# SHAKING TABLE TEST OF STEEL FRAME STRUCTURES SUBJECTED TO SCENARIO EARTHQUAKES

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Shaking table tests of the seismic behavior of a steel frame structure model were performed. The purpose of these tests was to estimate the effects of a near-fault ground motion and a scenario earthquake based on a probabilistic seismic hazard analysis for nuclear power plant structures. Three representative kinds of earthquake ground motions were used for the input motions: the design earthquake ground motion for the Korean nuclear power plants, the scenario earthquakes for Korean nuclear power plant sites, and the near-fault earthquake record from the Chi-Chi earthquake. The probability-based scenario earthquakes were developed for the Korean nuclear power plant sites using the PSHA data. A 4-story steel frame structure was fabricated to perform the tests. Test results showed that the high frequency ground motions of the scenario earthquake did not damage the structure at the nuclear power plant site; however, the ground motions had a serious effect on the equipment installed on the high floors of the building. This shows that the design earthquake is not conservative enough to demonstrate the actual danger to safety related nuclear power plant equipment.

KEYWORDS : Shaking table tests, near-fault ground motion, scenario earthquake, probabilistic seismic hazard analysis, steel frame structure

## 1. INTRODUCTION

The standard response spectrum [1] proposed by the US NRC has been used as a design earthquake for the design of Korean nuclear power plant (NPP) structures. A survey of some of the Quaternary fault segments near Korean nuclear power plants is ongoing [2]. It is likely that these faults will be identified as active ones. If the faults are confirmed as active ones, it will be necessary to reevaluate the seismic safety of the nuclear power plants located near the faults.

Near-fault ground motions are the ground motions that occur near an earthquake fault. In general, the near-fault ground motion records exhibit a distinctive long-period pulse-like time histories, with very high peak velocities. These features are generated by the slip of the earthquake fault. Near-fault ground motions, which have caused much of the damage in recent major earthquakes, can be characterized by a pulse-like motion that exposes the structure to a high input energy at the beginning of the motion.

In this study, shaking table tests of a 4-story, steel-frame structure were performed to estimate the near-fault ground motion effects on the seismic response of the structure. For this reason, three types of input motions were selected: the artificial time histories of the US NRC Regulatory Guide 1.60 spectrum [1], the probability-based scenario earthquake spectra developed for the Korean nuclear power plant site [3], and a typical near-fault earthquake record.

This study was undertaken to develop scenario earthquakes for the reevaluation of the seismic safety of a nuclear power plant near an active fault. The probabilistic seismic hazard analyses for most Korean NPP sites have been completed. The hazard-consistent earthquake scenario is being developed as a probability-based earthquake scenario , using the existing results of the probabilistic seismic hazard analyses (PSHA).

The scenario earthquake is specified in terms of the earthquake magnitude, M, and its distance, R, from the site under consideration. The probability-based scenario earthquake is developed by the de-aggregation of the probabilistic seismic hazard analysis results, according to the procedures of the US NRC R.G. 1.165 [4]. The spectral shape for the scenario earthquake is developed by using the attenuation equations adopted in the PSHA. The near-fault ground motion effect is incorporated into the response spectra, since the potentially active fault is located near a nuclear power plant site. Test results showed that the high frequency ground motions that appeared in the scenario earthquake did not damage the structure at the NPP site; however, the ground motions had a serious effect on the equipment installed on the high floors of the building. This shows that the design earthquake does not demonstrate the actual danger to safety related nuclear power plant equipment.

## 2. STEEL FRAME STRUCTURE MODEL

### 2.1 Model Design

Most nuclear power plant structures have fundamental frequencies in the 4 to 10 Hz range. In this study, the target frequency of the model was determined based on the fundamental frequency of the containment building. The containment building is generally a prestressed concrete shell-type structure with a spherical dome. The fundamental frequency of the containment building is about 4.7 Hz. Since it is both difficult and expensive to make a scale model of the prestressed concrete containment building, a steel frame structure with a similar fundamental frequency was used to estimate the effect of the frequency contents in the earthquake ground motions.

Figure 1 shows the dimensions of the test model, a 4-story, steel frame structure. Figure 2 shows a photo of the fabricated test model installed on the shaking table. The specifications of the test model are shown in Table 1. As shown in Table 1, a steel pipe was used for the column. The floor slab was made with a thick steel plate. The diameter of the steel pipe and the thickness of the steel plate were determined based on the target frequency. The slab and column were connected by 6 high-tension bolts at the end plate for a rigid connection.

