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# A SHAKING TABLE TEST FOR THE EVALUATION OF FLOOR RESPONSE SPECTRUM OF SEISMIC ISOLATED STRUCTURE

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## ABSTRACT

The development of a floor response spectrum (FRS) is very important for a seismic risk assessment of nuclear power plants. In the case of non-isolated nuclear power plants, the methodology regarding FRS generation has already been developed. Therefore, in this study, shaking table tests for a seismic isolated frame structure were performed for the development of the floor response spectrum. For the shaking table test, a two-story artificial frame structure was manufactured. For the isolation devices, a lead rubber bearing and an EradiQuake system (EQS) were used. An artificial input seismic motion, which was generated for the NRC Reg. guide 1.60 design spectrum, was used but a low-frequency range should be cut off for a decrease of the shaking table displacement. One-, two-, and three-dimensional seismic input motions were considered for the assessment of the horizontal bidirectional and vertical directional effects. Through this test, whether a horizontal bi-directional seismic input can make a difference in the floor response, and moreover, whether the vertical input motion can make a change in the horizontal floor response, were investigated.

## INTRODUCTION

Seismic isolation is one of the most appropriate solutions for increasing the safety of a nuclear power plant against a moderate or strong earthquake. As we already saw in the catastrophic disaster during the Fukushima accident in 2011 in Japan, an earthquake and a tsunami may be the main reasons for severe damage to a nuclear power plant. Even though seismic isolation is a good alternative against earthquake events, and many researches into seismic isolation have already been performed, there are only 6 nuclear power plant units in the world that apply seismic isolation systems. The reason is that design guidelines were not prepared in all Countries in the world without Japan and there are many uncertainties in seismic isolators. Even though Japan already developed seismic isolation design guidelines for nuclear power plants in 2000, there remain no seismic isolated nuclear power plants in Japan. One of the uncertainties is regarding the floor response behavior of seismic isolated nuclear power plants. The floor response spectrum (FRS) is very important for a seismic risk assessment for nuclear power plants. In the case of non-isolated nuclear power plants, the methodology regarding FRS generation was already developed. Therefore, in this study, shaking table tests for a seismic isolated frame structure was conducted for the development of a floor response spectrum. For the shaking table test, a two-story artificial frame structure was manufactured. For the isolation devices, a lead rubber bearing and an EradiQuake system (EQS) were used. An artificial input seismic motion generated for the NRC Reg. guide 1.60 design spectrum was used, but a low frequency range should be cut off for a decrease in the shaking table displacement. One-, two-, and three-dimensional seismic input motions were considered for an assessment of the horizontal bidirectional and vertical directional effects. Through this test, whether a horizontal bi-directional seismic input can make a difference in the floor response, and moreover, whether vertical input motion can make a change in the horizontal floor response, were investigated.

## OVERVIEW OF SHAKING TABLE TEST

For an evaluation of the floor response spectrum of a seismic isolated structure, a two-story frame structure was manufactured. We tried to consider the natural frequency of the containment structure. Also, lumped masses were added to the basement floor to increase the total weight. A detailed drawing and manufactured steel frame structure are shown in Figure 1. For the isolation systems, a lead rubber bearing (LRB) and EradiQuake system (EQS) were applied. Figures and detailed drawings of LRB and EQS are shown in Figures 2 and 3, respectively. A shaking table located in Pusan National University was used for this shaking table test. There are three shaking tables in the Seismic Simulation Test center at Busan National University. The specifications of the shaking table are shown in Table 1. As shown in Table 1, tables A and B are bigger than table C, but table C can move vertically, and thus we selected table C for use in the shaking table test. The pull payload of table C is 300 kN, and the horizontal maximum accelerations are 1.2 g for both horizontal directions. The pull payload should be considered for manufacturing the total weight of artificial steel frame structure.

For the shaking table test, we selected the US NRC Reg. Guide 1.60 design spectrum, but this design spectrum contains lots of low frequency contents. In this case, the shaking table displacement should be increased a lot. Because of the low frequency contents, the maximum acceleration level of the shaking table test should be relatively low. To reduce the table displacement, low frequency contents were cut off at about the 0.5Hz level, as shown in Figure 4.

