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Division V

AN EXPERIMENTAL STUDY ON CHARACTERISTICS OF VIBRATION CAUSED BY ROCKING MODES OF ELECTRIC CABINET UNDER SEISMIC LOADING

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ABSTRACT

Safety-related electrical cabinets which are installed in nuclear power plants require seismic qualification. The seismic performance evaluation for the electrical cabinets is conducted by the shaking table test or numerical analysis. When performing the seismic evaluation by the numerical simulation, it usually assumes that the electrical cabinets are rigidly anchored to the floor. This assumption may not be valid depending on how the cabinets are anchored. However, the rocking or uplifting could occur in a lower section of the cabinets that are anchored by the anchored bolts. Yang et al. (2002) and Han et al. (2018) conducted a study to calculate these effects numerically. However, a few research was conducted about rocking, uplifting and shifting mode of the cabinets by the shake table test. In this study, shaking table testing was conducted using an electrical cabinet to analyze the dynamic characteristics of the rocking mode by the shaking table test.

INTRODUCTION

The earthquake frequency and seismic damage have increased worldwide of late. In South Korea, many damage cases have been reported due to the Gyeongju and Pohang earthquakes that occurred in 2016 and 2017, respectively. The recent domestic and overseas seismic damage cases show that there has been more damage to non-structural elements than to structural elements. Of the non-structural elements, electric cabinets are important devices for maintaining such functions as central control and communication. The malfunction of these cabinets may lead to serious accidents. As such, many studies have been conducted to secure the excellent seismic performance of electric cabinets.

To estimate the seismic performance of electric cabinets, experimental studies have been conducted using finite element analysis and shaking table tests [Lin et al. (2017), Cosenza et al. (2015), Kim et al. (2009)]. A study for estimating the response of the interior of electric cabinets to earthquakes was also conducted [Gupta et al. (1999)]. The rocking stiffness was calculated to analyze the effect of the uplifting and rocking phenomena due to the local deformation around the cabinet bottom plate anchor bolt caused by seismic loads on the behavior of the cabinets [Yang et al. (2002), Han et al. (2018)]. For the cabinets, finite element analysis is generally conducted under the assumption that they are firmly fixed onto the floor. This assumption, however, may not be valid depending on the method of fixing the cabinets that is used. When the cabinets are fixed with anchor bolts, in particular, local deformation of the bottom plate may occur. Such deformation may cause rocking or uplifting, which generates impacts. It is difficult, however, to describe the collision between the cabinets and the floor through finite element analysis. Therefore, assessment and analysis through tests may be required. There are not many cases, however, in which the influence of rocking was analyzed through tests. As such, in this study, shaking table tests were conducted on an electric cabinet fixed with bolts, and its behavior under rocking was analyzed.

ROCKING OF AN ELECTIRC CABINET

In general, the bottom base of an electric cabinet is fixed onto the floor for finite element analysis. For the cabinet bottom plate composed of thin plates, however, anchor-localized deformation is likely to occur under strong earthquakes. Therefore, the uplifting and rocking phenomena may occur on the bottom plate, except the anchor unit, as shown in Figure 1. Impacts may also occur due to the collision between the bottom of the cabinet and the floor. Therefore, rocking is likely to amplify the acceleration response of the cabinet [Di Sarno et al. (2019)]. This study thus attempted to analyze the effects of rocking and uplifting on the electric cabinet through shaking table tests.