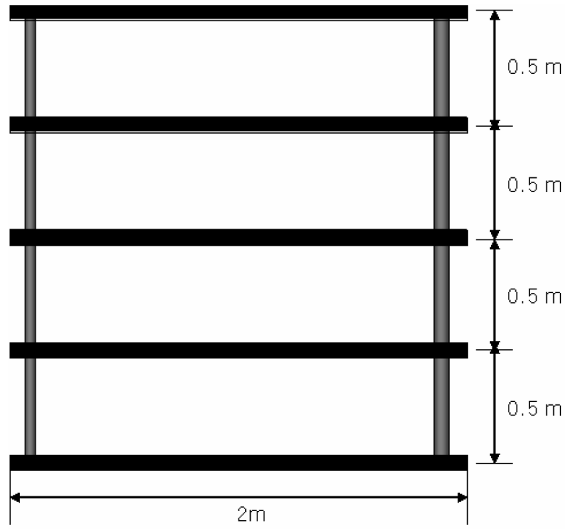



Fig. 1. Dimension of the Test Model

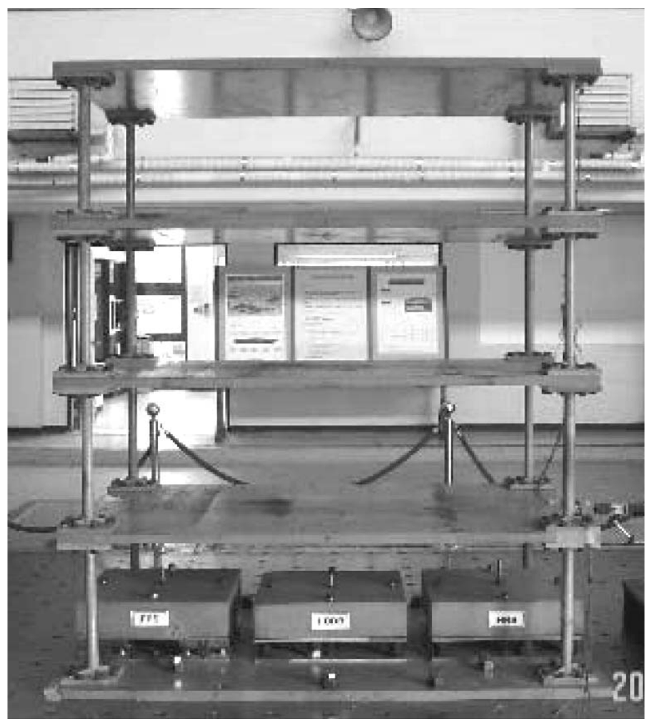


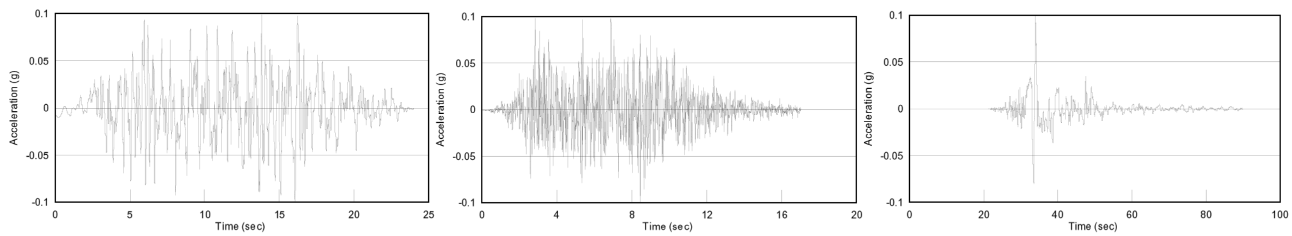

Fig. 2. Fabricated Test Model

**Table 1**. Model Specifications

| Member | Specification | Dimension (cm) |
|---|---|---|
| Column | Steel Pipe | OD : 4.27, t : 0.36 |
| Slab | Steel Plate | 200x120x4 |
| Slab-Column Connection | High-Tension Bolt at End Plate | |

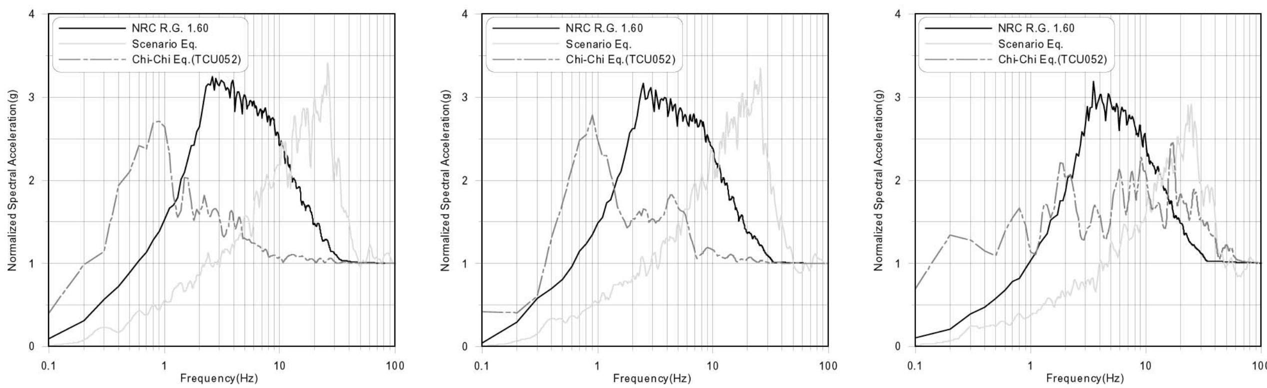
### 2.2 Input Ground Motions

Three sets of earthquake ground motions were used as input motions. The first input motion is the artificial time histories that correspond with the US NRC Regulatory Guide 1.60 spectrum [1], which is the design earthquake for Korean nuclear power plant structures. The second input motion is the artificial time histories of the probability-based scenario earthquake for Korean nuclear power plant sites. The scenario earthquake is specified in terms of the earthquake magnitude, M, and its distance, R, from the site under consideration. The probability-based scenario earthquake is developed by the de-aggregation of the probabilistic seismic hazard




(a) NRC (b) Scenario (c) Chi-Chi

Fig. 3. Input Ground Motion Time Histories




(a) EW Component (b) NS Component (c) UD Component

Fig. 4. Acceleration Response Spectra of the Input Ground Motions

analysis (PSHA) results, according to the procedures of the US NRC R.G. 1.165 [4]. The spectral shape for the scenario earthquake is developed by using the attenuation equations adopted in the PSHA. The magnitude and distance of the scenario earthquake used in this study is M6.4, 9 km [3]. The near-fault ground motion effect is incorporated into the response spectra, since the potentially active fault is located near a nuclear power plant site. The details of the scenario earthquake used in these experiments are presented in subsequent sections. The last motion input is the actual earthquake time histories recorded at the Chi-Chi, Taiwan earthquake. The station name of the recorded earthquakes is TCU 052.

