Structural and Equipment Performance of Base-isolated Medical Facility subjected to Strong Vertical Ground Motions

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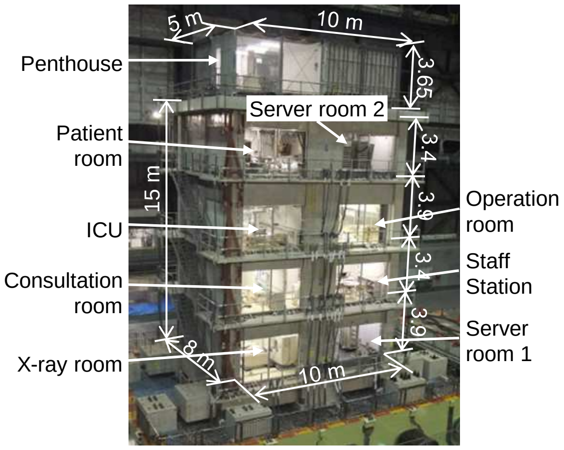
SUMMARY:
A series of full-scale shaking table tests were conducted at the E-Defense shaking table facility on a base-isolated four-story reinforced concrete hospital structure to examine the structural performance and equipment behavior under the vertical motions. The results showed that the vertical floor accelerations of the base-isolated system were dominated by a few mode responses, while several modes contribute to those of the fixed-base system. The lowest vertical natural frequency of the base-isolated system was estimated as 10.7 Hz, with the damping ratio recorded to be 3%. Damages to building contents in the base-isolated system under vertical motions may not be so detrimental in medical service. However some concerns were surfaced out, such as the toppling of containers stored in shelves and jumping of patients lying on the beds, when the maximum vertical floor acceleration exceeded 1 g.
Keywords: Full-scale shaking table test, Base-isolated, Vertical ground motions, and Functional continuity

1. INTRODUCTION

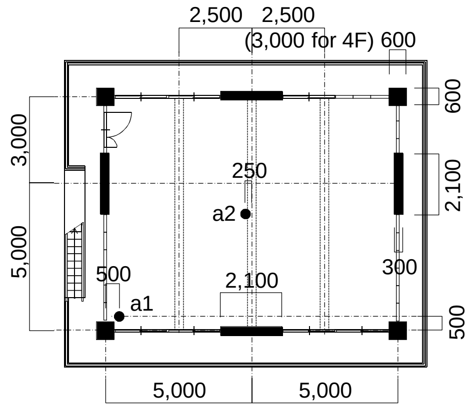
Vertical ground motions have a topic of concern, which may deteriorate performance of seismically isolated buildings. As the goal of seismic isolation is to achieve higher performance, the performance against vertical ground motions is of greater concern than in conventional base-fixed buildings. Until now, there has been no documented report that vertical floor acceleration recorded for isolated buildings exceeds 1 g (indicator that free standing objects start jumping), nor that damage occurs to contents of base-isolated buildings caused or aggravated by vertical motions. Yet, it cannot be concluded that vertical vibration does not reduce the functionality of base-isolated buildings, because (1) Range of the lowest natural frequencies of base-isolated buildings (5 to 16 Hz (e.g. Bozorgria, 1998)) overlaps with that of dominant frequencies of vertical ground motions (7 to 20 Hz (Elnashai, 1997)), and (2) Flexibility of the floor slab and resultant out-of-plane floor vibrations further amplify acceleration responses, whose ratio may exceed two (Higashino, 2006). To investigate the effect of vertical ground motions, a series of shaking table test were performed for a full-scaled four-story RC base-isolated building in 2010. The building was intended for use as a medical facility. Furniture and medical appliances were arranged in the building, and the nonstructural components were installed, all following the current practices adopted for Japanese medical facilities.

2. TEST PROGRAM

Figure 1 shows an overview of the base-isolated specimen tested in this study. The same superstructure was used as that used in the full-scale shaking table test of a base-isolated medical facility in 2008 (Sato, 2011). The superstructure was a four-story RC structure with an 8 m by 10 m floor plan and 15 m in total height, with high-damping rubber bearings at the four corners supporting the superstructure. The floor plan is shown in Figure 1(b). The slabs had the thickness of 150 mm. A penthouse was constructed on the roof to increase spaces to install additional furniture and medical appliances (Figure 1(a)). The total weight of the specimen including all contents and penthouse was 7,470 kN. The estimated natural period in the horizontal direction, found using the secant stiffness (Sato, 2011), was 2.41 s (0.41 Hz) for a bearing displacement of 300 mm. The vertical natural period was estimated as 0.049 s (20.3 Hz) if the superstructure was regarded as a rigid body. For comparison purpose, the shaking table test for a corresponding base-fixed system was also conducted using the same superstructure.