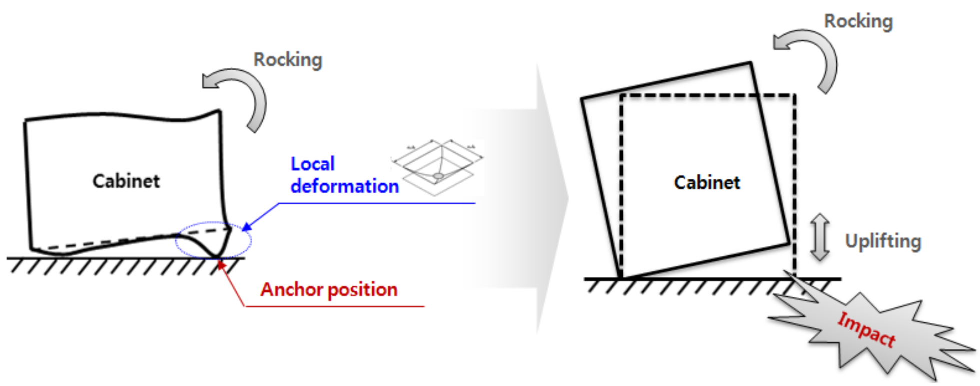


Figure 1. Cabinet uplifting and rocking

SHAKING TABLE TESTS FOR THE ELECTRIC CABINET

Test Specimen Description and Mounting on the Shake Table

The test specimen that was used in the shaking table tests in this study was a single-door electric cabinet model in which a 540g mass was added to the plate inside the cabinet. Table 1 shows the specifications of the test specimen, and Figure 2 shows a drawing of it. In the test specimen, the test fixture and the cabinet were connected using eight M16 bolts. The test fixture was fixed to the shaking table using M24 bolts.

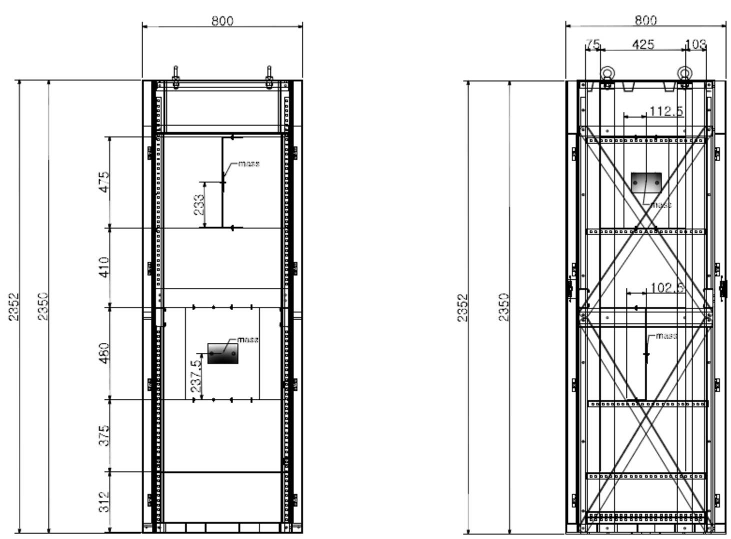


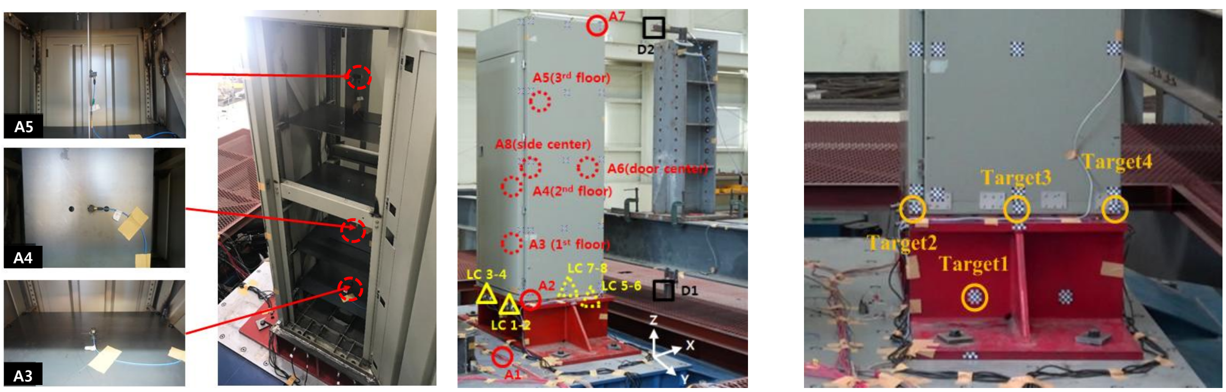
Figure 2. Drawing of test specimen

Table1. Specimens specifications

Specimen	Dimensions (mm)			Weight (kg)
	Length	Width	Height	
Single door cabinet	800	800	2,350	480

