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Seismic Qualification of Electrical Cabinet Using High-Fidelity Simulation under High Frequency Earthquakes

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Abstract: Most nuclear and nonnuclear power plants have been designed in the frequency range of 2 to 10 Hz, but now, the design guidelines for structural and nonstructural components such as electrical cabinets must be improved by including high frequency greater than 10 Hz for sustainable energy. The electrical cabinet is the essential piece of equipment for safety functions and the uncertainty of seismic capability in power plants. Consequently, the attention of this study focused on evaluating the seismic demands of the electrical cabinet under high frequency earthquakes and also, seismic qualification of the electrical cabinet using the identification of experimental tests and numerical models. An experimental test based on ICC-ES AC 156 and IEEE std.344 was conducted for seismic qualification of the cabinet and then, a high-fidelity finite element model to capture the significant deformation was developed in this study. It is observed that the fundamental frequencies were 16 and 24 Hz from the experimental tests, respectively. In order to verify the proposed high-fidelity simulation model, the target fundamental frequencies of the cabinet were evaluated in the ABAQUS platform. It was interesting to note that the reconciliation of experimental and analytical results was extremely identical. Furthermore, in order to evaluate seismic response characteristics of the cabinet subjected to high and low frequency earthquakes, time history analysis was conducted in this study, using the ABAQUS platform. As a result, the observation showed that the seismic response of the cabinet system under a high frequency earthquake was relatively higher than that of low frequency. It can be very important to note that the cabinet system was sensitive to high frequency vibration.

Keywords: electrical cabinet; high fidelity; high frequency; seismic qualification

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1. Introduction

An electric cabinet system, which is a nonstructural component, is the key facility to support electrical power distribution in power plants and it must be expected to remain functional during and after strong earthquakes. Over the past decade, most nonstructural components have received less attention in comparison to the structural system regarding their behavior and design, in spite of it being the cause of economic losses and mechanical damage during a seismic event. Such problems cause a loss of operation and a loss of electrical power in critical facilities, for example, due to overturning of the cabinet system, and component rocking and component sliding by inadequate restrain anchorage in the cabinet system during an earthquake [1]. During the 2010 Haiti Earthquake (magnitude 7.0), electrical equipment such as unanchored cabinets at a power plant was damaged physically, and a poorly anchored cabinet system was overturned due to the 1999 Izmit earthquake (magnitude 7.4) in Turkey [2]. Consequently, most damage of electrical cabinets was related to structural damage in terms of sliding or overturning and also, the damage was associated with sensitivity due to the amplification of acceleration in the cabinet. In recent years, many research works have addressed mitigating earthquake damage and capturing the seismic performance of the cabinet system. Gupta et al. [3] handled a new method to reduce the computational effort of the finite element method with the evaluation of seismic qualification of the electrical cabinet, using the Rayleigh–Ritz method. The method of seismic qualification of electrical cabinets was presented by Henkel et al. [4] and they proposed the method of a combination of shaking tests and numerical analyses to consider the ageing of materials in the cabinet system. Meanwhile, Lin et al. [5] evaluated the dynamic characteristics and responses of electrical cabinets in nuclear power plants, such as spectral amplification and in-cabinet response spectra (ICRS). In addition, Gupta et al. [6] presented the dynamic characteristics of cabinet systems using the simple method, which was called the Ritz vector approach and showed ICRS of a cabinet subjected to a high frequency ground motion by the simple approach, in comparison to a low frequency ground motion such as USNRC's RG 1.60 spectrum. Recently, the seismic fragility of the electrical cabinet was also studied to estimate the probability of failure due to seismic ground motions [7], but the selected ground motions mostly contained low frequency input motions. Historically, strong earthquakes over magnitude 5.0 have been very rare on the Korean peninsula, but two strong earthquakes (2016 Gyeongju and 2017 Pohang) over magnitude 5.0 have struck on the southeastern area of Korea, consecutively. The aftershocks of the 2016 Gyeongju and 2017 Pohang earthquakes occurred 115 times and 56 times, respectively, and these earthquakes caused significant damage to structural and nonstructural systems on the southeastern side of the Korean peninsula [8]. Furthermore, critical facilities such as nuclear and nonnuclear power plants are concentrated around Gyeongju and Pohang areas in Korea and these systems need to consider seismic design on high frequency motions because the ground motion contained high frequency. This high frequency motion can lead to the loss of functionality of the nonstructural component, especially, electric cabinets in critical structures. The cabinet instrument is related to the fundamental frequency of the components and it is sensitive to the response of acceleration during and after an earthquake [6,7]. However, most studies have focused on ICRS and the dynamic characteristics of the cabinet instruments using past earthquakes, except a few research works associated with high frequency earthquakes. Therefore, the purpose of this study is to present a reconciliation of experimental shaking table tests and numerical analyses of an electrical cabinet subjected to input motion ICC-ES AC156 [9]. More specifically, the detailed study of this paper shows the following subjects:

- Identification of the dynamic characteristics such as global and local modes of a single door cabinet on the shaking table test, by using sinusoidal sweep (2 octave/min, 1~50 Hz).
- Evaluation of the dynamic response such as acceleration time histories at the inside and outside of the cabinet, using measurement of accelerometers at the single door on the shaking table test due to ICC-ES AC156.
- Development of a 3D Finite Element (FE) model using the ABAQUS platform to validate the numerical model compared with the responses observed from the shaking table test.
- Analysis of the dynamic response of the single door cabinet system subjected to high and low frequency ground motions, using time history analyses of the 3D FE model.

In order to analyze the sensitivity of the dynamic response of the cabinet, corresponding to ground motion uncertainties, it is proposed that excessive computational effort for 3D FE analysis is needed. Consequently, this study analyzed the dynamic response of the cabinet under high frequency motions, using high-fidelity simulation with improvement of the accuracy of the FE model validated from the experimental test results.