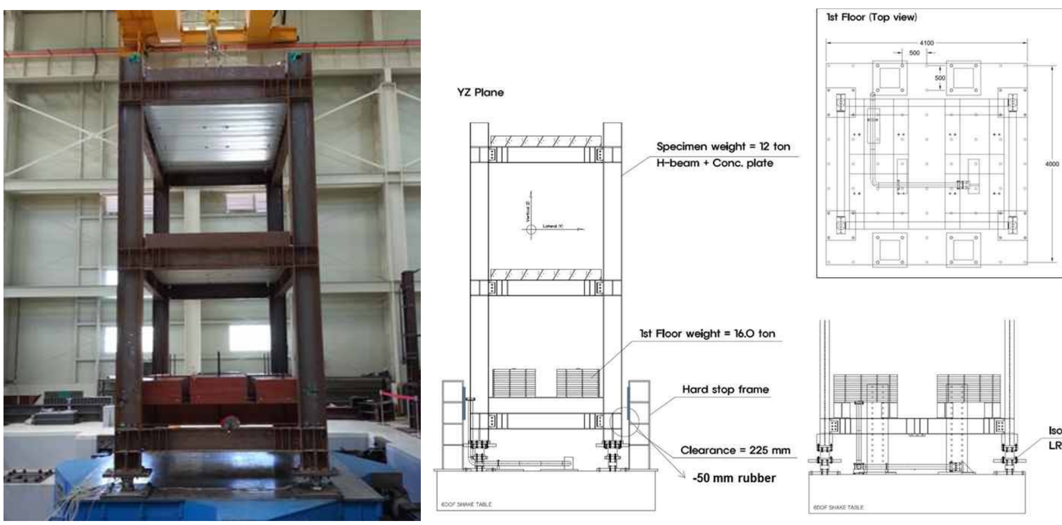



Figure 1. A Drawing and Figure of isolated steel frame structure

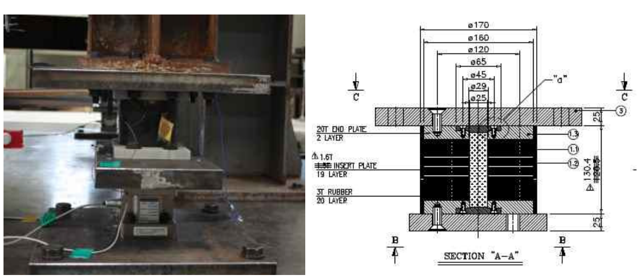



Figure 2. Lead rubber bearing (LRB).

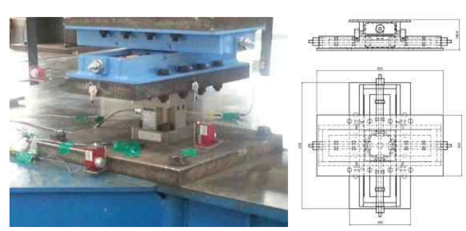


Figure 3. EradiQuake system (EQS).

Table 1: Dimension of shaking table in Seismic Simulation Test center at Busan National University.

| Items | Table A | Table B | Table C |
|---|---|---|---|
| Table Size(m) | 5.0×5.0 | 5.0×5.0 | 4.0×4.0 |
| Type | Moveable | Moveable | Fixed |
| Degree of Freedom | 3 | 3 | 6 |
| Full Payload(kN) | 300 | 600 | 300 |
| Nominal Payload(kN) | 200 | 500 | 200 |
| Desired Overturning Moment(kN-m) | 2,000 | 2,000 | 1,200 |
| Acceleration at Full Payload | | | |
| X-Axis(g) | 0.85 | 1.00 | 1.20 |
| Y-Axis(g) | 0.85 | 1.00 | 1.20 |
| Z-Axis(g) | - | - | 0.80 |
| Acceleration at Nominal Payload | | | |
| X-Axis(g) | 1.00 | 1.25 | 1.50 |
| Y-Axis(g) | 1.00 | 1.25 | 1.50 |
| Z-Axis(g) | - | - | 1.00 |

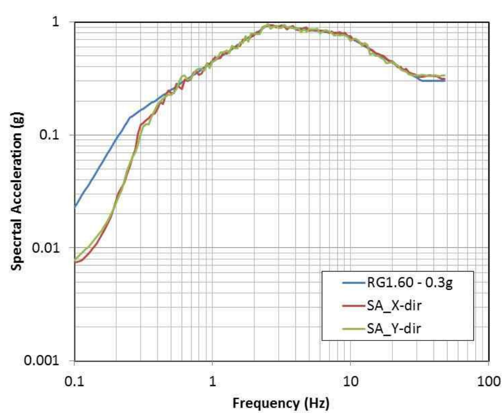


Figure 4. Input seismic motion for shaking table test.

