13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 164

ANALYTICAL AND EXPERIMENTAL STUDIES ON THE SEISMIC RESPONSE OF BASE ISOLATION SYSTEMS FOR ELECTRIC POWER EQUIPMENT

Young-Sun CHOUN[1] Min-Kyu KIM[2] Jeong-Moon SEO[3]

SUMMARY

Analytical and experimental studies of the base isolation systems installed in an electric power equipment model are presented. This paper investigates the response of several base isolation systems at different heights under various earthquake ground motions including near-fault ground motions. As for the base isolation systems, a natural rubber bearing (NRB), a high damping rubber bearing (HDRB), and a friction pendulum system (FPS) are selected. The shake-table experiments are carried out for two cases of equipment models with various isolation systems. One is directly mounted to the shaking table, and another is installed on the floor of a steel frame structure mounted to the table. As input motions, artificial time histories enveloping the US NRC Regulatory Guide 1.60 spectrum and the probability-based scenario earthquake spectra developed for the Korean nuclear power plant site as well as a typical near-fault earthquake record are used. Uniaxial, biaxial, and triaxial excitations are conducted with PGAs in the range of 0.1 to 0.25g. Acceleration responses are measured at the top of the equipment model and the floors using an accelerometer. The reduction of the seismic forces transmitted to the equipment models are estimated for different isolation systems and different input motions. The effect of the floor height and vertical motion on the reduction of seismic forces is discussed. Also, the effectiveness of the seismic isolation systems under near-fault ground motions is discussed.

INTRODUCTION

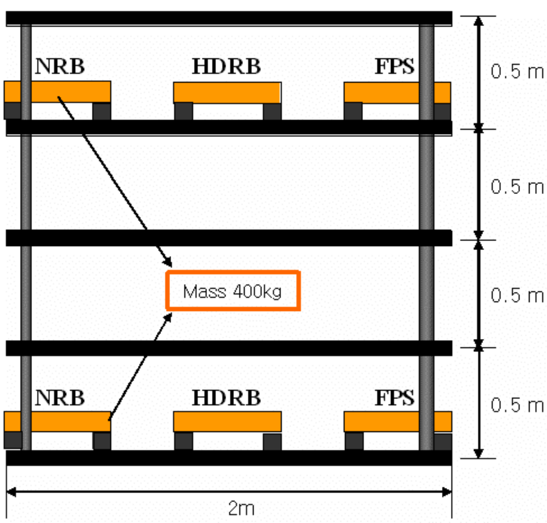
Many electric power equipment sustained significant damage in the recent earthquakes, for example, the 1995 Kobe and the 1999 Izmit earthquakes [1]. The electric power equipment is one of the major lifeline systems which have a vital role in maintaining human life. So, there are lots of efforts for the enhancement of the seismic capacity of electric power equipment. In this study, base isolation systems are introduced for the seismic safety improvement of the electric power equipment. For light-weight equipment, it is very difficult to adapt the base isolation systems. In this study, the base isolation systems for light electric power equipment are presented and the responses of each isolation system are investigated. As for the base isolation systems, a natural rubber bearing (NRB), a high damping rubber bearing (HDRB) and a

[1] Principal Researcher, Korea Atomic Energy Research Institute, Korea. Email: sunchun@kaeri.re.kr
[2] Senior Researcher, Korea Atomic Energy Research Institute, Korea. Email: minkyu@kaeri.re.kr
[3] Principal Researcher, Korea Atomic Energy Research Institute, Korea. Email: jmseo@kaeri.re.kr

friction pendulum system (FPS) are selected. The shaking table tests are carried out for two kinds of equipment models with various isolation systems. One is directly mounted to the 1st floor and another is installed on the 4th floor of a steel frame structure. As input motions, artificial time histories enveloping the US NRC RG 1.60 spectrum [2] and the probability-based scenario earthquake spectra developed for the Korean nuclear power plant site as well as a typical near-fault earthquake record are used. Uniaxial, biaxial, and triaxial excitations are conducted with PGAs of 0.1, 0.2 and 0.25g. Acceleration responses are measured at the top of the equipment model and the floors using an accelerometer. The reduction of the seismic forces transmitted to the equipment models are determined for different isolation systems and input motions. The effects of the floor height and vertical motion on the seismic reduction are discussed. Also, the effectiveness of the seismic isolation systems under near-fault ground motions is discussed. As a result, the applicability of the base isolation systems for the light weight electric power equipment is presented.

TEST MODEL

The test model is shown in the Fig. 1. As shown in the figure, the structure is constructed of 4 floor systems of steel frames. The equipment is installed on the 1st floor and 4th floor. For the modeling of the light weight equipment, 400kg steel masses are used. The dimensions of the frame structure are summarized in Table 1.



(a) Drawing


(b) Figure

Fig. 1 Test Model

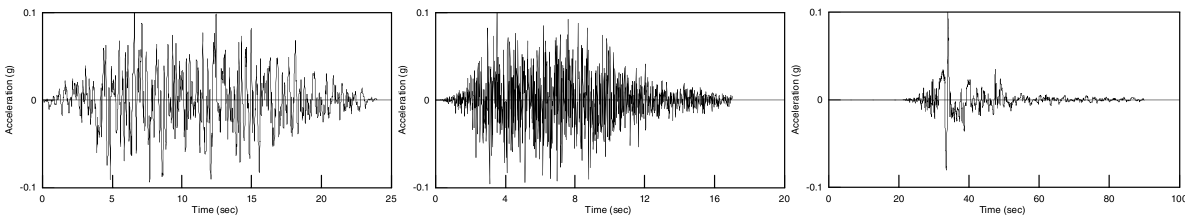
Table 1. Dimension of the Test Model

Members		Unit	Dimension
Steel Column	Outside diameter	cm	4.27
	Thickness	cm	0.36
Slab	Thickness	cm	4

For the determination of the dynamic characteristics of the test model, a pre-analysis using a commercial computer program called SAP2000 [3] is performed. After the modal analysis, the fundamental frequency is determined as 4.7Hz.