Test Setting and Procedure

The test specimen on the shaking table and the sensor location are shown in Figure 3. Table 2 shows the sensor specifications. As shown in Figure 3, the anchorage load was measured by installing the ring-type load cell at the anchor bolt. In addition, the relative displacement was measured by installing wire-type displacement meters at the top and bottom, respectively. To analyze the behavior of the bottom of the test specimen through digital image processing [Kim et al. (2011]], a target was attached at an appropriate location. Three axial accelerometers were also installed at appropriate locations inside and outside the test specimen. The tests were conducted using the 6DOF shaking table of the Seismic Research and Test Center at Pusan National University. Table 3 shows the test sequence. The time history tests were conducted in the order of Reg_G, Reg_A, UHS_G, and UHS_A. Resonance search tests were conducted before and after the time history test to investigate the dynamic characteristics of the test specimen.



(a) Sensor location

(b) Image processing target

Figure 3. Sensor location and image processing target location

Table 2. Sensor specifications

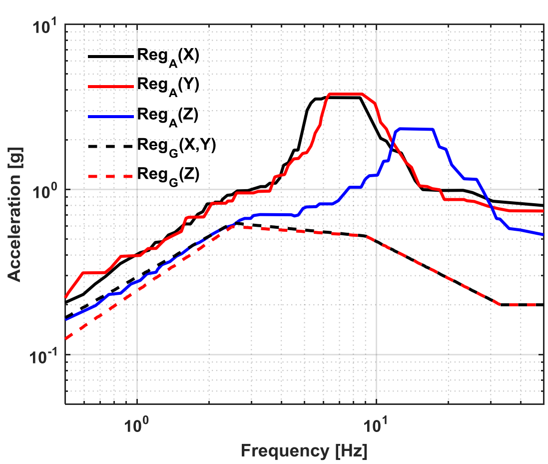
Sensor		Manufacturer	Model	Remark
Accelerometer	A1	Kistler	8315A010D0TA00	Red circle
	A2, A8	PCB	356A17	
	A3~A6		356A16	
	A7		3713B1130G	
Loadcell	LC 1 ~ LC 8	Dacell	CWH-T10	Yellow triangle
LVDT	D1, D2	TML	DP-1000E	Black box
Digital camcorder	Image Processing Target	SONY		

Table 3. Test sequence

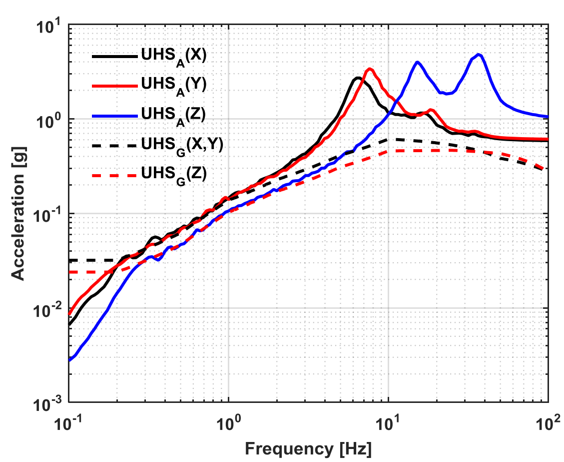
Step	Test Name	Dir.	Remarks
1	Pre-resonance search test	X	Sinusoidal sweep, 2 Otc./min., 1 Hz − 50 Hz, 0.07g
2		Y	
3		Z	
4	Time history test	Reg_G	Multi-frequency Seismic Simulation Tests, Triaxial Testing, Time duration 30s, Strong motion time duration 20s
5		Reg_A	
6		UHS_G	
7		UHS_A	
8	Post-resonance search test	X	Sinusoidal sweep, 2 Otc./min., 1 Hz − 50 Hz, 0.07g
9		Y	
10		Z	