## DEISGN AND MANUFACTURE OF SEISMIC ISOLATOR

Two types seismic isolator were designed and manufactured. Before performing a shaking table test, characteristic tests were performed for the designed condition. The design conditions of the seismic isolators are shown below:

- Total weight = 30tons
- No. of isolator = 4
- Response displacement = 60mm (for GMRS)
- Target period = 1.2s

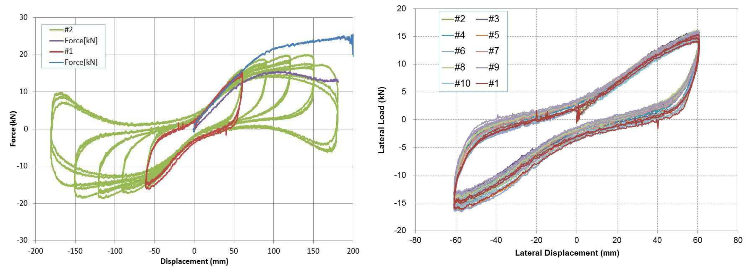
To satisfy the design specifications of the artificial steel frame structure and target period, LRB as the design parameters was chosen, and is summarized in table 2. We manufactured 10 LRBs for the shaking table test, 2 for testing the failure behaviour and 8 for a basic characteristic test for the 100% shear strain level. The test procedures and results are summarized in table 3. As shown in table 3, in the case of test #1, only a monotonic loading test was perform for the 500% shear strain level, and a test #2 cyclic test was performed until the 300% shear strain level. Test specimens #1 and #2 could not be used for the shaking table test because they experienced severe shear strain deformation. The test results for #1 and #2 are shown in figure 5(a) and all other test results are shown in figure 5(b). As shown in figure 5, because of the shape factor of the tested LRB, the LRB failed at almost the 300% shear strain level (200mm), and the failure mode was not a shear failure but a buckling failure. In the case of the 100% shear strain level test shown in figure 5(b), even though only a 100% shear strain level test was applied, the behaviour of the LRBs might not be only shear behaviour but also buckling behaviour. An EQS was manufactured with slightly different properties, and the characteristic test results are shown in figure 6.

Table 2: Design specifications of Lead Rubber Bearing.

| ITEM | Symbol | property |
|---|---|---|
| Elastic Stiffness | Ku | 11.6kN/mm |
| Second slope Stiffness | Kd | 0.13kN/mm |
| Zero displacement force intercept | Qd | 3.91kN |
| Equivalent Stiffness | Keq | 0.196kN |
| Equivalent Damping Ratio | Heq | 0.210 |

Table 3: Characteristic test procedures and results of LRB.

