delta W}{2\pi K_{eq} X_{\max}^{2}}$$

In modeling of the equivalent linear model for isolator, JOINT and DASHPOT elements of ABAQUS are used.

In the bilinear model of isolator, the hysteresis and skeleton curves are defined assuming that the isolator behaves to follow the outside line of the structural model. To use the user defined subroutine of ABAQUS, several parameters defining the hysteresis curve of isolator are required as follow.

A : Cross Section Area of Truss Element

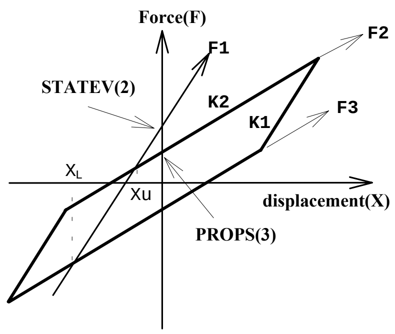
PROPS(1) : First Horizontal Stiffness (K1)

PROPS(2) : Second Horizontal Stiffness(K2)

PROPS(3) : Yield Load Value(Y)

PROPS(4) : Limiting Displacement Value of K1(Xy)

PROPS(5) : 100% Shear Displacement (X100)



And also some user's parameters as state variables are selected to define the unloading path of isolator. These parameters are the cross point with vertical axis by K1 slope line, current shear strain, and current yield load value, etc.

An element compatible with the user defined material function of ABAQUS is required to compose the structural model of isolator. For this purpose, a quite simple approach using *Material block and TRUSS element defined by a solid section is adapted. Since the hysteresis characteristic of isolator is given by the relation of force and shear displacement, the stress can be obtained by the force divided by section area of TRUSS element, the strain can be obtained by the deformation divided by the element length, which is equivalent to the 100% shear strain. The Young's modulus of this element can be obtained as following equation.

Force = Spring Stiffness(K) x Displacement(X)
= Axial Stress(S) x Section area(A)
= [Young's Modulus(E) x Strain(ε =X/L)] x Section area(A)
E = Spring Stiffness(K) x Displacement(X) / [Section area(A) x Strain(X/L)]
= KX/[A(X/L)]
= KL/A (A=1.0)
= KL
Jacobian (1 x 1) = del(S)/del(ε) = E , J=DDSDDE(1,1)

To determine the instant stiffness of structural model at any deformed position of an isolator under a movement, a user subroutine of ABAQUS is developed, catching the direction of increment or decrement of strain and giving a new stiffness fitting the skeleton or hysteresis curve according to the isolator shear strain.

The hysteresis curve is changeable to the yield load value of isolator, which is corresponding to the maximum shear strain taken just before. To compensate this characteristic feature, the magnitude of shear strain taken just before is linked to determine the yield load value of bilinear model.

RESPONSE ANALYSIS OF TEST STRUCTURE FOR ARTIFICIAL TIME HISTORY EXCITATION

A simple beam model having 16 nodes and 14 elements for reducing the computation time is used to do seismic response time history analysis. The dimension and material properties of each element are modified to compatible with the actual dynamic features of the test structure. The calculated natural frequencies are presented in Table 3 for the isolation case and the non-isolation case.

Table 3. Frequency analysis results of simple model of test structure

Non-isolation		Isolation			
MODE	Frequency (Hz)	Dominant mode	Frequency (Hz)	Effective mass (kg)	Participation factor
		Isolation (X,Y)	1.49	22,317	1.018
		Isolation (Z-rot)	7.25		
X1	9.43	X1	11.06	2.70	0.186
Y1	9.54	Y1	11.48	2.26	0.195
Z-rot	13.69	Z-rot	29.50		
X2	24.05	X2	28.77	0.12	0.0007
NOTE) Using the horizontal stiffness 49.6Kg_f/mm for 100% shear strain.					

Based on the test results of isolators with the shear displacement range of 25%-150%, the bilinear model parameters of the user-defined subroutine of ABAQUS are calculated as shown in Table 4. Here, K1 is an initial shear stiffness of isolator, K2 is the second stiffness, which has influence on isolation frequency, L is the length of 100% shear deformation of isolator, Xy is a value of X-coordinate of the crossing point of K1 and K2 lines. The figure in Table 4 represents the variation of the yield load value (Qd) with respect to the isolator shear strain of 25% to 150%. The Qd values of LLRB2 and LLRB3 are rapidly reduced in small strain region less than 50%. The maximum shear deformation of LLRB3 in Table 1 is about 12%, which is less than the minimum shear characteristic test value of 25%. For modeling in small shear strain of bilinear model of LLRB3, an extrapolation is adapted to calculate the seismic response results.

By ABAQUS analyses for ATH acceleration using the bilinear model parameters for the four kinds of lead plug isolators, the isolator shear deformation and the upper slab acceleration are calculated. The shear deformation histories of isolators are represented in Fig. 5.

Time history response analyses for ATH acceleration using the linear model parameters in Table 2 are performed to calculate the isolator shear deformation for the four kinds isolators by ABAQUS. The maximum shear deformations are represented in Table 5. The shear deformation of the equivalent linear stiffness model gives a good agreement with test results.

As shown in the response analysis results in Table 5 and Fig.6, the results of the bilinear model agree well with the tests in shear displacement. But the LLRB3 with a large lead plug gives about 5 Hz isolation frequency, which is a little higher than the test one as shown in Fig. 7.

