Research Article

Experimental Investigations of the Seismic Performance of a Base-Isolated Uninterruptible Power Supply (UPS) through Shaking Table Tests

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Seismic performance of a UPS through shaking table tests was investigated using the input acceleration time histories with scaling factors of 50%, 100%, and 200%. The first series consists of UPS specimens supported by snip single-corner rectangular pins, and the second series consists of UPS specimens supported by isolator systems. The UPS specimens in the second series significantly reduced the fundamental frequency, peak acceleration, and amplification factors but increased the damping ratio and displacement compared with those of the UPS specimens in the first series. The analytical results obtained from the analytical model agreed well with the experimental results.

1. Introduction

Existing buildings normally consist of primary structural systems, such as reinforced concrete (RC) (or steel) floors, beams, columns, walls, and secondary systems, which are termed nonstructural components. The function of the primary structural components is mainly to withstand a building’s axial and lateral loads, while nonstructural components are attached to or supported by their host structural components and do not contribute to the primary structural systems’ load-carrying capacity. Nonetheless, during an earthquake, the nonstructural components are subjected to the same dynamic environment as the structural components [1]. Miranda and Taghavi [2] reported that nonstructural components account for approximately 82% to 92% of the total economic investment in typical buildings, such as offices, hotels, and hospitals. Moreover, under seismic intensities, nonstructural components are much more sensitive to damage, compared with the requirements for structural components [2]. Therefore, the seismic losses associated with nonstructural damages could lead to huge replacement costs [3, 4]. This fact indicates that the nonstructural components mounted within buildings have to be designed to resist the forces and displacements that are moved upward due to the primary structural components’ seismic response. In addition, since the connection materials and supports play an important role in transmitting seismic forces from the host structural components to the nonstructural components, the latter’s ability to withstand seismic forces should receive due attention. According to the Federal Emergency Management Agency’s (FEMA) FEMA-74 [5], nonstructural components can be classified into three main categories: architectural components, mechanical and electrical components, and building furnishings and contents. Mechanical and electrical components include generators, power supplies, etc. Some of these mechanical and electrical nonstructural components may stand alone and resist seismic effects through seismic force-resisting systems (SFRS), while others may interact with the structural components, significantly affecting a building that is subjected to earthquake load [4]. Consequently, it is necessary to assess the substantial influences of mechanical and electrical nonstructural components on building performance to propose a proper design practice.
Recently, much research on the seismic performance of nonstructural elements attached to structural components has been executed via shaking table tests as well as theoretically analytical models [6–9]. Nevertheless, the number of studies on the electrical and mechanical components used in structural buildings for power systems is still limited. Lin et al. [10] conducted a test series of cyclic loading and shaking table tests to investigate the seismic behavior of a prototype power generator with spring isolator systems. From the test results, it was found that damage to the spring isolators was due to the lost connection between vertical restrained rods and the top plate. In addition, when using a vibration system consisting of only spring isolators, the connection between the generator and the isolators was loosened, causing damage to the restrained rods. In contrast, the use of a vibration system consisting of spring isolators and incorporating snubbers could retain the spring isolators in the elastic stage, and the vertical restrained rods were not damaged. Dinh et al. [11] experimentally investigated the seismic performance of an electrical mold transformer through tri-axial shaking table tests. The input ground motion intensities were applied with different scaling factors ranging from 25% to 300%. Several main objects of dynamic characteristics, such as fundamental frequency, damping ratio, acceleration time history responses, dynamic amplification factors, and relative displacement of the transformers, were analyzed and discussed in detail. During the test, the spacers were found to have slipped, and the connection bolts between the bottom beam and the bed beam were loosened. Pires et al. [12] developed a comprehensive model based on Monte Carlo simulations to evaluate the seismic reliability of electric power transmission systems subjected to actual earthquake data. From the proposed model, the power interruption in a transmission system could be predicted using probabilistic assessments of structural damage and abnormal power flow. Furthermore, fragility analysis of specific substations could provide additional necessary data for the seismic performance evaluation of electrical equipment in terms of probabilistic reliability analysis. A similar framework of seismic fragility analysis of electrical equipment was also introduced by Hwang et al. [13].

In the present study, shaking table tests of UPS were performed with the aim of expanding and improving the knowledge of mechanical and electrical nonstructural components’ seismic response. A 100 kVA UPS was used as the test specimen. Two different test series were performed: the first test series consists of UPS cabinets supported by four snip single-corner rectangular pins, and the second test series consists of UPS cabinets supported by isolator systems with high hysteresis-laminated rubber and stainless steel wire rope isolators, which are newly developed in this study. These supports were connected to a concrete slab via conventional anchoring bolts. The input acceleration time histories were artificially generated in accordance with the International Code Council Evaluation Services Acceptance Criteria 156 [14], with different scaling factors ranging from 50% to 200%. In addition, shaking table tests using random input signals were also carried out to evaluate dynamic system identification based on FEMA-461 [15]. From the test results, the effects of the isolators on the dynamic characteristics of the UPS under a given earthquake load were evaluated and compared with the original supports in terms of the fundamental frequency, damping ratio, acceleration time history responses, maximum displacement response, and dynamic amplification factors.

