Full-scale Shaking Table Tests for Improvement of Functional Maintenance in Medical Facility against Earthquake

E. SATO, H. SAKAI, T. INOUE
National Research Institute for Earth Science and Disaster Prevention, Japan

A. KAKEHI
Kogakuin University, Japan

K. KOBAYASHI, R. KOSUGE
National Institute of Public Health, Japan

S. FURUKAWA
Tohoku University, Japan

M. NAKASHIMA
Kyoto University, Japan

SUMMARY:
This research focuses on a hospital as one of the most critical facilities. The goal of this research is to improve seismic performance and function maintenance performance of the medical facilities and to ensure that the injured and wounded could be treated promptly after a major earthquake. Therefore shake table tests with the realistic hospital building specimen were conducted for the first time in the world. Some serious damages on the function occurred on the base-fixed structure against the large short-period ground motions and the seismic isolation structure against the long-period and the long-duration ground motions. The shake table tests on the medical facility prepared for the measures to prevent the damages were conducted again, and function maintenance performance of the medical facilities with the measures was verified. It was confirmed that the function of the medical facilities was maintained enough on the seismic isolation structure with the measures.

Keywords: Shake table test, Medical facility, Function maintenance, Seismic isolation structure, Long-period and long-duration earthquake

1. INTORODUCTION

At present, an M7 or greater (M7+) earthquake in the Kanto region has high potential to cause devastating loss of life and property with greater global economic repercussions.

The Central Disaster Management Council of Japan assumes extensive damage including a death toll of approximately 11,000 people, total collapse of 85,000 buildings and a maximum economic loss of 112 trillion yen in the earthquake with an epicentre in the northern part of Tokyo Bay (assumed scale of M7.3). This great earthquake is evaluated to occur with a probability of 70 % in 30 years by the Earthquake Research Committee of Japan. In this background, Special Project for Earthquake Disaster Mitigation in Tokyo Metropolitan Area had been carried out since 2007, which is sponsored by MEXT (Ministry of Education, Culture Sports, Science and Technology).

This project has three topics. The first topic is “Plate structure research and model formulation”, the second is “Evaluation and Assurance of Safety and Functionality of Urban Infrastructure” and the third is “Formulation of a Regional Risk Control/Disaster Mitigation System”. E-Defense works on the second topic.

The second topic aims to mitigate damage to urban facilities and contribute to disaster prevention/mitigation measures for maintaining the comprehensive continuity of buildings against the assumed massive near-field earthquake that can strike the capital. This topic consists of two subjects as following:

(1) Research Project on Assessment of Functionality in Medical and Telecommunication Facilities
(2) Research Project on Damage Reduction Measure for Long-Period Ground Motion

The purposes of the first subject are to protect the functions against earthquake and to enhance the seismic performance of important facilities such as medical facilities. The purposes of the second subject are to assess the seismic performance and to mitigate the damage to high-rise buildings that are vulnerable to long-period and long-duration ground motions. This paper describes about the first subject.

In both urban and rural areas, it is extremely important to prevent building collapse due to a large earthquake hit, and then the improvements of seismic performance of buildings are needed. In metropolitan areas such as Tokyo, it is also necessary to ensure the continuance of societal activities in the areas of government, economics, healthcare and communication of information because the suspension of these activities will cause a major impact on the spread of damage and subsequent reconstruction activities. However, at present, there is lack of knowledge of the seismic performance of equipment and related systems in the facilities that are vital to the municipal services. There is also lack of practical methods for countering the effects of earthquake in these facilities. So research and development regarding advancement of seismic performance was carried out. This research focused on maintaining functions of medical facilities, which become bases of emergency lifesaving during earthquakes and of life-sustaining after earthquakes.

Hence, the authors performed full-scale shake table tests on E-Defense (Three-Dimensional Full-Scale Earthquake Testing Facility) in order to examine seismic performance including function maintenance of medical facilities. A four-story RC building model on real medical facilities was used in the shake table tests and seismic performance against each earthquake ground motion was evaluated. In the shake table tests, this specimen of full-scale hospital was set as seismic resistant structure (base fixed structure) or as seismic isolation structure. Short-period earthquake ground motions and long-period and long-duration earthquake ground motions were input in each structure and seismic performance and function maintenance performance of each structure were verified.