INPUT MOTIONS

For the shaking table test, three kinds of seismic motions selected. Simulated earthquakes are based on the response spectrum of the US NRC RG 1.60 and the probability-based scenario earthquake spectra developed for the Korean nuclear power plant site as well as the measured time history of the 1999 Chi-Chi Earthquake. The three kinds of earthquake time histories and response spectra are shown in the Figure 2 and 3, respectively. NRC shown in the Fig. 2(a) is simulated based on the US NRC RG 1.60, which is used as a design spectrum of the nuclear power plants in Korea. SCE shown in the Fig. 2(b) is based on the new response spectrum which is developed by a probabilistic seismic hazard analysis of a Korean nuclear power plant site. TCU shown in the Fig. 2(c) is measured time history at the TCU052 when the Chi-Chi earthquake was happened. As shown in the response spectra in Fig. 3, the significant frequencies of three earthquakes are very different. The significant frequencies of NRC, SCE and TCU are 2-8Hz, 20Hz and 1Hz, respectively.



(a) NRC (b) SCE (c) TCU

Fig. 2 Input Earthquake Time Histories

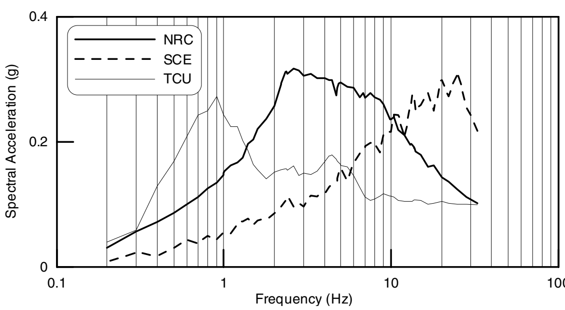


Fig. 3 Response Spectrum of the Input Motion

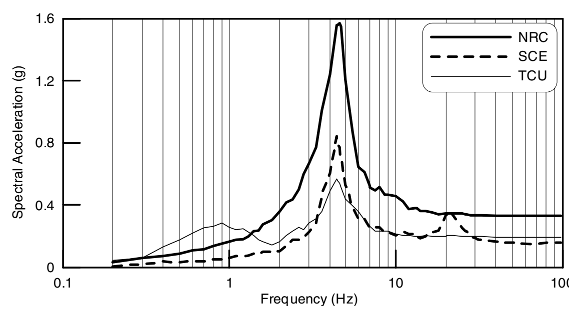


Fig. 4 Floor Response Spectrum of Structure

BASE ISOLATION SYSTEM

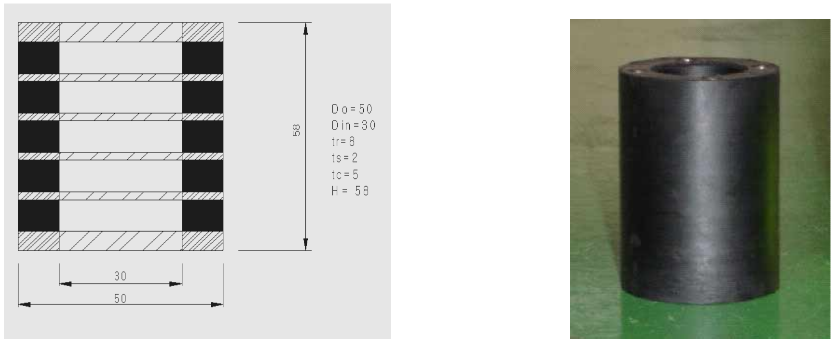
Determine the Floor Response Spectrum

For the design of the effective base isolation systems for the small equipment in the structure, the floor response spectra are determined using the simple numerical analysis model using the computer program SAP2000. The developed floor response spectra of the 4th floor are as shown in Fig. 4. As shown in the figure, the resonant frequency of the structure is about 4.7Hz. The response of the frame structure with fundamental frequency of 4.7Hz for NRC is the highest and the lowest for TCU.

Design of the Isolation Systems

Natural Rubber Bearing and High Damping Rubber Bearing

For the design of a NRB and a HDRB, the target frequency is decided as 2.3Hz. As shown in Fig. 4, 2.3 Hz is not sufficient for the equipment isolation, because the mass used in the experiment is just 400kg. In the case of light-weight equipment, it is very difficult to make an efficient isolator because of the small mass. In this case, if the stiffness of the isolator is large, the isolator will not work as an isolator. Finally, it is decided that the outside diameter of the isolator should be 50mm, the height should be 58mm and the rubber thickness should be 40mm. The NRB and HDRB are made with same shape and size as shown in Fig. 5.



