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FULL-SCALED SHAKING TABLE TEST OF A HOSPITAL MADE OF A BASE-ISOLATED FOUR-STORY CONCRETE STRUCTURE

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ABSTRACT

A series of full-scale shaking table tests are conducted using the E-Defense shaking table facility on a base-isolated four-story concrete structure that is intended to serve as a hospital building. Four ground motions are adopted, including synthesized long-period and long-duration ground motions. The results show that the base isolation system performed very effectively against near-fault ground motions. The operability and functionality of hospital service is improved significantly as compared to the corresponding base-fixed system, because the acceleration responses were alleviated greatly. Against long-period ground motion, however, maintaining the hospital service is found not to be easy mainly because of significant motion of furniture and appliances equipped with casters. Resonance accentuated large displacements and velocity in the base isolation floor, which causes large amount of sliding to the furniture with casters, sometimes resulting in collision with other furniture. It is noted that a key to maintain the function of the medical facilities is to lock the casters securely.

Introduction

Background of Research

Earthquake engineering has a long history of “learning from actual earthquakes and earthquake damages.” That is, we first understand problems by actual damage; then develop engineering to patch them. This nature of earthquake engineering, i.e., “learning from actual damage,” seems to make sense, because civil and building engineering traditionally place much emphasis on “experiences” compared to other engineering disciplines. In stable and mature countries like Japan, however, expectation toward insurance for “quality of life” naturally becomes very high. This means our society becomes less tolerable against actual damage, all the while most probably very large ocean-ridge quakes will hit many large cities in Japan within several ten years. Will we be able to maintain the expected quality of life after such large quakes? The answer is most likely NO.

Then, how shall we save our country and what should we do for the welfare of our offspring? One very practical and practicable approach is the change of our attitude from

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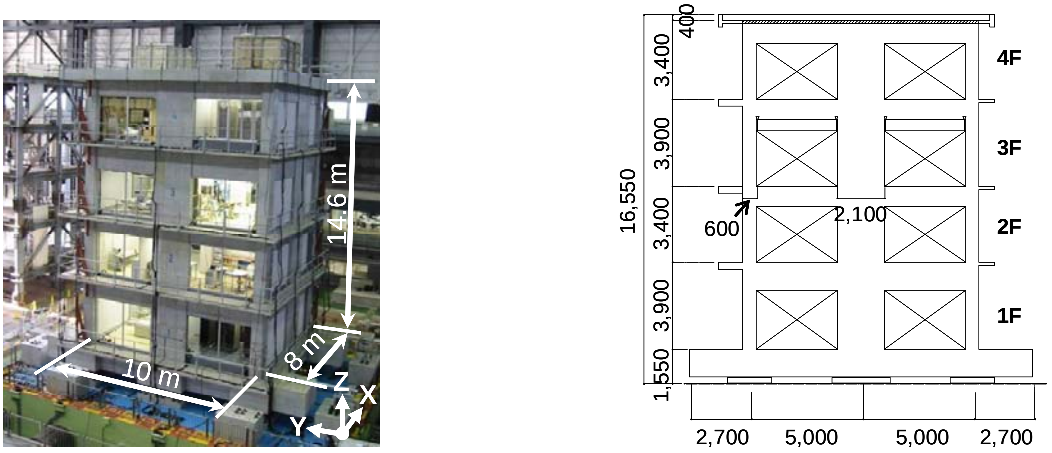
"learning from actual damage" to "learning from quasi-actual damage." "Very large-scale (or realistic-scale) tests," "tests using actual ground motions," and "tests on the entire structure (rather than members and elements)" is a solution.