The damages of the seismic isolation structure being hit by the long-period and the long-duration ground motion and the base-fixed structure being hit by the short-period ground motion were clarified. Measures to prevent the variety of earthquake damage which became clear by the tests were examined, and the full-scale shake table tests on the medical facility prepared for the measures were conducted again to verify its function maintenance performance.

In this report, the outline of the full-scale shake table tests with the imitated medical facility is described.

2. SHAKE TABLE TEST ON HOSPITAL BUILDING

2.1. Specimen of Hospital Building

Fig. 1 shows the hospital building prepared for the test and Table 1 shows the specification of the hospital building. The superstructure is a four-story RC structure with an 8 m by 10m floor plan and 16m in total height: 3.9m for the first and third floors, and 3.4 m for second and fourth floors. Two types of building, a seismic isolation structure or a seismic resistant (base fixed) structure, were prepared. The seismic isolation system was composed of rubber bearing and dampers (Fig. 2).

The functions of respective floors were arranged following the current design practice: rooms equipped with heavy medical equipment, such as CT scanners, were located in lower floors, while rooms that must be virus-free, such as an operation room and an intensive care unit (ICU), were arranged in upper floors. After consultation with designers experienced in hospital planning, the following arrangements were adopted in this test: an X-ray room and a server room were arranged in the first floor; a consultation room, a staff station, and a dialysis room were arranged in the second floor; an ICU and an operation room were arranged in the third floor; and a patient room and a server room were arranged in the fourth (top) floor. Fig. 3 shows the room arrangement adopted in the test.

All, medical equipment, furniture and service equipment units were placed also following the actual hospital practice. Fig. 4 shows some examples. Some appliances, i.e., dialyzers, a high-oxygen pressure unit, and an IT network that connected the server rooms arranged in different floors, were tested in the operational conditions.

A characteristic of furniture and medical equipment used in hospitals is that many of them are supported by casters at the bottom so that they are mobile. Whether the casters attached for each

equipment and furniture were locked or unlocked was also determined based on current practice. For example, all casters in the operation room remained unlocked because of mobility requirements during operations. Non-structural components were also installed, including a virus-proof wall of the operation room, plumbing, sprinklers, and hanging-type sliding doors.
Table 2 shows the list of a total of one hundred and ninety one furniture, medical appliances, and service utilities installed in the test specimen. In accordance primarily with the type of supporting system, Table 2 groups them into the following categories: “free-standing”, “with locked casters”, “with unlocked (free) casters”, “anchored”, “wall-mounted”, “doors”, and “service utilities”. Notable in the table is the large proportion (about 30% of the total) of items with casters, which apparently characterizes the medical facilities. Before each shake table test, the items and appliances were placed in their original positions, and after shaking their movement were carefully measured, and they were replaced in the original position before the next shake table test.

Fig. 1 Specimen of hospital building

Table 1 Specifications of hospital building

Item	Specification
Structure	RC
Floor	4
Mass	760t
Height	16.55m（at base fixed）
	17.115m（at isolation）
Floor area	10m×8m(per 1 floor)
Natural period of super structure	2.5s
Natural period of isolation structure	0.24 s

(a) Rubber bearings (b) Dampers

Fig. 2 Seismic isolator system

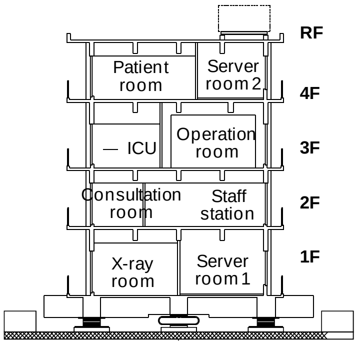
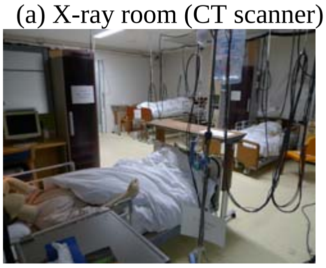


Fig. 3 Room assignment

(a) X-ray room (CT scanner)