Figure 3 shows the input acceleration time histories scaled to 0.1g PGA (Peak Ground Acceleration). The Chi-Chi earthquake time history shows a long period pulse-like motion. This pulse-like motion can dramatically influence the spectral content in large earthquakes. The ground response spectra of these acceleration time histories are shown in Figure 4. As shown in Fig. 4, the frequency contents of the input ground motions are very different. The response spectra of the Chi-Chi earthquake show rich frequency contents in the low-frequency range. However, the response spectra of the scenario earthquakes show rich frequency contents in a high-frequency range of greater than 10 Hz. The response spectra of the design earthquake show rich frequency contents in the medium frequency range. The fundamental frequencies of most nuclear power plant structures are located in this range.

## 3. SCENARIO EARTHQUAKES FOR A KOREAN NPP SITE

In this study, the probability based scenario earthquakes for a Korean NPP site were developed using the method proposed by the U.S. NRC Regulatory Guide 1.165[4]. The example NPP site is located in the southeastern part of the Korean peninsula. Detailed probabilistic seismic hazard analysis procedures were given in a previous study [3].

### 3.1 Scenario Earthquakes

The seismic hazard was de-aggregated to determine the dominant magnitudes and distances at the prescribed exceedance level. In this study, the seismic hazard was de-aggregated at 1Hz, 5Hz, and 10Hz at the $10^{-5}$ exceedance level in accordance with the U.S. NRC Regulatory Guide 1.165 [4]. According to the guide, the seismic hazard should also be de-aggregated at 2.5Hz. However, the ground motion attenuation equations proposed by the expert did not include an equation for 2.5Hz. The fractional contribution of the magnitudes and distance bin to the total hazard for 1Hz was used to develop a low-frequency scenario earthquake. Because the contribution of the distance bins greater than 100 km contained less than 5% of the total hazard for 1 Hz, additional calculations to consider the effects of distant and larger events were not needed.

Figs. 5 and 6 show the contributions of the magnitude and distance bins for 1 Hz and the average of the 5 Hz and 10 Hz, respectively. The scenario earthquakes for the example site were determined based on the contribution. Table 2 shows the magnitude and distance of the scenario earthquakes for the example Korean NPP site. As shown in Table 2, the magnitudes and distances of the scenario earthquakes are very similar. This may be due to the small contribution of the distant earthquakes of the 1Hz scenario earthquake.

**Table 2**. Probability-Based Scenario Earthquakes

| 1Hz | 5-10Hz |
|---|---|
| M6.4, 9.0Km | M6.2, 13.0km |

### 3.2 Near-fault Ground Motion Effects

Near-fault ground motions are ground motions that occur near an earthquake fault. In general, the near-fault ground motion records exhibit distinctive long-period pulse-like time histories, with very high peak velocities. These features are generated by the slip of the earthquake fault. Near-fault ground motions, which have caused much of the damage in recent major earthquakes (Northridge 1994, Kobe 1995, Chi-Chi 1999), can be characterized by a pulse-like motion that exposes a structure to a high input energy at the beginning of the motion. The recorded acceleration response spectra of recent major earthquakes are well correspond with the design response spectra of the codes in the medium-to-high frequency range, but not in the low-to-medium frequency range [5].

The near-fault effects, such as the pulse-like motions, can dramatically influence the spectral content in large earthquakes. Some of these effects are most pronounced within about 10 km. The fault normal component is about 30% larger than the fault parallel component in the frequency range of 0.2 to 0.5 sec, due primarily to rupture directivity. The rupture directivity effects are strongest for a strike slip motion on vertical faults, but can also be significant for cases of directivity for sites located near dipping faults. Other factors, perhaps strongest at close distances, include hanging wall/foot wall site locations, as well as thrust verses strike slip or normal slip mechanisms. These additional factors can have significant impacts on the spectral composition [6].

