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A SHAKING TABLE TEST STUDY ON SHEAR TENSILE PROPERTIES OF LEAD RUBBER BEARINGS

Demin FENG[1], Takafumi MIYAMA[2], Xilin LU[3], Masayoshi IKENAGA[4]

SUMMARY

In Japan high rise buildings with seismic isolation devices have increased rapidly in order to obtain both seismic safety and economical merits. In this paper, one, two and three-dimensional shaking table tests are carried out to study the hysteresis characteristics of lead rubber bearings (LRB) and especially cases subjected to tensile axial load. A 24-story high-rise building with an aspect ratio of four was the targeted structure. The super-structure of the testing model, consisting of three stories steel frame, had a total weight of 250kN and had a length scale of 1/12. Four same LRBs having 100mm-diameter were installed at the distance of 1.08m in the base of the model. In the measurement system, total of 61 sensors were used. The axial and shear forces acting on every LRB were measured by four three-dimensional load transducers. White noise was inputted to identify the fundamental characteristics of the model. The super-structure was found to have a natural frequency of 3.6Hz and a damping ratio of 2% in both horizontal directions. El Centro 1940, Taft 1952, Hachinohe 1968 and Kobe 1995(JMA), which were normalized by the peak velocity values to 25, 50, 75cm/sec, were used as earthquake excitations. Test results are summarized as follows. I. In total 55 test cases, there were 14 cases where the axial tension in a LRB occurred. All LRBs suffered over 2MPa tensile stress while the maximum tensile stress was 2.2MPa. After all shaking table tests, static fundamental property tests on the bearings show little change. II. Three-dimensional dynamic response analysis was conducted to simulate the test results. Although axial loads of the bearings were observed to vary severely, in a three-dimensional moderate input case, the displacements of the base isolation floor and the axial loads in the bearings were simulated well.

INTRODUCTION

After the 1995 Hyogo-ken Nanbu earthquake, buildings with seismic isolation devices have increased rapidly in East-Asian area. The number of buildings with isolation system has exceeded 1000 in Japan and exceeded 400 in China. At the same time, building codes are revised to include the design of buildings with seismic isolation devices in those countries. The building codes took effective in China and Japan in 2000 and in Taiwan in 2002. Static characteristics of lead rubber bearing (LRB) which is the most popular device have been studied systematically by Feng [1]. A new analytical model which is a combination of the modified bilinear and Ramberg-Osgood model (BRO) was also proposed by Feng [2].

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[1] Senior Engineer, Fujita Corp., Tokyo, Japan, feng@fujita.co.jp
[2] Chief Engineer, Fujita Corp., Tokyo, Japan, miyama@fujita.co.jp
[3] Professor, Tongji University, Shanghai, China, lxlst@mail.tongji.edu.cn
[4] Operating Officer, Oiles Corp., Tokyo, Japan, ikenaga@oiles.co.jp

On the other hand, high rise buildings with seismic isolation devices have increased rapidly in order to obtain both seismic safety and economical merits. In buildings having large aspect ratio, the tensile load in a bearing occurs easily. It is important to know characteristics of whole isolation floor under such conditions and how much characteristics of a bearing would change after suffering tensile loads. Kani *etc.*[3] and Takayama [4] have studied shear tensile characteristics based on static tests. They concluded that there is little change in properties after suffering smaller than 5% tensile strain.
In this paper, one, two and three-dimensional shaking table tests are carried out to study the dynamic hysteresis characteristics of lead rubber bearings by comparing with static characteristics. Only in the shaking table test, the effect of varying axial load on hysteresis loop could be confirmed. The BRO model is also checked over by simulating the dynamic test results. Test cases suffered tensile axial load are studied in detail. Results of a routine test on the bearing are compared before and after the shaking table test.

SHAKING TABLE TESTS

Test Model

Super-structure

A 24-story high-rise building with an aspect ratio of four was the targeted structure. The super-structure of the testing model consisting of three story steel frames had a total weight of 250kN and had a length scale of 1/12. Test model with measurement system are shown in Fig.1. The law of similitude between target building and test model is summarized in Table 1. In the test model, the super-structure had a plan of 1.8mX1.8m and a total height of 3.75m. Four concrete blocks having a weight of 48kN each were installed in every floor.

Table 1: The law of similitude between target building and test model.

	Target	Model
Height(m)	45	3.75
Floors	15	3
Plan(m)	13×13	1.08×1.08
Weight(kN)	36000	250
Natural frequency of super-structure(Hz)	1.0	3.45
Natural frequency of isolated system(Hz)	0.37	1.28

Isolation system

Four same G6 type LRBs shown in Fig.2 having 100mm-diameter were installed at the distance of 1.08m in the base of the model. Thus, all columns in super-structure were supported through cantilever beams to the lead rubber bearing, whose details are summarized in Table 2. The average axial pressure on each bearing was about 7.9MPa. A static routine test was carried out on each bearing before and after shaking table tests at the condition of axial load 60kN (7.9MPa) and a horizontal amplitude of 19.2mm (100% shear strain). The test hysteresis loop before the shaking table test is shown in Fig.3, and the result is summarized in Table 2, where Kd=242N/mm, Qd=2.3kN was obtained.

Table 2: Details of the lead rubber bearing used.

		ϕ100
Diameter*height (*mm*)		100*74.2
inner steel plate		1.0mmx15
inner rubber plate		1.2mmx16=19.2
diameter of lead (*mm*)		18
1st shape coefficient		15.6
2nd shape coefficient		5.2
Static test results	Kd(N/mm)	242
	Qd(KN)	2.3

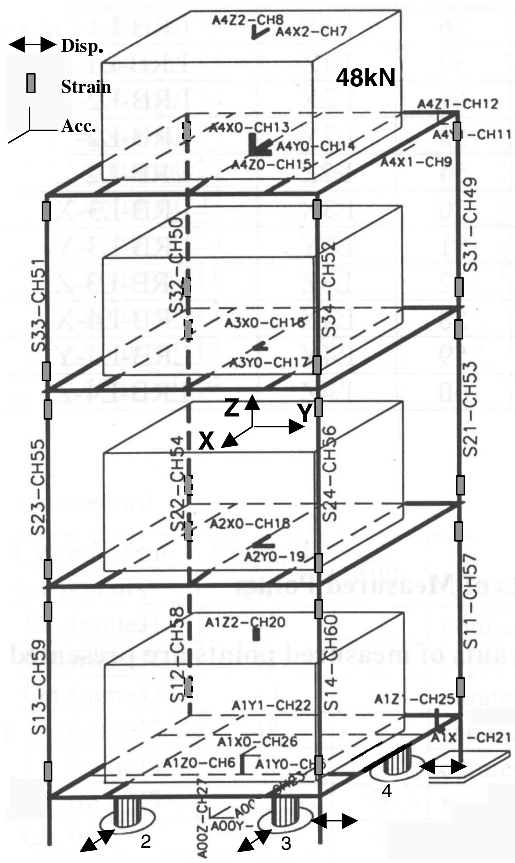


Fig.1: Test model shown with measurement system.