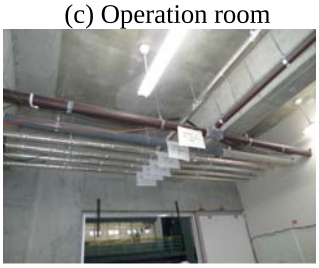
(b) Staff station

(c) Operation room



(d) Patient room

(e) Server room



(f) Plumbing

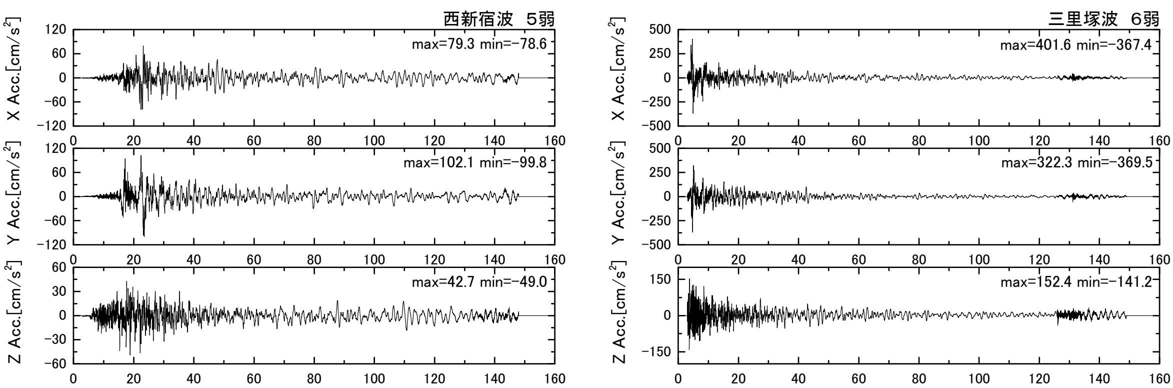
Fig. 4 Equipment arrangement

Table 2 Furniture items, medical appliances, and service equipment installed in test

Type	Classification according to Support Systems	Example Items and Appliances	Number of Items	Percentage of Items (%)
1	Free-standing articles	Medical shelves; Furniture (chairs, desks); Medical appliances (operation table, CT scanner)	31	16.2
2	Items with locked casters	Medical appliances; Precision mechanical devices; Dialysis treatment appliances; tanks; wagons	8	4.2
3	Items with unlocked casters	Medical appliances; Dialysis treatment appliances; tanks; wagons	41	21.5
4	Beds with locked casters	Beds	6	3.1
5	Beds with unlocked casters	Beds	2	1.0
6	Articles clamped with anchors	Medical shelves; Furniture items; Information & communication facilities	26	13.6
7	Articles suspended from ceiling	Ceiling pendants; Surgical lights	6	3.1
8	Articles mounted to walls	Oxygen bins; Suction bins; Lights	13	6.8
9	Doors	Sliding doors; Hinged doors	10	5.2
10	Others	Pipes; Service utilities	48	25.1
	Total		191	100

2.2. Input Earthquake Ground Motion

The shaking table tests were conducted with El Centro wave (50 cm/s) used as standard in earthquake resistant design, JMA Kobe wave observed at the Southern Hyogo prefecture earthquake in 1995, Yokohama wave obtained by the simulation of a hypothetical Kanto earthquake which is expected to hit Tokyo and Sannomaru wave of a Tokai/Tonankai earthquake expected to occur in the future. Moreover, when a M5.0 earthquake occurred in the northern part of Chiba on July 23th, 2010, the earthquake ground motions were observed in Nishi-Shinjuku (Tokyo) and Sanrizuka (Narita) with MeSo-net in other topic of Special Project for Earthquake Disaster Mitigation in Tokyo Metropolitan Area, then these earthquake ground which were amplified to scale of M7.3 analytical were used as PJ1 Nishi-Shinjuku wave and PJ1 Sanrizuka wave. Fig. 5 shows the time histories of PJ1 Nishi-Shinjuku wave and PJ1 Sanrizuka wave and Fig. 6 shows the acceleration response spectrum (h=5%) of each input earthquake ground motion. The direction of the input was two horizontal directions and three directions in El Centro wave and JMA Kobe wave, two horizontal directions in Sannomaru wave and Yokohama wave, three directions in PJ1 Nishi-Shinjuku wave and PJ1 Sanrizuka wave.