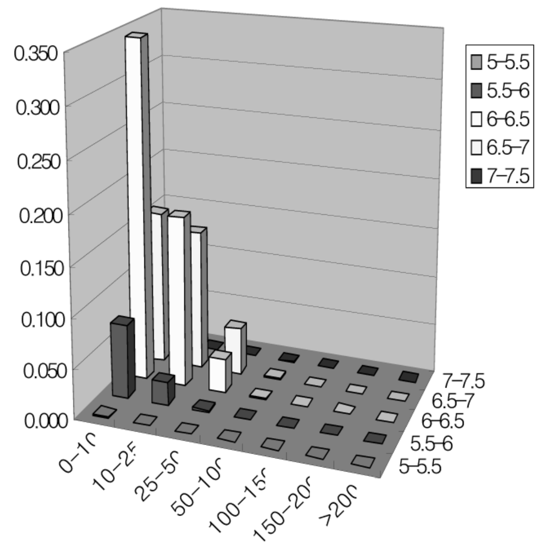



Fig. 5. Contribution Factors for 1 Hz

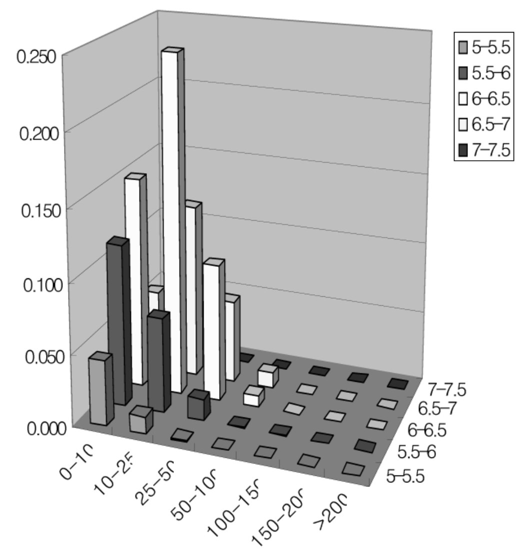



Fig. 6. Contribution Factors for Average of 5 and 10 Hz

### 3.3 RESPONSE SPECTRA FOR THE SCENARIO EARTHQUAKES

The spectral shape for the scenario earthquakes were developed by using the attenuation equations proposed in the PSHA study. The spectral shapes for the scenario earthquakes normalized to 0.2g ZPA (Zero Period Acceleration) are shown in Fig. 7. The spectral shapes for the western US (WUS) and the central and eastern US (CEUS) are also shown in Fig. 7 for a comparison. The seismic response spectral shapes for the design and analysis for the WUS and CEUS sites were proposed by McGuire. et al. [6, 7]. The response spectral shapes for the WUS site were developed from empirical attenuation equations in the WUS. For the CEUS, the WUS spectral shapes were modified with a transfer function based on the random vibration model of a strong ground motion that accounts for the differences in the source parameters, a crustal damping, and a near-surface damping. The spectral shapes for the WUS and CEUS sites can be obtained from the following equations, respectively.

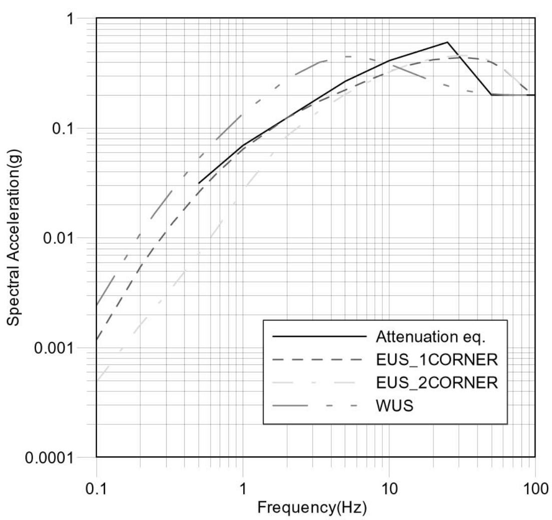
$$\ln[SA(f)/PGA] = \frac{C_1}{\cosh(C_2 f^{C_3})} + C_4\left[\frac{\exp(C_5 f)}{f^{C_6}}\right] \quad (1)$$

$$\ln[SA(f)/PGA] = \frac{C_1}{\cosh(C_2 f^{C_3})} + C_4\left[\frac{\exp(C_5 f)}{f^{C_6}} + \frac{C_7\exp(C_8 f)}{f^{C_9}}\right]^{1/2} \quad (2)$$

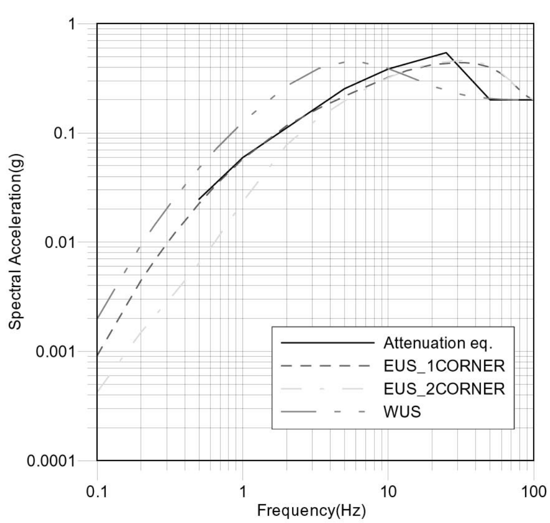
where, $SA(f)$ and $f$ are the spectral accelerations and frequencies, respectively. $C_i$ is a statistical coefficient defined as a function of the magnitude and/or the distance by creating a data set of response spectral shapes.

The spectral shapes for the scenario earthquakes using the WUS and CEUS spectral shapes are also shown in Fig. 7. As shown in Fig. 7, the spectral shapes from the proposed attenuation equations are similar to the shapes from the CEUS 1 corner frequency model.

Mean ground response spectra obtained from records of 261 earthquakes with magnitudes of 3 to 5 that occurred in Korea are shown in Fig. 8 [8]. For these results, 72 earthquake records used for magnitude 3, 168 for magnitude 4 and 21 for magnitude 5. The fluctuation in the spectrum for magnitude 5 earthquakes is due to the very limited number of data. Figures 9 and 10 show that the spectral shapes from the proposed attenuation equations are very similar to the mean response spectrum developed from the real earthquake data. The uniform hazard spectrum for the Korean nuclear power plant site was also very similar to the mean response spectrum developed from the real earthquake data [9]. This result shows that the ground motion attenuation equations used in the seismic