(a) Drawing (b) Figure

Fig. 5 NRB and HDRB

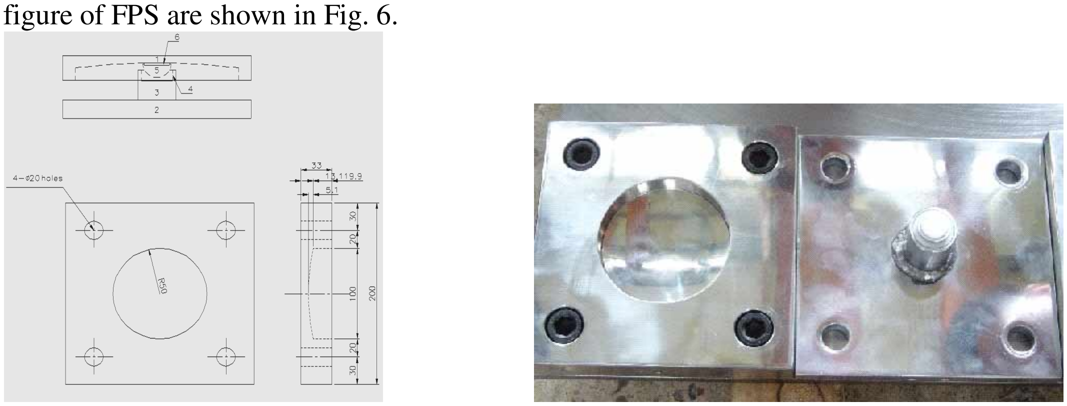
Friction Pendulum System

The natural frequency of the FPS of the experiment is decided as 1Hz. The period and the stiffness of the FPS can be determined as equations (1) and (2) [4].

$$T = 2\pi\sqrt{\frac{R}{g}} \tag{1}$$

$$K = \frac{W}{R} \tag{2}$$

where, T is the period of the FPS, R is the radius of the curvature, g is the gravity acceleration, K is the effective horizontal stiffness and W is the weight of the upper structure. Using the equations (1) and (2), the radius of the curvature is decided as 24.8cm and the effective stiffness is 4.02 kgf/cm^2. The drawing and the figure of FPS are shown in Fig. 6.



(a) Drawing (b) Figure

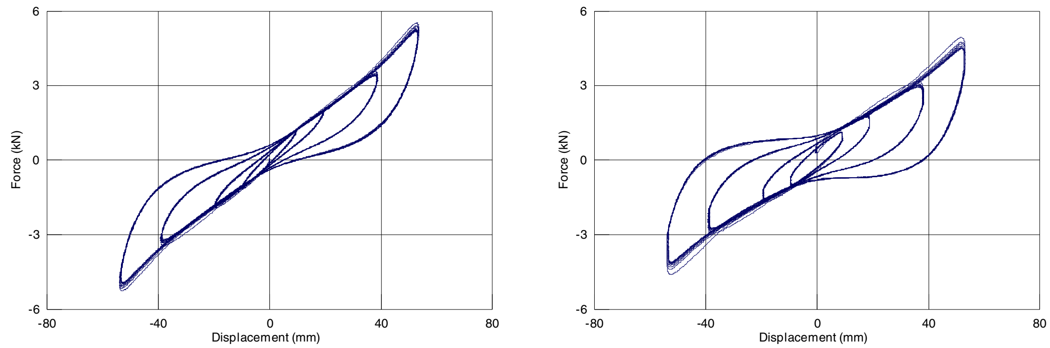
Fig. 6 FPS

Characterization Test

For the determination of the mechanical characteristics of isolation system, the characterization tests are performed by the actuator system. Vertical and horizontal forces are measured using the load cell and the displacements are measured using the LVDT.

Natural Rubber Bearing and High Damping Rubber Bearing

The characterization test is performed using the 0.1Hz sine wave for the NRB and the HDRB with maximum displacements 10, 20, 40, and 55mm. The displacement-force hysteresis curves of two isolators are obtained as shown in Fig. 7.



(a) NRB (b) HDRB

Fig. 7 Hysteresis of Rubber Bearing

As shown in the Fig. 7, the same shaped NRB and HDRB behave differently. The stiffness of the NRB is larger than that of the HDRB and the damping ratio of the HDRB is larger than that of the NRB. The variations of the damping ratio are shown in Table 2. As shown in the Table 2, the damping ratio of HDRB is larger than that of the NRB, but the differences are decreased as increasing the maximum displacements. It can be also recognized from Fig. 7 and Table 2 that the hardening is appeared at the maximum displacement 55mm, because the shape factor of the NRB and HDRB is not in the common range.

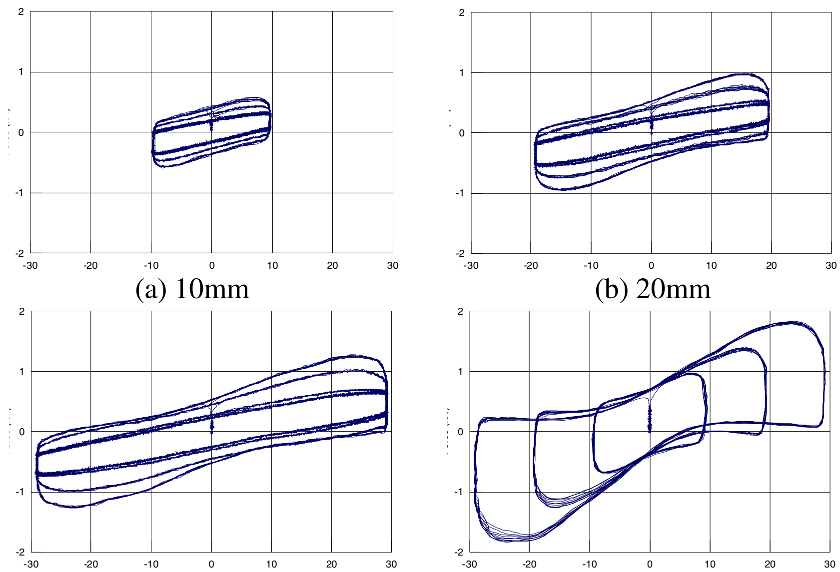
Table 2. Damping Ratio of NRB and HDRB

Maximum Displacement(mm)		10	20	40	55
Damping Ratio (%)	NRB	2.2	9.2	10.5	10.9
	HDRB	14.8	19.0	22.3	20.6