PJ1 Nishishinjyuku wave PJ1 Sanritsuka wave

Fig. 5 Time history of input wave ground motions

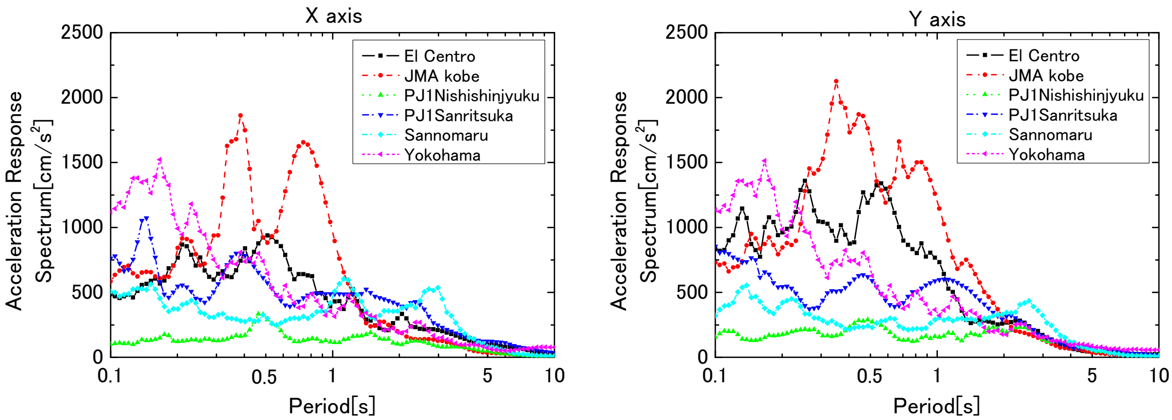


Fig. 6 Acceleration response spectrum (h=5%)

3. MEASURES AGAINST EARTHQUAKE DISASTER

The certain fixation of the equipment and furniture is the most effective method as measures to reduce various damage of the medical facilities during earthquakes. However, the permanent fixation of the equipment and furniture might be not realistic because it corresponds to various situations at the medical care. Therefore, the usage condition of the medical equipment and furniture is considered, the following four measures were proposed and the improvement of the function maintenance performance was verified by the shake table tests. And Fig.7 shows these measures.

3.1. Measures for Caster

A lot of equipment and furniture with the caster for the mobility such as the beds and wagons usually exist in the medical facility. The lock mechanism to fix the item is built into the caster usually, but the lock mechanism isn't built into the caster in some cases. Moreover the situation that the caster isn't locked often exists, as the lock mechanism is installed in the insanitary part. Therefore, the following measures were proposed and executed.

1) Fail-safe system such as that the caster is locked usually, and then the caster is unlocked when the equipment is moved.
2) Self-locking system such that the caster is locked automatically when a signal of an emergency or an outside is received.

3.2. Fixation to Wall and Floor of Equipment

Measures to fix the equipment with the casters simply using the band and buckle to the wall or the floor were executed

3.3. Protection of Wall against Collision

The case where the fixation system isn't built into the equipment or the lock of the caster is not executed is assumed. In this case, measures that protective equipment is set up on the wall to protect against collision of the equipment are executed. This protective equipment is able to be used as a part for the fixation of equipment and a handrail.

3.4. Floor Isolation and Partial Isolation

The inspection analysis room and the server room in where a lot of precision instruments that cause trouble by the vibrations exist are weak against the earthquake. A floor isolation system and partial isolation system were used for these rooms and the precision instruments in these rooms, respectively.

(a) Measures for caster

(b) Fixed to bed

(c) Fixed by band and protection of wall

(d) Partial isolation

Fig. 7 Measure against earthquake

4. TESTS RESULTS

4.1. Response of Specimen

Table 3 shows the maximum floor response acceleration of the base fixed structure and the seismic isolation structure, and the time histories of the main tests are shown in Fig. 8 and Fig. 9.

In the case of the seismic isolation structure, it was confirmed that the horizontal response acceleration of each floor is decreased to about 1/3 of the input acceleration by seismic isolate effect with JMA Kobe wave. The horizontal floor response acceleration is decreased to about 60 % of the input acceleration with PJ1 Sanrizuka wave, however the horizontal floor response acceleration had been amplified with Sannomaru wave. As the isolation structure resonated because element of isolation period proximity had been included in the input earthquake ground motions. It was confirmed that the relative displacement between the super-structure and the shake table is greatly generated because of the long period element on the first stage of PJ1 Sanrizuka wave, and the relative displacement is slowly greatly generated during the whole of the excitation test with Sannomaru wave.