Input Motion

In this study, four sets of acceleration time histories were generated for the shaking table tests. Table 4 and Figure 4 show the response spectrum for generating the acceleration time histories. The damping ratio for the spectrum was 5%. For Reg_G, the acceleration magnification of the peak ground acceleration of the Reg. Guide 1.60 [USNRC (2007)] response spectrum was adjusted to 0.2 g. In addition, Reg_A is the response spectrum of the 165ft location of an auxiliary building when the Reg_G response spectrum was set as an input earthquake. UHS_G is the uniform hazard response spectrum of the Uljin nuclear power plant [Rhee et al. (2013)], and UHS_A is the response spectrum of the 165ft location of an auxiliary building when UHS_G was set as an input.
For the acceleration time histories for the shaking table tests, the vertical and horizontal directions made up one set. A trapezoidal envelop function was used to generate time histories [ASCE (2000)]. The vibration duration was 30 seconds, and the duration of the strong earthquake was 20 seconds [ICCES (2015)]. For the time histories with two different directions, the correlation coefficient did not exceed 0.3 [IEEE (2013)]. The acceleration time histories were generated using the STEX program of MTS.



(a) Reg. 1.60 Spectrum



(b) UHS spectrum(Uljin NPP site)

Figure 4 Required Response Spectrum (5% damping)

Table 4. Input motion

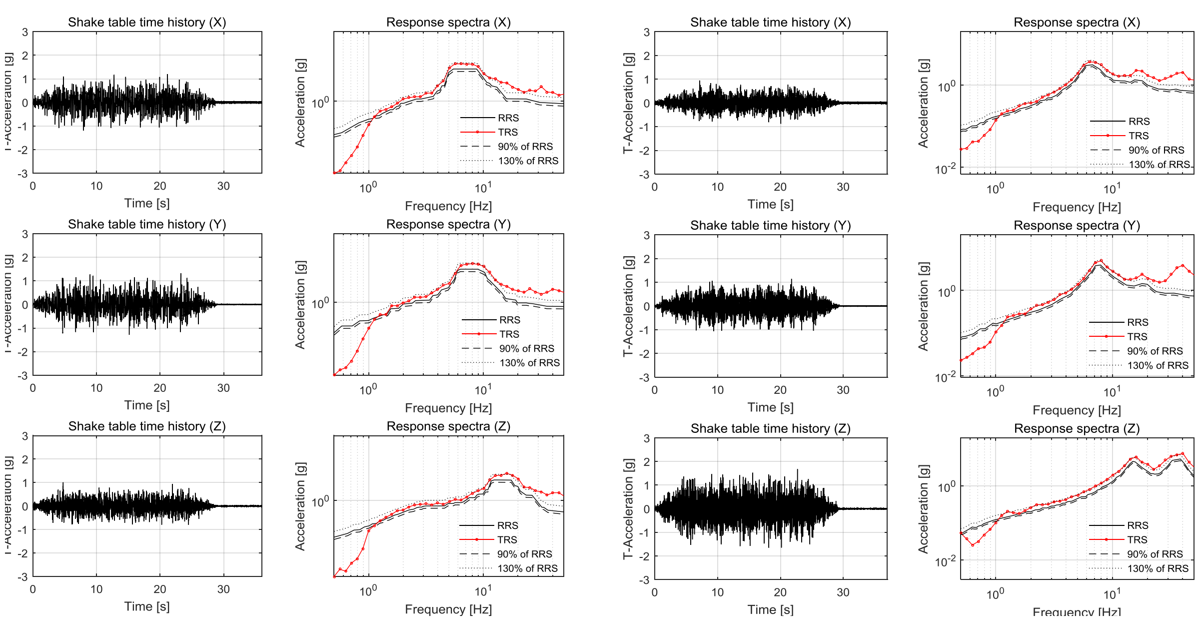
Response Spectrum	Description
Reg_G	Reg. 1.60 spectrum (PGA 0.2g)
Reg_A	165ft response spectrum of auxiliary building under Reg_A ground motion
UHS_G	Uniform Hazard Spectrum of Uljin NPP site
UHS_A	165ft response spectrum of auxiliary building under UHS_G ground motion

TEST RESULTS

Input Motion Check and Resonance Search Results

The test response spectrum (TRS) was generated using the responses of the three-axis accelerometer installed at the bottom of the shaking table to examine the envelopment of the required response spectrum (RRS) [IEEE (2013)]. Figure 5 shows the acceleration time histories and TRS/RRS plots of the Reg_A and UHS_A cases. In accordance with the requirements of the IEEE std 344 standards, the appropriateness of excitation was confirmed. As shown in equation (1), the transfer function *Hxy(f)* was determined using *Pxx(f)*, which was the acceleration signal measured at the bottom of the shaking table, and *Pyx(f)*, which was the transfer function of the response acceleration signal. Table 5 shows the results of the resonance search test. The change in the resonance point was less than 5%, except for the y direction of A3 before and after the time history test, confirming that the test specimen was structurally sound.

