DEMONSTRATION OF EFFECTIVENESS OF SEISMIC ISOLATION IN THE HANSHIN-AWAJI EARTHQUAKE AND PROGRESS OF APPLICATIONS OF BASE-ISOLATED BUILDINGS

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ABSTRACT

Since the Hanshin-Awaji earthquake of January 17, 1995 when the effectiveness of seismic isolation was demonstrated, base-isolated buildings have become more popular in Japan. This paper describes behavior of two base-isolated buildings in the earthquake, progress of applications and revised guidelines for safety evaluation of base-isolated buildings.

1. INTRODUCTION

When the Hanshin-Awaji earthquake occurred on January 17, 1995, there were two baseisolated buildings in a northern area of Kobe-city (Figure 1). One of them is the computer center of the Ministry of Posts and Telecommunications, and the other one is a laboratory building of a construction company. In both cases, good isolation performance was demonstrated. This success convinced structural engineers and architects of the very good earthquake resistance of base-isolated buildings. Since the earthquake, construction of base-isolated buildings has increased rapidly. This paper describes behavior of the base-isolated buildings, progress of applications of base-isolated buildings after the earthquake, and guidelines for safety evaluation of base-isolated buildings which were revised after the earthquake (Fujita, 1995; Fujita, 1997).

2. BEHAVIOR OF BASE-ISOLATED COMPUTER CENTER

Figure 2 shows the base-isolated computer center of the Ministry of Posts and Telecommunications, together with a smaller conventional office building. As shown in Figure 3, the superstructure of SRC-structure has 6 stories and a 46,823 m^2 total floor area, and the building is the largest base-isolated building in the world. Figure 4 shows the seismic isolation system comprising 54 lead-rubber bearings of a 1.2 m diameter and a 0.24 m total rubber thickness, 46 low-damping (natural) rubber bearings of a 1.0 m diameter and a 0.2 m total rubber thickness, 20 low-damping bearings of a 0.8 m diameter and a 0.16 m total rubber thickness, and 44 steel dampers.

The natural period of the base-isolated building was designed to be 2.8 sec for the design earthquakes of level-1 having a 0.2 m/sec maximum velocity, and to be 3.3 sec for the design earthquakes of level-2 having a 0.4 m/sec maximum velocity. The yielding coefficient of the lead-rubber bearings was designed to be 0.05, that of the steel dampers 0.03. The maximum displacement of the isolation system calculated for the level-2 earthquakes was 0.176 m. The allowable displacement of the isolation system is 0.4 m, and the width of the seismic gap is 0.6 m.

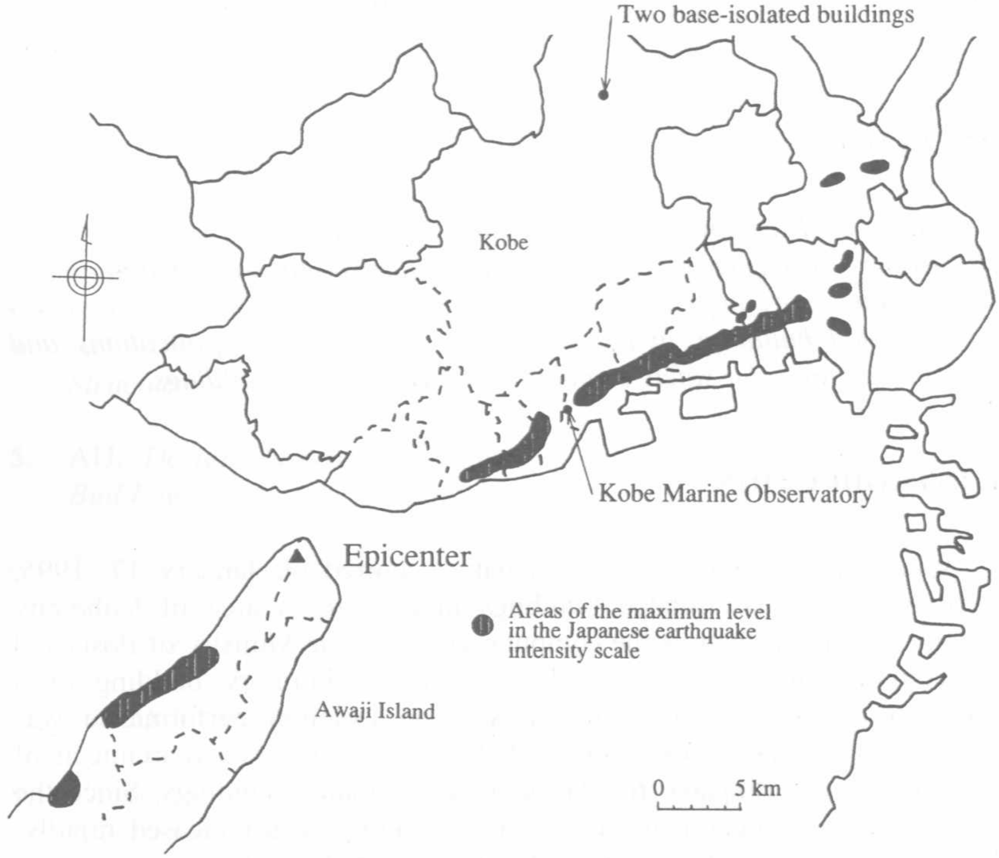

Figure 1. Location of two base-isolated buildings in Kobe-city

Figure 2. Base-isolated computer center of the Ministry of Posts and Telecommunications (the right building in the photo)