2. Experimental Tests of Electrical Cabinet

2.1. Test Configuration

The electrical cabinet system is typically constrained by a partially fixed support or fully anchored system and the bracing system in the cabinet is very complicated, in order to mitigate the damage and maintain the functionality of the equipment. In addition, it is quite difficult to describe a complex behavior and construct a FE model of the system. Hence, it is necessary to perform a laboratory test such as a shaking table test to understand the complicated behavior. A prototype of a single door cabinet was selected in this study, for the shaking table test. The width, depth, and height of the specimen were about 800, 800, and 2350 mm, respectively and also the weight of the cabinet was about 480 kg. The cabinet was anchored by eight M16 bolts as a support condition, as shown in Figure 1. The bolts connected onto two channels at the bottom in the specimen were integrated with a jig-plate and then, the jig was anchored onto a shanking table by M24 bolts at 8 positions.

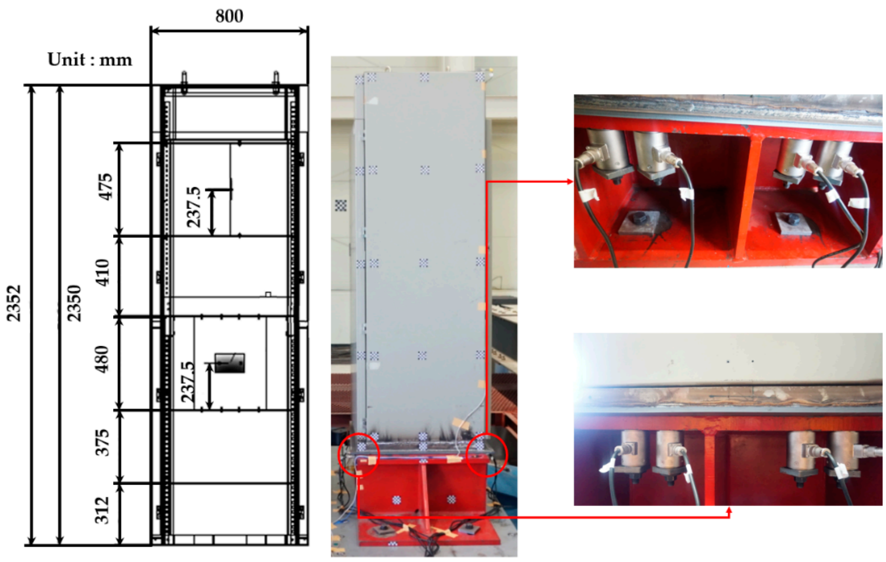


Figure 1. The prototype cabinet system for an experimental test.

As can be seen in Figure 1, a total of 7 accelerometers (direction: x, y, z) were used to investigate the dynamic characteristics of the cabinet and the accelerometer at point A7 was to depict the motion of rigid body at the jig-plate. Additionally, in order to represent the local modes and in-cabinet response of the cabinet, accelerometers at locations A8, A9, and A10 were applied and the global modes were mainly measured at points A11, A12, and A13. The procedure of the shaking table test, shown in Figure 2, was authorized to explore the dynamic characteristics, required response spectrum (RRS), and test response spectrum (TRS) of the cabinet and so on. Further information in terms of the procedure will be discussed on the next section.

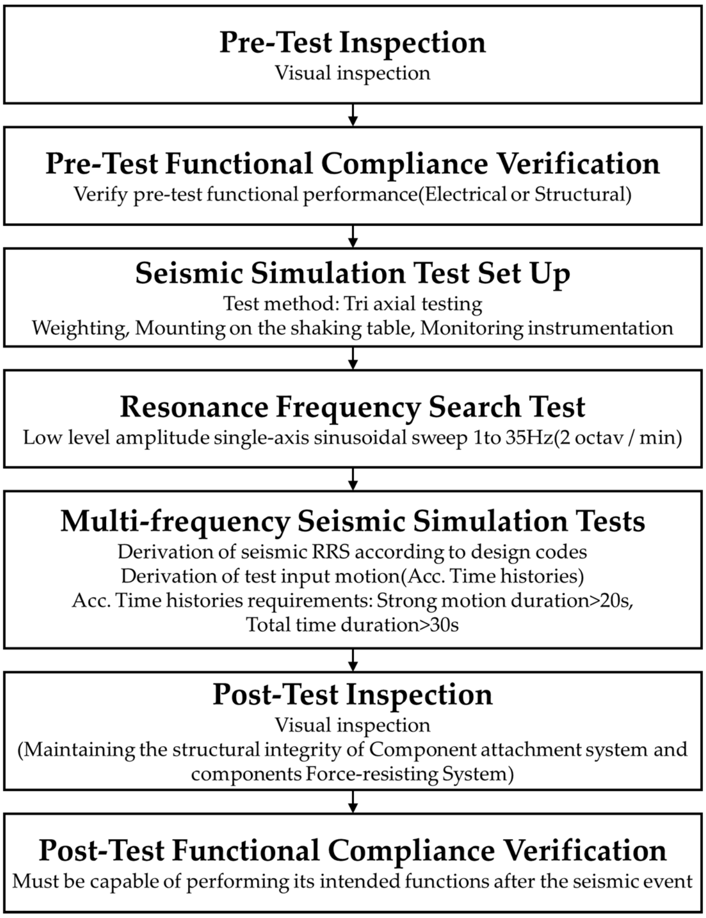


Figure 2. Procedure of shaking table test for the cabinet system.