Friction Pendulum System

Four cases of characterization test are performed for the maximum displacement and the velocity and four kinds of hysteresis curves are obtained as Fig. 8. Fig. 8(a), 8(b) and 8(c) present the maximum displacements as 10mm, 20mm and 30mm, respectively, where, the testing velocities varies as 2, 4, 20 and 40mm/sec. In the case of Fig. 8(d), the velocities are fixed at 80mm/sec but the maximum displacement varies as 10, 20 and 30mm.

As shown in the Fig. 8, the area of the hysteresis loof varies with the velocity. It can be said that the hysteresis is clearly dependent on the velocity. In Fig. 8(d), the responses are remarkably changed at the maximum displacement. It is because of the small radius of the curvature of this FPS. Actually since the radius of the curvature of the FPS is only 24.3cm, this small radius may increase the horizontal reaction forces for high velocity. Similar results can be found in the Fig. 8(b) and 8(c). Therefore, in this case, when the velocity is greater than 20mm/sec or the maximum displacement is greater than 20mm, the hardening effect will be appeared.



(a) 10mm (b) 20mm

(c) 30mm (d) 80mm/sec

Fig. 8 Hysteresis of FPS

SHAKING TABLE TEST

Test Procedure

The shaking table test procedures are tabulated in Table 3. During the seismic response tests, several times of modal tests are performed for checking the variation of natural frequencies and the damage of the frame structure. The PGA varies as 0.1g, 0.2g and 0.25g and 1-D, 2-D and 3D tests are performed. The accelerometers are used for measuring the 3-D acceleration of the isolated equipment and the floor.

Table 3. Shaking Table Test Procedure

Run	Input Motion	PGA	Remark
1	Modal Test		Frequency Check
2	SCE	0.1g	1-D, 2-D, 3-D
3	TCU	0.1g	1-D, 2-D, 3-D
4	NRC	0.1g	1-D, 2-D, 3-D
5	Modal Test		Frequency Check
6	SCE	0.2g	1-D, 2-D, 3-D
7	TCU	0.2g	1-D, 2-D, 3-D
8	NRC	0.2g	1-D, 2-D, 3-D
9	Modal Test		Frequency Check
10	SCE	0.25g	1-D, 2-D, 3-D
11	TCU	0.25g	1-D, 2-D, 3-D
12	NRC	0.25g	1-D, 2-D, 3-D
13	Modal Test		Frequency Check

Test Results

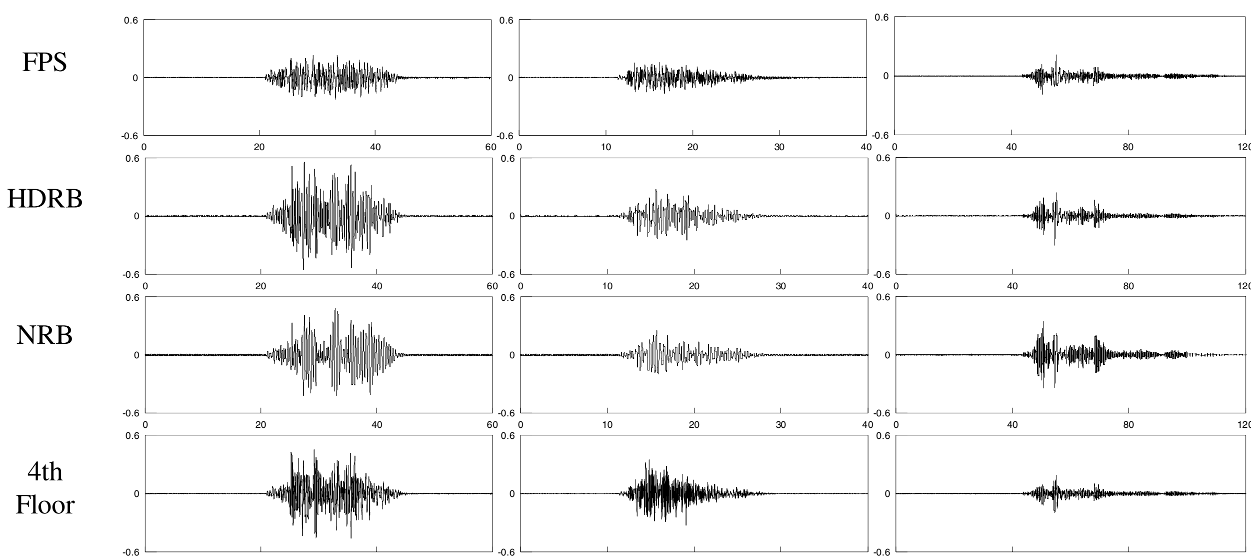
The PGA results of the experiment are presented in Table 4. In this case, only the 1-D experimental results are compared. As shown in the table, the target and the real PGA are different. These differences are caused by the shaking table itself. The floor response of the 4th floor is different according to the input motions. In the case of SCE, the response of the 4th floor is decreased, but for TCU and NRC input motion, the acceleration responses are increased. This is dependent on the significant frequency of the input motions.