Moreover, in the present study, an analytical model was developed to investigate the UPS cabinets’ seismic vulnerability. For the purpose, two independent linear Kelvin–Voigt models consisting of a linear spring and a dashpot (viscous dampers) were used. The analytical model’s input dynamic characteristics (stiffness and damping ratio) were obtained from the shaking table tests. The analytical model was verified by comparing the experimental and analytical results.

2. Experimental Program

2.1. Details of the Test Specimen. A prototypal nonstructural electrical component called a UPS was introduced to investigate performance under earthquake loading through a shaking table test. A UPS is an electrical apparatus that provides emergency power to a load when the input power source or main power supply is disrupted. It is typically used to protect hardware, such as computers, data centers, telecommunication equipment, or other electrical equipment, where an unexpected power disruption might cause injuries, fatalities, serious business disruption, or data loss. The UPS used in this study was designed as an electrical cabinet using heat and electrically insulated materials, according to ICE-60950 (International Electrotechnical Commission 2019), with a maximum capacity of 100 kVA [16]. With the current design, the UPS has a height of 1,800 mm, a length of 800 mm, a width of 750 mm, and a total weight of 800 kg, as depicted in Figures 1(a)–1(d). Figures 1(e) and 1(f) briefly describe the major components of the tested UPS in this study. The UPS has two side covering sheets attached using a cabinet frame via bolt connections (Figure 1(c)), front and back doors with vent holes, and various accessories, including a control switch, a cooling system, and a transformer.

In the present study, two different test series were prepared and performed: Series A (first series) and Series B (second series). In Series A, the UPS cabinets are supported by four snip single-corner rectangular pins, which are fixed to the cabinet base via bolt connections, as shown in Figure 2. These pins are made from steel and coated with a special layer of paint for electrical insulation, as indicated by the manufacturer. In Series B (Figure 3), the isolator systems were used instead of snip single-corner rectangular pins and were attached to the UPS cabinet base using bolts. At each corner of the UPS cabinet, one isolator was used, and the isolators were linked together along the Y-direction using C-channel cold-formed steel (100 × 50 × 5 × 7.5 mm, web length × flange length × web thickness × flange thickness) made of SS400 grade steel (yielding strength equal to 400 MPa). An isolator consists of two stories: the first story consists of a high hysteresis-laminated rubber isolator covered by stainless steel plates (SS400) at the top and...
bottom bases, and the second story consists of a wire isolator made from stainless steel wire rope and an aluminum alloy retainer. The wire rope is made of STS 304 and has a yield strength of 205 MPa and an ultimate tensile strength of 520 MPa, as provided by the manufacturer. Table 1 summarizes the detailed characteristics of the rubber and wire isolators used in this study. Figure 4 presents the load-displacement relationship of a single isolator system developed in this study and subjected to predefined cyclic loading. Figure 4 shows that no pinching or stiffness degradation was observed until the end of testing.

2.2. Test Setup. Figure 5 presents the shaking table test setup for the UPS test specimens. The shaking table used for the tri-axial test has the following primary characteristics: 4.0 × 4.0 m plan dimensions; six degrees of freedom (6DOF); a maximum payload of 300 kN; peak accelerations of 1.5, 1.5, and 1.0 × g in the X-, Y-, and Z-directions, respectively, for the maximum payload; and a maximum overturning moment of 1,200 kNm. This shaking table reproduces earthquake input ground motions through a system of eight hydraulic actuators. Table 2 presents the specifications of the shaking table [11]. The UPS test
Figure 2: Details of a snip single-corner rectangular pin. (a) Top view. (b) Side view. (c) Section A-A, unit: mm. (d) 3D view. (e) Photo of snip single rectangular pin.

Figure 3: Continued.
specimen was anchored to an RC slab using pins or through isolator systems with eight M16 anchor bolts with diameters of 15.88 mm, as specified in the manufacturer’s installation manual. The concrete slab was connected to the shaking table using M40 anchor bolts with a diameter of 40 mm [11].
2.3. Measuring Instruments. The measuring instruments used for the tests are six tri-axial accelerometers (T-Ac), seven-wire linear variable displacement transducers (LVDTs), and one static LVDT. The tri-axial accelerometers had a maximum capacity of ±200g and provided simultaneous measurements in three orthogonal directions to record the UPS test specimens’ acceleration response. Wire LVDTs and a static LVDT were employed to measure the displacement of the UPS. Figure 5 describes the locations of the measuring instruments used in this study. Two tri-axial accelerometers were attached to the UPS cabinet at the top and bottom frames. The other three tri-axial accelerometers were installed on three major internal components, namely the cooling system, the control switch, and the transformer. The final tri-axial accelerometer was mounted on top of the RC slab to measure the input earthquake wave. As shown in Figure 5, wire LVDTs were mounted on the UPS cabinet at the top left, top right, and bottom right sides and aimed along the X-, Y-, and Z-directions. A static LVDT was mounted on the UPS cabinet at the bottom left side and only aimed along the Z-direction to monitor the anchored behavior between the UPS and the RC slab.