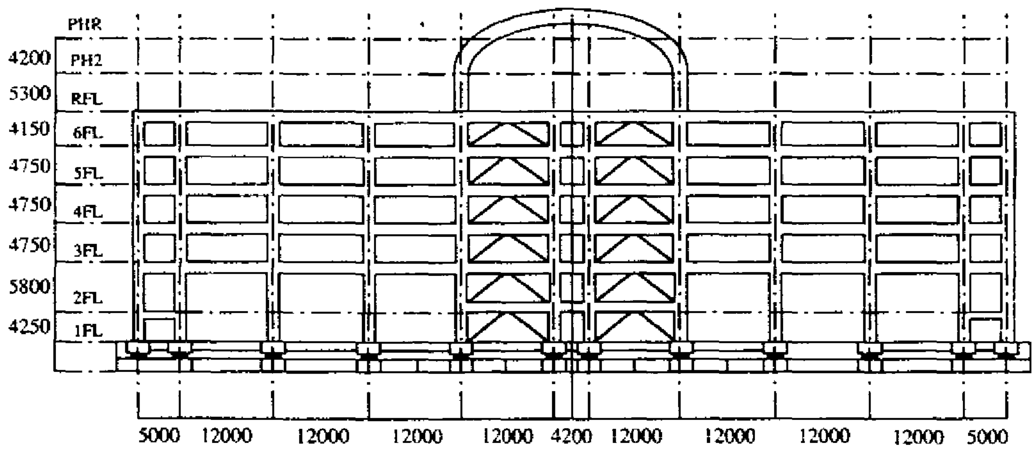

Figure 3. Section of the base-isolated computer center

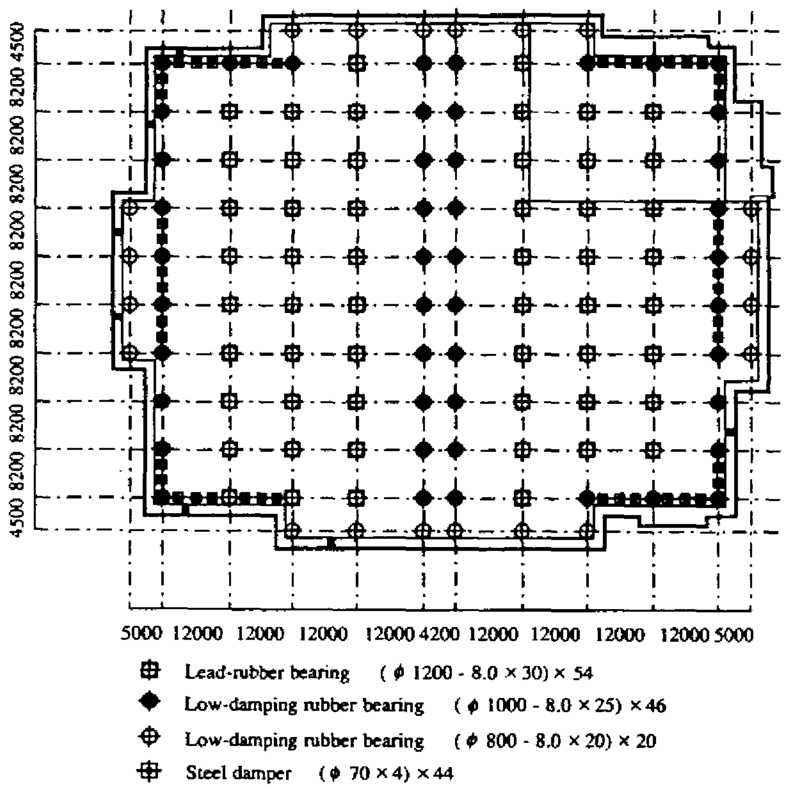

Figure 4. Seismic isolation system of the computer center

Figure 5 shows peak accelerations measured on the foundation, the 1st floor and the 6th floor in the NS-, EW-, and UD-directions (Osada and Kawata, 1995). In the NS-direction, the response accelerations on the 1st and 6th floors were reduced to about 1/4 of that on the foundation, and in the EW-direction, the response accelerations were reduced to about 1/3 of that on the foundation. In the UD-direction, no amplification was observed between the foundation and the 1st floor, although the response acceleration on the 6th floor was considerably amplified because of dynamic characteristics of the superstructure.