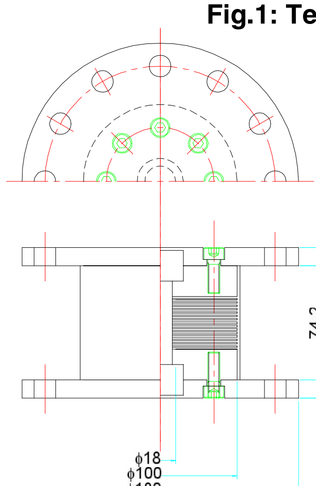


Fig.2: Drawing of LRB.

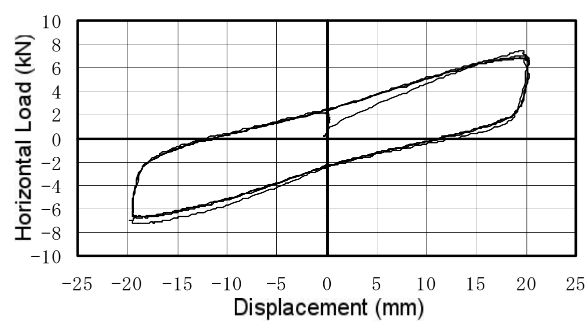


Fig.3: Static routine test result of LRB.

Input Motion

Input motions used in the test are summarized in Table 3. White noise(wn) motions were inputted to understand the fundamental dynamic characteristics of both fixed and isolated models. Four earthquake waves, 1940 El Centro (El), 1952 Taft(Ta), 1968 Hachinohe(Ha), 1995 Kobe(Ko)(JMA Kobe), were used as excitations, which are normalized by the peak velocity amplitude of the horizontal component. Corresponding to the design procedure, in cases of one-dimensional horizontal input, the horizontal wave was normalized to the determined amplitude level. In cases of two-dimensional horizontal input, the vector of the two horizontal inputs was normalized to the determined amplitude level. For cases of 1995

Kobe input, the amplitude of peak acceleration was normalized to 800 gal due to the limitation of the shaking table. To investigate the residual displacements after the earthquake, the duration is taken as 50s, 50s, 90s and 50s each. The NS direction of the input earthquake waves corresponds to X direction in Fig.1.

Table 3: Earthquake waves used in the shaking test.

Abbreviation	Earthquake waves	Duration(sec)	Level
Wn	White noise	500	100gal
El	1940 El Centro	50	25,50,75 cm/sec
Ta	1952 Taft	50	
Ha	1968 Hachinohe	90	
Ko	1995 Kobe JMA	50	800gal

Measurement System

In the measurement system, total of 61 sensors were used as shown in Fig.1. There were 26 components of acceleration sensors, 11 components of displacement, 12 components of load and 12 components of strain sensors. The axial and shear forces acting on every LRB were measured by four three-dimensional load transducers. The acceleration in each floor, the shear force of columns and the relative displacement in each floor were also measured.

Test Schedule

Total 55 cases of excitation are scheduled as shown in Table 4. White noise excitation was input first to understand the fundamental characteristics of the test model. The earthquake waves were then inputted from one-dimensionally to three-dimensionally, while the amplitude of the peak velocity increased from 25 cm/sec to 75 cm/sec. In each excitation knot, El 25cm/sec was inputted as a standard case to investigate any changes in the test model. After all excitations, characteristics of a bearing was studied to compare the static test result before the shaking table tests.

Table 4: Test schdule.

No	Test name	X(g)	Y(g)	Z(g)	Level	No	Test name	X(g)	Y(g)	Z(g)	Level
1	wn-010	0.10	0.10	0.10	100gal	29	Ha-0.16xyz	0.16	0.13	0.08	25kine
2	El-0.26x-1	0.26			25kine	30	Ha-0.32xyz	0.32	0.26	0.16	50kine
3	El-0.18xyz	0.18	0.11	0.11	25kine	31	Ko-0.22xyz	0.22	0.16	0.09	25kine
4	El-0.36x	0.36			50kine	32	Ko-0.43xyz	0.43	0.33	0.18	50kine
5	El-0.22y		0.22		50kine	33	El-0.26x-6	0.26			25kine
6	El-0.22z			0.22	50kine	34	El-0.54x	0.54			75kine
7	El-0.26x-2	0.26			25kine	35	El-0.33y-ew		0.33		75kine
8	Ta-0.19xyz	0.19	0.21	0.13	25kine	36	El-0.33z			0.33	75kine
9	Ha-0.13x-ew	0.13			25kine	37	Ha-0.49x	0.49			75kine
10	El-0.52x	0.52			50kine	38	El-0.26x-7	0.26			25kine
11	Ta-0.51x-ew	0.51			50kine	39	Ha-0.40y-ew		0.40		75kine
12	Ha-0.34x	0.34			50kine	40	El-0.26x-8	0.26			25kine
13	Ha-0.26x-ew	0.26			50kine	41	Ha-0.45z			0.25	75kine
14	El-0.36xy	0.36	0.22		50kine	42	El-0.78x	0.78			75kine
15	Ha-0.16xy	0.16	0.13		25kine	43	Ha-0.39x-ew	0.39			75kine
16	Ha-0.32xy	0.32	0.26		50kine	44	El-0.26x-9	0.26			25kine
17	El-0.36xz	0.36		0.22	50kine	45	El-0.54xyz	0.54	0.33	0.33	75kine
18	Ha-0.13xz-ew	0.13		0.08	25kine	46	Ta-0.56xyz	0.56	0.64	0.38	75kine
19	Ha-0.26xz-ew	0.26		0.16	50kine	47	Ha-0.49xyz	0.49	0.395	0.25	75kine
20	El-0.26x-3	0.26			25kine	48	Ko-0.65xyz	0.65	0.49	0.26	75kine
21	El-0.36xyz	0.36	0.22	0.22	50kine	49	El-0.26x-10	0.26			25kine
22	Ta-0.37xyz	0.37	0.43	0.25	50kine	50	Ko-0.82x	0.82			800gal
23	El-0.54xy	0.54	0.33		75kine	51	Ko-0.82x-ew	0.82			800gal
24	El-0.54xz	0.54		0.33	75kine	52	El-0.54xz2	0.54		0.65	75kine
25	Ha-0.49xy	0.49	0.40		75kine	53	Ko-0.82xz-ew	0.82		0.44	800gal
26	Ha-0.40xz-ew	0.40		0.25	75kine	54	El-0.26x-11	0.27			25kine
27	El-0.26x-4	0.26			25kine	55	wn-010	0.10	0.10	0.10	100gal
28	El-0.26x-5	0.26			25kine						