2.4. Testing Protocol. In the present study, the seismic performance of nonstructural components subjected to acceleration on two principal horizontal axes and the vertical axis simultaneously (or tri-axial accelerations) was evaluated. The input acceleration over time for the shaking table was artificially generated in agreement with the reference protocol the AC156 code [14], of which the required response spectrum (RRS) for nonstructural components is fundamentally defined in the range of 1.3 Hz to 33.3 Hz. For the input protocol in this study, the spectral acceleration at short periods ($S_{D5}$) was used as a parameter characterizing ground motion and was defined in accordance with the

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**Table 2: Detailed specifications of the shaking table test.**

| Properties                          | Values or features | Unit |
|-------------------------------------|--------------------|------|
| Table size                          | 4 × 4              | m    |
| Type                                | Fixed              |      |
| Degrees of freedom                  | 6                  |      |
| Maximum payload                     | 300 kN             |      |
| Overturning moment                  | 1200 kNm           |      |
| Peak acceleration at maximum payload| X-dir: 1.5         | g    |
|                                     | Y-dir: 1.5         |      |
|                                     | Z-dir: 1.0         |      |
|                                     | X-dir: ± 300       |      |
|                                     | Y-dir: ± 200       | mm   |
|                                     | Z-dir: ± 150       |      |
| Operational frequency range         | 0.1–60 Hz          |      |

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**Figure 5: Shaking table test setup and measurement instrumentation. (a) Front view. (b) Plan view. (c) Locations of triaxial accelerometers.**
Korea Building Code [17]. $S_{DS}$ is functionalized by the site soil and geographic location, as described in the following:

$$S_{DS} = \frac{2}{3} F_s S_s,$$

(1)

where $F_s$ is the site soil coefficient and $S_s$ is the mapped risk-targeted maximum considering earthquake spectral acceleration at over a short period. In this study, $S_{DS}$ is set to 0.498 g.

The RRS levels for both the horizontal and vertical directions, according to the AC156 code [14], are presented in Figure 6. The seismic parameters used to develop the RRS levels include $A_{FLX-H}$, $A_{RIG-H}$, $A_{FLX-V}$, and $A_{RIG-V}$, as shown in Figure 6. Regarding horizontal RRS, the horizontal spectral acceleration ($A_{FLX-H}$) for flexible components and that ($A_{RIG-H}$) for rigid components were evaluated as

$$A_{FLX-H} = S_{DS} \left(1 + \frac{2z}{h}\right) \leq 1.6S_{DS},$$

(2)

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

where $z$ and $h$ are the height of the component’s attachment point to the structure and the average height of the building roof with respect to the base, respectively. In the present study, since the UPS was anchored to the RC slab considered to be the base of the structure, the ratio $z/h$ was assumed to be equal to 0.

For vertical RRS, the vertical spectral acceleration ($A_{FLX-V}$) for flexible components and the vertical spectral acceleration ($A_{RIG-V}$) for rigid components were defined as

$$A_{FLX-V} = 0.6A_{FLX-H},$$

$$A_{RIG-V} = 0.27A_{RIG-H}.$$  

(3)

In addition, the AC156 code [14] and the EC8 [18] recommend that the elastic response acceleration spectra obtained from the artificial acceleration time histories developed in this study should not be less than 0.9 times RRS or larger than 1.3 times RRS. In addition, the adjustment of the acceleration spectra shall be validated for a range of frequency from 1.3 Hz to 33.3 Hz. The acceleration spectra were calculated using a damping ratio of 5%.

In the present study, the initial input acceleration time histories in the X-, Y-, and Z-directions, denoted as AC156_100 and artificially generated according to the AC156 code [14], were put up for test specimens no. 5A in Series A and no. 5B in Series B. Figure 7 introduces the typical input acceleration time histories in the X-, Y-, and Z-directions of AC156_100, which were used for test specimen no. 5A in Series A. Meanwhile, Figure 8 compares the results of the input acceleration spectra of AC156_100 in the X- and Y-directions and the AC156 target spectrum. In Figure 8, the lower and upper bounds of spectral acceleration, which were scaled to 90% and 130% RRS, respectively, are also presented. From the figure, it can be seen that the execution range of the AC156_100 input spectra falls into the limited region induced by the lower and upper bounds. Furthermore, the current seismic load was designed to correspond to a 2,400-year recurrence earthquake, as specified in the Korean Design Standard (KDS 41–17) [19]. For the test specimens in Series B, according to the same procedure, the input acceleration time histories were also generated and used in shaking table tests.

The information and the order of the tests in this study are summarized in Table 3. Test nos. 4A, 5A, and 9A in Series A and 4B, 5B, and 9B in Series B are the main loading tests. In test nos. 4A and 4B, the input acceleration time histories were applied with a scaling factor of 50% from AC156_100, corresponding to an $S_{DS}$ of 0.249 g and denoted as AC156_50. Meanwhile, in test nos. 9A and 9B, the input acceleration time histories were applied with a scaling factor of 200% from AC156_100, corresponding to an $S_{DS}$ of 0.996 g and denoted as AC156_200.

In addition to the main loading tests, white noise sweep tests, namely, test nos. 1A–3A, 6A–8A, and 10A–12A in Series A and test nos. 1B–3B, 6B–8B, and 10B–12B in Series B, were also performed for dynamic identification of the test specimen and were used to define the dynamic properties, such as fundamental frequency ($f$) and damping ratio ($\xi$). These tests were performed by applying low-amplitude random input signals in the X-, Y-, and Z-directions, with the frequency domain ranging from 1 Hz to 50 Hz for 30 seconds [15]. In order, test nos. 1A–3A (or 1B–3B) were carried out before test no. 4A (or 4B), with the AC156_50 input signal; test nos. 6A–8A (or 6B–8B) were carried out after test no. 5A (or 5B), with the AC156_100 input signal; and test nos. 10A–12A (or 10B–12B) were carried out after test no. 9A (or 9B), with the AC156_200 input signal. It should be noted that although the input acceleration time history for these dynamic identification tests differed, their peak acceleration amplitude was almost the same, with a magnitude of approximately ±0.2 g.