$$H_{xy}(f) = P_{xy}(f) / P_{xx}(f) \quad (1)$$



(a) Reg_A case (b) UHS_A case

Figure 5 Acceleration time histories and TRS/RRS plot

Table 5. Resonance search test results

Location	Resonant frequency (Hz)					
	Pre			Post		
	X	Y	Z	X	Y	Z
Bottom jig (A2)	N/A	N/A	16.3	N/A	N/A	16.0
Inside 1st story (A3)	16.0	21.8	22.3	16.3	21.8	22.3
Inside 2nd story panel center (A4)	26.3	16.0	22.3	26.3	22.0	22.3
Inside 3rd story panel center (A5)	30.3	16.8	17.0	30.3	17.0	17.0
Door center (A6)	16.0	16.3	16.0	16.00	16.5	16.0
Top (A7)	22.3	N/A	N/A	21.8	N/A	N/A
Side panel center (A8)	22.5	16.0	16.0	21.5	16.0	16.0

Anchorage Load Response

Figure 6 shows the time history of the maximum anchor load of the test specimen for each input motion. In the LC1 and LC5 graphs in Figure 7, at five seconds of the anchor load response of blue Reg_A, the signals estimated to be the impacts of rocking were measured. LC1 and LC5 were load cells located outside the test specimen. For LC1, a load 9 times higher than the responses of the load cells of the other test cases and 1.5 times higher than the UHS_A case was measured during the excitation of the Reg_A case.