Objective

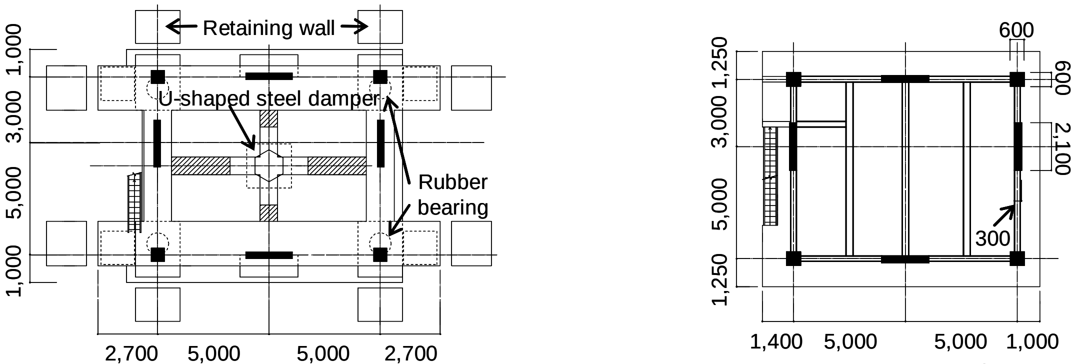
One example in which "learning from quasi-actual earthquake damage" is required is the performance of base-isolation. The application of base-isolation has grown very significantly in Japan after the 1995 Hyogoken-Nanbu (Kobe) earthquake (Pan et al 2001), with the premise that base-isolation is a reliable solution not only to assure the safety but to promote functionality and operability of the base-isolated facilities as well. One most important facility in which functionality and operability shall be preserved during and after a large quake is the hospital, and indeed applications of base-isolation to hospitals and other medical facilities have been extensive in Japan. Here is a naïve question, however. Does base-isolation indeed ensure the expected seismic performance? The structural safety may be ensured, but what about the safety of numerous medical appliances inside? Many numerical simulations have been conducted, base-isolation devices have been checked for their performance, but… no base-isolated structures have ever been encountered a large quake.

To this end, a full-scale four story RC hospital was constructed and dynamically tested in E-Defense in which the world largest shaking table is operated. The paper is a preliminary report of the test, including the design of the hospital and base-isolation system, installation of various medical appliances, input ground motions, structural responses, and performance of and damage to the installed medical appliances. Base-fixed system also was tested to facilitate comparisons.



(a) Overview of specimen

(b-1) Elevation plan



(b-2) First floor plan

(b-3) Second – Fourth floor plan

Figure 1 Overview and structural plans

Test Program

Design of Test Structure

Figure 1 (a) shows the hospital specimen placed on the shaking table. The surrounding concrete blocks represent retaining walls. The specimen is a 4-story RC structure with an 8 m by 10 m in floor plan and 16 m in total height: 3.9 m for the first and third floors, and 3.4 m for second and fourth floors. The total weight was 7,450 kN, 37.8% of which was that of the base beams and the first floor slab. The structure had one shear wall in each bay, which was designed to sustain gravity load. The first natural period of the superstructure was 0.24 s. Figures 1(b-1) to (b-3) show an elevation and floor plans. The design base shear of 0.3 was adopted, which was 1.5 times the code-specified design base shear of 0.2 in Japan. This intentional increase was to avoid excessive damage of this facility even in large earthquakes. This design scheme is similar to the concept of important factor adopted in IBC (ICC 2003): an important factor of 1.5 for hospital buildings in California.

Two commonly used isolation systems were adopted; one was natural rubber bearings (NRB) combined with a parallel U-shaped steel damper (designated as NRB+U hereinafter), and the other was high-damping rubber bearings (designated as HDRB). The layout of the base isolators is also shown in Figure 1 (b-2). If the superstructure was assumed to be rigid, the period of NRB+U corresponding to the 300 mm base-isolator's displacement was 2.56 s and the period of HDRB was 2.41 s. The major properties of the base isolators are shown in Table 1. For HDRB, the clearance between the superstructure and surrounding retaining wall were set at 300 mm, intending slight to medium pounding during the test. Due to space limitation, the responses with pounding will not be presented in this paper.