| specimen | Test Item | Temp. (℃) | Strain (%) | Disp. (mm) | Vert. Load(kN) | +30% Vert. Load(kN) | -30% Vert. Load(kN) | Freq. (Hz) | Velocity. | | Cycles | Remark |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| #1 | Comp. | 23 | - | - | 68.647 | 89.2411 | 48.0529 | 0.01 | 1.647528 | kN/sec | 3 | ISO 기준 0.001Hz 이상 |
| | Shear | 23 | 100% | 60.0 | 68.647 | - | - | 0.10 | 24 | mm/sec | 3 | ISO 기준 0.001~0.5Hz 사이 |
| | Fracture | 23 | 500% | 300.0 | 68.647 | - | - | 0.08 | 24 | mm/sec | - | 500%를 파단기준(예상)으로 실시 |
| #2 | Comp. | 23 | - | - | 68.647 | 89.2411 | 48.0529 | 0.01 | 1.647528 | kN/sec | 3 | - 300%초과 시험불가(시험기 최대 스트로크 ±200mm) |
| | Shear | 23 | 100% | 60.0 | 68.647 | - | - | 0.10 | 24 | mm/sec | 3 | |
| | | 23 | 150% | 90.0 | 68.647 | - | - | 0.067 | 24 | mm/sec | 3 | |
| | | 23 | 200% | 120.0 | 68.647 | - | - | 0.050 | 24 | mm/sec | 3 | |
| | | 23 | 250% | 150.0 | 68.647 | - | - | 0.040 | 24 | mm/sec | 3 | |
| | | 23 | 300% | 180.0 | 68.647 | - | - | 0.033 | 24 | mm/sec | 3 | |
| | Fracture | 23 | 500% | 300.0 | 68.647 | - | - | 0.08 | 24 | mm/sec | - | - Cyclic 파괴가 안될시 |
| #3 | Comp. | 23 | - | - | 68.647 | 89.2411 | 48.0529 | 0.01 | 1.647528 | kN/sec | 3 | ISO 기준 0.001Hz 이상 |
| | Shear | 23 | 100% | 60.0 | 68.647 | - | - | 0.10 | 24 | mm/sec | 3 | ISO 기준 0.001~0.5Hz 사이 |
| #4 | Comp. | 23 | - | - | 68.647 | 89.2411 | 48.0529 | 0.01 | 1.647528 | kN/sec | 3 | ISO 기준 0.001Hz 이상 |
| | Shear | 23 | 100% | 60.0 | 68.647 | - | - | 0.10 | 24 | mm/sec | 3 | ISO 기준 0.001~0.5Hz 사이 |
| #5 | Comp. | 23 | - | - | 68.647 | 89.2411 | 48.0529 | 0.01 | 1.647528 | kN/sec | 3 | ISO 기준 0.001Hz 이상 |
| | Shear | 23 | 100% | 60.0 | 68.647 | - | - | 0.10 | 24 | mm/sec | 3 | ISO 기준 0.001~0.5Hz 사이 |
| #6 | Comp. | 23 | - | - | 68.647 | 89.2411 | 48.0529 | 0.01 | 1.647528 | kN/sec | 3 | ISO 기준 0.001Hz 이상 |
| | Shear | 23 | 100% | 60.0 | 68.647 | - | - | 0.10 | 24 | mm/sec | 3 | ISO 기준 0.001~0.5Hz 사이 |
| #7 | Comp. | 23 | - | - | 68.647 | 89.2411 | 48.0529 | 0.01 | 1.647528 | kN/sec | 3 | ISO 기준 0.001Hz 이상 |
| | Shear | 23 | 100% | 60.0 | 68.647 | - | - | 0.10 | 24 | mm/sec | 3 | ISO 기준 0.001~0.5Hz 사이 |
| #8 | Comp. | 23 | - | - | 68.647 | 89.2411 | 48.0529 | 0.01 | 1.647528 | kN/sec | 3 | ISO 기준 0.001Hz 이상 |
| | Shear | 23 | 100% | 60.0 | 68.647 | - | - | 0.10 | 24 | mm/sec | 3 | ISO 기준 0.001~0.5Hz 사이 |
| #9 | Comp. | 23 | - | - | 68.647 | 89.2411 | 48.0529 | 0.01 | 1.647528 | kN/sec | 3 | ISO 기준 0.001Hz 이상 |
| | Shear | 23 | 100% | 60.0 | 68.647 | - | - | 0.10 | 24 | mm/sec | 3 | ISO 기준 0.001~0.5Hz 사이 |
| #10 | Comp. | 23 | - | - | 68.647 | 89.2411 | 48.0529 | 0.01 | 1.647528 | kN/sec | 3 | ISO 기준 0.001Hz 이상 |
| | Shear | 23 | 100% | 60.0 | 68.647 | - | - | 0.10 | 24 | mm/sec | 3 | ISO 기준 0.001~0.5Hz 사이 |




(a) Ultimate capacity test (b) 100% shear test

Figure 5. Characteristic test results of LRB

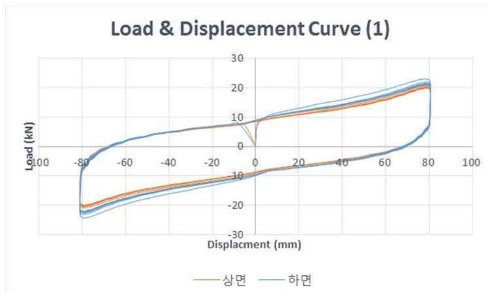



Figure 6. Characteristic test resu6lts of EQS

## TEST RESULTS

A shear failure could not be determined during the shaking table test, and only a buckling failure was determined. One failure mode of an LRB during the shaking table test is shown in figure 7. As shown in figure 7, the LRB was totally failed and a loss of restoring force occurred during the shaking table test.

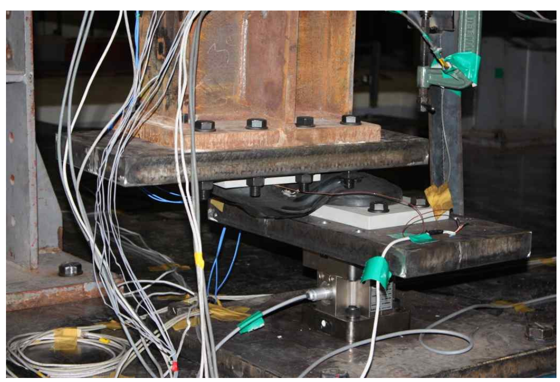


Figure 7. Characteristic test resu6lts of EQS

### *Load Cell Data*

For the measurement of vertical load, load cells were applied for each of the four supports, as shown in figure 8. The installed load cells can also be determined in figure 7. All load cells can measure 3-dimensional force-time histories. The vertical force time histories according to the shaking directions are shown in figure 9. Because load cell #4 was out of order, it could not measure the support forces. As shown in figure 9, the vertical forces for each of the four supports are basically not the same. Two are about 4 tons and others are 10 tons. The total weight might be around 28 tons according to the test results. Figure 9 shows the force time histories for the one-dimensional, two-dimensional and three-dimensional shaking table test results, respectively. As shown in figure 9, the one-dimensional shaking table test can underestimate the vertical forces. Even in the case of the horizontal two-dimensional shaking table test, vertical forces increase more than those of the one-dimensional shaking table test.