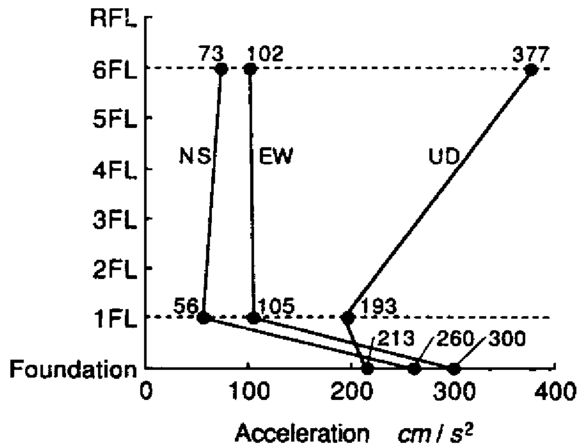

Figure 5 Isolation performance in the base-isolated computer center

Figures 6,7 and 8 are time histories of the accelerations measured on the foundation, the 1st floor and the 6th floor, and acceleration response spectra of them in the NS-, EW-, and UD-directions respectively (Osada and Kawata, 1995). The response spectra in Figures 6 and 7 show that the horizontal ground motion had dominant components around a 1.5 sec period. This implies that the horizontal ground motion was one in which many base-isolated buildings could not achieve good isolation performance; nevertheless the isolation performance of the base-isolated computer center was excellent.

3. BEHAVIOR OF BASE-ISOLATED LABORATORY BUILDING

Figure 9 shows the base-isolated laboratory building of the Matsumura Corporation, a construction company, which is adjacent to a non-isolated office building of steel structure and the same height. As shown in Figure 10, the superstructure of RC-structure has 3 stories and a 480 m^2 total floor area. Figure 11 shows the seismic isolation system comprising 4 high-damping rubber bearings of a 0.7 m diameter and a 0.135 m total rubber thickness and 4 high-damping bearings of a 0.6 m diameter and a 0.137 m total rubber thickness.

The natural period of the base-isolated building was designed to be 1.9 sec for the level-1 design earthquakes, and 2.3 sec for the level-2 design earthquakes. The maximum displacement of the isolation system calculated for the level-2 earthquakes was 0.154 m. The displacement limit of the isolation system is 0.4 m, and the width of the seismic gap is 0.675 m.

Figure 12 shows peak accelerations measured on the foundation, the 1st floor and the roof of the base-isolated building and those on the roof of the conventional building in the NS-, EW-, and UD-directions (Kai et al., 1995). In the NS- and EW-directions, the response accelerations on the roof of the base-isolated building were 1/5 and 2/5 of those on the roof of the non-isolated building respectively, while, in the UD-direction, the response acceleration of the base-isolated building was almost the same as that of the non-isolated building. However, comparing with the ground accelerations, reduction in the horizontal response accelerations of the base-isolated building was not so good, particularly in the EW-direction. This was caused by the fact that the effective natural period of the base-isolated building was 1.5 sec in this earthquake, and coincided with a major dominant period of the ground motion, particularly in the EW-direction, as shown in the following.