Table 1 Fundamental mechanical and material properties of base isolation devices

	NRB	HDRB
Diameter [mm]	1,000	750
Thickness of rubber [mm]	285	200
Primary shape factor S_1 (*1)	37.31	36.75
Secondary shape factor S_2 (*2)	3.51	3.75
Shear stiffness [kN/m]	0.81×10^3	1.37×10^3 (*3)
Equevalent damping ratio	---	0.24 (*3)
Vertical modulus [kN/m]	$2{,}200\times10^3$	3090×10^3

	U-shaped steel damper
Number of rods	6
Thickness of rods [mm]	40
Yield strength [kN]	348
Yield displacement [mm]	27.9
Initial stiffness [kN/m]	12500
Second stiffness [kN/m]	216

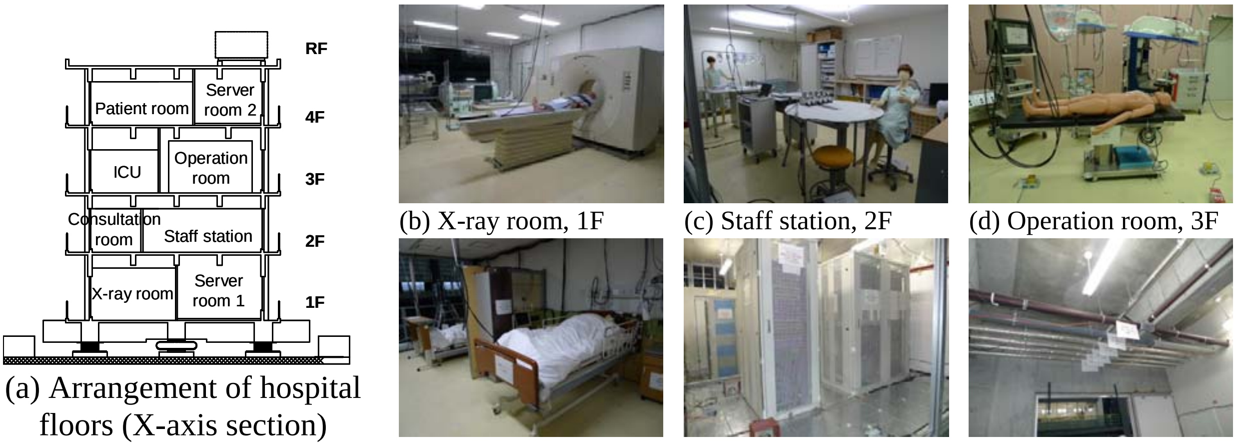
(*1) Primary shape factor defined as sectional area divided by circumferential area of each rubber layer
(*2) Secondary shape factor defined as diameter divided by total height of rubber
(*3) Equeivalent shear stiffness and damping ratio estimated for 200mm displacement

Arrangement of Medical Appliances

Functions of respective floors were arranged following the current design practice; rooms equipped with heavy medical appliances, such as a CT scan, were located in lower floors, while rooms that must be virus-free, such as operation rooms and intensive care unit, or ICU, were arranged in upper floors. The following arrangements were adopted in this test:

First floor:	X-ray room and server room
Second floor:	Consultation room, staff station, and dialysis room
Third floor:	ICU and operation room
Fourth floor:	Patient room and server room

Figure 2 (a) shows the room arrangement adopted in the test.



(a) Arrangement of hospital floors (X-axis section)

(b) X-ray room, 1F

(c) Staff station, 2F

(d) Operation room, 3F

(e) Patient room, 4F

(f) server room, 4F

(g) Plumbing, 1F

Figure 2 Arrangement of hospital floors and various apparatus installed in specimen

All furniture and medical appliances were also arranged following the actual hospital practice, as shown in Figure 2 (b) to (f). Some appliances, like dialyzers and IT network to connect between the first and fourth floor's server rooms, were tested in an operated condition. One characteristic of furniture and appliances used in hospitals is that many of them are supported by casters at the bottom so that they keep mobile. Whether the casters for each appliance were locked or unlocked were also decided based on the current practice. For example, almost all casters in the operation room remained unlocked because of mobility requirement during operation.

Nonstructural components were also installed, as shown in Figure 2 (g): a virus-proof wall of the operation room, plumbing, sprinklers, and hanging-type sliding doors. In addition, two rooftop tanks were installed with water filled with 2/3 of its capacity.