2.2. *Shaking Table Test Procedure*

2.2.1. Resonance Frequency Search Test

A shaking table test of the cabinet was conducted at the Seismic Research and Test Center, Pusan National University, in which a 6-degrees-of-freedom shaking table can be performed. Before time history tests, a resonance search test carried out for evaluation of the fundamental frequencies and dynamic characteristics of the electrical cabinets. The resonance test was carried out through uni-axial swept sine waves with 2 octave/min and amplitude of 0.07 g, in order to minimize the damage of the cabinet during the test. In addition, it was sequentially performed once within the range of 1 to 50 Hz, corresponding to each orthogonal principal axis, since it had to include the scope of frequency 1.3 to 33.3 Hz during the test.

2.2.2. Input Motion: AC156

This study generated the input motions to determine the functionality of the nonstructural components such as electrical cabinets, in accordance with ICC-ES AC156 related to ASCE 7 and International Building Code (IBC). Hence, this test procedure was to take account of the seismic qualification test of the cabinet system based on ICC-ES AC156 and IEEE std. 344 [10]. For seismic qualification of the electrical cabinet, it is necessary to determine the Required Response Spectrum (RRS) for compatibility between the shake table test and building code of nonstructural components. RRS can be generated from ICC-ES AC156 and it is related to lateral force requirements for nonstructural components in accordance with KBC2016 [11]. The design lateral acceleration requirement of nonstructural components based on the lateral force requirement is the following [9–11] (Equation (1)):

$$A = \frac{0.4 a_p S_{DS}}{\left(\frac{R_p}{I_p}\right)}\left(1 + 2\frac{z}{h}\right) \tag{1}$$

where, a_p is the amplification factor; S_{DS} is the design spectral response acceleration in a short period; R_p is the response modification factor; I_p is the importance factor; z is the height in the structure at the location of the component; h is the roof height relative to the base level.

The RRS can, now, be constructed by resulting in the Formula (1) and it can be classified into two components: (1) flexible component (A_{FLEX}) and (2) rigid component (A_{RIG}). A_{FLEX} is described by the following equation (Equation (2)). Component amplification factor and the ratio between response modification factor and importance factor are equal to 2.5 and 1.0 in Equation (2), respectively. In addition, it is noted that A_{FLEX} cannot exceed 1.6 times the design spectral response acceleration in the short period (S_{DS}) (Equation (2)).

$$A_{FLEX} = S_{DS}\left(1 + 2\frac{z}{h}\right) \tag{2}$$

The RRS of the rigid component is generated by Equation (3), identified as an amplification factor equal to one, and the ratio between response modification factor and importance factor is also equal to one.

$$A_{RIG} = 0.4 S_{DS}\left(1 + 2\frac{z}{h}\right) \tag{3}$$

In this study, design spectral response acceleration in the short period is defined by substituting the site coefficient equal to 1.5 and the seismic zone factor equal to 0.22 g and it assumed that the cabinet was installed on the top floor of a building, i.e., the value of z/h is equal to one in Equation (2) and Equation (3). Consequently, based on the definition of A_{FLEX} and A_{RIG}, seismic qualification of RRS, corresponding to AC156, was characterized with frequency domains, as shown in Figure 3. In addition, a 5% damping ratio was applied for the RRS, and the frequency associated with A_{FLEX} and A_{RIG} was 1.3 and 33.3 Hz, respectively. Figure 4 shows acceleration time histories with longitudinal, transverse, and vertical direction, based on the RRS of the cabinet system.

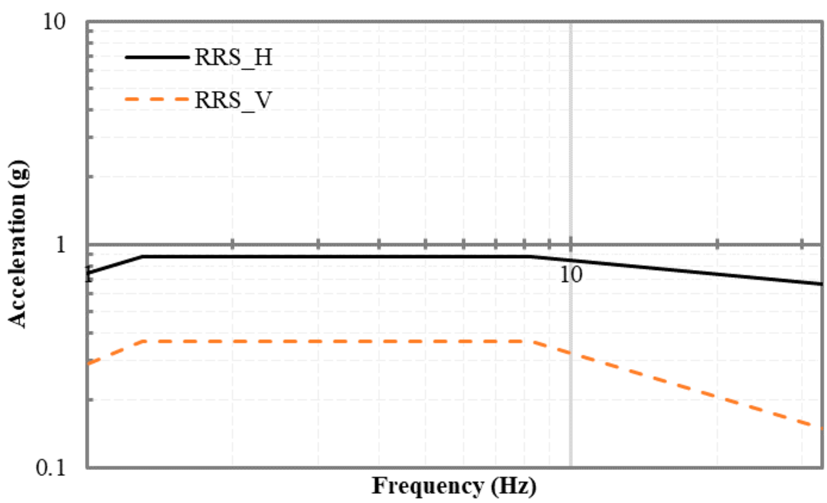


Figure 3. Required response spectrum of AC156 for electrical cabinet.