(a) 1 Hz Scenario Earthquake




(b) 5-10 Hz Scenario Earthquake

Fig. 7. Ground Response Spectra for a Scenario Earthquake

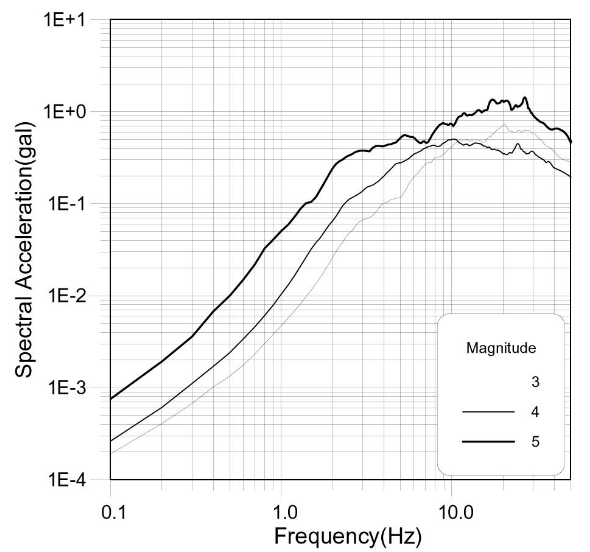



Fig. 8. Mean Response Spectra for the Real Earthquake Records

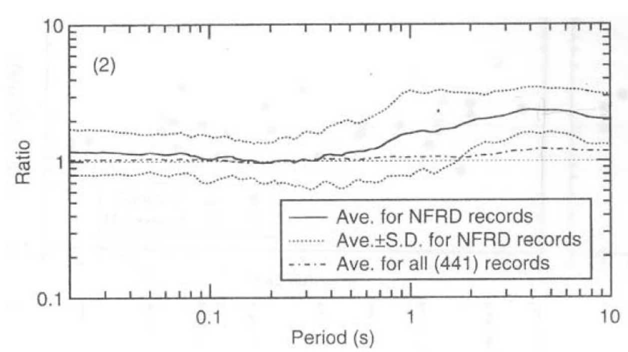



Fig. 9. FN to FP Response Spectral Ratio [13]

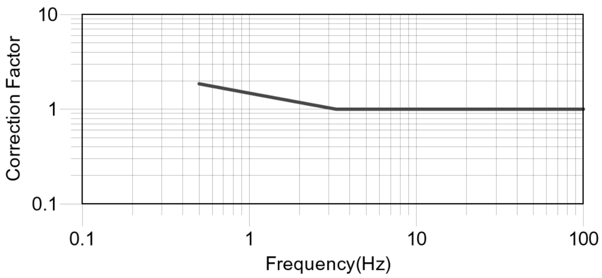



Fig. 10. Correction Factor for the NFRD Effects

probabilistic hazard analysis adequately reflected both the ground-motion attenuation characteristics and the site soil conditions.

Generally, these features of a near-fault ground motion are disregarded during the seismic design of nuclear power plant structures and components. Many studies have been performed to identify the characteristics of a near-fault ground motion [10, 11, 12]. Ohno et al. [13] reported on the range where the near-fault rupture directivity effect is dominant, and they proposed a method to correct the predefined response spectrum by considering this effect. Figure 9 shows the FN (Fault Normal) to FP (Fault Parallel) response spectral ratio from 37 records of the 11 very strong earthquakes. These records reveal that the very strong ground motions were greatly affected by the near-fault directivity effect. Based on this study, Nishimura et al. [14] proposed a correction factor to modify the response spectrum. The correction factor, $\lambda(T_i)$, can be obtained from the following equations:

$$\lambda(T_i) = 1 \qquad \text{for } T_i \le T_D \qquad (3)$$

$$\lambda(T_i) = 10^{\log(2.5)\cdot\log(T_i/T_D)/\log(T_H/T_D)} \qquad \text{for } T_D < T_i \qquad (4)$$

where, $T_i$ denotes the period. $T_D$ (= 0.33sec) and $T_H$ (= 5sec) are the control points of the design ground response spectrum. These equations state that, in a long period of greater than 0.33 sec, only the spectral acceleration increases, due to the near-fault rupture directivity effect . In addition, it is assumed that the spectral acceleration amplification due to the near-fault rupture directivity effect does not appear in a short periods of less than 0.33 sec.

Figure 10 shows the correction factor incorporating the near-fault directivity effect on the response spectrum shape. As shown in this figure, the correction factors from the equation can express the near-fault rupture directivity effect as it appears in the strong earthquake records.

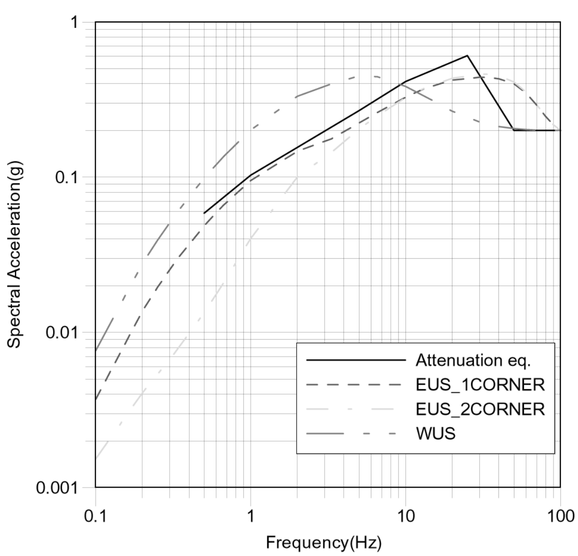
Using the proposed equation, the spectral shapes for the scenario earthquakes were modified to incorporate the near-fault rupture directivity effect. Figure 11 shows the modified response spectral shape for the two scenario earthquakes.

## 4. SHAKING TABLE TESTS

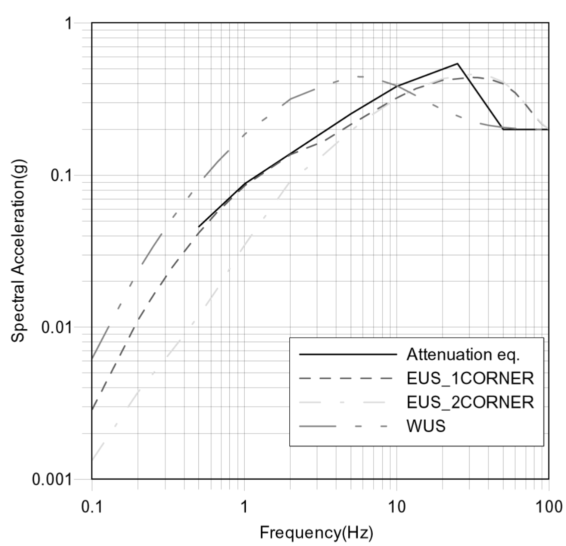
By using the developed scenario earthquake and the two previously mentioned types of earthquake records, the shaking table tests were performed.