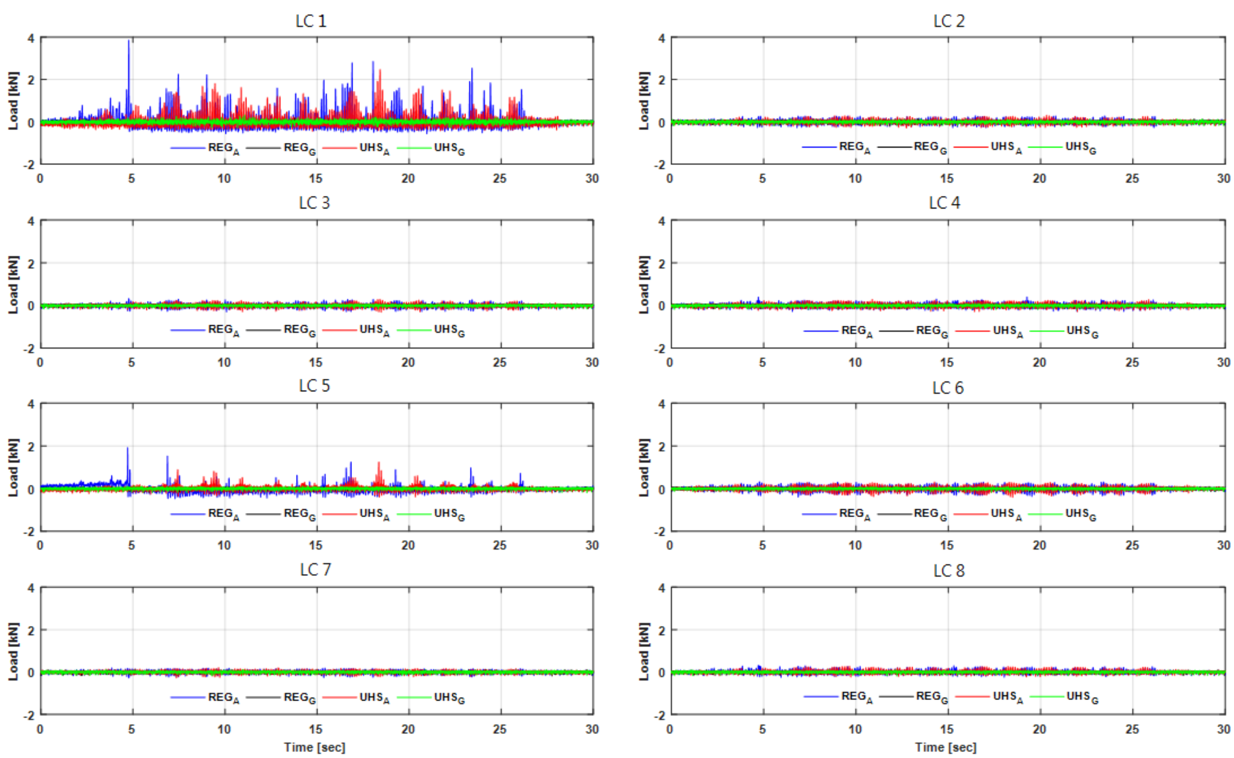


Figure 6 Anchorage load response

Relative Displacement

The relative displacement was calculated using the difference in displacement response between the top and bottom of the cabinet. Table 6 shows the maximum relative displacement between the top and bottom of the cabinet. The maximum relative displacement was the largest for the Reg_A case and the smallest for the Reg_G case. The Reg_A case with more low frequency components exhibited a larger maximum relative displacement than the UHS_A case, which had fewer low frequency components despite its high ZPA(Zero Period Acceleration). Therefore, it is estimated that large relative displacement occurred in the Reg_A case due to the bending deformation or rocking of the cabinet. It is difficult, however, to determine the rocking of the cabinet using only the relative displacement between the top and bottom of the cabinet. Therefore, in this study, the relative displacement between the test fixture and the cabinet bottom was calculated using digital image processing for the reliable analysis of the behavior of the cabinet bottom. Figure 3(b) shows the image processing target used for examining the rocking motion. Table 7 shows the maximum relative displacement between the text fixture and the cabinet bottom. The Reg_A case exhibited the largest relative displacements in the horizontal and vertical directions. The maximum relative displacement was 2.55 mm for the horizontal direction and 1.74 mm for the vertical direction. This indicates the occurrence of rocking in the Reg_A case.

Table 6. Relative displacement of cabinet bottom with top

Abs. maximum relative displacement, D1-D2 (mm)			
Reg_A	Reg_G	UHS_A	UHS_G
3.59	0.99	2.97	1.01

Table 7. Relative displacement at the cabinet bottom with the test fixture measured via digital image processing

	Abs. maximum relative displacement (mm)					
	Horizontal			Vertical		
Calculated Target	T1 - T2	T1 - T3	T1 - T4	T1 - T2	T1 - T3	T1 - T4
Reg_G	0.73	0.49	1.46	0.99	0.99	1.26
Reg_A	0.90	1.03	2.55	1.40	1.35	1.74
UHS_G	0.41	0.59	1.01	0.59	0.58	0.67
UHS_A	0.54	0.73	1.19	1.00	0.89	1.37

Acceleration Responses in the Time History Tests

To analyze the acceleration amplification phenomenon caused by the input earthquake, transfer functions were used. Figure 7 shows the transfer functions obtained from the acceleration responses in the time history tests. In the figure, the black and blue lines represent the Reg_G and Reg_A cases, respectively, and the red and green lines represent the results of the UHS_G and UHS_A cases. Among these cases, Reg_A was the case in which the occurrence of rocking was estimated. The frequency of the dominant mode on the floor inside the cabinet, which was the test specimen, was similar to the resonance search results shown in Table 5. In the case of the 1st and 2nd floors shown in Figure 7, it was found that the amplification of the response inside the cabinet due to rocking was not significant. In the case of the 3rd floor, however, the horizontal amplitude amplification caused by Reg_A excitation was large compared to the responses in the other tests. In particular, in the case of the Y-axis direction, amplitudes more than twice larger than the results of the other tests were confirmed. The results at the top confirmed comparatively clear dominant modes in the tests except for the Reg_A case. In the case of the Reg_A case, however, where rocking occurred, tendencies like white noise were found at 20 Hz or higher. This appears may be because the impacts caused by the collision between the cabinet bottom and the test fixture due to rocking and uplifting were transferred to the top through the frame of the cabinet.