Input Ground Motion

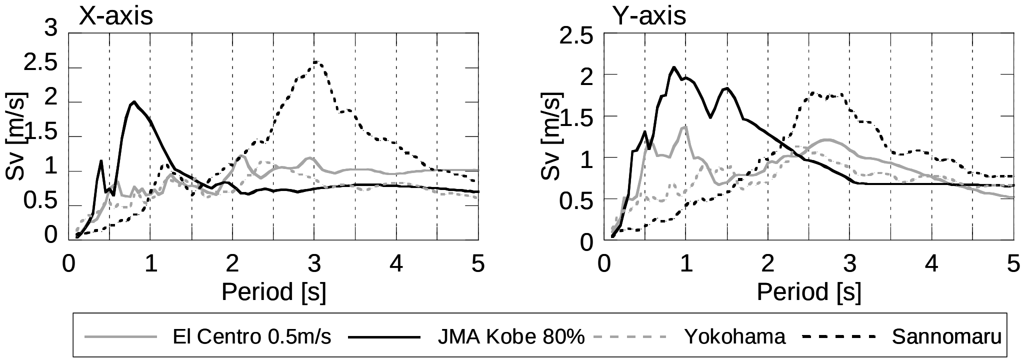


Figure 3 Response spectra of input motions

Four ground motions were used for the test. Three of them were classified as near-fault ground motion, whose dominant frequencies were less than 1.5 second. One was El Centro (Imperial Valley Earthquake, 1940) with PGV=0.5 m/s, which has been extensively used in Japanese design practice. One was JMA Kobe (Hyogoken-Nanbu Earthquake, 1995) with 80% in scaled magnitude, resulting in PGV= 0.60 m/s and 0.64 m/s for NS and EW directions. This scaling was adopted to avoid excessive structural damage so that the test specimen could be used for many times of shaking. Only in JMA Kobe 80% a vertical component was added in the shaking. The other was a synthesized ground motion, Yokohama, yielded by the simulation of a hypothetical Kanto earthquake which was expected to hit our capital, Tokyo. A synthesized long-period and long-duration ground motion named Sannomaru was also adopted, which has a high possibility to resonate with base-isolated system. Figure 3 shows the pseudo velocity spectra of the four input motions. The direction of input ground motions are oriented so that the NS component corresponds to the longitudinal direction Y, and the EW component to the transverse direction X, as shown in Figure 1(a).

Shaking Table Test

All tests were conducted on the E-Defense shaking table, which has a table dimension of 15 m by 20 m and can accommodate a specimen up to 12 MN in weight. The detail of this unique facility is presented elsewhere (N. Ogawa et al 2001; M. Nakashima 2008; M. Nakashima et al 2008). The series of experiments began from the two base-isolated systems, NRB+U and HDRB, then the superstructure was securely anchored to the shaking table, and the base-fixed system was tested. Both the near-fault ground motion and long-period ground motion were input for each system. Table 2 shows the sequence of the shaking.

A total of 700 channels were used for measuring; 170 channels for measuring the structural responses and 530 channels for examining the appliances’ responses. In addition, about 50 CCD cameras were installed inside the rooms to record the furniture behavior in the rooms.