kine:cm/sec; gal:cm/sec^2

TEST RESULTS

Comparison between Fixed and Isolated Test Results

To understand the fundamental dynamic properties, white noise excitation was inputted. The natural frequencies obtained are summarized in Table 5. Natural frequencies in both X and Y directions were almost same and agreed well with designed values. Damping ratio corresponding 1st mode of the super-structure was estimated to be about 2% from the transfer function.

Table 5: Natural frequencies obtained from white noise excitations.

Mode		1st	2nd	3rd
Frequency(Hz)	X	3.66	11.2	22.2
	Y	3.58	11.2	22.1

Comparison of peak response acceleration values distributing along the height between fixed and isolated model tests is shown in Fig.4. The peak acceleration in the top of the model has been amplified from two to three times in base-fixed model tests, while decreased in base-isolated model tests.

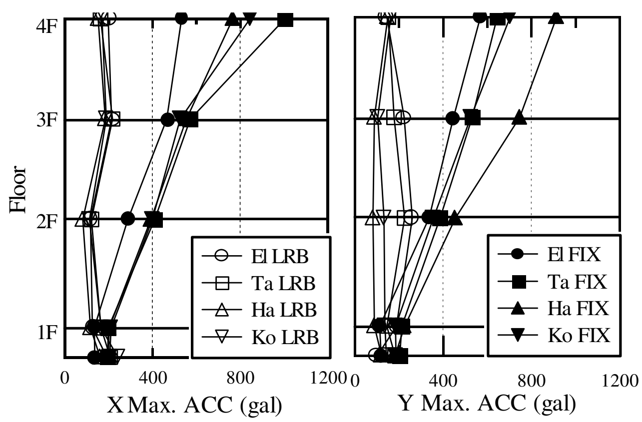


Fig.4: Comparison of shaking table test results between fixed and isolated models.

Residual Displacement

Since the response displacement of the isolation floor is very large during an earthquake, the customers may concern the residual displacement after the earthquake. In Fig.5 are shown residual displacements of all 55 test cases. The maximum value was 1.2mm which corresponded 15mm in a real size building. It is too small to consider in a design practice.

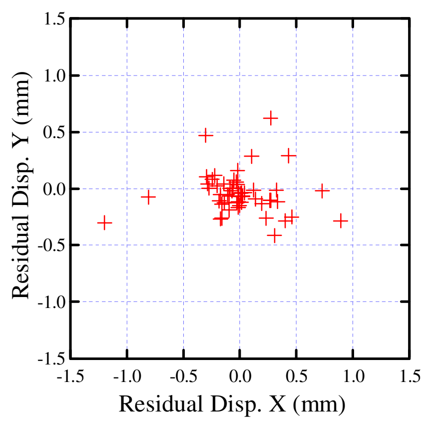


Fig.5: Residual displacements of all 55 test cases.

Axial Load Variation of LRB

Performance test of a bearing is usually conducted under a constant axial load. But it is well known that axial load on a bearing varies during an earthquake. It is important to know how much the axial load varies and how much the hysteresis loop in the horizontal direction is affected by variation of the axial load.

Variation of Axial Load

In this study there were only four bearings in the test model. Axial load during excitation is expected to vary seriously than that in a normal usage, thus test results are evaluated to a safety side. As a typical case, test results of No.30 in Table 4 is shown in Fig.6 where three-dimensional Ha 50cm/sec waves were inputted. Hysteresis loops in X and Y directions and axial load time history are shown laterally. Test results of four bearings are shown vertically in the increasing order. The summation of all bearings' test results or in the other word, the characteristics of isolation floor, is shown in the last row. In Table 6, results of four test cases with level 50cm/sec input are summarized. The maximum variation of axial load in the four bearings ranged from -80% to +130%.

Table 6: Maximum variation of axial loads during 50cm/sec inputs.

Input / Axial load	El	Taft	Ha	Ko
Decrease	-90%	-100%	-80%	-100%
Increase	+100%	+100%	+130%	110%

Influence on Hysteresis Loop

From Fig.6, the influence of axial loads on the hysteresis loop could be observed. In loops of bearing No.1 and No.2, the unloading stiffness became larger when unloading from the minus largest deformation. This is considered to be caused by the increase of axial load when unloading. To the contrary, in loops of bearing No.3 and No.4, the unloading stiffness became smaller due to the decrease of axial load. The summation of all bearings results became close with that in a static test.

Multiple Dimensional Input Effect

Characteristics of LRB such as post-yield stiffness, yield load and hysteresis loop is usually obtained by a static test. The analytical model of LRB is also based on one-dimensional static test. There is yet no any effective response analysis system to consider the influence of axial load on hysteresis loop. Thus, in an analysis study, the same analytical results will be obtained in spite of one or two-dimensional inputs. Only in the shaking table test, multiple dimensional inputs' effect can be studied.