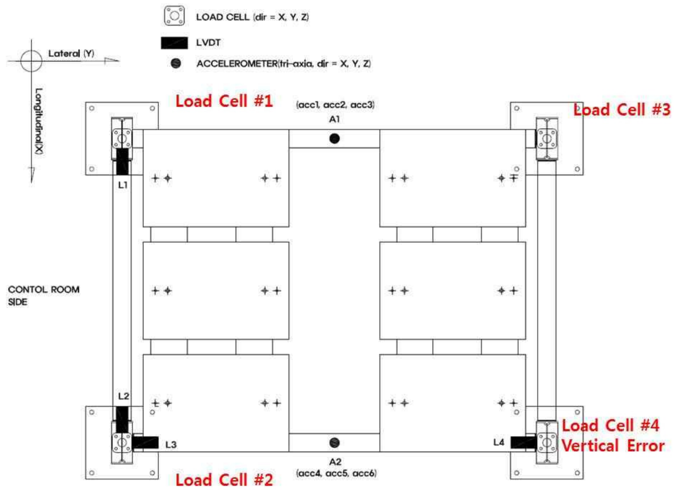
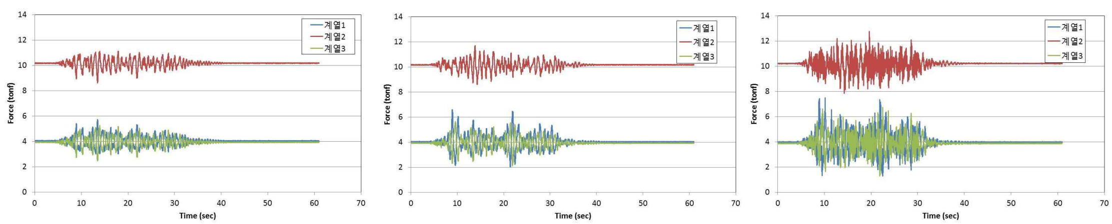



Figure 8. Arrangement of load cells for shaking table test




(a) LRB 0.1g_X (b) LRB 0.1g_XY (c) LRB 0.1g_XYZ

Figure 9. Vertical force-time histories for each support

***Floor Response Spectrum***

The floor response spectra (FRS) of a fixed steel structure are shown in figure 10. As shown in figure 10, this test used just 0.1 g of the target peak ground acceleration. The upper three graphs are shown to compare the one-, two-, and three-dimensional acceleration inputs. The red lines represent the shaking table motion, and the purple and blue lines represent the second and third floors, respectively. The lower two graphs compare the same floor response based on the one-, two-, and three-dimensional excitation. As shown in figure 10, the FRS of one- and two-dimensional excitations are similar, but in the case of the three-dimensional shaking test in which vertical motion is included, the FRS was changed. These phenomena can be recognized in the lower graph. Through this test, although the structure was fixed, the FRS can be changed through vertical input motion.

The FRS of the steel frame structure isolated by LRB in the case of the 0.1g level seismic input are shown in figure 11. All lines represent the same aspects as those in figure 10. The isolation frequency can clearly be recognized in figure 11 as 1.0 Hz. However, all responses are too small to recognize the differences between each other. The FRS of the steel frame structure isolated by EQS in the case of a 0.1g level seismic input are shown in figure 12. As shown in figure 12, in the case of EQS, the isolation frequency can be clearly recognized. Although the structural frequency was around 5Hz, as shown in figure 10, the EQS isolated structure frequency was aground 4Hz. In addition, in the case of the 2nd floor, a higher frequency of around 20Hz can be identified. Both the LRB and EQS isolated structure, and the vertical input motion, could not achieve many differences compared with horizontal motion.