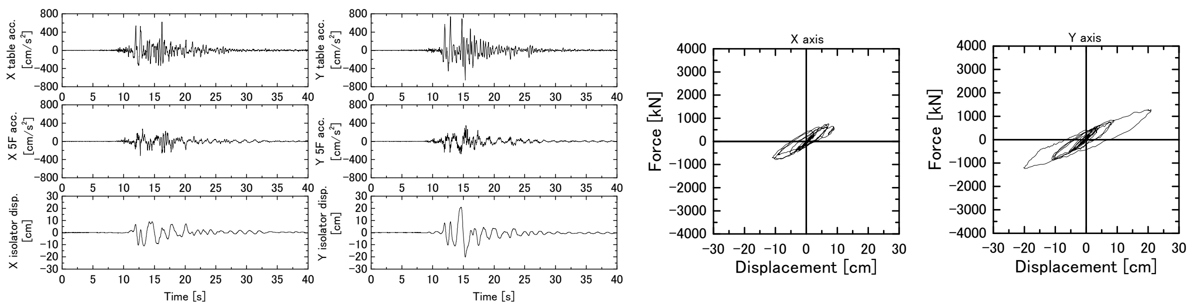
However, the maximum floor response acceleration was about 350 cm/s^2 or less on all excitation tests except the result of X direction on Sannomaru wave. The maximum floor acceleration was greatly generated on the X direction on Sannomaru wave because the super structure collided with retaining walls which were set around isolation structure for safety.

The vertical response of the seismic isolation structure was the same level as the vertical response of the base fixed structure or was larger than those. The super structure of the seismic isolation structure was hardly damaged with each excitation test.

In the case of the base fixed structure, the floor response was amplified on all the excitation tests, and the response acceleration of the roof floor was amplified to twice or more the input ground motions except Sannomaru wave. In the excitation tests of the base fixed structure, an input wave (JMA Lv.1) whose maximum velocity of JMA Kobe wave was adjusted to 25cm/s was used in addition to the input waves which was described above. Some cracks occurred in some columns and beams, huge damages occurred by the base of the wall column on the first floor. A part of width of the crack was about 3mm, but the width of most of cracks except it was 1mm or less. The specimen after the all excitation tests was judged the minor damage (damage level I-II) by the postearthquake quick inspection of damaged buildings and the postearthquake damage evaluation.