(a) Overview



(b) Location of accelerometers

(c) Operation room

(d) Patient room

(e) Server room

(f) Plumbing

Figure 1 Specimen overview and arranged medical facility

All rooms were furnished and equipped with medical appliances and service equipment (Figure 1 (c)-(f)). As an example, the operating room on the third floor and the patient room on the fourth floor are shown in Figure 1(c) and (d), respectively. Appliances including a high-oxygen pressure unit, dialyzers, and an IT network that connected the server rooms (Figure 1(e)) arranged in different floors, were tested in the operational conditions. Nonstructural components were also installed, including hanging-type sliding doors, antibacterial wall panels of the operating room, a suspending ceiling, lights, sprinklers, and plumbing systems (Figure 1(f)). Also arranged were supplemental items such as mannequins on the operation table (Figure 1(c)), books and containers stored in the shelves, monitors on a ceiling pendant, and other miscellaneous objects placed on furniture.

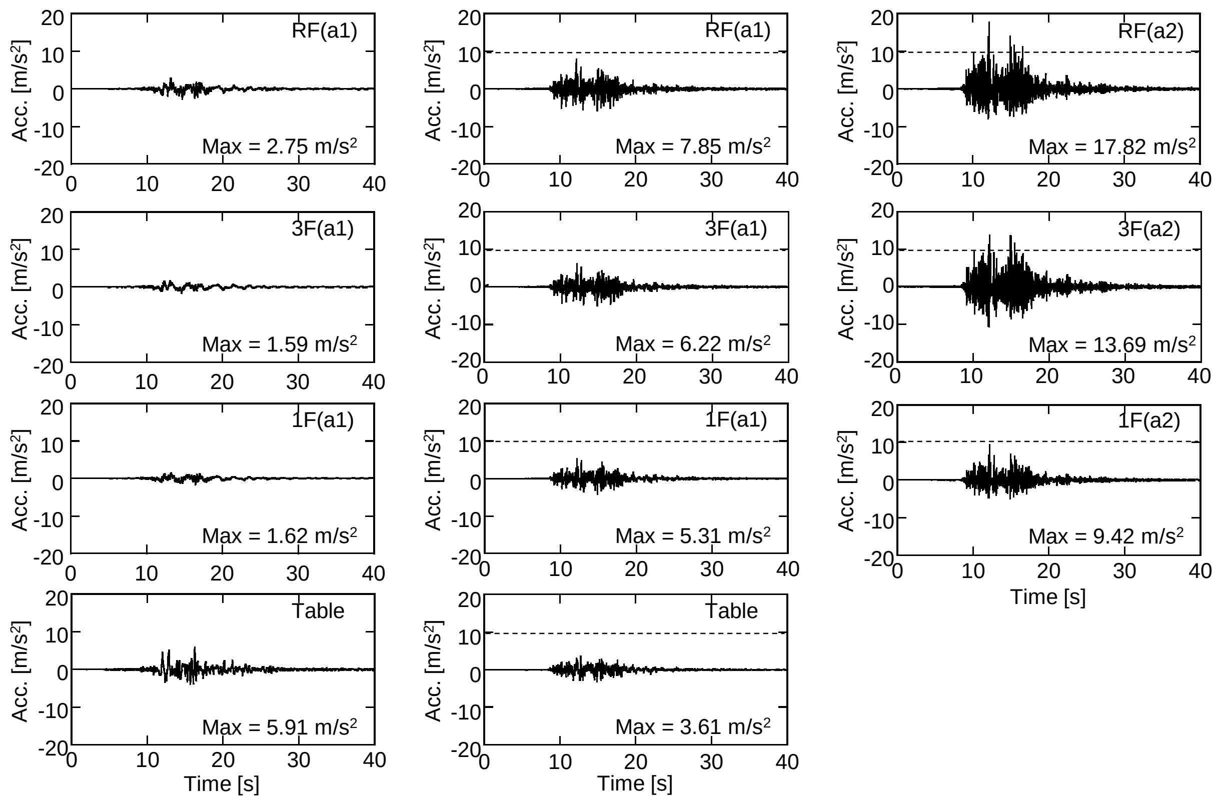
Two recorded ground motions were adopted to study the effects of three dimensional motions on the performance of the base-isolated facility. One was the JMA Kobe ground motion (designated as JMA Kobe XYZ), one of the strongest records obtained from the 1995 Kobe earthquake. The amplitude of the original record was scaled down to 80% to avoid excessive damage to the superstructure. The scaled PGA of JMA Kobe was 4.94 m/s^2, 6.54 m/s^2 and 2.66 m/s^2 in the NS, EW and UD directions, respectively. The other was the 1940 El Centro ground motion (designated as El Centro XYZ), with the motion scaled such that its horizontal PGV would be 0.5 m/s. With this scaling, PGA of El Centro was 3.14 m/s^2, 5.10 m/s^2 and 3.08 m/s^2 in the NS, EW and UD directions, respectively. For JMA Kobe, another case was implemented only with the vertical component (designated JMA Kobe Z).