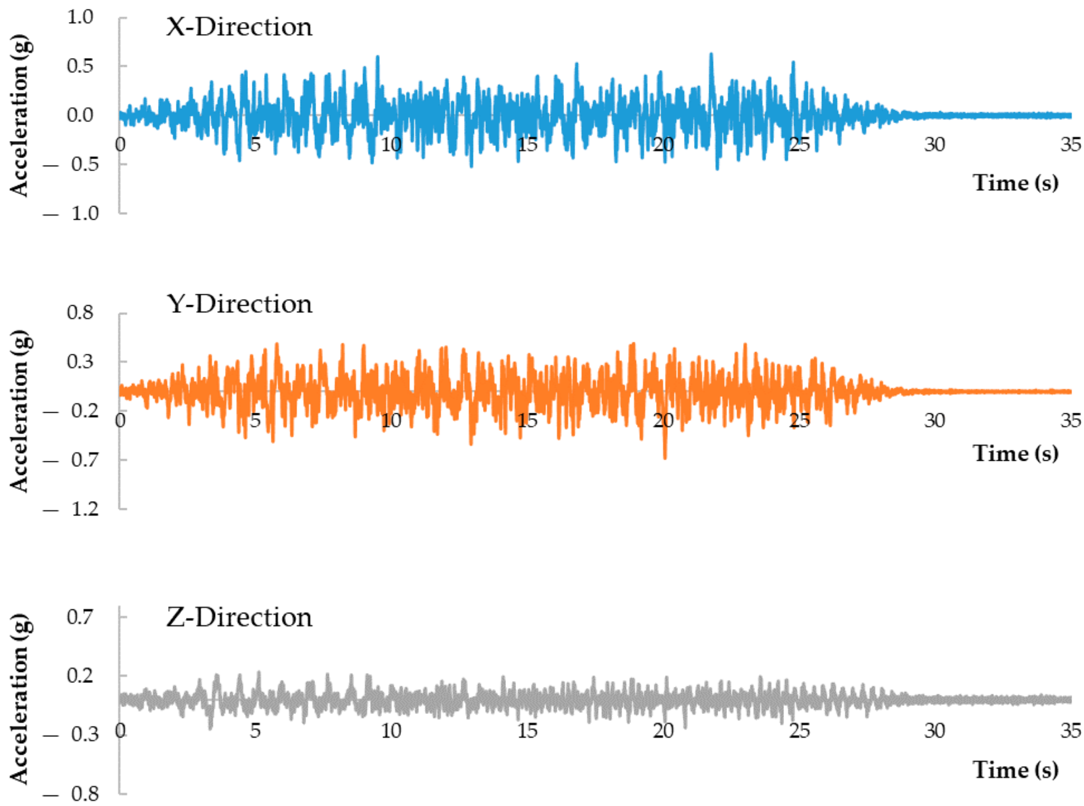


Figure 4. Input motions of AC156 for electrical cabinet.

3. Experimental Test Results

As mentioned earlier, the experimental test was conducted based on seismic test methods for telecommunication facilities [12], IEEE std. 344 and ICC-ES AC 156. The duration of vibration was 30 seconds and the period for strong motion was kept at 20 seconds during the vibration. In addition, deformation and damage of the cabinet was visually confirmed, before and after the test. Test response spectrum was analyzed through the response of tri-axial acceleration sensors on the bottom of the shaking table, for the comparison to the RRS. The correlation coefficient is identified by the ratio of the cross-correlation function based on each direction of the signals, and it should be less than 0.3, since the ground motions are statistically independent [10]. Figure 5 illustrated the cross-correlation related to IEEE 344 and it can be noted that the absolute value was clearly less than the coefficient of correlation function 0.3 at each plane during all time periods.

In order to mitigate the uncertainty of experimental tests such as banging and rattling, a door of the cabinet system was fixed. The fundamental frequency of each measurement for the accelerometers was listed in Table 1. The fundamental frequencies of the cabinet through the accelerometers were measured in a range from 13 to 23 Hz and further details will be discussed in the next section, corresponding to the target fundamental frequency.

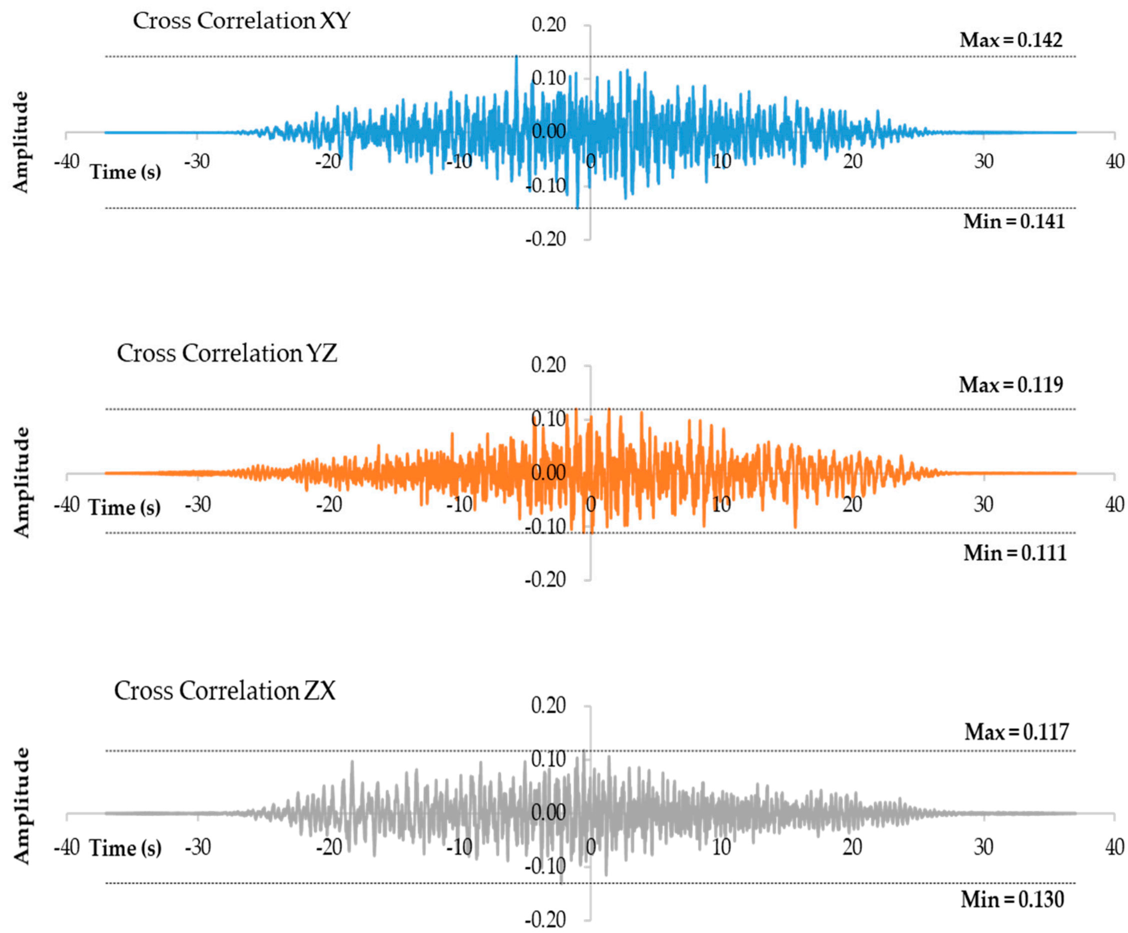


Figure 5. Correlation coefficient based on AC156.