### 3. Test Results and Discussion

#### 3.1. Dynamic Identification

As previously mentioned, the dynamic properties, including the fundamental frequency ($f$) and damping ratio ($\xi$), were investigated in both the horizontal directions (the X- and Y-directions) by analyzing...
the acceleration responses obtained from the dynamic identification tests. The fundamental frequencies were computed using the transfer function method in the frequency domain. The transfer functions, characterized by magnitude-frequency curves (or transfer curves), were evaluated as the ratio between the Fourier transformations of

FIGURE 7: Initial input acceleration time histories in the X-, Y-, and Z-directions of the AC156_100 used in test specimen no. 5A. (a) X-direction. (b) Y-direction. (c) Z-direction.

FIGURE 8: Input spectral acceleration (AC156_100) used in test specimen no. 5A versus the AC156 target spectrum with its limited boundaries. (a) X-direction. (b) Y-direction.
the input signals and the response output signals acquired from the accelerometers installed on several preassigned locations of the UPS (refer to Figure 4). In the present study, for the resolution of the transfer curves, the size of each data block (window) was set to 5,120, and the sampling frequency of the accelerometer was equal to 512 Hz. According to Dinh et al. [11], the transfer function amplitude reaches its local peak values at the system’s natural frequency (or the fundamental frequency, \( f_0 \)).

Typical dynamic identification results and transfer function curves evaluated from the data recorded at the top of the UPS (T-Ac1) are presented in Figures 9 and 10. From the transfer function curves, the results for the fundamental frequency, which is determined at the point where the transfer function amplitude reaches its first local peak values, are presented in Figure 11 as a function of the scaling factor at different locations of the test specimen, namely, the top of the UPS, the control switch, the cooling system, and the transformer. Figures 9 and 11 show that the initial fundamental frequencies in the X-direction (or Y-direction) at most locations of the UPS specimens using pins (Series A) were not considerably different. In addition, the fundamental frequency in the Y-direction is around two times higher than that in the X-direction, which is attributed to the higher total stiffness of the UPS in the Y-direction. In Table 4, the average initial fundamental frequencies in the X- and Y-directions were 8.45 Hz and 16.14 Hz, respectively. When the scaling factor increases up to 200%, the damping ratios showed a slight increase, with average values of 20.5% in the X-direction and 19.0% in the Y-direction. This could be due to the damage accumulation of the UPS using isolators during the test; however, the inspected damage was not serious. The test specimens in Series B were almost the same as those in Series A. However, at each location, the damping ratios of the test specimens in Series B were higher than those of the test specimens in Series A, approximately 2.0 times in the X-direction and 2.4 times in the Y-direction (Figure 12). This is because the use of the isolator systems might improve the energy dissipation capacity of the UPS; the damping ratio \( \xi = c/2\sqrt{mk} \), where \( c \) is the damping coefficient, \( m \) is the mass, and \( k \) is the stiffness [21] showed an increasing trend and reached higher values than those of the test specimens using pins (Series A).

Moreover, from the transfer function curves in the frequency domain, the damping ratios were also evaluated at the first peak of the frequency response function (or fundamental frequency; see Figures 9 and 10) based on the classical half-power bandwidth method, after Wang et al. [20]

\[
\xi = \frac{f_{02} - f_{01}}{2f_0} \times 100\% ,
\]

where \( f_{01} \) and \( f_{02} \) are the frequencies at the half-power points, which are related to transfer function amplitudes equal to \( f_0/\sqrt{2} \) in the ascending and descending branches, respectively.

Figure 12 presents the damping ratio versus the scaling factor at different locations of the test specimens in this study. The figure shows that the damping ratios in the X- and Y-directions of the test specimens in Series B were almost the same. The average initial damping ratios in the X- and Y-directions were approximately 17.5% and 18.1%, respectively. When the scaling factor increases up to 200%, the damping ratios showed a slight increase, with average values of 20.5% in the X-direction and 19.0% in the Y-direction. This could be due to the damage accumulation of the UPS using isolators during the test; however, the inspected damage was not serious. The test specimens in Series A displayed almost the same damping ratio trend as those in Series B. However, at each location, the damping ratios of the test specimens in Series B were higher than those of the test specimens in Series A, approximately 2.0 times in the X-direction and 2.4 times in the Y-direction (Figure 12). This is because the use of the isolator systems might improve the energy dissipation capacity of the UPS; the damping ratio \( \xi = c/2\sqrt{mk} \), where \( c \) is the damping coefficient, \( m \) is the mass, and \( k \) is the stiffness [21] showed an increasing trend and reached higher values than those of the test specimens using pins (Series A).