To examine the vertical acceleration amplification induced in the floor slab, accelerometers were located at two locations on each floor. One was attached to the corner (a1 in Figure 1(b)), and the other to the center (a2 in Figure 1(b)). The adopted sampling time interval was 1,000 Hz.

3. STRUCTURAL RESPONSE UNDER VERTICAL MOTION

The vertical floor acceleration is a best indicator to estimate the furniture behavior under vertical floor vibrations. Figure 2 shows horizontal (longitudinal) and vertical floor acceleration time histories recorded on the shaking table and at the center of the first, third and roof floors when JMA Kobe XYZ was input. Upward acceleration, which may cause items to lift from the floor, is represented in the positive domain.

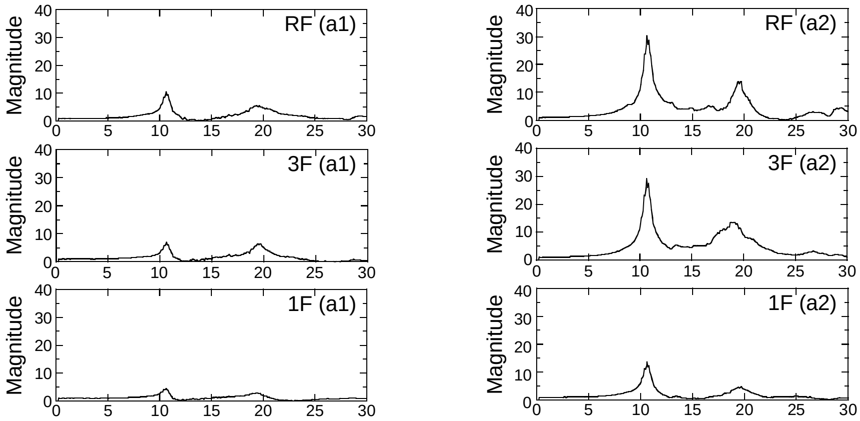
It is notable that the dominant period of the horizontal acceleration was significantly elongated by the base isolation layer to 2 to 3 s, and the input acceleration was successfully reduced from 5.91 m/s^2 by 0.47 times to 2.75 m/s^2 at the roof (Figure 2(a)). The difference in acceleration recorded at the corner and the center of the X axis remained less than 5 %, which shows the assumption of rigid diaphragm for in-plane deformation to be reasonable. On the other hand, high frequencies in the input wave remained unchanged or were amplified through the specimen in the vertical direction (Figure 2(b)). The vertical input acceleration for JMA Kobe XYZ with the maximum of 3.62 m/s^2 (Table, Figure 2(b)) was amplified by 5 to 17.82 m/s^2 at the roof center (a2, Figure 2(b)). This large vertical amplification of acceleration response was mainly contributed to the floor vibration, whose amplification factor from the corners to the centers was about 2. The disparity between horizontal and vertical accelerations at the roof center became 1:6.5. This ratio indicates that the floor accelerations were dominated by the vertical accelerations.