Table 1. Fundamental frequencies through the location of single door cabinet.

Description	Location	Resonant Frequency (Hz)		
		X	Y	Z
A7	Base jig	N/A	N/A	16.00
A8	Inside 1st story horizontal panel	16.00	16.00	22.25
A9	Inside 2nd story vertical panel center	16.00	13.75	23.25
A10	Inside 3rd story vertical panel center	15.75	17.75	16.00
A11	Door center	16.00	16.25	16.00
A12	Edge top	15.25	14.25	16.00
A13	Side panel center	23.00	14.25	16.00

4. Finite Element Model and Validation of the Cabinet

4.1. FE Model of the Cabinet

To understand the more complex behavior of the single door cabinet, it is necessary to perform a finite element model (FEM) of the electrical cabinet and it is important that the FEM must be reconciled with the data from the experimental test. Often, a simplified model of electrical cabinet system is applied using a lumped mass model with the link element but such a model, while capturing the significant deformation of electrical cabinet subjected to strong ground motions, can be unrealistic. Consequently, this study used a three-dimensional cabinet system to overcome such a weakness, using the ABAQUS platform [13]. In addition, elastic modulus, density, and Poisson's ratio as the material properties in the cabinet were 2.1×10^5 MPa , 7.85×10^{-9} t/mm^3, and $\nu = 0.28$ respectively. The three-dimensional FE model of the cabinet system using ABAQUS was demonstrated in Figure 6 and the boundary conditions at the base were implemented to be hinge supports. The shell element (S4R) for frames and panels was used in the FE model. The total number of elements and nodes was 117,655 and 128,198, respectively. In addition, this model was assumed to have linear elastic behavior, since there was no significant damage such as connection failure between panels and frames and local buckling during the experimental test. More specifically, Figure 7 illustrated the type of connection at the FE model in ABAQUS. Two types of connection method were utilized in this study. Figure 7a showed the location of welding parts among longitudinal and transverse directions of the frames, and the location between the strut and main frames. In order to present the performance and reduce the nonlinearity such as local buckling at the location of welding parts, the Constraints-Tie element was concerned in this study. Another type of connection, which was Constraints-Coupling in the ABAQUS ver. 2020 (Dassault Systèmes, Vélizy-Villacoublay, France) platform, was assigned to implement bolt motion in the FE model, as can be seen in Figure 7b. The bolt joints were mainly utilized in the part between the C-channel and the main frame and the location between the horizontal panel and strut.

4.2. Validation of FE Model

Based on the preliminary experimental test, a high-fidelity simulation model with a 5% damping ratio was developed using the shell element in the ABAQUS platform. It was interesting to find that the accurate mode shapes of the cabinet system were able to be demonstrated through the high-fidelity FE model. As can be seen in Figure 1, the dynamic characteristics of the cabinet on the shaking table were measured by accelerometers. The fundamental frequencies were also obtained from the resonance test using sine sweep function during the shaking table test. Figure 8 depicted the results obtained from the resonance search tests, and there was no amplification up to 15 Hz among x, y, and z directions. Subsequently, the first amplification occurred at 16 Hz of all accelerometers, which can be determined as the primary global mode of the cabinet. Furthermore, after the 1st mode, the second targeted global mode was decided at 24 Hz, as shown in Table 1 and Figure 8. In order to reconcile the results of the experimental test with the high-fidelity FE model, modal analysis, corresponding to the target fundamental frequencies, was performed in ABAQUS. The first global mode of the cabinet obtained from the numerical model is shown in Figure 9a, and it was investigated as 16.08 Hz. Besides, Figure 9b describes the second global mode (24.21 Hz) of the system from the modal analysis. It was revealed that the dominated modes were the first and second mode, since mass participation was over 90% at those modes. As a result, the modes obtained from the high-fidelity simulation model were slightly higher than the fundamental frequencies obtained from the resonance tests, but the frequencies were extremely identical to the target frequencies, which is less than 1% error. Therefore, it can be now shown that significant deformation, such as elastic buckling and the failure of the connections, will be capable of being captured by the verified high-fidelity FE model. In addition, it is interesting to note that the primary objective of the high-fidelity model is to accurately evaluate the failure criteria of the cabinet system under high frequency internal/external events. Next, we present the seismic performance of the cabinet subjected to high frequency earthquakes.

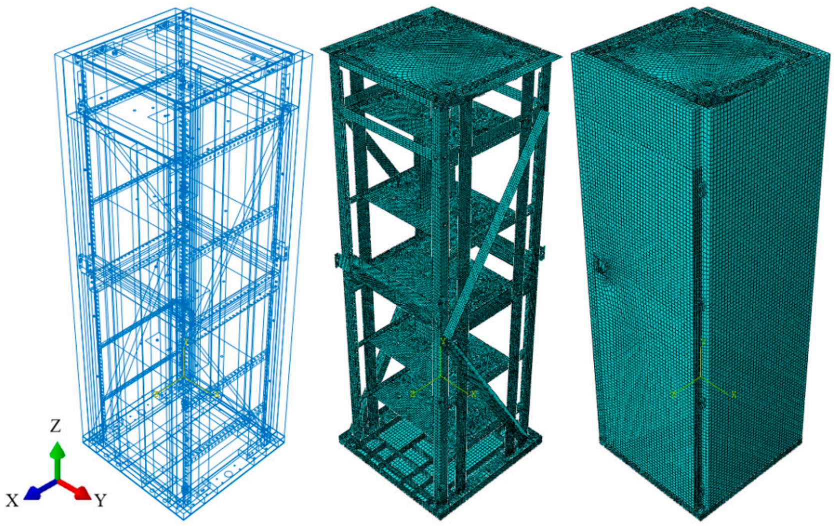


Figure 6. Detailed FE model of the cabinet system.