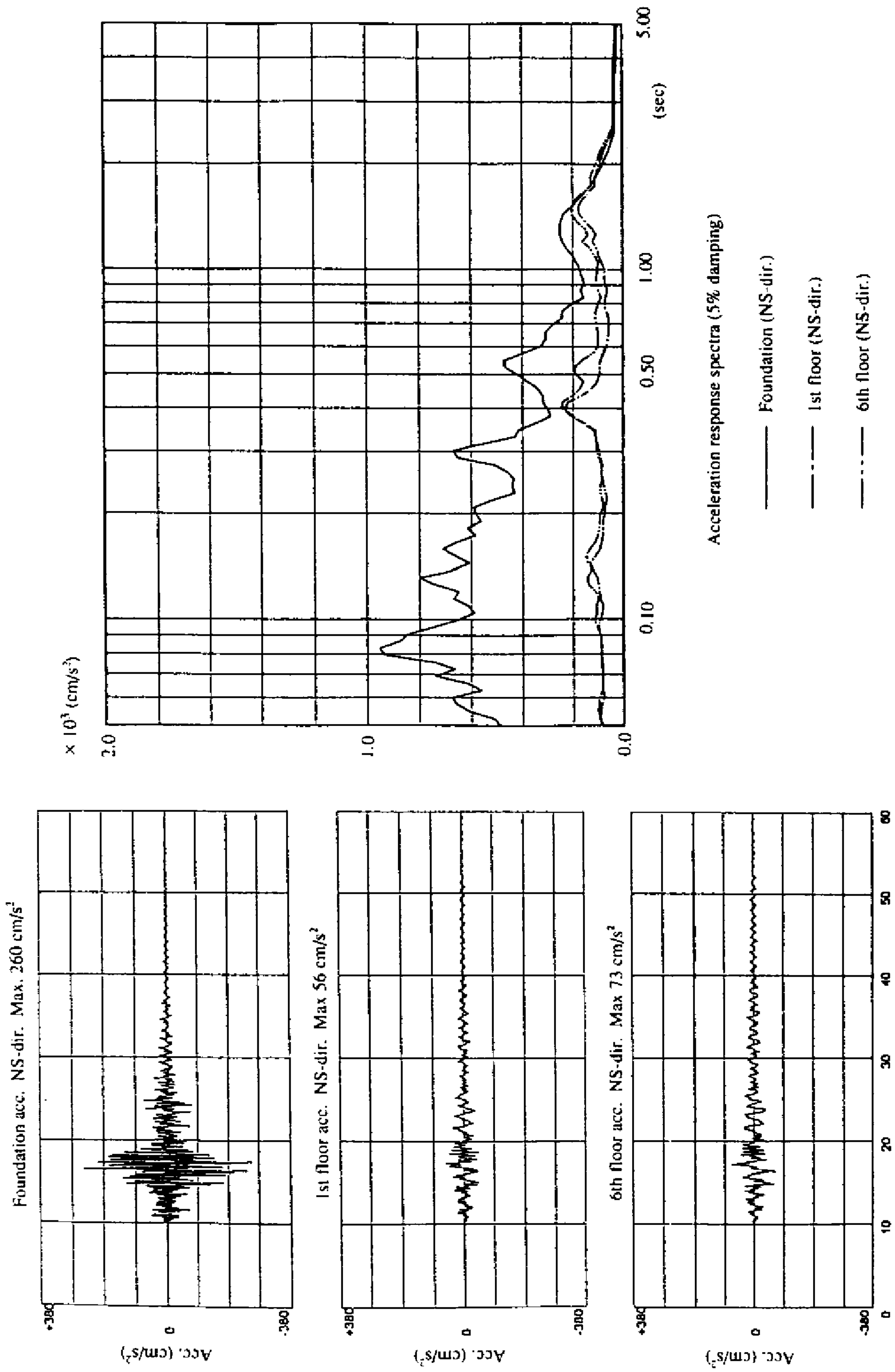

Figure 6. Time histories and response spectra of acceleration records (NS-direction)