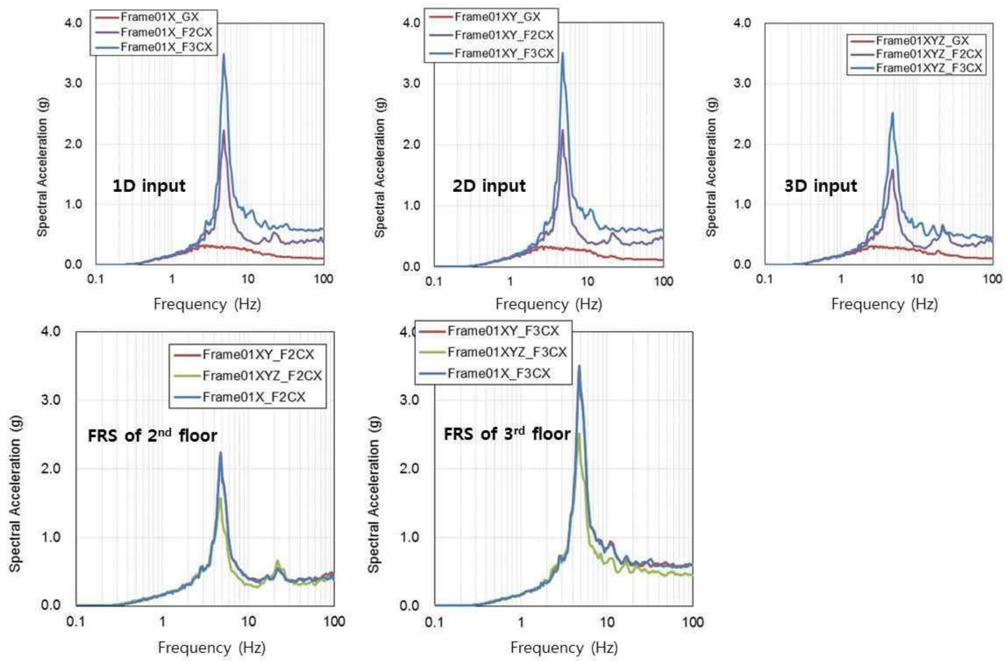



Figure 10. FRS of fixed steel frame structure in the case of 0.1g level seismic input

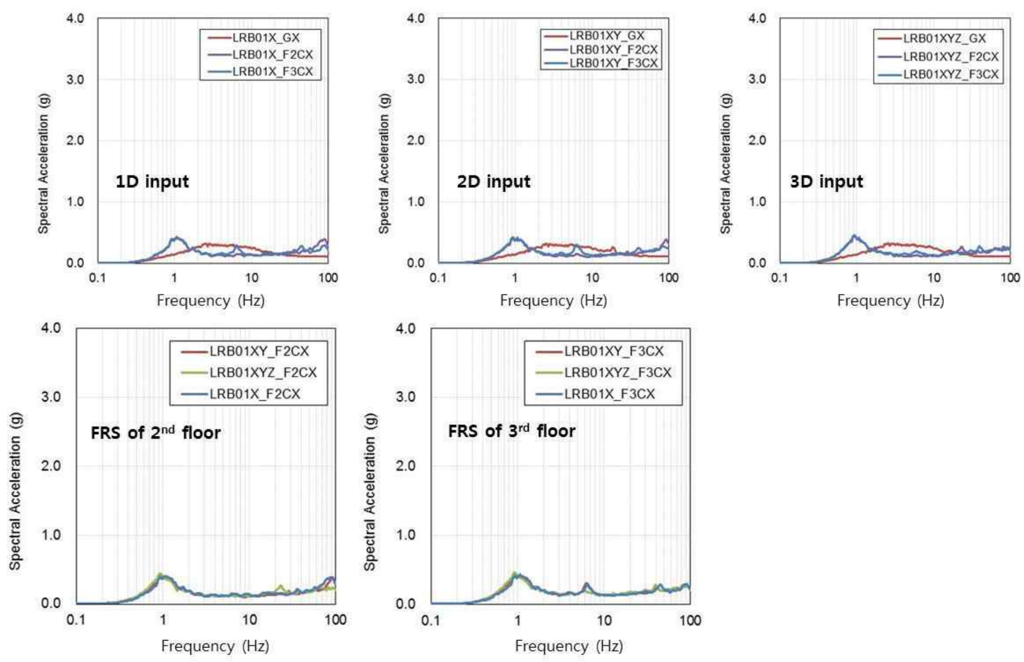



Figure 11. FRS of steel frame structure isolated by LRB in the case of 0.1g level seismic input