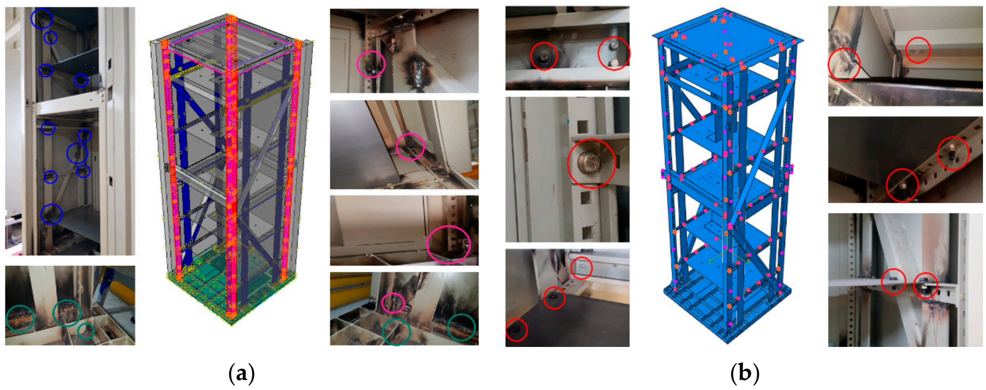


Figure 7. Location of connection in FE model: (**a**) Tie; (**b**) Coupling.

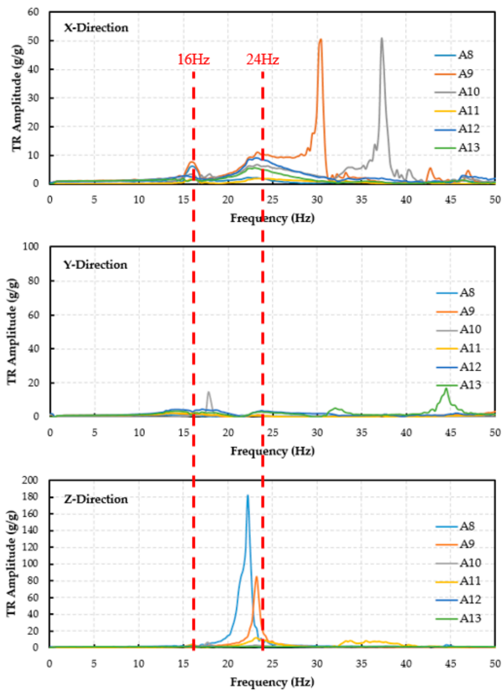
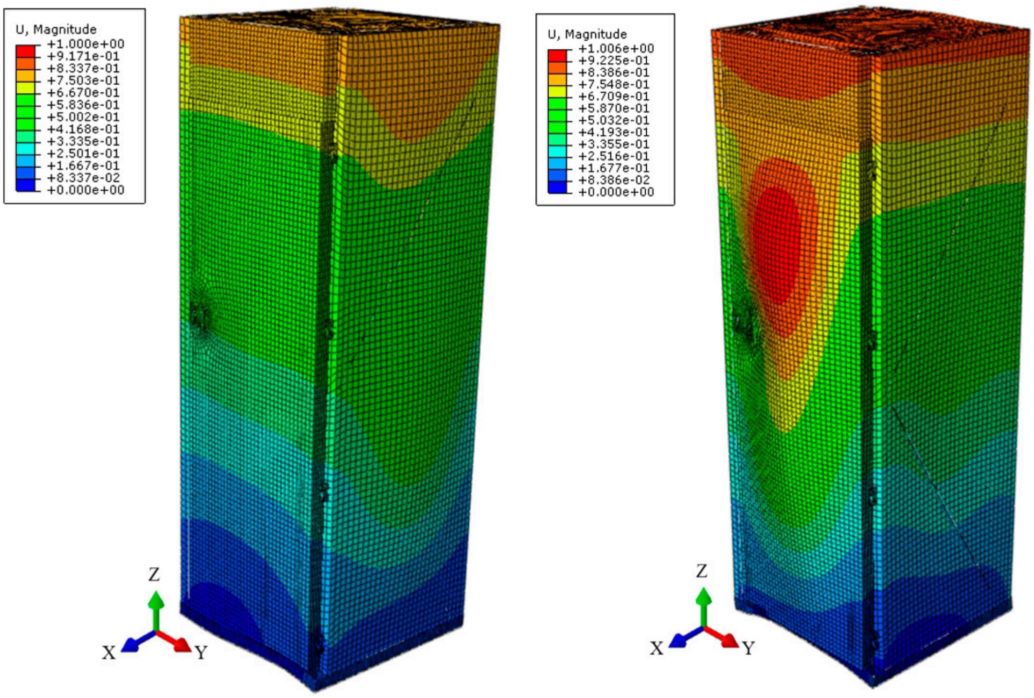


Figure 8. Resonance data obtained from experimental tests.



(**a**) (**b**)

Figure 9. Mode shapes of the cabinet using high-fidelity FE model: (**a**) 1st Global Mode Shape (16.08 Hz); (**b**) 2nd Global Mode Shape (24.21 Hz).