Table 4. PGA Results of Experiment (unit:g)

Input Motion	Input PGA		1st Floor			4th Floor			
	Target	Real	FPS	NRB	HDRB	Floor	FPS	NRB	HDRB
SCE	0.1	0.133	0.157	0.123	0.117	0.130	0.176	0.167	0.184
	0.2	0.322	0.232	0.177	0.198	0.352	0.164	0.251	0.275
	0.25	0.414	0.204	0.230	0.213	0.389	0.279	0.301	0.315
TCU	0.1	0.085	0.116	0.126	0.108	0.136	0.127	0.168	0.210
	0.2	0.158	0.876	0.233	0.185	0.202	0.213	0.346	0.298
	0.25	0.192	0.997	0.278	0.207	0.285	0.303	0.295	0.391
NRC	0.1	0.132	0.143	0.266	0.191	0.210	0.139	0.319	0.340
	0.2	0.287	0.175	0.550	0.333	0.459	0.236	0.482	0.556
	0.25	0.331	0.274	0.605	0.391	0.663	0.398	0.570	0.716

In case of SCE, the structure and the equipment responses are decreased. Although the isolators are designed for the 4th floor equipment, the isolation effects can be found on the 1st floor equipment. This is because the significant frequency of the SCE is much higher than that of the isolation system. The isolation effects of the 4th floors equipment are significant than that of the 1st floor. The reason might be the isolation systems are designed from the 4th floor response spectrum.

In the case of TCU and NRC, the structure responses are increased. The equipment responses of these two cases are very different for the location of the equipment. On the 4th floor, the equipment responses are decreased but on the 1st floor they are increased. These results are compared as another point of view as follow. All of these cases of the acceleration time histories are presented in Fig. 9 and 10. In these figures, the acceleration time histories for the input motion and the equipment location are presented. As shown in the figures, one can clearly recognize that the isolation effects are dependent on the input motion, isolation systems and the equipment location. In these figures, the horizontal axis indicates time (second) and the vertical axis indicates the acceleration (g).



NRC SCE TCU

Fig. 9 Equipment Response of the 4th Floor (Input Target PGA=0.2g, 1-D)

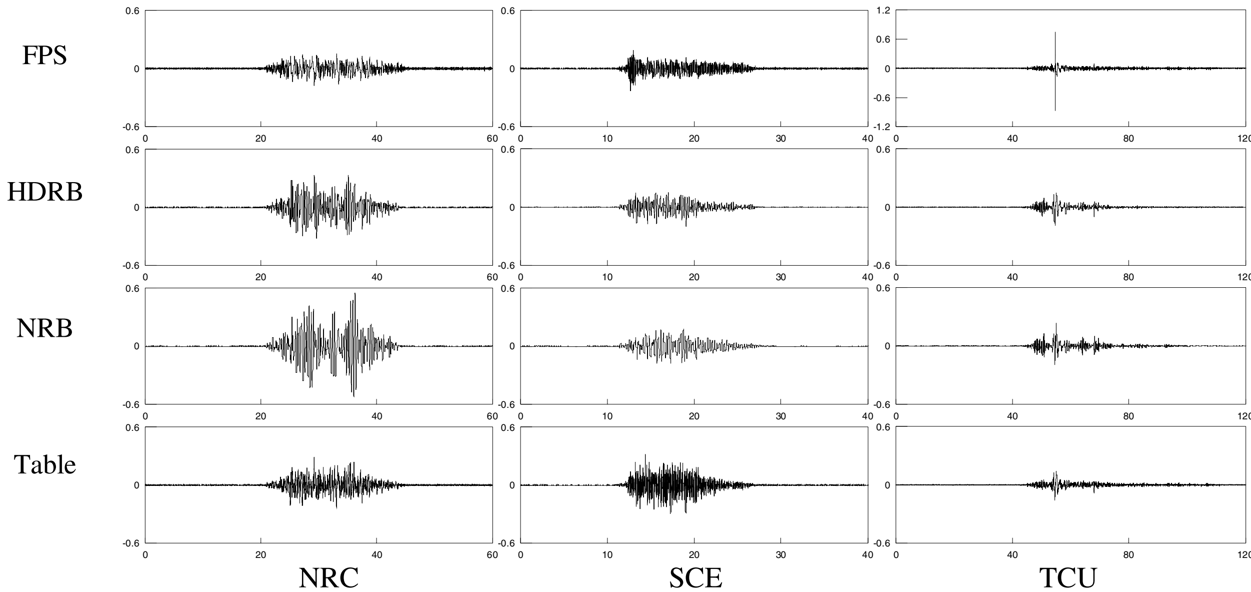


Fig. 10 Equipment Response of the 1st Floor (Input Target PGA=0.2g, 1-D)

Response Ratio

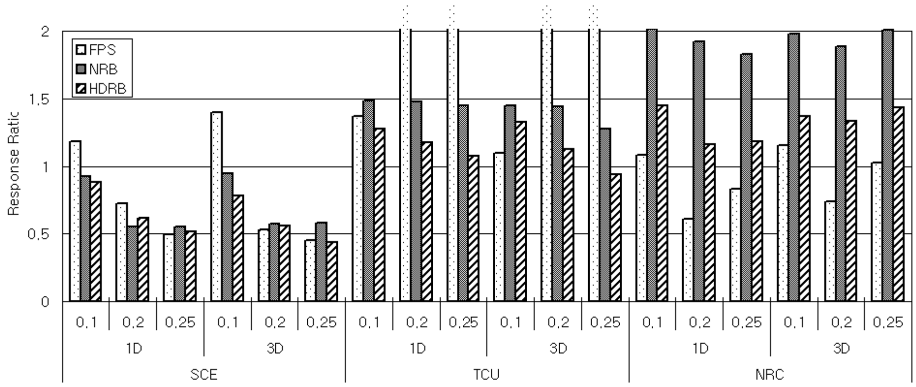
For the detailed investigation of the seismic isolation effect, the response ratios are shown in Tables 5 and 6, and Fig. 11. Here, the vertical seismic motion effect is investigated by comparing the test results of 3 dimensional cases.