Table 4. Bilinear model parameters used in ABAQUS analysis

Excitation frequency	Isolator type	Stiffness 1 (Kg_f/mm)	Stiffness 2 (Kg_f/mm)	Yield load (Kg_f)	Xy (mm)	L (mm)
0.5 Hz (100% Shear strain)	NRB	79.3	45.2	15.3	0.45	34.0
	LLRB1	278.6	41.7	244	1.03	34.0
	LLRB2	448.3	55.2	1005	2.56	34.0
	LLRB3	608.3	58.1	1733	3.15	34.0

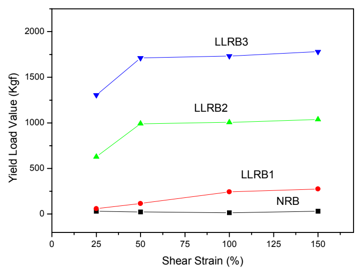


Table 5. ABAQUS analysis results using the structural model

Isolator	Disp. of LRB test results (mm)		Disp. of LRB linear model (mm)		Disp. of LRB bilinear model (mm)		Upper slab acc. bilinear model (g)	
	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.
NRB	25.8	-22.26	27.2	-25.25	27.9	-22.9	0.235	-0.208
LLRB1	17.7	-15.5	15.24	-15.65	20.8	-16.1	0.187	-0.152
LLRB2	10.3	-5.0	4.57	-6.84	10.2	-5.0	0.375	-0.363
LLRB3	4.5	-2.25	2.84	-5.04	5.64	-3.92	0.456	-0.491

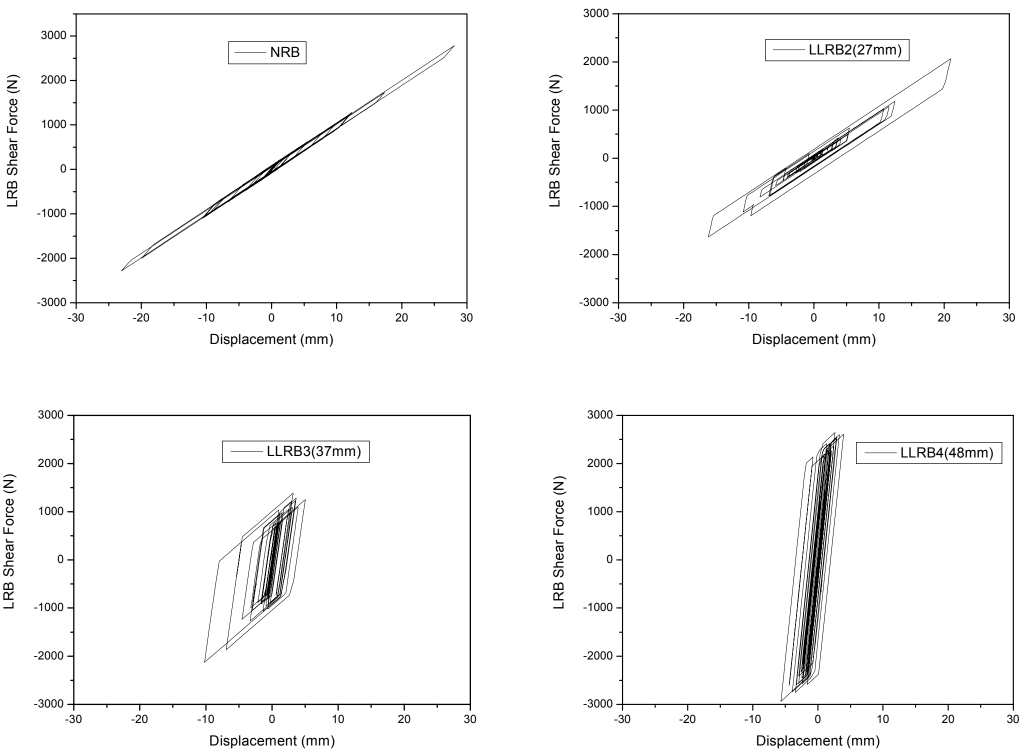
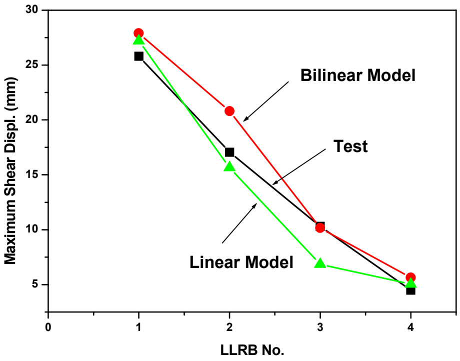


Fig. 5 Shear deformation hysteresis curves by bilinear structural model



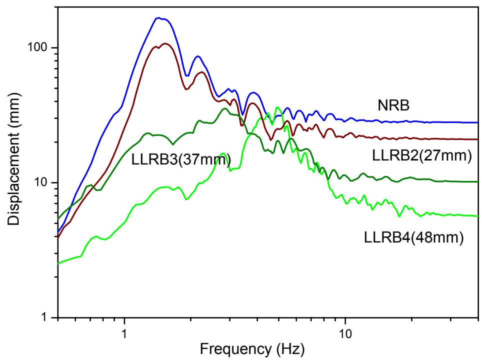


Fig. 6 Maximum shear deformation of isolators   Fig. 7 Displacement spectra of bilinear model

CONCLUSIONS

From the excitation test results of the seismically isolated test structure, the response acceleration and the shear deformation of isolators are summarized. The simple model to be compatible with the actual test structure and the equivalent linear and bilinear models based on the performance test data of isolators are used to simulate the excitation feature.

From the seismic response time history analyses using the structural models of isolators and isolated test structure, the linear model and bilinear model for the lead rubber bearing gives a good agreement with test results in shear displacements and isolation frequencies. However, the bilinear model gives a high isolation frequency for the LLRB3 of lead plug diameter of 48mm.

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