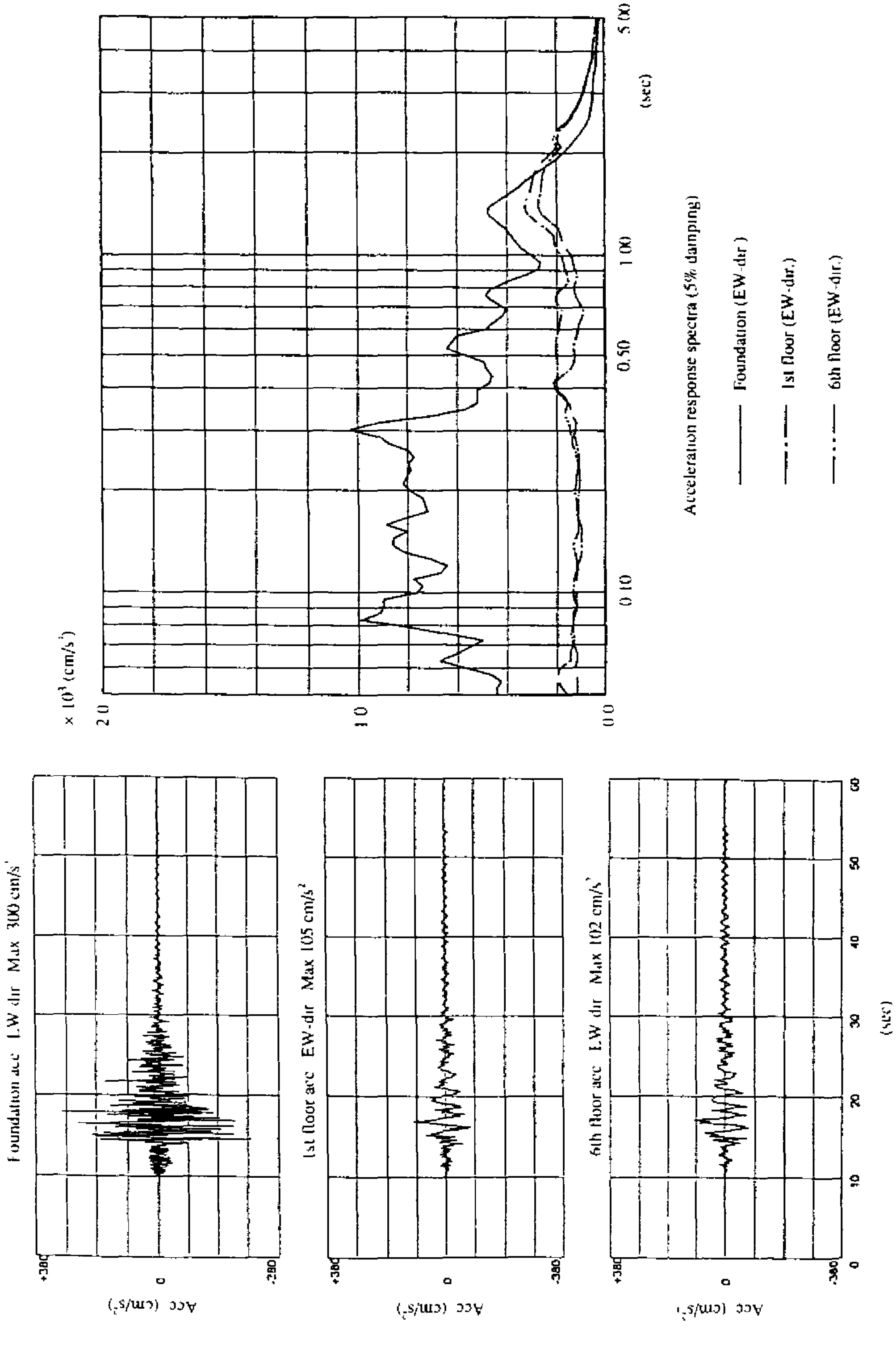

Figure 7. Time histories and response spectra of acceleration records (EW-direction)

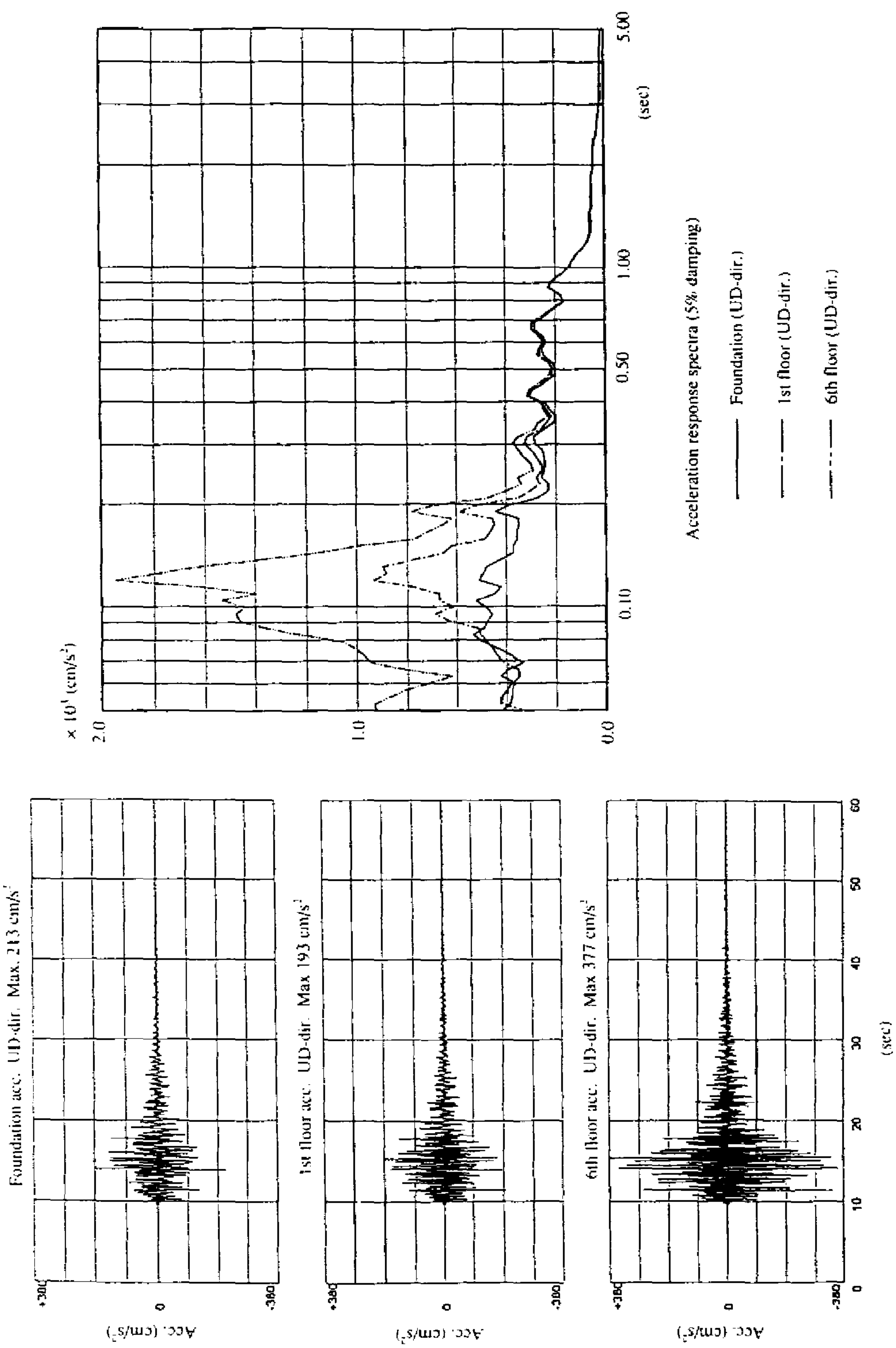

Figure 8. Time histories and response spectra of acceleration records (UD-direction)