Table 5. Response Ratio of the 1st Floor Equipment

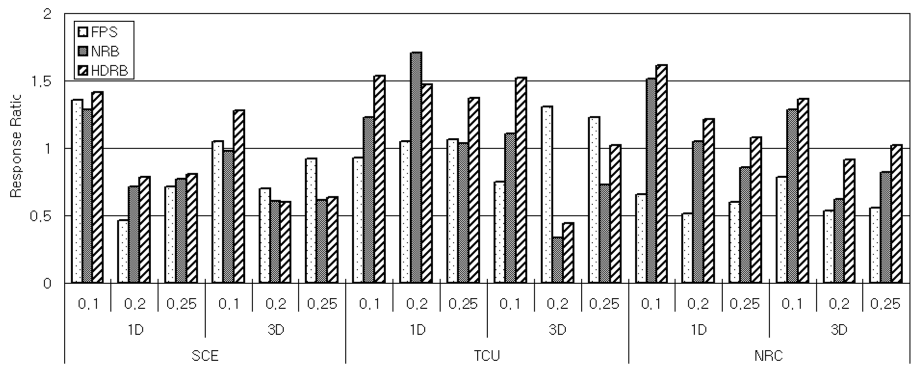
Input Motion		SCE			TCU			NRC		
Target PGA \ Isolator		FPS	NRB	HDRB	FPS	NRB	HDRB	FPS	NRB	HDRB
1D	0.1g	1.185	0.926	0.879	1.371	1.482	1.277	1.083	2.015	1.445
	0.2g	0.721	0.550	0.615	5.555	1.475	1.176	0.610	1.918	1.160
	0.25g	0.493	0.555	0.515	5.189	1.448	1.078	0.829	1.826	1.182
3D	0.1g	1.401	0.945	0.781	1.098	1.446	1.327	1.151	1.977	1.372
	0.2g	0.528	0.571	0.557	7.070	1.443	1.125	0.738	1.884	1.332
	0.25g	0.453	0.582	0.434	4.258	1.273	0.941	1.023	2.005	1.431

Table 6. Response Ratio of the 4th Floor Equipment

Input Motion		SCE			TCU			NRC		
Target PGA \ Isolator		FPS	NRB	HDRB	FPS	NRB	HDRB	FPS	NRB	HDRB
1D	0.1g	1.358	1.288	1.417	0.93	1.228	1.539	0.659	1.516	1.618
	0.2g	0.466	0.715	0.783	1.05	1.710	1.47	0.514	1.050	1.211
	0.25g	0.716	0.772	0.808	1.064	1.036	1.375	0.601	0.860	1.081
3D	0.1g	1.048	0.976	1.278	0.752	1.104	1.520	0.783	1.285	1.367
	0.2g	0.698	0.606	0.601	1.305	0.334	0.44	0.536	0.618	0.917
	0.25g	0.919	0.613	0.636	1.228	0.726	1.019	0.558	0.820	1.020



(a) 1st floor equipment



(b) 4th floor equipment

Fig. 11 Seismic Response Ratio of Test

The response ratio is defined as the response PGA to the input PGA. It means that when the response ratio is equal to one, there will be no isolation effect. Moreover, the response ratio greater than one means that the isolation systems cannot work well as isolation systems. As shown in Table 5 and Fig. 11(a), the response ratio of the 1st floor is mostly over one. This means that the isolator used in these experiments is not a proper one for the 1st floor. These are natural results because the isolation systems used in these experiments are designed for the 4th floor response spectrum. But in the case of SCE on the 1st floor, there are isolation effects in the higher PGA level. This is because the frequency ranges of SCE are very high, so no resonance occurs in this case. Moreover it is hardly find the correlation about the response ratio and the PGA but it can be said that the isolation effect is increased by increase of higher PGA.

As shown in the Table 6 and Fig. 11(b), the response ratio is greatly decreased for the equipment of the 1st floor and the many of them are still greater than one. The reason is that the resonant frequency of the structure is changed by the mass of the equipment. Actually the comparison of the modal test results of the structure with equipment and the without equipment changes remarkably. The results of the modal tests for the equipment are shown in the Fig 12. The resonant frequency of the frame structure is decreased by the isolated masses. As stated before, the target frequency of the NRB and HDRB is 2.3 Hz, so the decreasing natural frequency of the structure affects to the isolation effect. But the target frequency of the FPS is 1 Hz, so the response ratio of FPS is almost below one except some special cases. In case of TCU which significant frequency is very low, the response ration is higher than other input motions. Therefore it is very difficult to isolate small equipment.