### 4.1 Test Outline

The size of the shaking table is 4 m x 4 m with a 6 degree of freedom excitation axes. The capacity of the




(a) 1Hz Scenario Earthquake




(b) 5-10Hz Scenario Earthquake

Fig. 11. Ground Response Spectra with NFRD Effects

table is limited to a maximum specimen weight of 30,000 kg, a maximum acceleration of 1.5 g and 1.0 g in the horizontal and vertical directions, respectively. The maximum frequency range of the table is 50 Hz. The table is controlled by an electro-hydraulic servo system. The steel frame model was fixed to the shaking table with high-tension bolts for a rigid connection.

The input ground motion levels are 0.2 g and 0.5 g. In a related but separate test, random white noise was inputted to check the change of the natural frequency and the damage conditions at each step. The test procedures are summarized in Table 3. As shown in Table 3, 1-D, 2-D, and 3-D tests were performed using three kinds of input motions. The 0.5 g level tests using the Chi-Chi earthquake records could not be performed due to the displacement limit of the shaking table. The maximum displacement of the Chi-Chi earthquake records, at 0.5 g PGA, exceeds the table displacement limit (10 cm). A total of 12 accelerometers were installed to measure the acceleration responses. The acceleration responses of three directions, two horizontal directions and one vertical direction, at each story were measured using the 12 accelerometers.

## 4.2 Test Results

### *4.2.1 Natural Frequencies*

The fundamental natural frequencies of the model measured at the elastic range for the 3-D white noise input with a peak acceleration of 0.025 g are shown in Table 4 with the analysis results. As shown in Table 4, the natural frequencies from the white noise tests coincided well with the analysis results. The natural frequencies of the two horizontal directions were very similar, since the shape of the model structure is regular.

Figure 12 shows the transfer functions and the phase angle obtained from the white noise tests. As shown in Figure 12, the results were similar for the five modal tests. It can be seen from the transfer functions of the modal tests that the natural frequencies of the model did not change even when the model experienced a strong earthquake of up to 0.5 g. This indicates that the material properties of the steel structure did not change even after a certain level of nonlinear behavior. In Figure 12, the

**Table 3**. Test Procedures

| Step | Input Motion | Direction | PGA (g) |
|---|---|---|---|
| 1 | White Noise | 3-D | 0.025 |
| 2 | Chi-Chi | 1-D | 0.2 |
| 3 | Scenario | 1-D | 0.2 |
| 4 | NRC | 1-D | 0.2 |
| 5 | White Noise | 3-D | 0.025 |
| 6 | Scenario | 1-D | 0.5 |
| 7 | NRC | 1-D | 0.5 |
| 8 | White Noise | 3-D | 0.025 |
| 9 | Chi-Chi | 2-D | 0.2 |
| 10 | Scenario | 2-D | 0.2 |
| 11 | NRC | 2-D | 0.2 |
| 12 | White Noise | 3-D | 0.025 |
| 13 | Scenario | 2-D | 0.5 |
| 14 | NRC | 2-D | 0.5 |
| 15 | White Noise | 3-D | 0.025 |
| 16 | Scenario | 3-D | 0.5 |
| 17 | NRC | 3-D | 0.5 |
| 18 | White Noise | 3-D | 0.025 |

**Table 4**. Modal Frequencies Obtained from the Test and Analysis

| Mode No. | Frequency (Hz) | |
|---|---|---|
| | Analysis | Test |
| 1 | 4.1 | 4.1 |
| 2 | 12.1 | 12.7 |
| 3 | 19.2 | 19.9 |
| 4 | 24.1 | 25.0 |