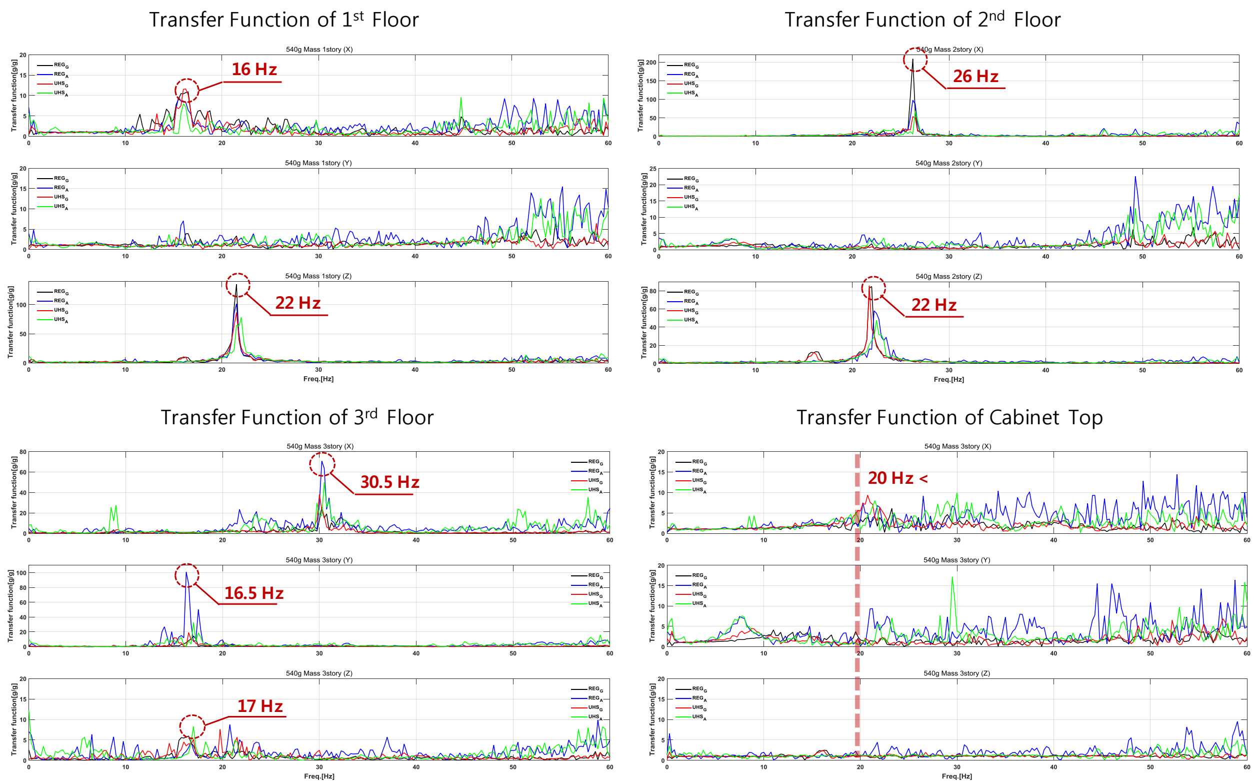


Figure 7. Transfer function of acceleration responses

In this study, to analyze the tendency of the acceleration response due to the rocking and uplifting of the cabinet, the amplitude of the transfer function of each measurement location was summarized as shown in Figure 8. In general, the magnitude of the vibration acceleration signal measured from a structure can be defined as the peak value. When the vibration signal is complex, however, the peak value is inappropriate for representing the vibration signal, and thus can be replaced with the root mean square (RMS) value, which is an average concept. Therefore, in this study, the transfer functions of the acceleration response were summarized as the RMS values at 10Hz intervals using equation (2). In equation (2), H is the value of the transfer function [IEEE (2003)].

$$H_{rms} = \sqrt{\frac{1}{N}\sum_{n=1}^{N}|H_n|^2} \tag{2}$$

Figure 8 shows the RMS values of the transfer functions calculated at 10Hz intervals. For the amplitudes on the 1st and 2nd floors, high values were confirmed in the resonance region of each location in all the tests. In addition, it was estimated that the magnitude of the peak acceleration of the input motion did not significantly affect the amplitudes of the transfer functions. On the 3rd floor, however, the amplitude of the Reg_A case, where rocking occurred, was the largest. At the top, the amplitude of the Reg_A case was the largest at all the frequencies above 20 Hz.