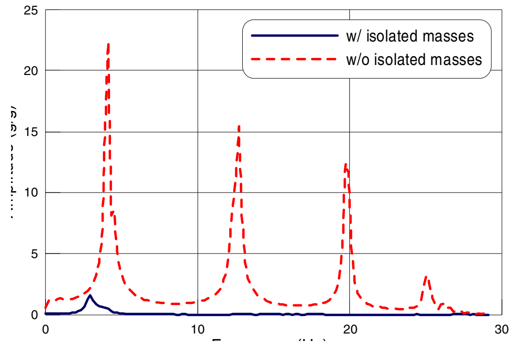
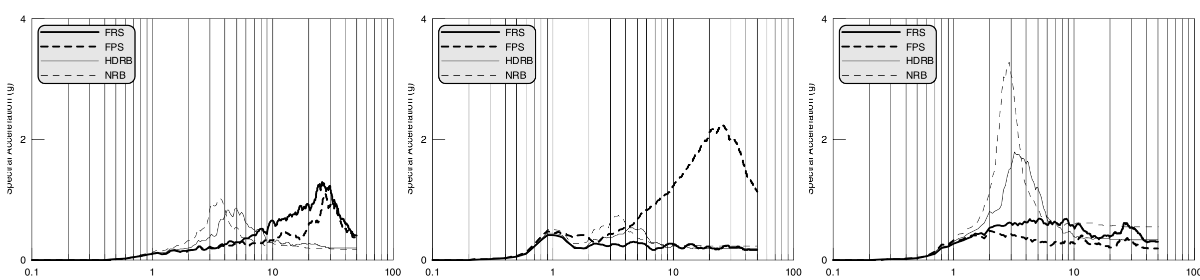


Fig. 12 Modal Test Results associated with the Isolated Masses

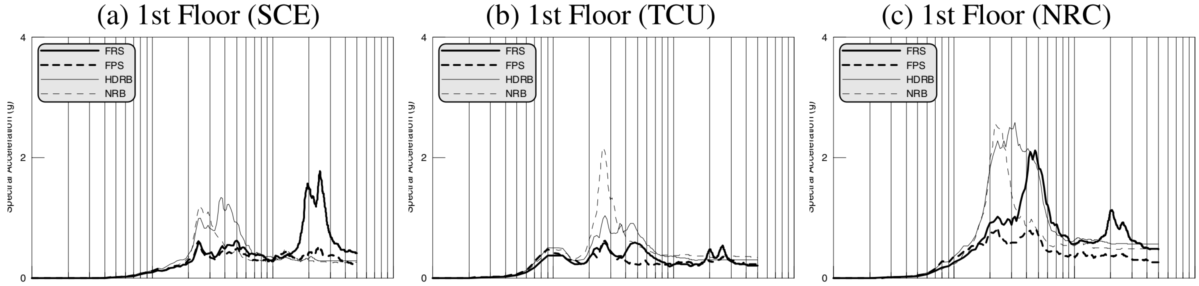
For the vertical input motion, it is hardly find the relation of the vertical motion and the seismic response ratio. But since it can be said that the vertical input motion have a few effect on the isolation results, it should be considered with great care,

Response Spectrum

The acceleration response spectra for the input motion and equipment are compared in this section. The response spectra are compared for input motions, isolation systems and the location of the equipment. All the response spectra for the equipment are presented in Fig. 13. As shown in Fig. 13, all the response of the NRB and HDRB are different. The reason is that the damping ratio of the HDRB is higher than that of the NRB and the stiffness of the NRB is higher than that of the HDRB. Therefore the resonant frequencies of the NRB are lower than those of the HDRB, while the amplitudes are higher. These characteristics can be found in all the cases of the response spectra. Then the FPS has generally a good performance for the seismic isolation except several cases. Especially, in the case of TCU, like the near fault motions, a poor behavior was determined. It means that the FPS is very difficult to isolate for the near fault earthquake motions which have long period contents and high velocities. Especially for the 1st floor case of the TCU motion, enormous response at 25Hz are measured shown in the Fig. 13(b). The reason is that the articulate friction slider of the FPS collides with the cover of the FPS. This result can be found in the acceleration time history of Fig. 10. This abnormal response can be removed by increasing the sliding limit of the slider.



(a) 1st Floor (SCE) (b) 1st Floor (TCU) (c) 1st Floor (NRC)

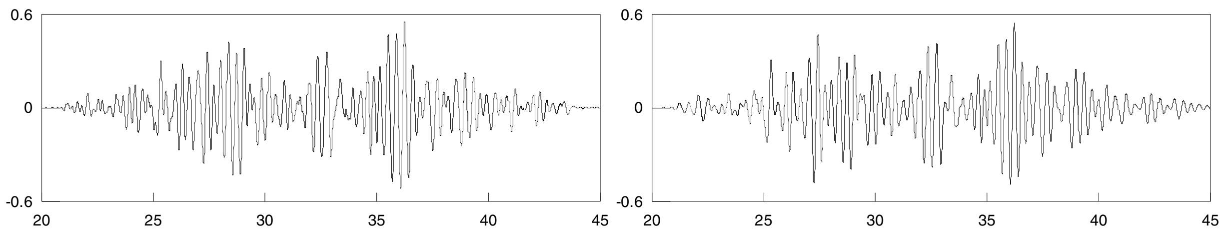


(d) 4th Floor (SCE) (e) 4th Floor (TCU) (f) 4th Floor (NRC)