In Fig.7, the maximum response acceleration and shear force distribution along the height are shown for cases of No.4,14,21,12,16,30, where the El and Ha are inputted one, two and three-dimensionally. The input level was the same in all one, two and three-dimensional inputs, where the maximum velocity was normalized to 50 cm/sec. The maximum acceleration distribution showed the same tendency at both input waves. In the one and two-dimensional excitations, the acceleration in the top was about half of the input. While in the three-dimensional excitations, the acceleration was about 80% of the input. On the other hand, the maximum shear force showed the same tendency in all inputs. In this test model, all columns in super-structure were supported through cantilever beams to obtain a larger aspect ratio. In this situation, the horizontal acceleration may be amplified by the vertical input. The variation of axial load when inputted one, two and three-dimensionally are compared in Table 7. It changed from -90% to +150 in the three-dimensional inputs. Hysteresis loops in X direction are shown in Fig.8. Results from one-dimensional input were almost the same as that from a static test, disturbed little from the axial load variation. Hysteresis loops from two and three-dimensional inputs were almost the same, despite the axial load in a three-dimensional case varied more, but differed with the result of one-dimensional input.

Table 7: Maximum variation of axial loads when inputted one, two and three-dimensionally.

Input / Axial load	El			Ha		
	1D	2D	3D	1D	2D	3D
Decrease	-50	-70	-90	-70	-80	-80
Increase	+40	+100	+100	+70	+90	+150

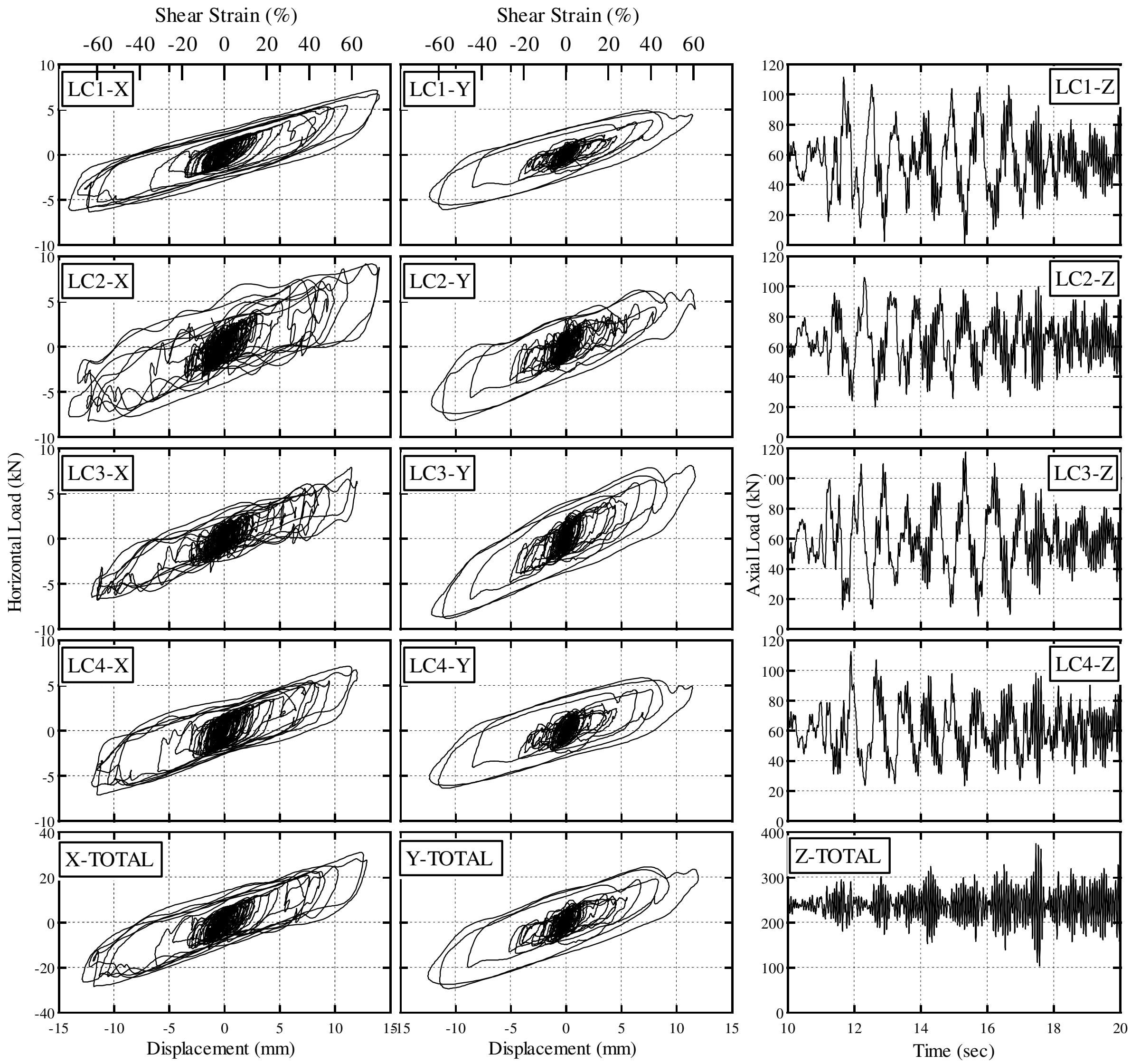


Fig.6: Test results of No.30 shown in Table 4. The influence of axial loads on the hysteresis loop was studied.