Figure 9. Base-isolated laboratory building of Matsumura Corporation (the left building in the photo)

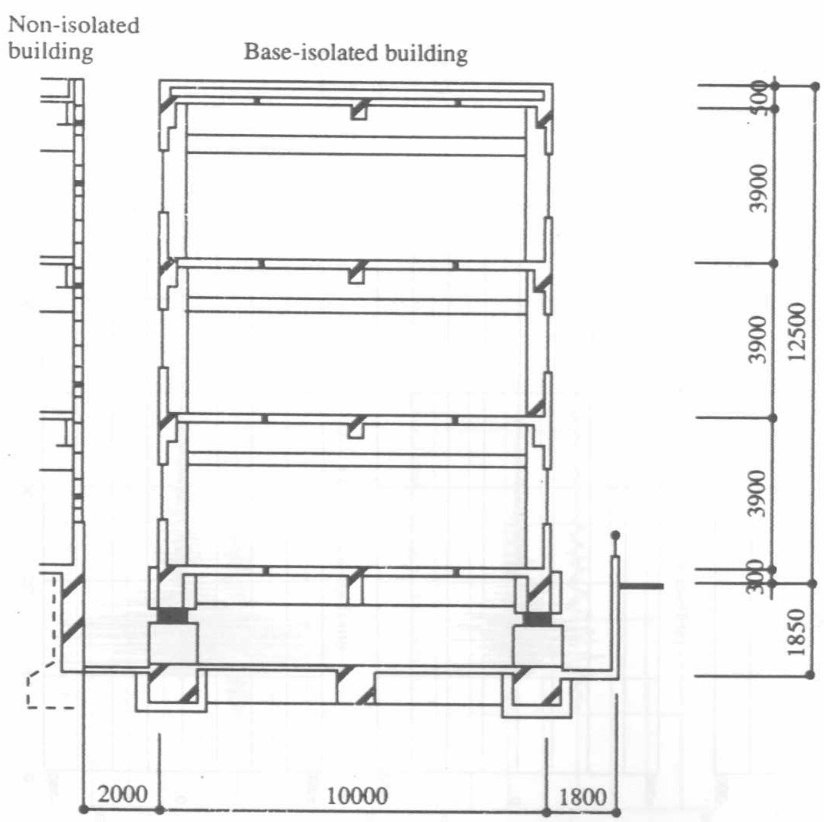

Figure 10. Section of the base-isolated laboratory building

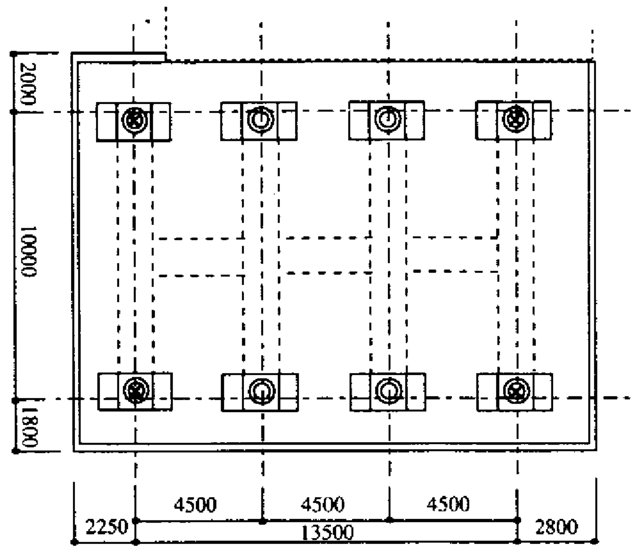

Figure 11. Seismic isolation system of the laboratory building

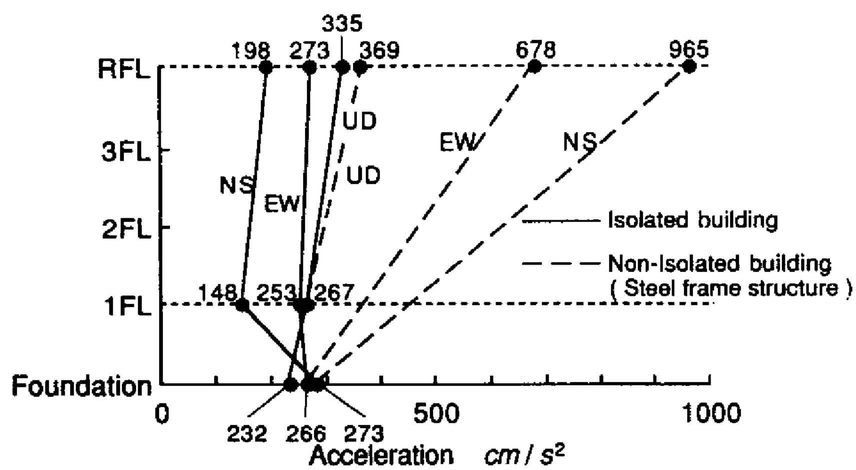

Figure 12. Isolation performance in the base-isolated laboratory building

Figure 13 shows time histories of the accelerations measured on the foundation, the 1st floor and the roof of the base-isolated building and those on the roof of the non-isolated building in the NS-, EW-, and UD-directions, together with the displacements of the isolation system in the NS- and EW-directions which were obtained from integration of the acceleration records (Kai et al., 1995). The responses of the base-isolated building in the FW-direction indicate pseudo-resonance of the building to the ground motion in the EWdirection. Figure 14 shows acceleration, velocity and displacement response spectra of the ground accelerations measured on the foundation in the NS-, EW-, and UD-directions. The velocity response spectra show the horizontal ground motion, particularly the EW-component, had a major dominant period of 1.5 sec.