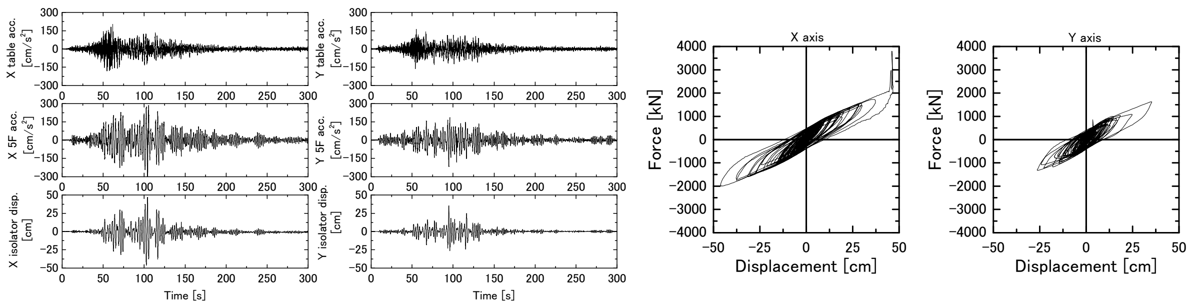
Table 3 Test results（Max. response）

Strcuture		Seismic isolation structure								Seismic-resistant (base fixed) structure										
Input wave		PJ1 Sanrizuka 6 Lower			JMA Kobe 6 Upper			Sannomaru 5 Upper		PJ1 Sanrizuka 6 Lower			JMA Kobe 6 Upper			JMA Kobe Lv1 6 Lower			Sannomaru 5 Upper	
Axis		X	Y	Z	X	Y	Z	X	Y	X	Y	Z	X	Y	Z	X	Y	Z	X	Y
Max. Acc. (cm/s^2)	R	270	241	244	228	348	728	801	217	1007	708	221	1394	1913	686	583	849	183	353	253
	4	251	205	225	189	258	649	513	217	713	586	206	1052	1563	605	510	621	190	243	197
	3	231	192	205	159	267	655	738	218	729	482	189	852	1278	748	398	452	313	252	185
	2	227	179	198	145	245	581	567	215	574	424	177	768	916	711	313	317	191	220	172
	1	230	181	182	164	205	533	716	220	463	315	137	642	677	403	210	275	114	202	166
	T	486	342	165	620	738	369	202	163	434	305	134	605	684	388	206	275	113	203	165
Max. relat. story disp. (mm)	4	1.8	1.9	-	3.1	1.9	-	11.1	3.8	7.0	4.7	-	14.1	18.1	-	6.0	8.3	-	2.7	2.0
	3	3.6	3.6	-	3.8	3.4	-	13.9	4.3	12.0	9.6	-	23.3	32.5	-	11.5	16.3	-	5.0	3.5
	2	3.8	3.3	-	3.4	3.2	-	10.8	3.1	11.4	9.2	-	20.0	31.3	-	11.3	15.0	-	4.9	3.4
	1	3.3	2.8	-	2.5	2.5	-	6.8	2.8	9.6	7.4	-	17.2	25.0	-	8.9	11.5	-	3.6	2.8
	is	344	297	-	114	206	-	470	339											



(a) Time history (b) Hysteresis

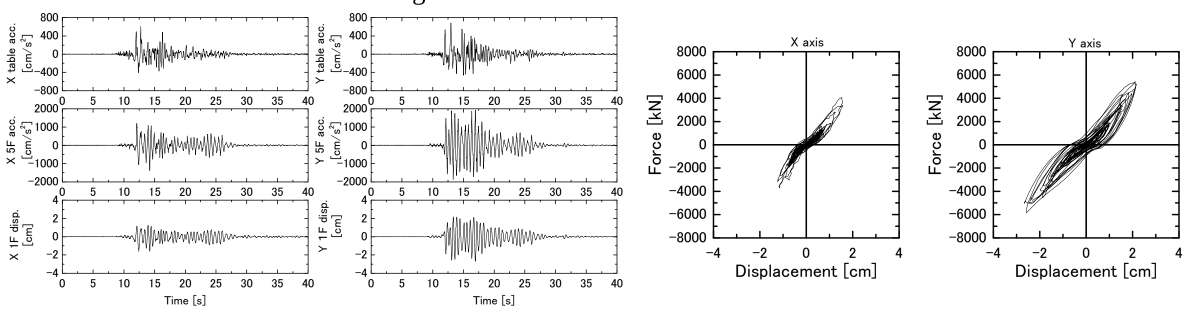
Input JMA Kobe wave



(a) Time history (b) Hysteresis

Input Sannomaru wave

Fig. 8 Results of isolation structure



(a) Time history (b) Hysteresis

Input JMA Kobe wave

Fig. 9 Results of base fixed structure

4.2. Response of equipment and furniture

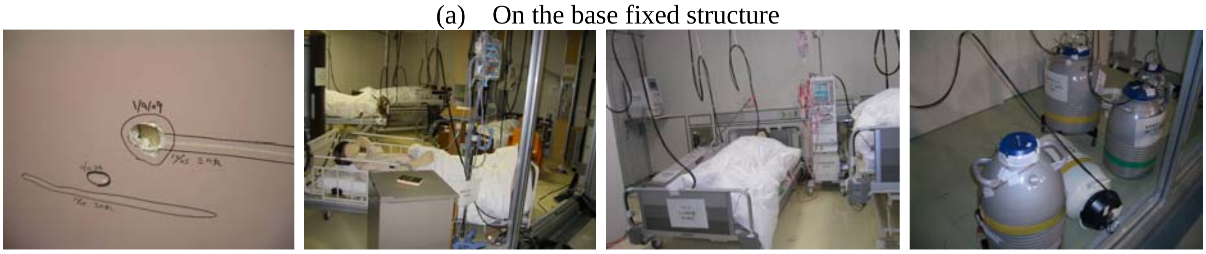
Fig. 10 shows the main situation of the equipment and furniture without the measures against earthquakes after the excitation tests, and Fig. 11 shows the main situation of the equipment and furniture with the measures.