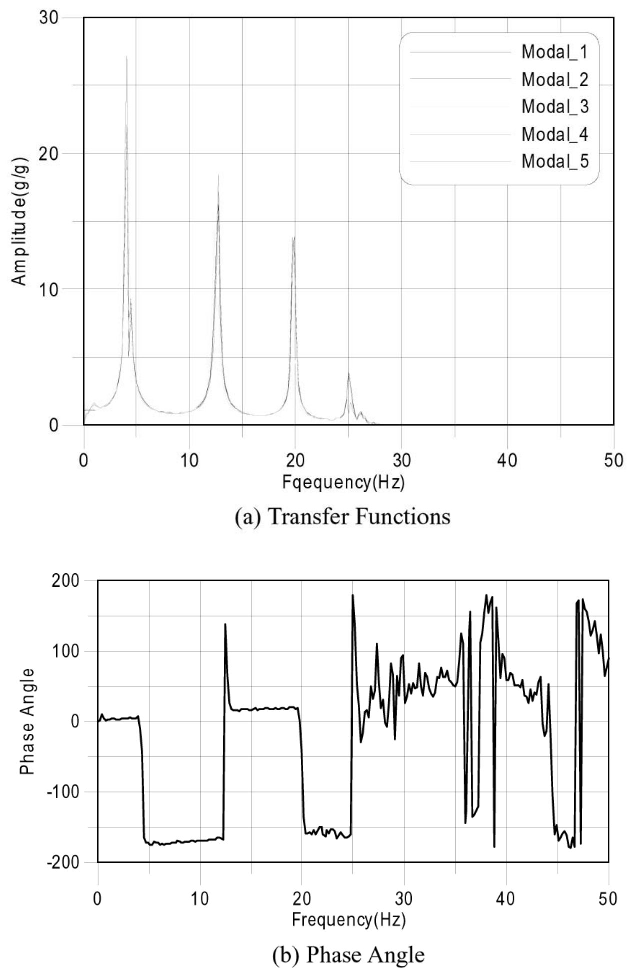


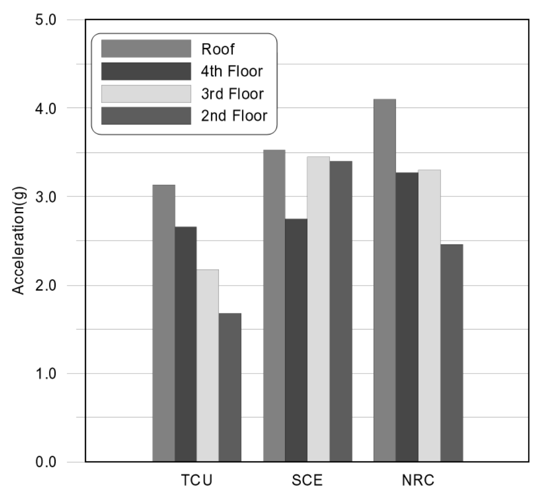

Fig. 12. Transfer Function and Phase Angle form the Modal Tests

difference of the amplitude was caused by a difference of the table motions.

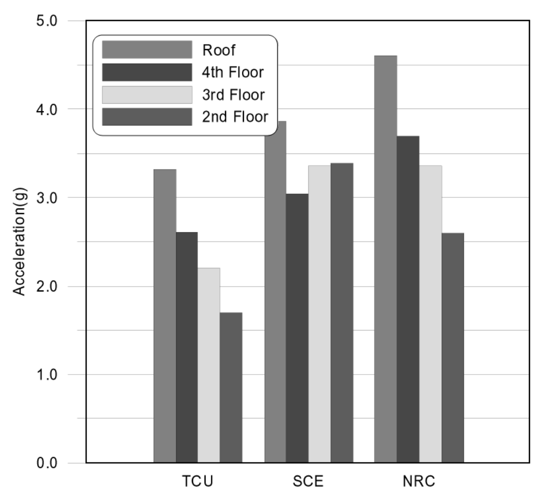
### 4.2.2 Acceleration Response

The acceleration responses of the model were measured in three directions for each floor. To compare the peak acceleration responses, it is necessary to normalize the peak acceleration response to the required peak input acceleration. In general, the shaking table cannot precisely simulate the required motions, due to its limited capacity. Therefore, a direct comparison of the peak acceleration response is impossible.

In this study, the peak acceleration responses were normalized to 1g input levels. Figure 13 shows the average normalized peak acceleration responses of the transverse direction from all the tests and the 1-D tests for the three input motions at each floor, respectively.




(a) All Test Data




(b) 1-D Test Data

Fig. 13. Average Peak Acceleration Responses Normalized to Input Levels

The average peak acceleration response from the NRC input is larger than that from the other inputs. The average peak acceleration from the 1-D tests is higher than that from all of the test data. These results indicate that a multi-directional input does not always produce a higher response for normal structures.

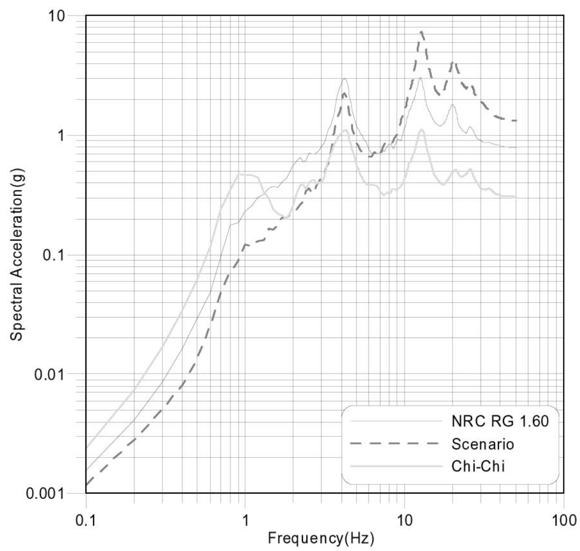
From the acceleration response of the model, it was concluded that the near fault ground motion did not always cause a large acceleration response. The observed acceleration response shows that the relation between the frequency content of the input ground motion and the fundamental frequency of the structures are very important factors for the acceleration response of structures. From this observation, it can be assumed that the near-fault ground motion effect is rather insignificant for general nuclear power plant structures in the elastic range, since the fundamental frequency of the massive nuclear power plant structures is about 4 – 10 Hz. However, if the structure is beyond the yielding point due to a large displacement, then the frequency of the structure will be reduced, and the displacement response will be increased dramatically because of the characteristics of the near-fault ground motion, which is a long-period impulsive motion occurring at an early stage. This impulsive long-period motion, roughly 1-second period can cause a significant damage to the long-period structures.

### *4.2.3 Floor Acceleration Response*

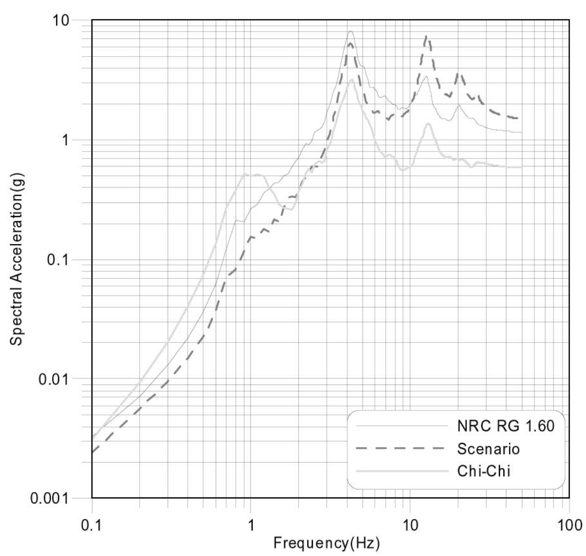
The seismic responses of the structure were investigated in the previous section. Based on the test results, it seems that the design earthquake for Korean nuclear power plants is conservative, because the fundamental frequency of the major nuclear power plant structures is greater than 5 Hz. From a structural point of view, the nuclear power plant structures have sufficient safety margins to bear the earthquake ground motions. In nuclear power plant structures, many kinds of equipment which are important for its safety are installed on the floors or walls using a welded or bolted anchorage. The dynamic characteristics of this equipment are various, and the failure mode due to an earthquake is composed of a structural failure mode and a functional failure mode. A structural failure mode, such as an anchorage failure, is mainly dominated by the global modal response of the structures. A functional failure mode is dominated by the local response of the equipment. It is noted from the fragility analyses performed for the probabilistic seismic risk assessment that the dominant failure mode of the active components is a functional failure due to a chattering of the relay attached to the electrical equipment mounts, such as on a panel, rack, or cabinet [15].