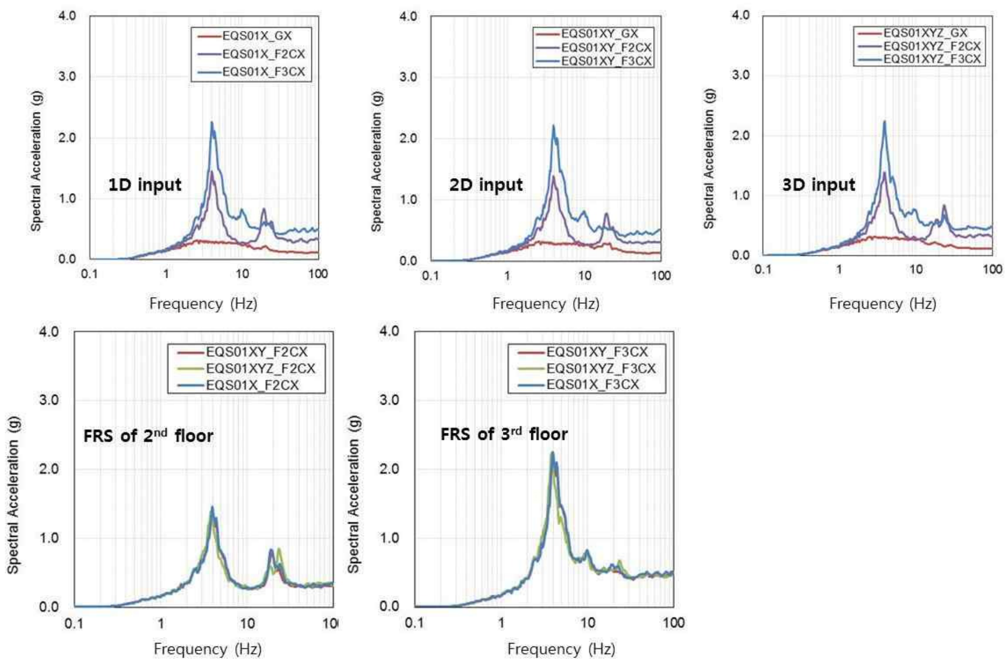



Figure 12. FRS of steel frame structure isolated by EQS in the case of 0.1g level seismic input

The FRS of the steel frame structure isolated by LRB in the case of a 0.4g level seismic input are shown in figure 13. As shown in figure 13, the first mode frequencies were determined to be around 0.7 Hz and the second mode frequencies were around 5 Hz. The 5 Hz of the second frequencies might be structural frequencies, but the 0.7 Hz might come from the buckling behaviour of LRB because of a large deformation. It is very difficult to determine the trend of the FRS in the case of 0.4g input seismic motion for an LRB isolated structure. However, the structural responses are more clear for the 2nd floor response than for the 3rd floor response. In addition, two- and three-dimensional seismic motion can decrease the horizontal FRS of each floor.

The FRS of the steel frame structure isolated by EQS in the case of 0.4g level seismic input are shown in figure 14. Similar to the LRB isolated structure, two- and three-dimensional seismic motion decrease the horizontal FRS of the structure. In addition, similar to the 0.1g input EQS isolated structure, the isolation frequencies could not be found, but only 4Hz frequencies determined.