In the base fixed structure and with the short-period earthquake ground motions, the floor acceleration became very large up to 10 m/s^2. In the case without the measures against earthquake, some free-standing furniture moved by about 0.5 m, and the medical equipment and furniture with the casters slid up to about 0.7 m. Even when the casters were locked, they still moved to about 0.5 m, and were toppled in some cases. Patient beds moved to about 1.0 m when the casters were unlocked. Moreover, locked casters of a bed were released by impact of the earthquake; as a result the bed began to move. A mannequin that had been placed on an operation bed slipped off. In addition, contents of tables or inside shelves scattered and fell down, and hanging-type sliding doors were derailed and fell down. In the case with the measures of the equipment and furniture against earthquake, though the functional damage is not evaluated only by the scale of the earthquake ground motions, if the maximum floor response acceleration is smaller than about 500cm/s^2~600cm/s^2, the movement and the fall of the equipment and the scatter of the items are hardly generated. Therefore, in the excitation test with JMA Kobe Lv1 such as the response acceleration of each floor was smaller than about 650cm/s^2, the functional damage was hardly confirmed because the measures against earthquakes were effective. However, when the floor response exceeded 1G, the functional damages were generated though the measures were conducted.

In the seismic isolation structure and with the long-period and the long-duration earthquake ground motions, most notable is the wild movement of the medical equipment and the patient beds with unlocked casters. The equipment and the beds moved back and forth many times, with a maximum displacement of over 3 m, and not a few of them bumped into other appliances and wall panels and boards, which caused damage to the wall panels and boards. Other equipment and furniture that stood directly on the floor showed no movement at all. There was no structural damage because the response acceleration was small. The results obtained from the long-period and the long-duration earthquake ground motion clearly indicate that the seismic isolation structure is not necessarily invincible against this type of earthquake ground motion.

On the other hand, a lot of these functional damages were able to be reduced with the measures of the equipment and furniture against earthquake on the seismic isolation structure. The most of fixed equipment and furniture by the above-mentioned measures were not moved during the excitation tests. The protection of the walls against collisions of equipment was effective on all excitation tests. It was confirmed that the function of the medical facilities was maintained enough on the seismic isolation structure with the measures of the equipment and furniture against the short-period earthquake ground motion generated extremely uncommonly and the long-period and the long-duration earthquake ground motion.

(a) On the base fixed structure



(b) On the seismic isolation structure

Fig. 10 Situation of the equipment and furniture without the measures after the tests

(a) On the base fixed structure

(b) On the seismic isolation structure

Fig. 11 Situation of the equipment and furniture with the measures after the tests

4. CONCULUSIONS

A series of shake table tests with the realistic hospital building specimen were conducted at E-Defense on a full-scale four-story RC structure serving as a hospital for the first time in the world. A variety of medical equipment, furniture, and non-structural components were also installed following the actual hospital practice.

Major findings obtained from the results of the shake table tests without the measures against earthquake are summarized as follows:

(1) Structural performance of the seismic isolation structure was satisfactory for both the short-period ground motions and the long-period and the long-duration ground motions.

(2) The medical equipment and furniture with unlocked casters for both the seismic resistant and seismic isolation structure and for both the short-period ground motions and the long-period and the long-duration ground motions moved largely. Due to such large movement, much equipment and furniture collided each other or against the surrounding walls, causing damage and serious disorder.

(3) In the seismic resistant structure against short-period ground motions, the equipment and furniture with locked casters and some free-standing furniture moved and the contents of tables or inside shelves scattered and fell down, and hanging-type sliding doors were derailed and fell down.

On the other hand, major findings obtained from the results of the shake table tests with the measures against earthquake are summarized as follows:

(4) In the seismic resistant structure against short-period ground motions, the damages of function were able to be decreased. However some damages were generated against the short-period earthquake generated extremely uncommonly because limit performance of the measures was exceeded.

(5) The function of the medical facilities was maintained enough on the seismic isolation structure with the measures of the equipment and furniture against the short-period earthquake ground motion and the long-period and the long-duration earthquake ground motion.

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