### Table 3: Input and test protocol for PGA.

| Test no.  | Input levels                           | Scaling factor (%) | X-dir.   | Y-dir.   | Z-dir.   |
|-----------|---------------------------------------|--------------------|----------|----------|----------|
| Series A  | Series B                               |                    |          |          |          |
| 1A-3A     | 1B-3B                                 | 50                 | 0.12 (0.13)* | 0.15 (0.16) | 0.09 (0.11) |
| 4A        | 4B                                    | 100                | 0.21 (0.24) | 0.32 (0.33) | 0.18 (0.19) |
| 5A        | 5B                                    |                    |          |          |          |
| 6A-8A     | 6B-8B                                 |                    |          |          |          |
| 9A        | 9B                                    | 200                | 0.44 (0.44) | 0.69 (0.69) | 0.36 (0.37) |
| 10A-12A   | 10B-12B                               |                    |          |          |          |

*The values in parentheses belong to the test specimens in Series B.

3.2. Acceleration Response. Previous studies have demonstrated that the technical benefits gained from the isolator supports (or friction sliding bearing systems) were owing to their insensitivity to earthquake ground motions [22]. In order to validate the effectiveness of the isolator systems developed in this study in mitigating the acceleration of a base-isolated UPS, the seismic responses at different locations, namely, the top of the UPS, the control switch, the cooling system, and the transformer of the test specimens in Series A and B, were analyzed in terms of acceleration response time histories based on the experimental data acquired from the corresponding tri-
A low-pass filter was used during output data acquisition, and the Gaussian window was employed in the response-acceleration analysis, to remove noise in the high-frequency region.

Figure 13 compares the acceleration response time histories of the test specimens in Series A and B subjected to 50% tri-axial AC156 input ground motion (AC156_50 test). The amplitudes of peak accelerations of the test specimens in Series A and B in the X- and Y-directions are summarized in Table 5. In Figure 13, it is noteworthy that the acceleration response of the test specimens (Series B) using isolator supports was considerably less than that of the test specimens (Series A) using pins. The peak accelerations of the test specimens in Series B along the X- and Y-directions were reduced by approximately 10.0% to 68.8% compared to the test specimens in Series A. This fact shows that the effectiveness of isolator supports is excellent in mitigating the floor acceleration of a base-isolated UPS. Figure 13 shows that under the AC156_50 test, the acceleration responses in the X-direction at each location of the test specimens in Series A presented peak acceleration with a range of 0.414 g to 0.680 g, which was higher than those with a range of 0.291 g to 0.576 g in the Y-direction. When the input intensity increases up to 200% (AC156_200), a similar trend was observed.
input intensity of 200%, the top and cooling system zones of the test specimens using isolator systems did not show a considerable difference in vibration in the X- and Y-directions. In contrast, in the control switch and transformer zones, the peak accelerations in the Y-direction were higher than those in the X-direction, attaining the values of 0.730g and 0.675g at AC156_200, respectively. Furthermore, due to the high intensity of input ground motion (AC156_200), the test specimens in both Series A and B displayed higher vibrations than those using low intensity of input ground motion (AC156_50 and AC156_100). In Table 5, the largest values of the peak accelerations in the X- and Y-directions of the test specimens in Series A at AC156_200 input ground motion were 2.291g and 1.328g, respectively. For the test specimens in Series B under AC156_200 input ground motion, the largest peak acceleration values in the X- and Y-directions were 0.926g and 0.928g, respectively.

Figure 14 examines the relationship between the peak response acceleration (PRA) and the peak input acceleration (PGA) at different locations of the test specimens in Series A and B. The figure shows that the peak acceleration of all test specimens increased with an increase in the peak input acceleration. In addition, in both the X- and Y-directions, it can be observed that at the same peak input acceleration, the peak response accelerations of the test specimens in Series A exhibited greater values than those of the test specimens in
Series B regardless of location. The most significant difference in PRA was found in the control switch zone (Figure 14(b)). In the X-direction, at a PGA of approximately 0.45 g, PRAs of the test specimens in Series A and B were 1.861 g and 0.668 g at AC156_200, respectively. In the Y-direction, at a PGA of approximately 0.69 g, the PRAs of the test specimens in Series A and B were 1.328 g and 0.730 g at AC156_200, respectively.

3.3. Dynamic Amplification. In this study, the dynamic amplification of the UPS can be estimated by means of the acceleration amplification factor ($a_p$), which is defined as the ratio between the PRA of the test specimen and the PFA [8]:

$$a_p = \frac{\text{PRA}}{\text{PFA}}$$ (5)
Figure 12: Damping ratio versus scaling factor of the test specimens at different locations: (a) at the top of the UPS, (b) at the control switch, (c) at the cooling system, and (d) at the transformer.

Figure 13: Continued.
Figure 13: Acceleration response time histories of the test specimens in Series A and B of the AC156_50 test. (a) At the top of the UPS. (b) At the control switch. (c) At the cooling system. (d) At the transformer.

Table 5: Peak accelerations of the test specimens in Series A and B at different locations.