5. Seismic Performance of the Cabinet

In recent years, it has been one of the most important issues to strengthen the seismic criteria or demands of structural and nonstructural components since the 2016 and 2017 strong earthquakes in Korea. The verification of seismic performance of the cabinet is a considerably noteworthy problem to distribute essential energy and operate functionality in nuclear and nonnuclear power plants. Especially, based on the experimental test and high-fidelity simulation model, this study aims to verify the seismic performance of electrical equipment such as the cabinet system. In order to consider the frequency domain of seismic ground motions, five different seismic ground motions were selected, as described in Table 2.

Table 2. Details of selected seismic ground motions.

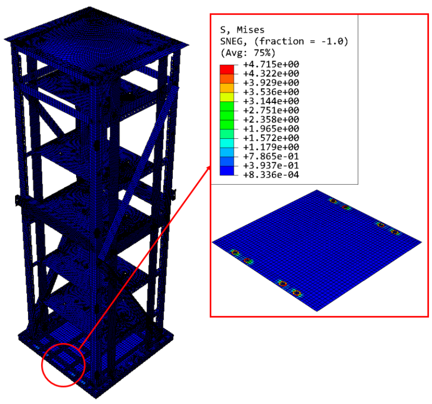
No.	Date	Seismic Events	Location	Magnitude (Mw)	PGA(g)
1	1979.10.15	Imperial Valley	El Centro	6.5	0.3796
2	1994.01.17	Northridge	Beverly Hills	6.7	0.5165
3	1999.08.17	Kocaeli	Duzce	7.5	0.3579
4	2016.09.12	Gyeongju	Ulsan (USN)	5.4	0.4425
5	2017.11.15	Pohang	Pohang (PHA)	5.4	0.2828

The 2016 Gyeongju earthquake can be a representative high frequency earthquake and other earthquakes over moment magnitude greater than 5.0 were selected to explore the diversity of ground motions in a wide range of frequencies. Based on the high-fidelity FE model and the different ground motions, time history analyses were conducted in this study. As shown in Figure 10, it was noted that the stress concentration of the cabinet system occurred at the support conditions, more specifically, of the connection between the anchors and the bottom plates. The stress obtained from the 2016 Gyeongju earthquake included high frequency in the seismic event and was relatively higher than the results from other ground motions. The intriguing observation of the cabinet from the 2016 Gyeongju earthquake was larger than 3 times, in comparison to the value from the Kocaeli earthquake, as seen in Figure 11. Consequently, such results can be explained by the following equation (Equation (4)) and the response spectra (Figure 12). Equation (4) represents the transmissibility provided of an amplitude of the force due to input motions at the foundation, where β is the frequency ratio with circular frequency and excitation frequency.

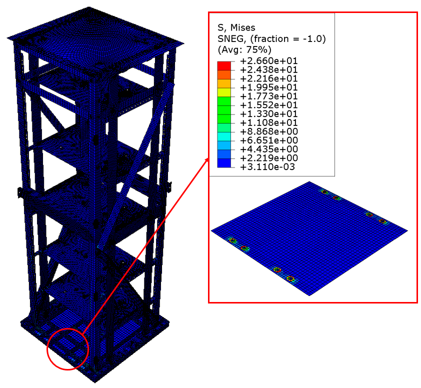
Figure 12 showed the spectra for the input ground motions containing two vertical lines. These two vertical lines demonstrated the first and second global mode frequencies of the cabinet system. With the comparison of the response spectra and the high-fidelity FE model, it was quite evident that

$$TR = \sqrt{\frac{1 + (2\xi\beta)^2}{(1 - \beta^2) + (2\xi\beta)^2}} \tag{4}$$

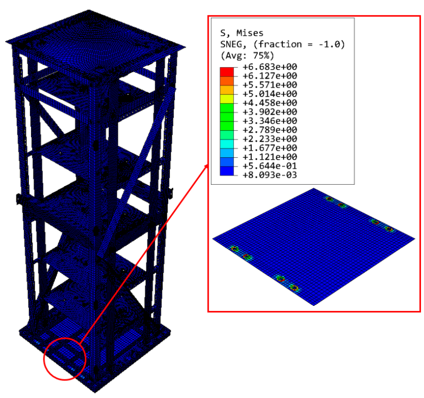
The significance of the first and second global mode of the cabinet was determined, because the acceleration of 2016 Gyeongju at the first and second global modes of the cabinet was the highest among the earthquakes and the next level was the Northridge earthquake. It must be noted that it was quite possible to increase the stress of the cabinet because of the amplification between natural frequency and excitation frequency. In other words, the cabinet system was sensitive to high frequency ground motions.



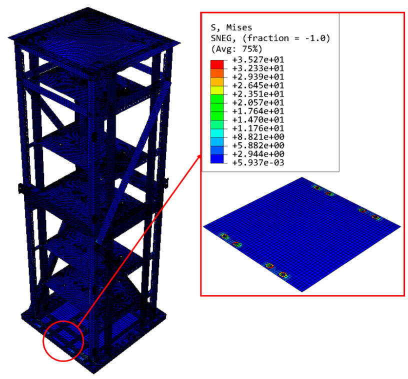
(a) Imperial Valley



(b) Northridge

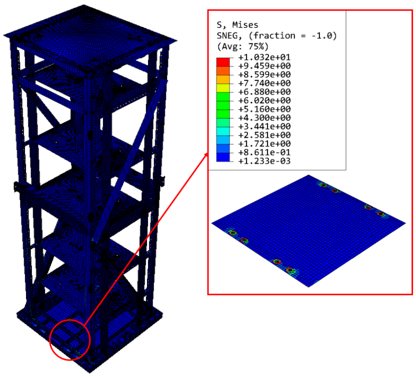


(c) Kocaeli



(d) Gyeongju

Figure 10. *Cont.*



(**e**) Pohang

Figure 10. The results of the cabinet using time history analyses. (**a**) Imperial Valley, (**b**) Northridge, (**c**) Kocaeli, (**d**) Gyeongju, (**e**) Pohang.