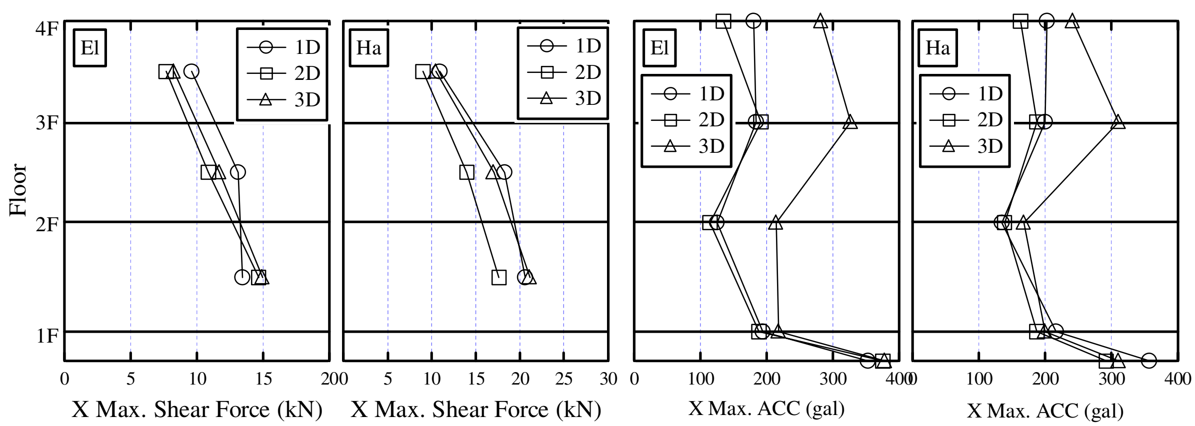


Fig.7: The maximum acceleration and shear force distribution along the height are shown for test cases of No..4,14,21,12,16,30, where the El and Ha are inputted one, two and three-dimensionally.

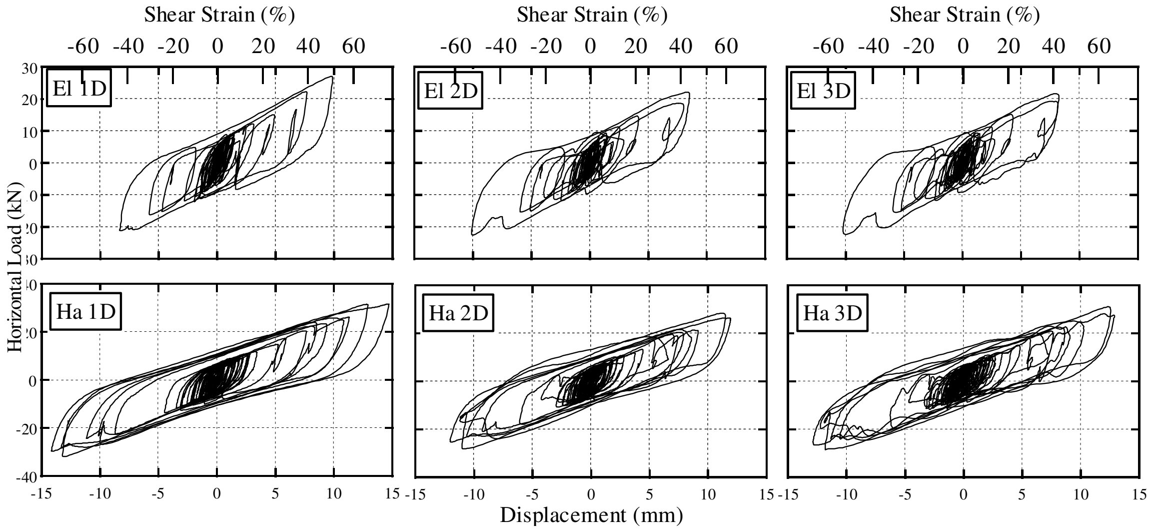


Fig.8: Hysteresis loops when inputted one, two and three-dimensionally. The test cases are No. 4,14,21,12,16,30 shown in Table 4.

Tensions Occurred in LRB

High rise buildings with seismic isolation devices have increased rapidly in order to obtain both seismic safety and economical merits. In buildings having large aspect ratio, the tensile load in a bearing occurs easily. It is important to know the characteristics of whole isolation floor under such conditions and how much characteristics of a bearing would change after suffering tensile loads.

Test cases where a tensile load in a bearing occurred are summarized in Table 8. There were 14 cases where the tensile load occurred in all 55 test cases. The maximum tensile pressure was 2.2MPa in No.53. The maximum tensile load occurred is marked with a box. In Fig.9 and Fig.10, are shown results in EL and Ha three-dimensional inputs. In the time history of axial load, the time is marked with a circle when a tensile load occurred. The hysteresis loops were stable in spite of the tensile load. In all 55 test cases, the maximum compressive pressure was 23.2MPa which is almost three times of the design load.

After shaking table tests, a routine static test was carried out. The characteristics was summarized in Table 9. The hysteresis loops in X and Y direction are shown in Fig.11. The post-yield stiffness changed -4%, while the yield load changed -8%. There was little change considering such amount number of tests.

Table 8: Test cases where the tensile load occurred

Test case	Input wave	Tensile load occurred in bearings (kN)			
		No.1	No.2	No.3	No.4
23	El-0.54xy	—	3.04	—	8.53
25	Ha-0.49xy	2.06	—	—	—
26	Ha-0.40xz-ew	14.31	—	2.35	7.74
32	Ko-0.43xyz	—	1.67		0.88
41	Ha-0.45z	14.90	**16.27**	**13.62**	14.50
42	El-0.78x	—	—	3.92	—
43	Ha-0.39x-ew	—	—	0.88	—
45	El-0.54xyz	—	7.94		7.84
46	Ta-0.56xyz	7.35		10.58	6.86
47	Ha-0.49xyz	9.70	—	6.27	—
48	Ko-0.65xyz	—	17.50	2.35	12.05
50	Ko-0.82x	3.53	—	—	—
51	Ko-0.82x-ew	—	12.25	**13.62**	—
53	Ko-0.82xz-ew	**17.05**	14.41	13.23	**15.58**