| Specimens | Scaling factor (%) | UPS top | Control switch | Cooling system | Transformer |
|-----------|--------------------|---------|----------------|----------------|-------------|
|           |                    | X-dir.  | Y-dir.         | X-dir.         | Y-dir.      | X-dir.      | Y-dir.      |
| Series A  |                    |         |                |                |             |             |             |
| 4A        | 50                 | 0.443   | 0.375          | 0.512          | 0.576       | 0.680       | 0.336       | 0.414       | 0.291       |
| 5A        | 100                | 0.694   | 0.599          | 0.960          | 1.088       | 1.038       | 0.511       | 0.618       | 0.548       |
| 9A        | 200                | 1.575   | 0.861          | 1.861          | 1.328       | 2.291       | 1.038       | 0.880       | 1.240       |
| Series B  |                    |         |                |                |             |             |             |
| 4B        | 50                 | 0.210   | 0.209          | 0.196          | 0.214       | 0.253       | 0.216       | 0.181       | 0.262       |
| 5B        | 100                | 0.418   | 0.385          | 0.316          | 0.339       | 0.442       | 0.360       | 0.296       | 0.338       |
| 9B        | 200                | 0.926   | 0.928          | 0.668          | 0.730       | 0.897       | 0.833       | 0.570       | 0.675       |
Note that the PRA values were evaluated based on the experimental data acquired from the accelerometers (T-Ac1 to 4) mounted on the test specimens at different locations, while the PFA values were evaluated based on the experimental data acquired from the accelerometer (T-Ac5) mounted on top of the RC slab (see Figure 4).

Figure 15 presents the relationship between the amplification factor computed at the top of the UPS, the control switch, the cooling system, and the transformer of the test specimens in Series A and B with respect to the X- and Y-directions and the PGA. In the figure, the design component amplification factor recommended by FEMA E-74 [5] and the American Society of Civil Engineers (ASCE) 7–16 [23] standards is also presented for comparison. The design component amplification factor is set as 1.0 for rigid components and 2.5 for flexible components. The figure shows that the amplification factors in the X- and Y-directions of the test specimens in Series B were in the range of those for nonstructural components, as delimitated in FEMA E-74 [5].

A similar observation was made for the test specimens in Series A in the UPS’ top zone (Figure 15(a)) and in the transformer zone (Figure 15(d)). Meanwhile, the acceleration amplification factors in both the X- and Y-directions in the control switch zone (Figure 15(b)) and in the X-direction at the cooling system (Figure 15(c)) of the test specimens in Series A were over 2.5, as specified in FEMA E-74 [5]. Moreover, in Figure 15, it can be observed that the dynamic amplification factors of the test specimens in Series A were higher than those of the test specimens in Series B regardless of location. This means that the effect of the isolator systems used for connecting the nonstructural components to the RC slab was evident. In addition, the dynamic amplification factors in the X- and Y-directions of the nonstructural components in this study were significantly lower than those recommended by FEMA E-74 [5] and ASCE 7–16 [23] standards.

![Figure 14: PRA with respect to PGA at different locations of the test specimens in Series A and B. (a) At the top of the UPS. (b) At the control switch. (c) At the cooling system. (d) At the transformer.](image-url)
This is attributed to the difference in the response accelerations of the test specimens in the X- and Y-directions, which might be caused by the difference in the details of pin supports versus isolator systems in the X- and Y-directions.

3.4. The Test Specimens’ Displacement Response. As previously mentioned, wire and static LVDTs were utilized to measure the displacement of the UPS. The UPS specimens’ relative displacement response was evaluated based on the test data acquired from the wire and static LVDTs. The relative displacement response in the X- and Y-directions at different locations of the UPS specimens could be computed from a system of quadratic equations, as follows:

\[
\begin{align*}
(x - x_0)^2 + y^2 + z^2 &= d_x^2, \\
x^2 + (y - y_0)^2 + z^2 &= d_y^2, \\
x^2 + y^2 + (z - z_0)^2 &= d_z^2,
\end{align*}
\]

where \(x, y,\) and \(z\) are the calculated relative displacements in the X-, Y-, and Z-directions at an assigned location of the UPS specimen, respectively; \(x_0, y_0,\) and \(z_0\) are the distances between the locations of the wire LVDTs and the measured locations of the UPS specimen in the X-, Y-, and Z-directions, respectively; and \(d_x, d_y,\) and \(d_z\) are the absolute displacement values acquired from the wire LVDTs in the X-, Y-, and Z-directions, respectively.

Figure 16 compares the relative displacement response time histories at the top and bottom of the test specimens in Series A and B subjected to a 100% tri-axial AC156 input ground motion (AC156_100 test). The figure shows that the relative displacement response of the test specimens using isolator systems (Series B) in both the X- and Y-directions was considerably higher than that of the test specimens using pins (Series A) regardless of location. When using the other input ground motions, namely, the AC156_50 and the AC156_200 tests, similar observations were also made. For instance, as shown in Table 6, at the top of the UPS, the maximum relative displacements in the X- and Y-directions of test specimen no. 5B in Series B were 20.01 mm and 27.61 mm, respectively, while the maximum relative displacements in the X- and Y-directions of test specimen no. 5A in Series A were...
2.89 mm and 1.25 mm, respectively. In fact, an increase in the displacement of the test specimens using isolator systems in comparison with the test specimens without isolators is inevitable due to its flexibility. Peng et al. [22] also reported similar observations. In addition, in Table 6, the maximum relative displacement of the test specimens is shown to increase with higher input intensities.

Figure 17 presents the maximum relative displacement response of the test specimens evaluated in the X- and Y-directions at the top and bottom of the UPS specimens according to the PGA. The figure shows that the maximum relative displacement of the test specimens in Series B increased significantly as the PGA increased. Regarding the test specimens in Series A, at the bottom of the UPS, the relative displacement also increased along with the increase of PGA, while at the top of the UPS, the relative displacement was almost constant regardless of the increase in PGA.