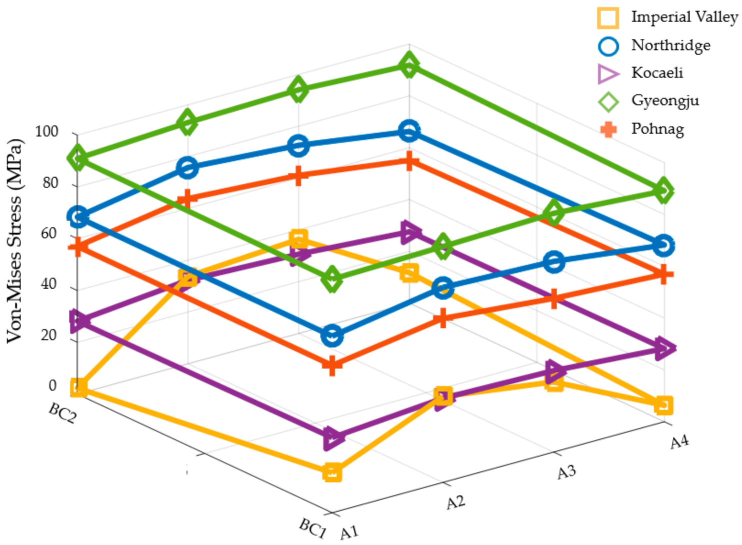


Figure 11. Stresses of the cabinet system at the base.

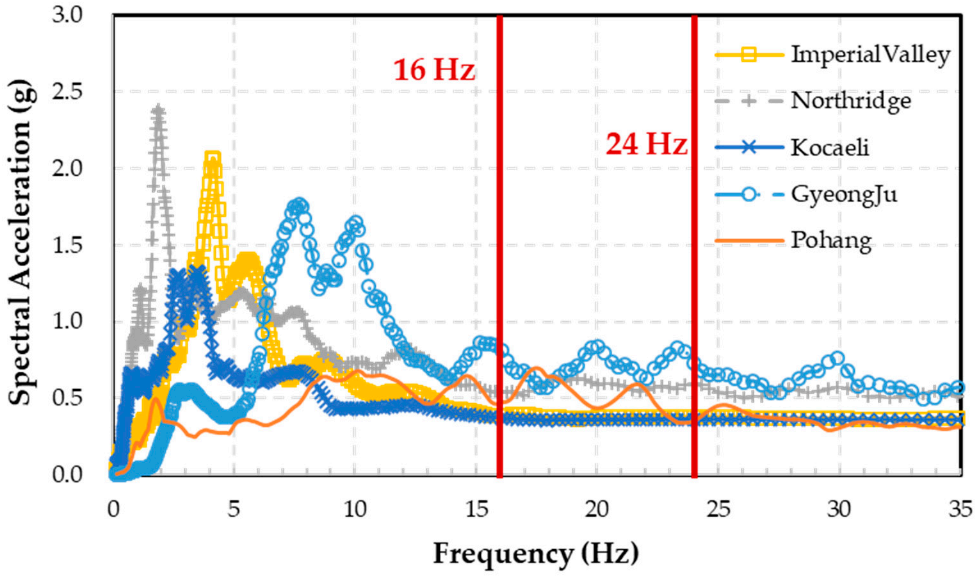


Figure 12. Response spectra of the input motions.

6. Conclusions

In order to support sustainable energy distribution and operation, the cabinet system is one of the essential pieces of electrical equipment in nuclear and nonnuclear power plants. This study presented the seismic qualification of the cabinet system by the observation of the experimental test based on shaking table and the high-fidelity simulation model. The particular focus was on evaluating the dynamic properties of the electrical cabinet under the shaking table test. The fundamental frequencies were obtained from the resonance search test with the sine swept waves in the range of 1 to up to 50 Hz. It was observed that the first and second global modes of the single door electrical cabinet were 16 and 24 Hz, respectively. Furthermore, for the seismic qualification of the electrical cabinet, RRS based on ICC-ES AC156 and IEEE std. 344 was developed in this study and it was revealed that the correlation coefficient function was absolutely less than 0.3 at each orthogonal direction from the shaking table test. Then, based on the observation of experimental tests, the high-fidelity simulation model of the cabinet was developed in this study, using the ABAQUS platform. It incorporated the linear elastic panels in the frames, since there was no nonlinearity such as the failure between the joints and local buckling among members in the cabinet during the tests. The high-fidelity FE model was validated with the results from the resonance search test. Comparisons of the fundamental frequencies of the cabinet obtained from the experimental test and the high-fidelity FE model demonstrated that the high-fidelity FE model was very slightly conservative because it was measured with a value whose fundamental frequency (1st 16.08 Hz and 2nd 24.21 Hz) exceeded about 1%. The target frequencies from the FE model of the cabinet, however, were extremely close to the fundamental frequencies obtained from the experimental test. Therefore, these results verified the accuracy of the dynamic properties established for the high-fidelity FE model using the ABAQUS platform. In addition, this study considered the effect of high frequency earthquakes for the cabinet system in power plants. Five different seismic ground motions, including a high frequency earthquake, were selected and then, linear time history analysis was conducted in the ABAQUS platform. As a result of the linear time history analysis, the cabinet system, dominated by the first and second global mode, was significantly sensitive to the high frequency ground motion. Such phenomenon can be explained by the effect of transmissibility and degree of tuning between the cabinet and foundation during input motions. Additionally, further details of the cabinet system such as in-cabinet response spectra, the influence of local modes, and the validation of acceleration of time history between experimental tests and the high-fidelity FE model must be conducted.

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Conflicts of Interest: The authors declare no conflict of interest.

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