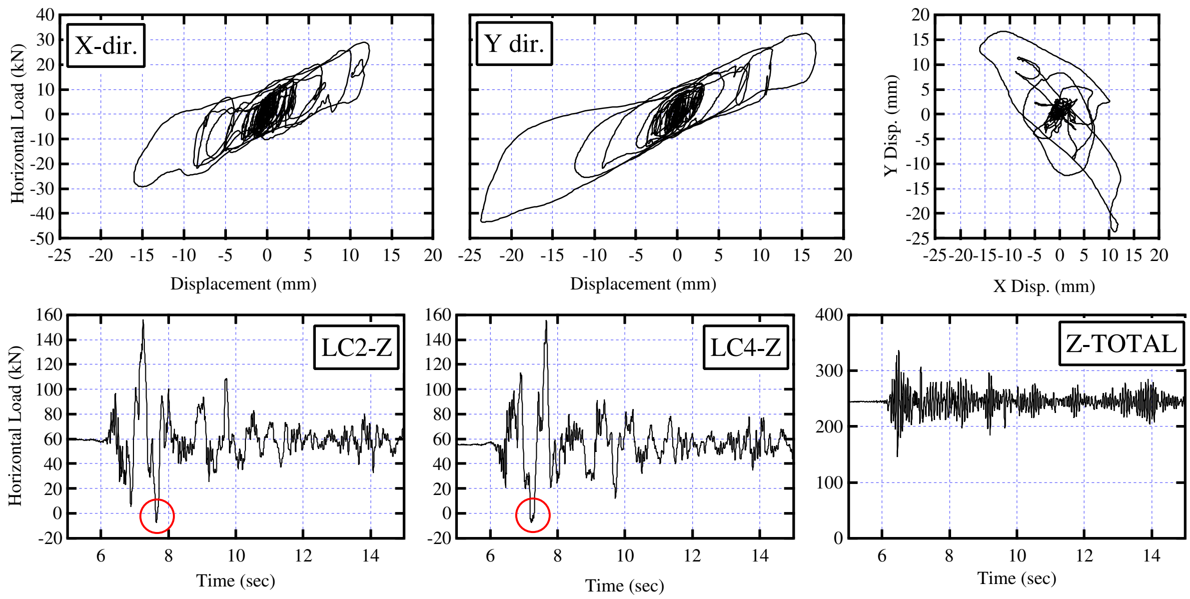


Fig.9: Results of test case No.45 where El 75cm/sec were inputted three-dimensionally.

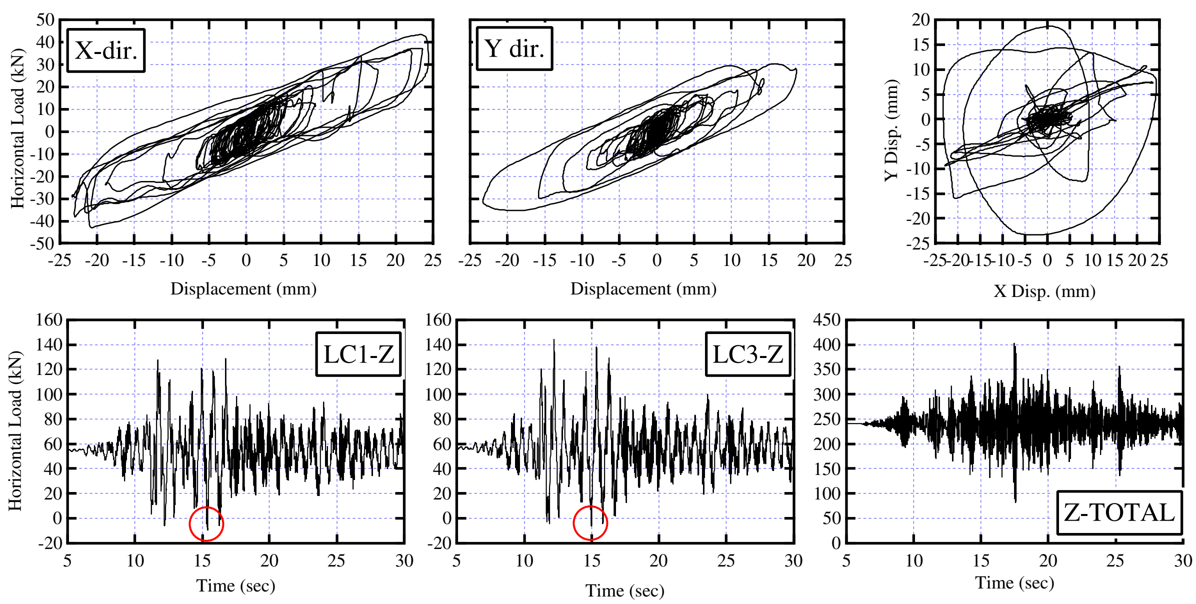


Fig.10: Results of test case No.47 where Ha 75cm/sec were inputted three-dimensionally.

Table 9: Test results of a LRB before and after the shaking table test.

State	Post-yield stiffness (N/mm)	Yield load (kN)
Before test	242	2.3
After test (X direction)	230	2.1
After test (Y direction)	231	2.1
Change	-4%	-8%

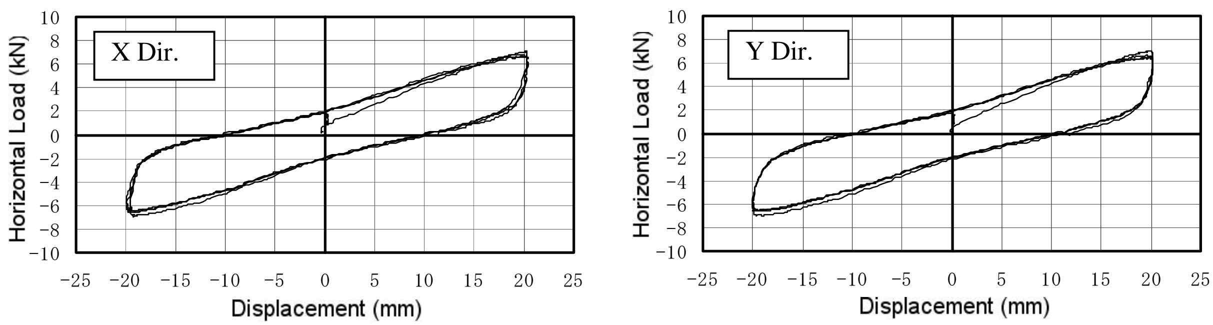


Fig. 11: Static test results after the shaking table test.

RESPONSE ANALYSIS RESULTS

Model

Super-structure

The response analyses were carried out using 3D FEM dynamic response analysis program ADAM/3D DYNAMIC [5]. Columns, beams and girders were modeled as elasto-plastic members in the model. Masses were concentrated in the column-beam joints or beam-beam joints. Analytic natural frequencies of the base-fixed model are compared with test results in Table 10. Ratios of the 1st mode natural frequency between analyses and test results were within 5% in both X and Y directions.