Furthermore, the relative displacement in the X-direction of test specimens in both Series A and B was not considerably different from that in the Y-direction during the shaking table tests. Figure 17 also confirms that the relative displacement of the test specimens in Series B was higher than that of the test specimens in Series A.

The Korean National Radio Research Agency [25] limited the maximum displacement of the nonstructural components to be equal to 75 mm in order to guarantee their safety and functional operation as well as that of the adjacent components. In Figure 17, the upper boundary condition of 75 mm is also presented for comparison with the test results. From the figure, it can be seen that maximum relative displacements in both the X- and Y-directions at the top of the UPS using isolator systems exceeded the limit of 75 mm at PGAs of approximately 0.39 g and 0.63 g, respectively.

### Table 6: Peak displacement at tops and bottoms of the UPS test specimens.

| Specimens | Scaling factor (%) | X-dir. Top | Y-dir. Top | X-dir. Bottom | Y-dir. Bottom |
|-----------|--------------------|------------|------------|---------------|---------------|
| Series A  |                    |            |            |               |               |
| 4A        | 50                 | 1.05       | 0.75       | 1.04          | 0.67          |
| 5A        | 100                | 2.89       | 1.25       | 1.05          | 1.01          |
| 9A        | 200                | 8.38       | 2.55       | 1.53          | 1.43          |
| Series B  |                    |            |            |               |               |
| 4B        | 50                 | 5.25       | 8.77       | 2.45          | 4.98          |
| 5B        | 100                | 20.01      | 27.61      | 7.55          | 17.73         |
| 9B        | 200                | 97.45      | 84.61      | 29.45         | 47.06         |

Figure 16: Displacement response time histories of the test specimens in Series A and B of the AC156_100 test. (a) At the top of the UPS. (b) At the bottom of the UPS.
Figure 17: Maximum relative displacement response versus PGA for the test specimens in Series A and B. (a) At the top of the UPS. (b) At the bottom of the UPS.

Figure 18: Analytical model used in the analysis program. (a) Configuration of the UPS. (b) Idealization of the model. (c) Schematic diagram of the model by MIDAS GEN.
4. An Analytical Model of the UPS Specimens Subjected to Earthquake Loading

4.1. Model Development. In the present study, an analytical model was settled using the MIDAS GEN commercial structural analysis program [26]. Figure 18(a) presents two independent single degrees of freedom (SDOF) systems of the UPS specimens used in this study. The reason for the independent modeling of the cooling system and the transformer is that the transformer is directly installed on the bottom steel frame and separated from the side steel frames. Considering that the mass \( m_1 \) (460 kg) is contributed by the transformer components and the mass \( m_2 \) (300 kg) is contributed by the cooling system components, two separate SDOF systems are presented in Figure 18(b). In Figure 18(b), the supporting column was assigned using the linear Kelvin–Voigt (K–V) model [27] comprising a linear spring with stiffness \( k_{ij} \) representing the renovating capacity provided by the structure and a dashpot representing the viscous damping with a damping coefficient \( c_{ij} \) (or damping ratio, \( \xi_{ij} \)) in parallel, where \( i \) indicates the SDOF1 and SDOF2, and \( j \) indicates the X-, Y-, and Z-directions. The stiffness \( k_{ij} \) and damping ratio \( \xi_{ij} \) were evaluated based on the effective stiffness and damping parameters presented in Table 7: Dynamic parameters of the UPS.

| Parameters                        | Values                     |
|-----------------------------------|----------------------------|
| Damping ratio (%)                | 9.1 X-dir. 6.3 Y-dir. 1 Z-dir. | 8.7 X-dir. 7.3 Y-dir. 1 Z-dir. |
| Effective stiffness (kN/m)        | 1,494 X-dir. 5,279 Y-dir. 65,376 Z-dir. | 107,174 X-dir. 10,329 Y-dir. 496,004 Z-dir. |
| Transformer mass, \( m_1 \) (kg) | 460                        |
| Cooling system mass, \( m_2 \) (kg) | 300                        |

Figure 19: Peak acceleration versus PGA at the cooling system of the UPS specimens, as obtained from the experimental and analytical results. (a) Series A. (b) Series B.
damping ratio obtained from the shaking table test results, as presented in Table 7. Finally, using the MIDAS GEN program [26], a schematic diagram of the model was constructed, as shown in Figure 18(c).

In addition, in the analytical model, for the test specimens in the first series (Series A), the constraint was defined to be fixed (fully rigid). This is because during the earthquake loading, no damage was observed at the supports made from snap single-corner rectangular pins or at the bolts anchoring the UPS to the RC slab. For the test specimens in the second series (Series B), since the isolator systems were used as supports, the hysteretic behavior of the constraint was considered based on the obtained test results for a single isolator system, as shown in Figure 4.

In this study, Newmark’s generalized acceleration method [21], which has been widely used to directly integrate the dynamic equations of a structural system, was utilized to compute the acceleration response time histories of the nonstructural components, such as the UPS. The dynamic equations of the SDOF1 and SDOF2 systems under a specific earthquake ground motion can be expressed as follows:

\[
\begin{align*}
    m_1 \ddot{u}_1 + c_1 \dot{u}_1 + k_1 u_1 &= -m_1 \ddot{u}_g \text{ for SDOF1,} \\
    m_2 \ddot{u}_2 + c_2 \dot{u}_2 + k_2 u_2 &= -m_2 \ddot{u}_g \text{ for SDOF2,}
\end{align*}
\]  (7)

where \(u_{1j}\) and \(u_{2j}\) are the motion vectors \((j = X-, Y-, Z\)-directions) and \(\ddot{u}_g\) is the ground motion acceleration vector.