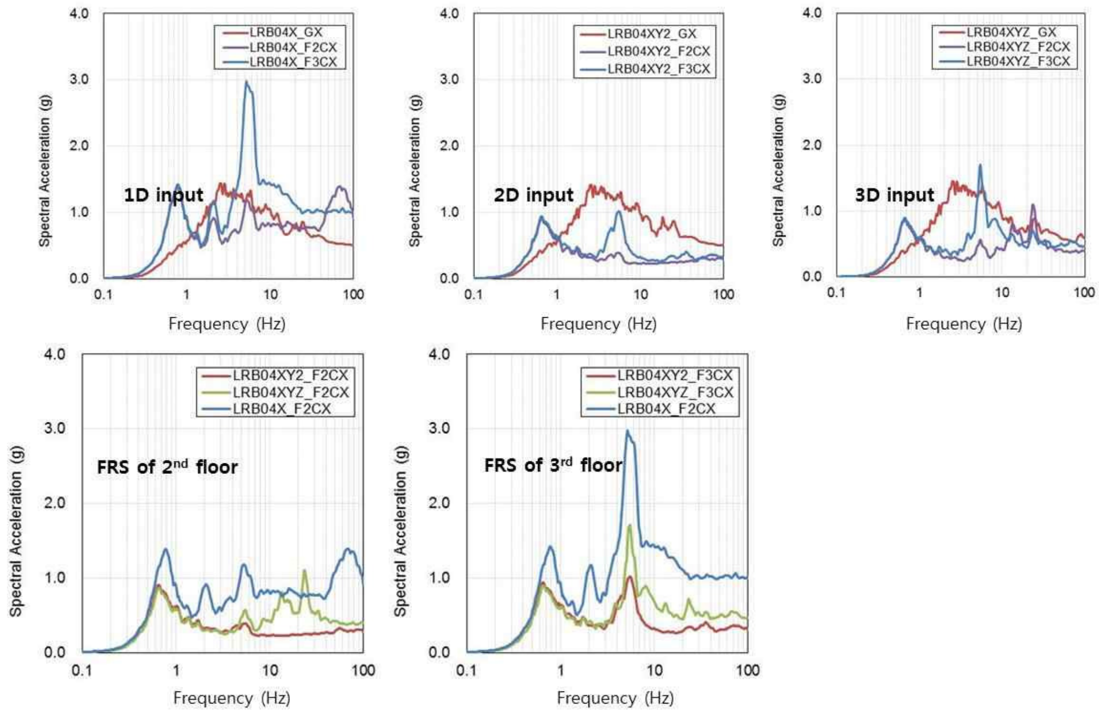



Figure 13. FRS of steel frame structure isolated by LRB in the case of 0.4g level seismic input

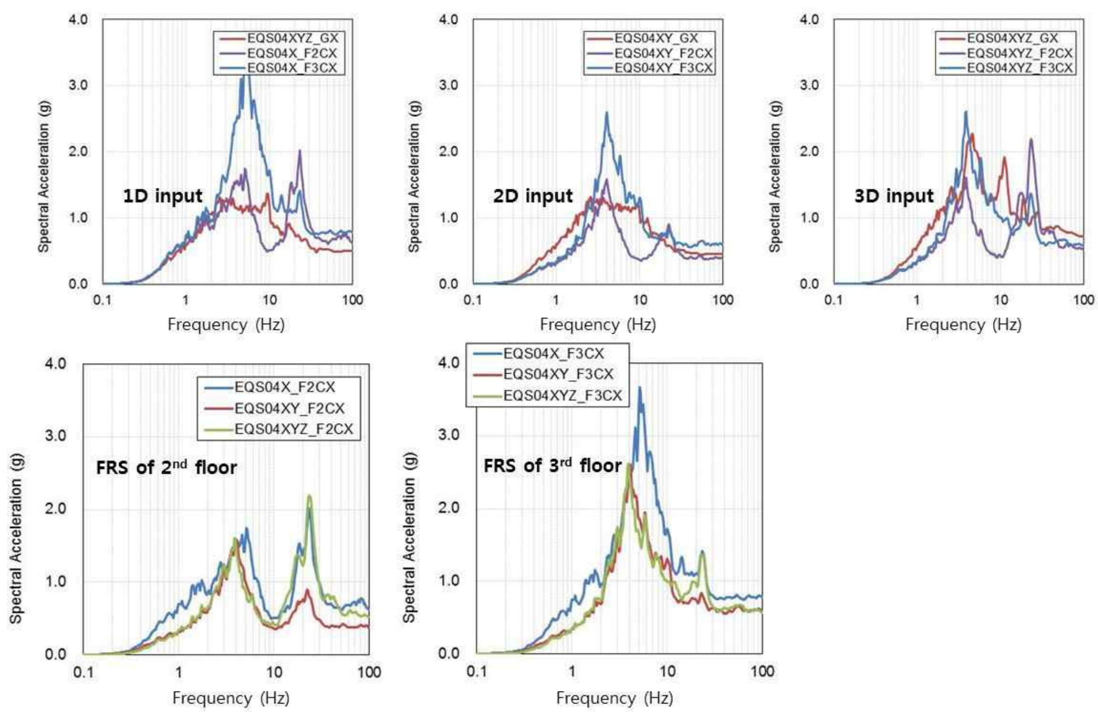



Figure 13. FRS of steel frame structure isolated by EQS in the case of 0.4g level seismic input

**SUMMARY**

In this study, shaking table tests for a seismic isolated frame structure were performed for the development of the floor response spectrum. For the shaking table test, a two-story artificial frame structure was manufactured. For the isolation devices, a lead rubber bearing and an EradiQuake system (EQS) were used. Artificial input seismic motion generated for the NRC Reg. guide 1.60 design spectrum was used, but a low frequency range should be cut off for a decrease in the shaking table displacement. One-, two-, and three-dimensional seismic input motions were considered for an assessment of the horizontal bidirectional and vertical directional effects.
At first, we tried to find the ultimate status of the isolation system, but it was impossible to reach the ultimate status because of the capacity of the shaking table. Only the buckling failure of the LRB was determined, and the shear failure could not be determined during this test. In the case of the floor response spectra, two- and three-dimensional input motion could affect the horizontal floor response spectrum, but it is very difficult to recognize whether the vertical vibration can affect the horizontal floor response spectrum.

**REFERENCES**

US NRC Regulatory Guide 1.60, 1973. Design Response Spectra for Seismic Design of Nuclear Power Plants.