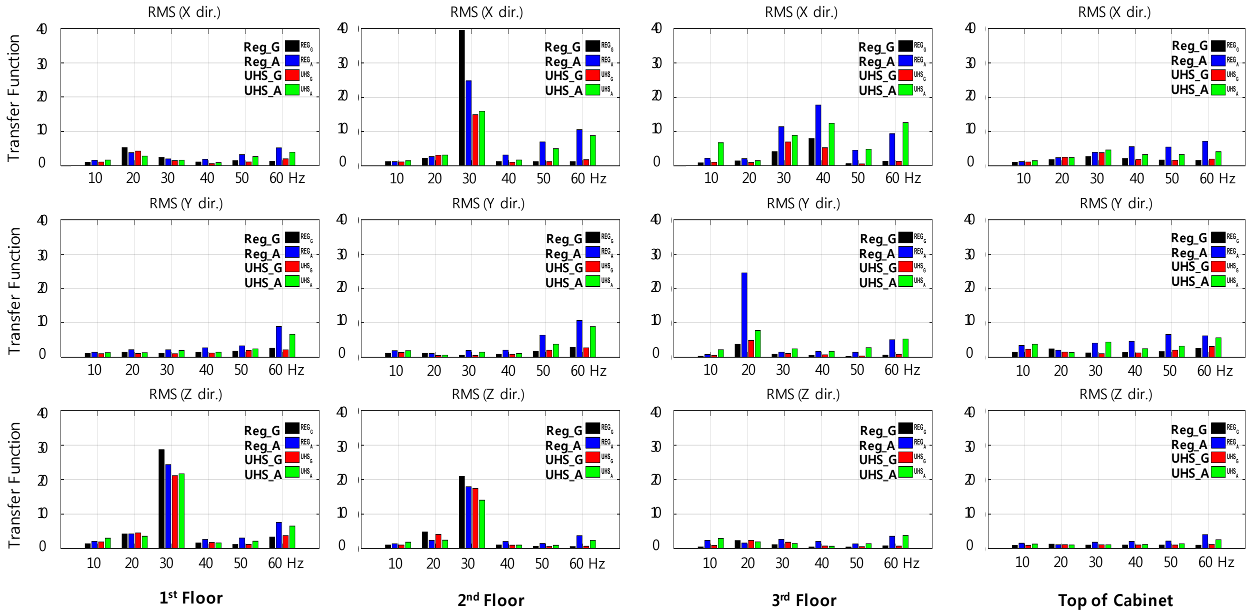


Figure 8. RMS values of the transfer functions in the 10Hz range (0.5-60 Hz)

CONCLUDING REMARKS

In this study, shaking table tests were conducted, fully considering the boundary conditions of the anchor unit applied to actual field situations, to analyze the behavior of an electric cabinet during an earthquake. In addition, the differences depending on the occurrence of rocking were examined. Below are the results.
When the cabinet is fixed with anchor bolts, uplifting and rocking may occur due to the seismic loads. This may cause impacts on the bottom of the cabinet. It was confirmed that rocking of the cabinet may not occur if the intensity of the input signal is low, and that rocking is likely to occur in the case of an input earthquake with a large spectral acceleration value in the low-frequency region.
It is estimated that the impacts caused by rocking and uplifting are transferred to the top through the frame of the cabinet. In the shaking table tests, it was found that the impacts caused by rocking and uplifting significantly affected the frequencies above 20 Hz at the cabinet top. It was confirmed that the transfer functions of the 3rd floor inside the cabinet significantly increased due to the influence of the rocking or uplifting. The responses of the cabinet's 1st and 2nd floors, however, were not significantly affected by the impacts. Therefore, it is estimated that the influence of rocking or uplifting is concentrated on the cabinet top.
The results of this study are expected to be utilized as the basic data required for the analysis of the rocking or uplifting of electric cabinets due to seismic loads.

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