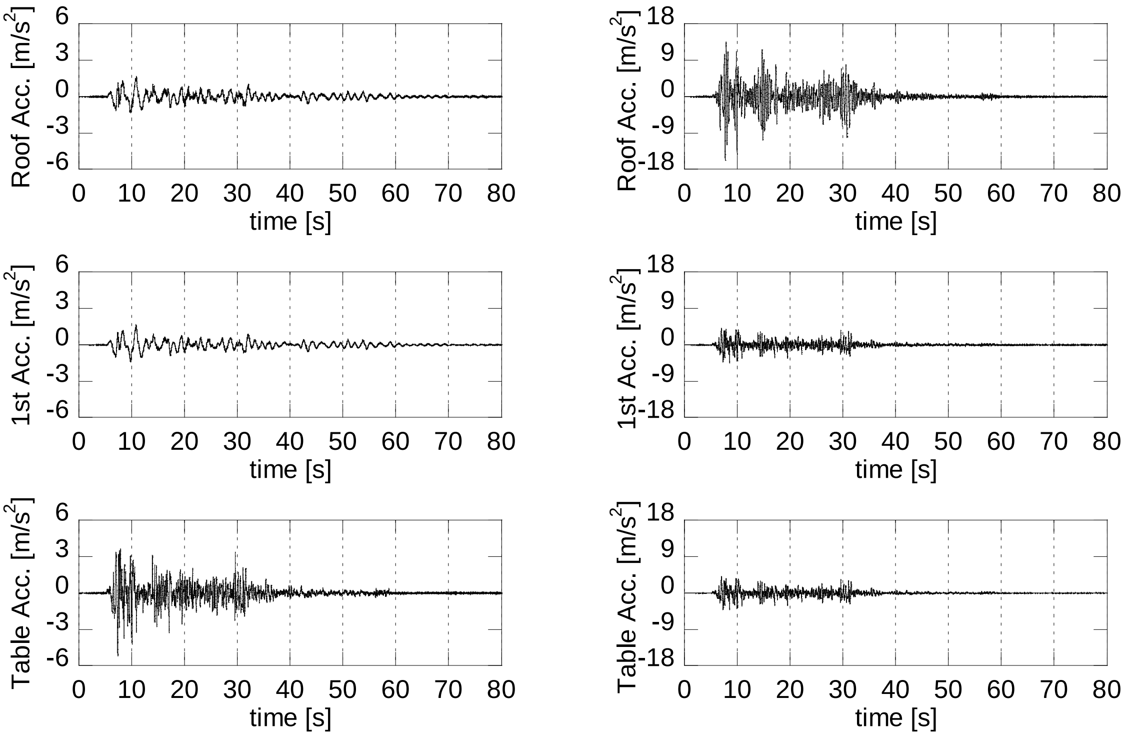
Table 2 Sequence of shaking tests

		Order	Ground Motion	Direction	Max. Acc. [m/s^2]		
					X	Y	Z
Base-isolated system	NRB+U	1	El Centro 0.5 m/s(*1)	X, Y	3.14	5.11	
		2	JMA Kobe 80%(*2)	X, Y, Z	4.93	6.54	2.66
		3	Sannomaru	X, Y	1.86	1.66	
	HDRB	4	El Centro 0.5 m/s	X, Y	3.14	5.11	
		5	JMA Kobe 80%	X, Y	4.93	6.54	
		6	JMA Kobe 80%	X, Y, Z	4.93	6.54	2.66
		7	Sannomaru	X, Y	1.86	1.66	
Base-fixed system		8	Sannomaru	X, Y	1.86	1.66	
		9	Yokohama	X, Y	4.79	4.99	
		10	El Centro 0.5 m/s	X, Y	3.14	5.11	
		11	JMA Kobe 80%	X, Y, Z	4.93	6.54	2.66