Fig. 13 Response Spectra of Equipment

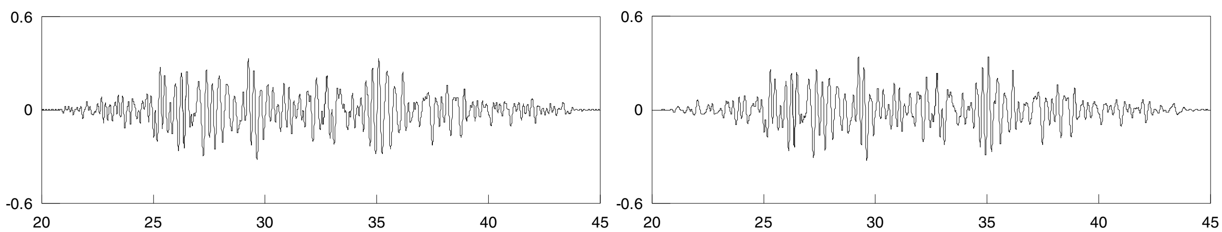
Analysis Results

For the comparison between the seismic responses of the experiment and numerical analysis, numerical analysis was performed using commercial program SAP2000. The seismic response of the 1st floor equipment which is isolated with NRB and HDRB is compared. The NRB and HDRB are modeled by linear damping model based on the properties of the characteristic test. The responses of NRC motion are shown in the Fig. 14, 15and 16. Fig. 14 and 15 shows the acceleration from histories for NRB and HDRB respectively, and Fig. 16 shows the response spectra. As shown in Fig. 14 to Fig. 16, the results of the experiment and analysis are fairly good agreements. So, it can be said that the results of the equipment isolation effects are possibly expected using analytical method.



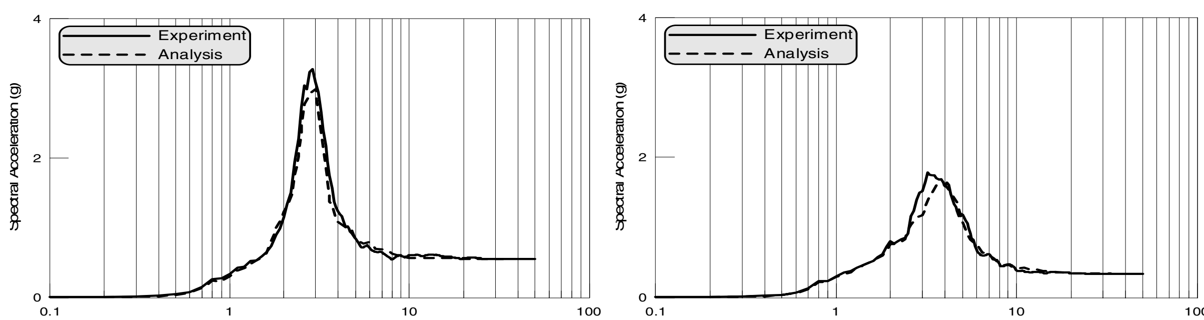
(a) Experiment (b) Analysis

Fig. 14 Comparison of Experimental and Analytical Results (NRB)



(a) Experiment (b) Analysis

Fig. 15 Comparison of Experimental and Analytical Results (HDRB)



(a) NRB (b) HDRB

Fig. 16 Compare of the Response Spectrum

CONCLUSION AND DISCUSSION

In this study, base isolation systems for electric power equipment are presented and their behavior is investigated. As base isolation systems, a natural rubber bearing (NRB), a high damping rubber bearing (HDRB), and a friction pendulum system (FPS) are selected. Three kinds of input motions, different PGA levels and locations of the equipment are considered in the experiment.

The NRB and the HDRB can be used for light weight electric power equipment. But they need careful design consideration because the rubber bearings are very sensitive in the resonant frequency regions. The high damping characteristics of the HDRB decrease the amplitude in the resonant frequency region. But it is not so good in the other frequency regions, because the damping of HDRB is not much helpful for the equipment isolation. The FPS can be used as a good isolation system for electric power equipment for all frequency regions but the displace limit of FPS should be considered with the greatest possible care. Specially, the vertical motion barely affect to the isolation effect. Finally, the response of equipment isolation system using the NRB and the HDRB can be reasonably simulated using the simple numerical analysis. As a result, seismic isolation for electric power equipment is possible using several kinds of isolators but more detailed investigation on the effectiveness of the isolators is needed.

ACKNOWLEDGEMENT

This research was supported by the Mid- and Long-Term Nuclear Research & Development Program of the Ministry of Science and Technology, Korea.

REFERENCES

1. Ersoy, S., Ala Saadeghvaziri, M., Liu, G.Y. and Mau, S.T., "Analytical and Experimental Seismic Studies of Transformers Isolated with Friction Pendulum System and Design Aspects," Earthquake Spectra, 17(4), 569-595, 2001.
2. US NRC Regulatory Guide 1.60, Design Response Spectra for Seismic Design of Nuclear Power Plants, 1973.
3. SAP2000, Computers and Structures, Inc., 1998.
4. Zayas, V., Low, S., Bozzo, L. and Mahin, S., "Feasibility and Performance Studies on Improving the Earthquake Resistance of New and Existing Buildings Using the Friction Pendulum System," UCB/EERC-89/09, University of California, Berkeley, 1989.
5. Hwang, J.S. and Ku, W., "Analytical Modeling of High Damping Rubber Bearings," Journal of Structural Engineering, Vol. 123, No. 8, August 1997.
6. Watanabe, Y., Kato, A., Somaku, T., Umeki, K. and Sato, N., "Table Test and Analysis on Base Isolated FBR Plant Model with High-Damping Rubber Bearing," 12-WCEE, 2000.
7. Abe, M., Fujino, Y. and Yoshida, J., "Dynamic Behavior and Seismic Performance of Base-Isolated Bridge in Observed Seismic Record," 12-WCEE, 2000.