4.2. Validation of the Analytical Model. For validating and estimating the reliability of the analytical modeling approach, the results obtained from the analytical model were compared with the experimental results obtained from the shaking table tests. The input acceleration time histories of AC156_50, AC156_100, and AC156_200 were used and applied to the analytical model.

Figures 19 and 20 compare the peak acceleration and displacement obtained from the analytical and experimental results at the cooling system of UPS specimens, as obtained from the experimental and analytical results. (a) Series A. (b) Series B.

Figure 20: Displacement versus PGA at the top (cooling system) of the UPS specimens, as obtained from the experimental and analytical results. (a) Series A. (b) Series B.

\begin{align*}
\text{Displacement (mm)} & \quad \text{PGA (g)} \\
\text{X-dir.} & \quad \text{Y-dir.} \\
\hline
\text{Analytical results} & \quad \text{Experimental results} \\
\text{Analytical results} & \quad \text{Experimental results} \\
\text{Analytical results} & \quad \text{Experimental results} \\
\text{Analytical results} & \quad \text{Experimental results}
\end{align*}
that the peak accelerations in the X- and Y-directions obtained from the analytical results were in agreement with the experimental data. A similar observation was made for the test specimens in Series A and B. The displacement results at the cooling system of the test specimens in Series A and B (Figure 20); similar to the peak acceleration, the displacements in the X- and Y-directions obtained from the analytical results also showed good agreement with the experimental data.

5. Conclusions

The primary goal of this study is to experimentally investigate the seismic performance of the UPS via tri-axial shaking table tests. The input acceleration time histories were artificially generated based on the guidance specified in the ICC-ES AC156 code, with different amplitudes of 50%, 100%, and 200%. Two different test series were prepared and performed: the first test series consists of UPS cabinets using snip single-corner rectangular pins as supports, and the second test series consists of UPS cabinets using isolator systems as supports. In total, 24 shaking table tests were carried out in two test series. Moreover, an analytical model was developed to investigate the seismic vulnerability of the UPS through a comparison of the dynamic analyses and the experimental results. From the obtained test results, primary conclusions can be drawn, as follows:

(1) The dynamic properties of the UPS specimens were assessed via dynamic identification tests using random input signals. In general, the natural frequencies of the UPS showed a slight increase with the increase of the input motion amplitude due to damage to the UPS specimens, which was not serious. For the UPS specimens in the first series, the fundamental frequency in the Y-direction was around two times higher than that in the X-direction, with average values of 8.45 Hz and 16.14 Hz, respectively. For the test specimens in the second series, the fundamental frequency in the X- and Y-directions was almost the same, with average values of 3.89 Hz and 3.30 Hz, respectively. In addition, the fundamental frequencies of the test specimens in the first series were almost two (in the X-direction) and five times (in the Y-direction) higher than those of the test specimens in the first series.
(2) The damping ratios of the UPS specimens were evaluated using the half-power bandwidth method. In general, the damping ratios of the UPS showed a slight increase with an increase in the input intensity, but the difference was not considerable. For the UPS specimens in the first series, the damping ratio in the X-direction was slightly higher than that in the Y-direction, with average values of 9.06% and 7.65%, respectively. For the test specimens in the second series, the damping ratio in the X- and Y-directions was almost the same, with average values of 18.19% and 18.10%, respectively. In addition, the damping ratios of the test specimens in the second series were almost two times higher than those of the test specimens in the first series.

(3) The effectiveness of the isolator systems developed in this study in mitigating the acceleration of a base-isolated UPS was verified. The acceleration response of the test specimens in the second series was considerably less than that of the test specimens in the first series. The peak accelerations of the test specimens in the second series along the X- and Y-directions showed a reduction of approximately 10.0% to 68.8% in comparison with the test specimens in the first series.

(4) The acceleration amplification factor, which represents the dynamic amplification of the UPS specimens, was evaluated. The amplification factors of the test specimens in the second series were in the range of 1.0 to 2.5 at all locations, which conforms to ASCE 7–16 and FEMA E-74. Meanwhile, the acceleration amplification factors in both the X- and Y-directions in the control switch zone and in the X-direction at the cooling system of the test specimens in the first series were over 2.5, as specified in FEMA E-74.

(5) The maximum relative displacement of the test specimens in the first series was much less than the boundary limit of 75 mm, as recommended by the Korean National Radio Research Agency. Meanwhile, the maximum relative displacements in both the X- and Z-directions at the top of the test specimens in Series B exceeded the limit of 75 mm at PGAs of approximately 0.39 g and 0.63 g, respectively. In addition, the relative displacement of the test specimens in Series B was higher than that of the test specimens in Series A. Overall, the maximum relative displacements of the test specimens in the second series were relatively high. Thus, reducing relative displacement at the top of the isolator-based UPS is necessary and deserves further research.

(7) The results obtained from the analytical model were in a good agreement with the data obtained from the shaking table test in terms of peak acceleration and displacement in the X- and Y-directions.

Data Availability
The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest
The authors declare that they have no conflicts of interest.

Authors’ Contributions
Gia Toai Truong and Seung-Jae Lee are contributed equally.

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