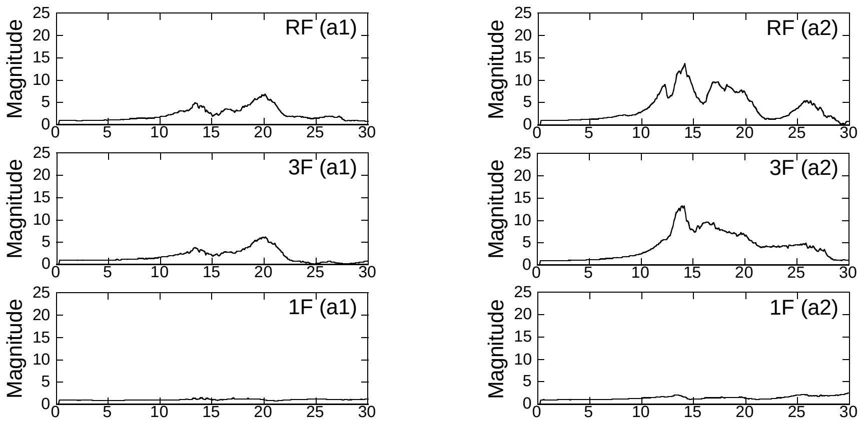
(a) Horizontal acceleration (b) Vertical acceleration

Figure 2 Horizontal (longitudinal) and vertical floor acceleration time histories on the shaking table, and at first, third and roof floor centers for JMA Kobe XYZ

Figures 3 show the acceleration response amplifications obtained from the transfer functions of the vertical accelerations recorded at a1 (corner) and a2 (center) of the second and roof floors with respect to those recorded at the shaking table. The transfer functions were obtained as a quotient of the auto-spectral density of the output signal over the cross-spectral density of the input and output signals, adopting the Welch method (Bendat J. S., and Piersol, A. G.). An averaging technique was also adopted, and a Hanning window was applied to reduce leakage effect. In Figures 3, two distinct peaks are notable for the base-isolated system for the range lower than 20 Hz, while for the base-fixed system a few more peaks are present between 12 and 20 Hz. This suggests that the base isolation layer acted like a filter, which enhanced some selected modes. The largest peak value for the base-isolated system was twice as large as that for the base-fixed system. The lowest natural frequency was estimated as 10.7 Hz and 13.6 Hz for the base-isolated and base-fixed systems. For the base-isolated system, which exhibited a clear peak, the corresponding damping ratio was estimated as 3% by the frequency domain curve-fitting algorithm.



(a) Base-isolated system



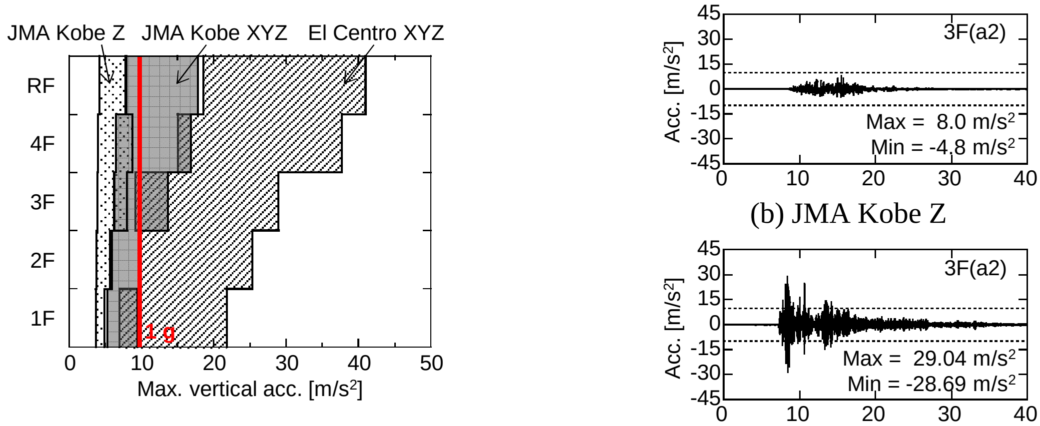
(b) Base-fixed system

Figure 3 Response amplification of vertical floor acceleration obtained by white noise wave

4. EQUIPMENT PERFORMANCE UNDER VERTICAL MOTION

Figure 4(a) summarizes the maximum (upward) vertical floor accelerations recorded in each shaking. Because the vertical floor accelerations were different between a1 (corner) and a2 (center) by the ratio of 1.3 to 3.1, these shown in Figure 4(a) are represented as a band. The vertical floor accelerations recorded when JMA Kobe Z, JMA Kobe XYZ, and El Centro XYZ were input had a ratio of 1:2:4.5. The amplification difference between JMA Kobe Z and JMA Kobe XYZ was primarily due to errors in reproduction waves on the shaking table around the first vertical natural frequency of the base-isolated system (9 to 11 Hz). Further amplification occurred for El Centro XYZ because of resonance. The dominant frequency of the vertical motion of El Centro (about 10 Hz) was close to the vertical first natural frequency of the base-isolated system. Figure 4(b) and (c) show vertical floor accelerations at the third floor center for JMA Kobe Z and El Centro XYZ. The corresponding vertical floor acceleration for JMA Kobe XYZ was presented in Figure 2(b). Figure 5 shows medical appliances and some notable damages.