In general, the relay chattering is very sensitive to high frequency ground motions [16]. The local vibration mode of the panel induces a high frequency response of the panel. In this study, the floor acceleration response was estimated by using the floor acceleration response spectra. The floor response spectrum is used for the design of the components installed in a building structure. Figure 14 shows the floor response spectra for the second floor and the roof. These spectra were developed from two-dimensional tests with a 0.2 g PGA. As shown in Figure 14, the difference of the spectral amplitude increases with an increase of the frequency. The floor response spectra due to the scenario earthquake show high amplitude in a high-frequency range greater than 10 Hz.

Figure 15 shows the floor response spectra corrected by the spectral acceleration ratio of the spectral acceleration of the table motion to that of the target motion at every frequency. As shown in Figure 15, the response spectrum shapes are very similar to the uncorrected spectra, but the spectral amplitude is somewhat different, due to a simulation error of the shaking table. Based on this result, it is noted that high frequency ground motions can affect the safety of the equipment installed in a building. The near-fault ground motion is not as damaging to equipment that has high natural frequencies.

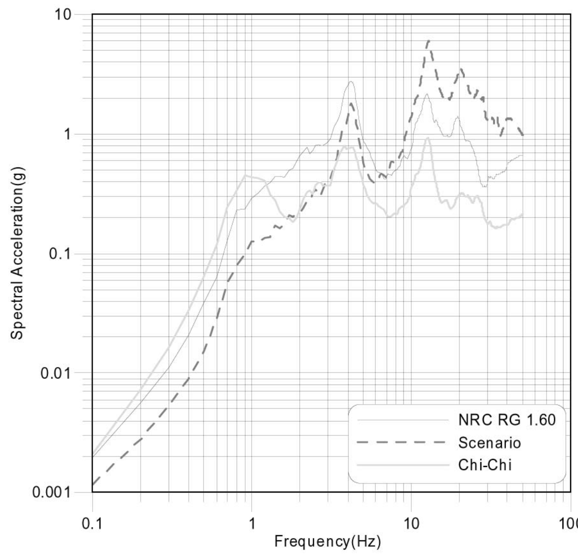



(a) 2nd Floor

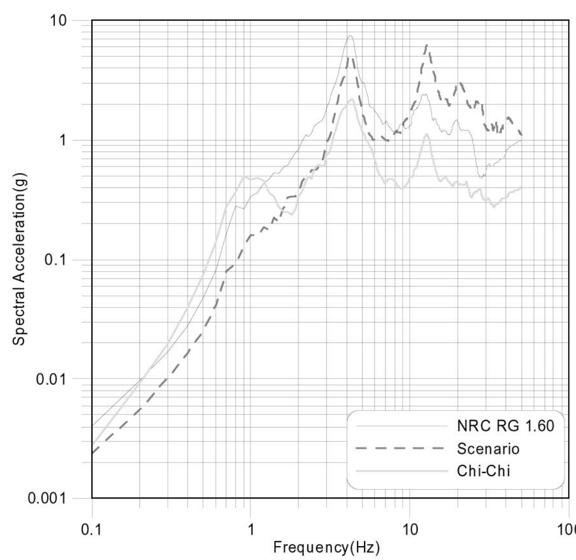



(b) Roof

Fig. 14. Floor Acceleration Response Spectra




(a) 2nd Floor




(b) Roof

Fig. 15. Corrected Floor Acceleration Response Spectra

## 5. CONCLUSIONS

In this study, shaking table tests of a steel frame structure were performed using three different input ground motions. Three kinds of input motions were used for the tests to estimate the safety of nuclear power plants: the design earthquake, the probability-based scenario earthquake developed for nuclear power plant sites, and the actual earthquake records from the Chi-Chi earthquake.

The probability-based scenario earthquakes for Korean NPP sites were developed by using the PSHA results. The spectral shapes for the scenario earthquakes were developed by using the ground motion attenuation equations, as proposed by an expert in PSHA, and the empirical spectral shapes for the WUS and CEUS sites. In this study, using correction factors that took into consideration the near-fault rupture directivity effect, the response spectra for the scenario earthquakes were developed.

The acceleration responses of the structure brought about by the design earthquake were larger than those that were brought about by the other input earthquakes. It seems that the design earthquake for the Korean nuclear power plants is conservative, and that the near-fault earthquake and scenario earthquake would not be exceedingly damaging to nuclear power plant structures, because the fundamental frequencies of the nuclear power plant structures are generally greater than 5 Hz.

The high frequency ground motions that appeared in the scenario earthquake can be damaging to the equipment installed on the high floors of an NPP building. This shows that the design earthquake is not conservative enough to demonstrate the actual danger to safety related nuclear power plant equipment.

This test was limited to steel frame structures. The steel frame structure did not show large stiffness degradation due to the large displacement in the earthquake intensity range that was used in this test. However the near-fault ground motion effect should be estimated for reinforced concrete structures in which a frequency shift due to stiffness degradation by cracks is inevitable.

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