Table 10: Analytic natural frequencies of the base-fixed model. In () shown ratio to test results.

Mode		1st	2nd	3rd
Frequency (Hz)	X	3.86(1.05)	12.1(1.08)	22.4(1.01)
	Y	3.62(1.01)	11.1(0.99)	20.0(0.90)

LRB

Each LRB was modeled horizontally as Multi Shear Springs (MSS) consisting of eight springs and vertically as an elastic spring. The hysteresis characteristic of the horizontal spring was modeled using a modified Bilinear RO(BRO) model proposed by Feng [2]. The post yield stiffness and yield load of the LRB were determined from both static routine test results and the shaking table test results as Kd50=343N/mm, Qd50=2.06kN. Parameters in the BRO model were assumed as follows: Kt=3.0Kd, Ku=40Kd, γ=3.5. The vertical elastic spring had different compressive and tensile stiffness determined from routine static tests. The tensile stiffness was assumed as 1/7 of the compressive one.

Damping Ratio

Damping type was assumed to be proportional with momentary horizontal stiffness. Corresponding with the 1st mode of the super-structure, a damping ratio of 2.5% was used. As discussed in the test result, 2.0% was obtained in the white noise shaking table tests.

Input Wave

The input waves for analyses were acceleration waves, which were recorded on the shaking table.

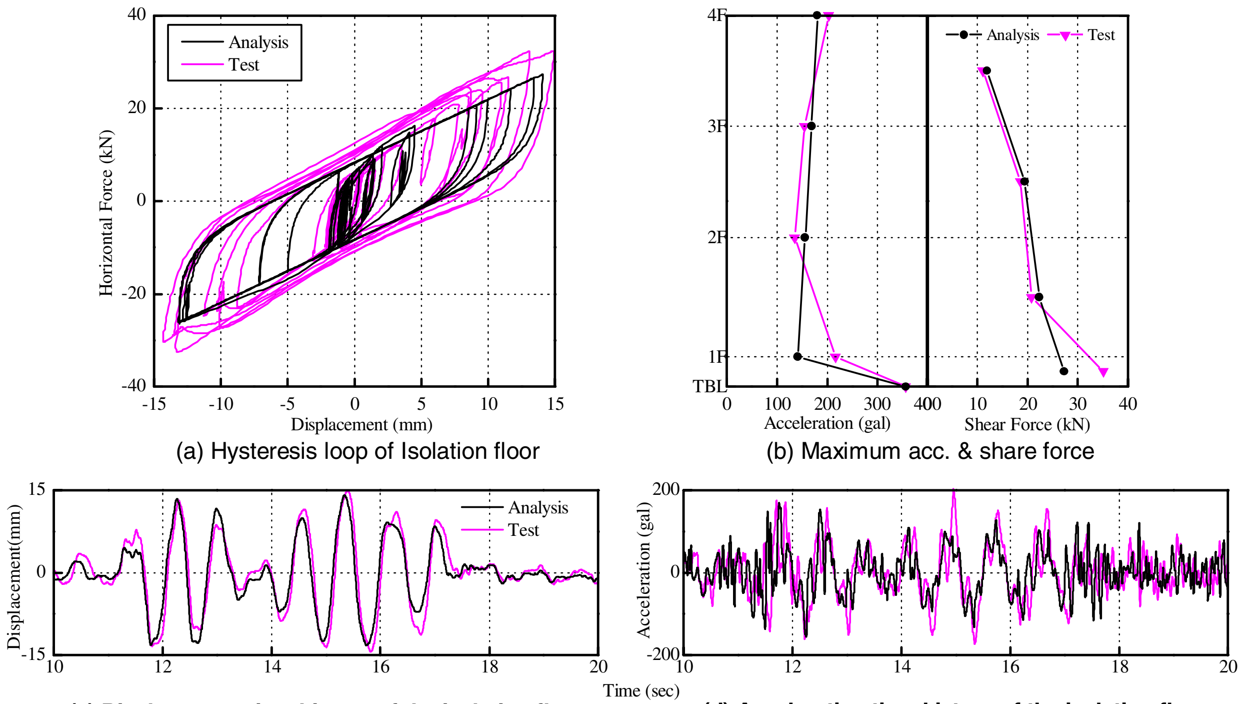
Results

One-Dimensional Input

Results of one-dimensional input are considered to be near the result of a static test. Thus analytical model could be checked over using one-dimensional input result. Analytical results are compared with test results for No.12 when Ha 50 cm/sec was inputted one-dimensionally in Fig.12. The maximum displacements of isolation floor agreed well as shown in Table 11 with results from other test cases. This was the same situation in other test cases, although test result in No.10 was 17% larger than analytical result. In Fig.12 (a) hysteresis loops are compared. Usually yield load of LRB become larger as the axial load increases, which is not considered in the analytical model. Thus, although the maximum displacements agreed well, the analytical hysteresis loop became expanded to include the test result. In Fig.12 (b), the maximum response acceleration and the maximum response shear force are compared. In Fig.12 (c), displacement time histories of the isolation floor are compared. In Fig.12 (d), acceleration time histories at 4th floor are compared. Good agreements were found in all comparisons.

Table 11: Comparison of maximum displacement of isolation floor.

	Test cases	El(No.10)	Ta(No.11)	Ha(No.12)
Maximum displacement(cm)	Analysis	17.2	15.2	14.1
	Test	14.6	15.4	14.9



(a) Hysteresis loop of Isolation floor

(b) Maximum acc. & share force

(c) Displacement time history of the isolation floor

(d) Acceleration time history of the isolation floor

Fig.12: Comparison between test results and analytical results for No.12 when Ha 50cm/sec was inputted one-dimensionally.

Three-Dimensional Input

In this analytical model of LRB, influence of variation of the axial load on hysteresis loop is not considered. How much the test results can be simulated well by this analytical model of LRB will be checked over here.

In Fig.13, analytical results are compared with test results for No.21 when El 50 cm/sec was inputted three-dimensionally. Hysteresis loops in X and Y directions were shown in Fig.13(a),(b). Although the analytical result was same with the test result in X direction, the test result in Y direction expanded around the minus maximum displacement. This phenomenon was observed only in Y direction when El was inputted. Further study is required. The displacement locus is shown in Fig.13(c). As noted above, the displacement in Y direction agreed not well. But the whole tendency of the displacement trace was almost the same. In Fig.13(d),(e), the displacement time histories are compared. Good agreements were found here.