When JMA Kobe XYZ and El Centro XYZ were input, the maximum horizontal accelerations remained below 3.5 m/s^2, and no movement occurred for most of furniture and medical appliances except those supported by unlocked casters. Therefore, notable behavior of the furniture observed in the tests in which the vertical motion was applied was believed to have occurred because of the vertical floor vibration.



(a) Range of vertical floor accelerations (c) El Centro XYZ

Figure 4 Vertical floor accelerations recorded for JMA Kobe Z, JMA Kobe XYZ and El Centro XYZ

Behavior in JMA Kobe Z (maximum acceleration not greater than 1g)

When the absolute maximum vertical floor accelerations at the floor center was less than 1 g (JMA Kobe Z), no damage was observed in almost all items. One exception was the head portion of the baby mannequin placed in the incubator lifted slightly and hit gently on the thin mattress for several times (Figure 5(a)).

Behavior in JMA Kobe XYZ (maximum acceleration ranging 1 g to 2 g)

When the absolute maximum vertical accelerations at the floor center ranged between 9 to 18 m/s^2 (JMA Kobe XYZ), the following damage was notable: (1) The mannequins on the operating table and the incubator jumped; (2) Monitors on the ceiling pendant (in ICU of the third floor) jumped; (3) Bottles stored by the shelves toppled and fell down (Figure 5(b)); and (4) Furniture with vertical eccentricity showed rocking or jumping. No damage was observed for furniture directly placed on the floor. This is because, although the maximum vertical floor acceleration exceeded 1 g, the duration of such accelerations over 1 g was small (Figure 2(b)). On the other hand, items placed on the furniture were disturbed. This suggests that the vertical floor acceleration was amplified by the flexibility of the furniture itself, resulting in accelerations at the top of the furniture larger enough to cause items to jump. Furniture with vertical eccentricity, including the CT scan gantry (Figure 2(c)), also showed rocking or jumping.

Behavior in El Centro XYZ (maximum acceleration greater than 2 g)

More severe damage was observed when the maximum vertical accelerations at the floor center ranged between 21 to 41 m/s^2 (El Centro XYZ), in which the vertical floor acceleration amplitude exceeded 1 g more often and for a longer time than observed in the JMA Kobe XYZ motion (Figure 4(c) and 2(b)). The vertical floor accelerations were large enough so that even the furniture directly placed on the floor also jumped. Not only did the mannequin placed on the operating table, but the table itself jumped as well (by not greater than 5 mm). The parts of the heart-lung bypass machine were derailed due to jumping (Figure 5(d)). It is also notable that even with this level of vertical accelerations, no functional error occurred in the high-oxygen pressure unit (1F), dialyzers (2F), and an IT network (1 and 4F). Furthermore, the nonstructural components, i.e., the plumbing system, suspended ceiling, sprinklers, walls and doors remained undamaged as well.

In summary, damage to furniture, medical appliances, and associated items caused by the vertical ground motion was not detrimental in the base-isolated system unless the vertical floor acceleration would exceed 2 g, comparing with the very serious damage to such furniture placed in the base-fixed system when subjected to the same horizontal ground motions (JMA Kobe XYZ and El Centro XY) [7]. At the same time, some concerns were revealed, including the vibration induced to the patient lying on the bed, the jumping and dislocations of furniture with large vertical eccentricity, and the scattering and falling down of bottles stored in shelves, which may occur when the vertical floor acceleration would exceed 1 g.

(a) Incubator (b) Containers on shelve (c) CT scan gantry (d) Heart-lung bypass

Figure 5 Medical appliances and notable damages

5. SUMMARY AND CONCLUSION

The effects of the vertical floor acceleration to building contents were examined by a series of shaking table tests. A full-scale base-isolated four-story RC structure was constructed, and the inside was arranged with a variety of medical appliances, furniture, service equipment, and nonstructural components. The results revealed that damages to the building contents in the base-isolated system most unlikely are not so detrimental in medical service. However some concerns are surfaced, such as the toppling of containers stored in shelves and jumping of patients lying on the beds, when the maximum vertical floor acceleration exceeded 1 g.

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