(*1) El Centro with PGV=0.5m/s
(*2) JMA Kobe with 80% in scaled magnitude

Structural Response

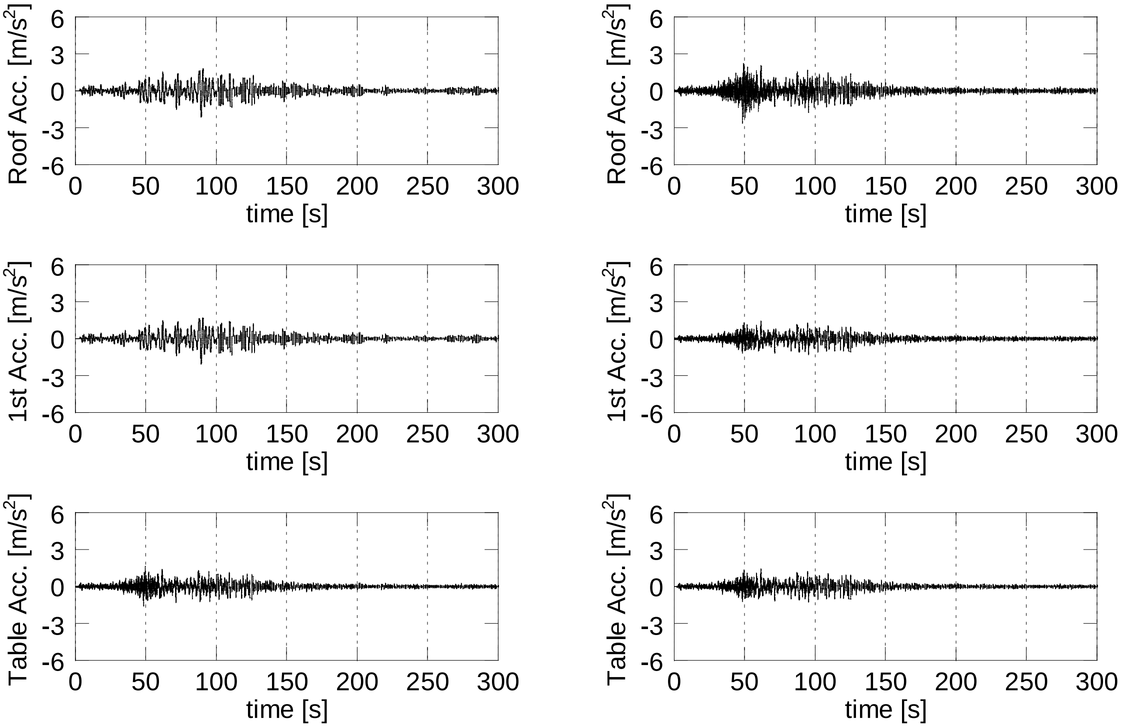
Among all shakings for the three types of structural systems, the base-fixed system with JMA Kobe 80% exhibited the largest maximum story drift of 0.29%. The damage obtained was yet minimal; hence in what follows, the floor acceleration responses are examined carefully as the acceleration responses are believed to be the best indicators to assess the functionality and operability of the structure. Here, NRB+U and the base-fixed system are chosen for detailed investigation, because the responses obtained from HDRB were found to be very similar to those of NRB+U.



(a) NRB+U system

(b) Base-fixed system

Figure 4 Y-axis floor acceleration responses for El Centro 0.5m/s



(a) NRB+U system

(b) Base-fixed system

Figure 5 Y-axis floor acceleration responses for Sannomaru (long-period ground motion)

Near-Fault Ground Motion

Figure 4 shows the floor acceleration responses in the longitudinal direction, Y-axis, for El Centro 0.5 m/s. Note that the vertical full scale of the figures are different for respective structural types; 6 m/s^2 for NRB+U and 18 m/s^2 for the base-fixed system.

In the base-fixed system, the maximum input acceleration of 4.38 m/s^2 was amplified by 3.60 times to the roof maximum acceleration of 15.76 m/s^2. For NRB+U, the maximum input acceleration of 5.18 m/s^2 was reduced by 0.32 times to the roof maximum acceleration of 1.64 m/s^2, which equaled 0.10 times that of the base-fixed system. The first floor's maximum acceleration was 0.31 times smaller than the maximum input acceleration, and the amplification along the superstructure was not greater than 2%. This indicates that the superstructure behaved nearly as a rigid body. The base isolation system performed very effectively against the near-fault ground motions.

Long-Period and Long-Duration Ground Motion

Figure 5 shows the Y-axis floor acceleration responses obtained from Sannomaru.

For the base-fixed system, the maximum input acceleration of 1.43 m/s^2 was amplified to the roof maximum acceleration of 2.66 m/s^2, which was 1.86 times the maximum input. For NRB+U, the maximum acceleration increases by 1.32 times from the input to the roof response. The amplification of acceleration responses was still mitigated by base isolation (from 1.86 down to 1.32), but the effectiveness of base isolation was significantly lowered. This was because resonance was induced by the long-period ground motion, Sannomaru, which has its predominant period of about 2.6 s for the Y axis, close to the natural period of NRB+U at the 300 mm displacement, 2.56 s. The resulting acceleration was relatively small, 2.13 m/s, so that there was nearly no influence on the performance of superstructure. It was also true for the base-fixed system in which the maximum roof acceleration remained 2.66 m/s^2. The maximum displacement in the base-isolation level reached X=409 mm and Y=322 mm; this was twice as large as that recorded under El Centro 0.5m/s for X axis. In terms of the rubber shear strain, these values equaled to X=143% and Y=113%, which were quite acceptable in common base isolation design. No structural damage was observed in this experiment.