The maximum acceleration distribution is shown in Fig.13(f), where the test results of No.14 are shown together when only X and Y were inputted. The analytical results agreed well with test results of No.14, but not well with No.21. In the test case No.21, the rocking was more amplified than that expected due to the vertical input. In this test model, all columns in super-structure were supported through cantilever beams to obtain a larger aspect ratio. In this situation, the horizontal acceleration may be amplified by the vertical input. However, the analytical result of shear force agreed well with the test result. In Fig.13(g), time history of X direction at 4th floor was shown. High frequency component which was considered to be affected by the vertical input was observed too. In Fig.13(h), variation of axial load is compared. The test result agreed well with the analytical result.

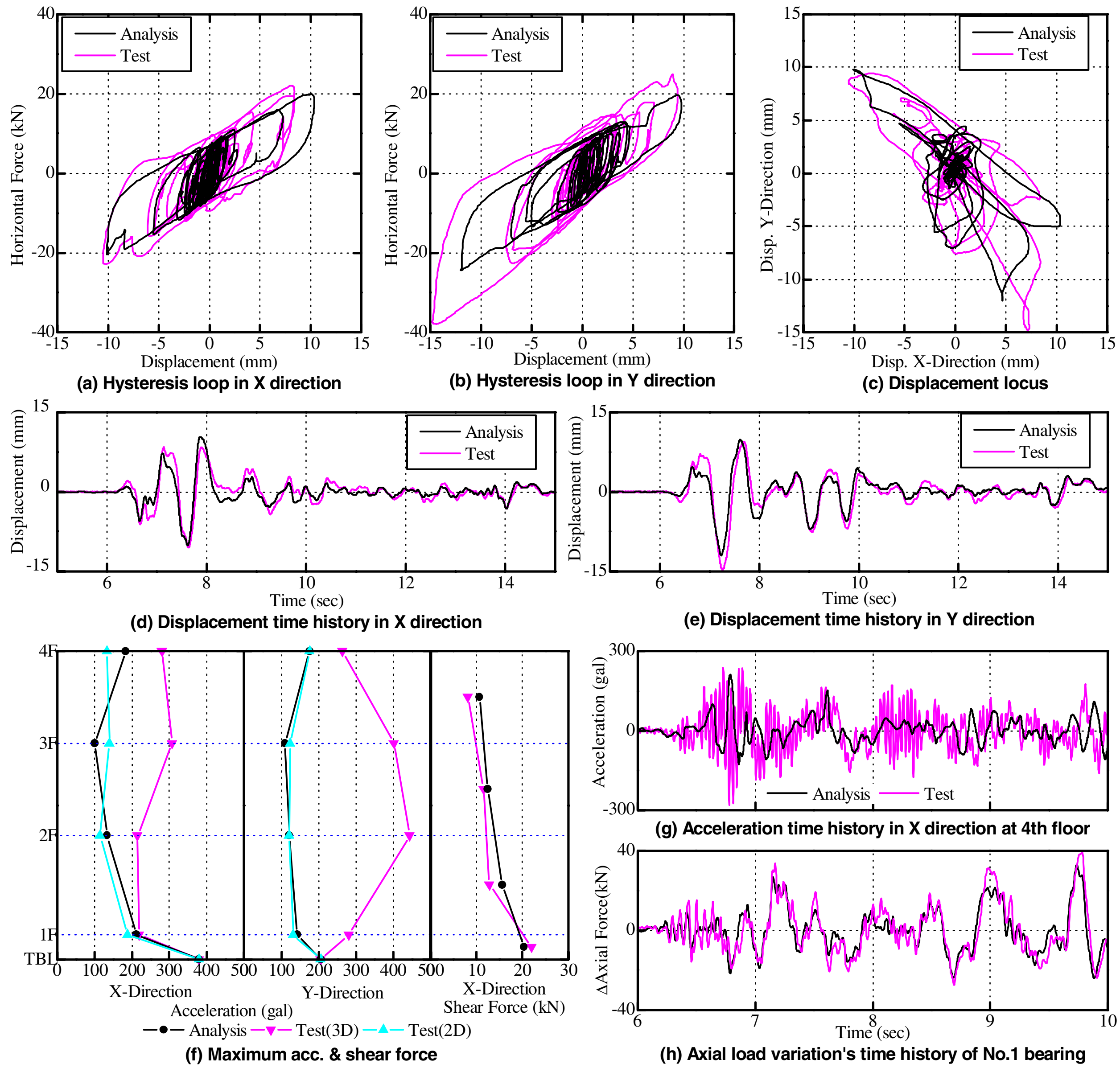


Fig.13: Comparison between test results and analytical results for No.21 when El 50cm/sec was inputted three-dimensionally.

CONCLUSIONS AND DISCUSSIONS

Three-dimensional shaking table test was carried out. A 24-story high-rise building with an aspect ratio of four supported by LRB is the targeted structure model. Conclusions could be remarked as follows.

I. In total 55 test cases, the maximum residual displacement was 1.2mm which corresponded 15mm in a real size building. It is too small to consider in a design practice.
II. The variation of axial load during the test had clear influence on the hysteresis of LRB. In the hysteresis loop, the unloading stiffness became larger when the axial load increased. Otherwise, the unloading stiffness became smaller when the axial load decreased.
III. In one-dimensional input test, the hysteresis loop looked the same as that from a static test. In two or three-dimensional input, the hysteresis loop was disturbed heavily by the variation of the axial load than that in one-dimensional input.
IV. In total 55 test cases, there were 14 cases where the axial tension in a LRB occurred. All LRBs suffered 2MPa tensile stress while the maximum tensile stress was 2.2MPa. After all shaking table tests, static fundamental property tests on the bearings showed little change.
V. Three-dimensional dynamic response analysis was conducted to simulate the test results. Although axial loads of the bearings were observed to vary severely, in a moderate three-dimensional input case, the displacements of the isolation floor and the axial loads in the bearings were simulated well.

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