Performance of Medical Appliances

The performance of furniture and medical appliances are summarized in Table 3 with respect to the types of ground motion. Those items are divided into five categories: furniture without anchoring, heavy medical facility, appliances with casters, contents on tables and in shelves. For the casters, two sub-categories are added: whether those wheels were locked or unlocked. Table 3 also shows the maximum accelerations to expedite the comparison. Figure 6 shows some damage examples.

Base-fixed System

Near-Fault Ground Motion

Because the acceleration responses became relatively large up to 20.2 m/s^2, almost all free-standing furniture and medical appliances including locked casters slid around 0.2 to 0.7 m on the average. Even heavy medical appliances slid up to about 0.5 m. In addition, contents on tables or inside shelves, for example, a monitor on a suspended rack at ICU, fell down. A mannequin on the operation bed was also slipped off as in Figure 6(a-2). Lock-free casters also moved about 1 m. Hanging-type sliding doors were derailed and fell down, as shown in Figure 6(a-3). The communication speed of the running IT network also dropped temporarily, although the duration was so short that no actual inconvenience had occurred. There were only minor damages on plumbing system.

Long-Period and Long-Duration Ground Motion

The response accelerations were generally small so that no free-standing furniture except for lock-free casters was dislocated.

Table 3 Performance of furniture

	Ground motion	Floor	Max Acc. m/s^2	Furniture & appliances	Heavy medical appliances (*2)	With casters		Contents on tables and in shelves
						Locked	Free	
Base-fixed	near-fault	Roof 1F	22.10 18.00	move -0.5m, toppled	move -0.5m	move -0.5m	move 0.5-1.0m	toppled, fell down
	long-period	Roof 1F	2.73 1.98	no movement	no movement	no movement	move 0.5-1.0m	no movement
Base-isolated	near-fault	Roof 1F	2.81 2.15	no movement	CT scan slid by about 50mm (*1)	no movement	move 0.5-1.0m	no movement
	long-period	Roof 1F	2.56 2.44	no movement	no movement	no movement	move 1.0-3.5m	no movement

(*1) under 3D input of JMA Kobe 80%

(*2) hyperbaric oxygen capsule (7.4 kN) and computerized tomography (16.7 kN), for example

Base-Isolated System

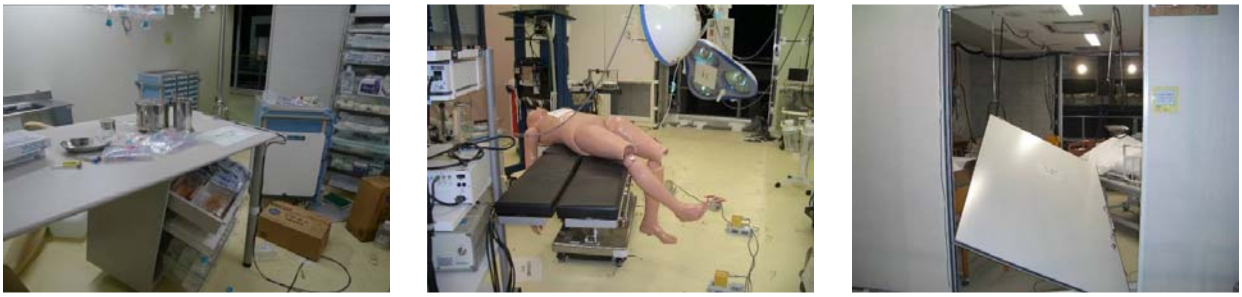
Near-Fault Ground Motion

Because of the reduction of acceleration response by base isolation, all free-standing furniture except for lock-free casters did not slide. Those with casters slid up to about 1 m. The CT scan with a weight of 16.7 kN and located on the first floor moved several ten mm under the 3D input of JMA Kobe 80%. It is notable that the same CT scan did not move for the corresponding 2D input. Comparing with the base-fixed system, the overall performance was improved significantly although lock-free casters tended to keep moving during shakings.

Long-Period and Long-Duration Ground Motion

Acceleration responses were not large, avoiding all free-standing furniture from motion except for lock-free casters. Large amplitudes of floor movement induced by resonance between the base-isolation system and input ground motion caused the large amplitudes of sliding of casters, resulting in the maximum residual displacement of 3.5 m. During the shaking, casters gained high speed so that some hit on and broke the virus-proof wall in the operation room (Figure 6(b-2)), and some others crashed into other appliances, resulting in toppling. The performance of the operation room filled with lock-free casters was exceptionally unacceptable. A hanging-sliding door repeatedly collided with its end stoppers with a speed high enough to break the stoppers. This type of door in hospitals is commonly designed so light that inertia force enables it to open and close very easily. Sloshing water of the rooftop tanks broke the lid and splashed from the roof, as shown Figure 6(b-3). This is because the period of sloshing and base-isolation system was relatively close: 1.67 s to 2.22 s for the sloshing period and 2.41 s and 2.56 s for NRB+U and HDRB.

In summary, the results indicate the difficulties to maintain the performance required for a hospital when it is base-fixed and subjected to large near-fault earthquake due primarily to its large acceleration responses. The same base-fixed system experienced nearly no damage when subjected to long-period ground motion. On the other hand, for the base-isolation system, significant reduction of acceleration responses resulted in superior performance against near-fault ground motions. For long-period ground motions, however, functionality performance was deteriorated mainly because of furniture and contents equipped with casters; large amplitude of movement and collision would occur. A key to maintain the function of the medical facilities is to lock the casters.

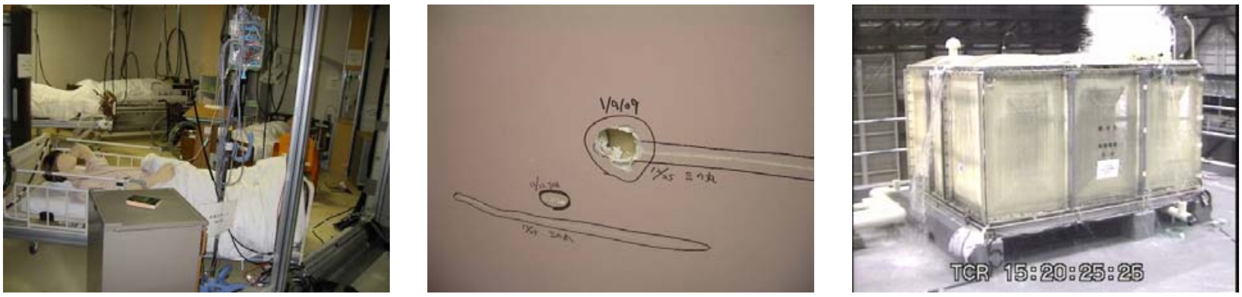


(a-1) Scattered contents (Staff station, 2F)

(a-2) Dislocated patient (Operation room, 3F)

(a-3) Toppled sliding door (Patient room, 4F)

(a) Base-fixed system (near-fault ground motion)



(b-1) Slid beds (Patient room, 4F)

(b-2) Punched hole on the wall (Operation room, 3F)

(b-3) Splashing water (Roof)

(b) Base-isolated system (long-period and long-duration ground motion)

Figure 6 Damage examples

Conclusion

A series of shaking table tests were conducted at E-Defense on a full-scale 4-story RC structure serving as a hospital. Medical appliances, furniture and nonstructural components were also installed following the actual hospital practice. The results obtained from this study are summarized as follow:

Base isolation performance:
(1) Against the near-fault ground motion, base isolation successfully mitigated the input acceleration to the superstructure, which behaved almost as a rigid body.
(2) Against the long-period ground motion, base isolation resonated and failed to reduce the input acceleration, although this resonance did not impair the structure because the maximum acceleration response remained less than 2.5 m/s^2.

Maintenance of hospital functionality:
(3) For the base-fixed system, the results show the difficulties to maintain the performance required for the hospital against the near-fault earthquakes. No damage was observed for the long-period ground motion.
(4) For the base-isolated system, the reduction of acceleration resulted in superior performance for the near-fault ground motion. Against the long-period ground motion, however, functionality performance was deteriorated. This is because of sliding casters on floors with large absolute displacement; large amplitude of movement and collision with other furniture occurred. A key to maintain the function of the medical facilities with casters is to lock the casters.

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