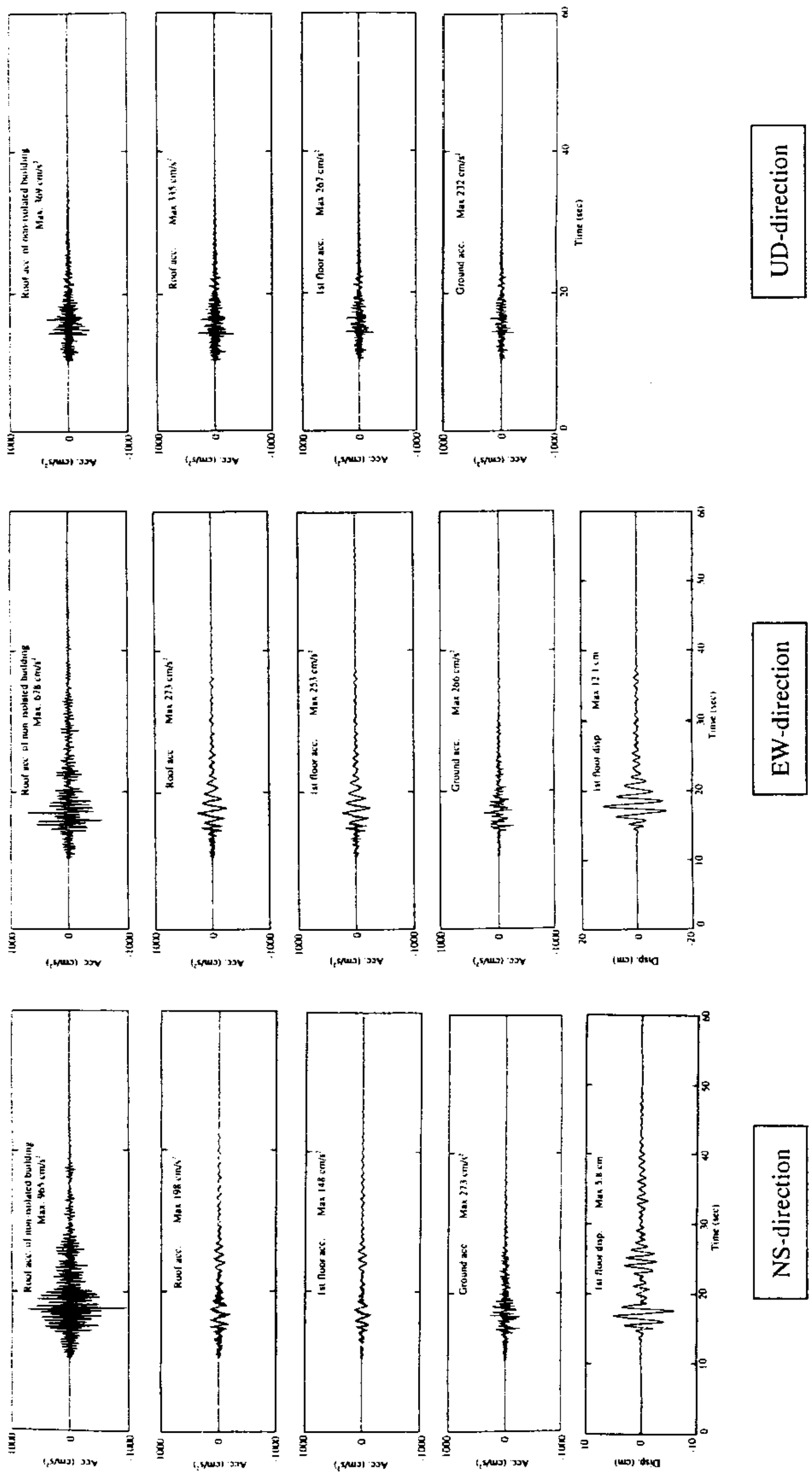

Figure 13. Time histories of acceleration and displacement records

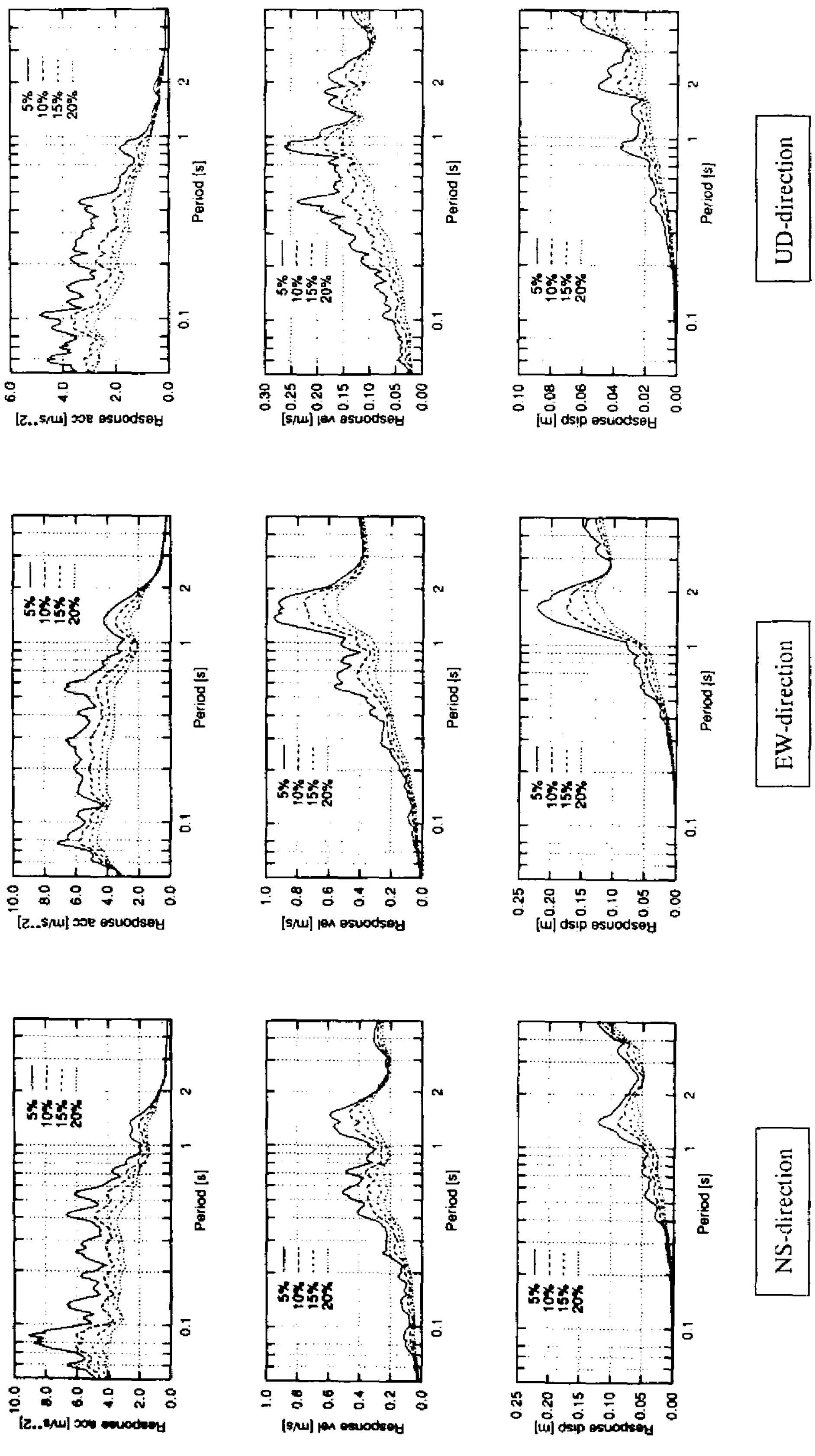

Figure 14. Response spectra of ground accelerations at the base-isolated laboratory building

The isolation performance in the base-isolated laboratory building might be an example in the worst cases possible for the base-isolated buildings; nevertheless the performance was satisfactory.

4. ESTIMATED BEHAVIOR OF BASE-ISOLATED BUILDINGS ASSUMED IN MORE SEVERELY DAMAGED AREAS

As shown in Figure 1, the two base-isolated buildings are far from the areas of the maximum intensity level (level-7) in the Japanese earthquake intensity scale where a great many structures including houses, buildings, elevated motorways, elevated railways and so forth were most severely damaged. If base-isolated buildings had been in the areas, how would they behave in the Hanshin-Awaji earthquake? To estimate such behavior, some calculations were carried out, using ground accelerations measured at the Kobe Marine Observatory which is near the areas of the maximum intensity level (Figure 1).

The ground accelerations at the Kobe Marine Observatory are representative records for ground motions of the Hanshin-Awaji earthquake, time histories of which are shown in Figure 15. Figure 16 shows acceleration, velocity and displacement response spectra of the KS-, EW-, and UD-components of the ground motion. When base-isolated structures are expressed by linear single-degree-of-freedom systems, their responses can be estimated from the response spectra.

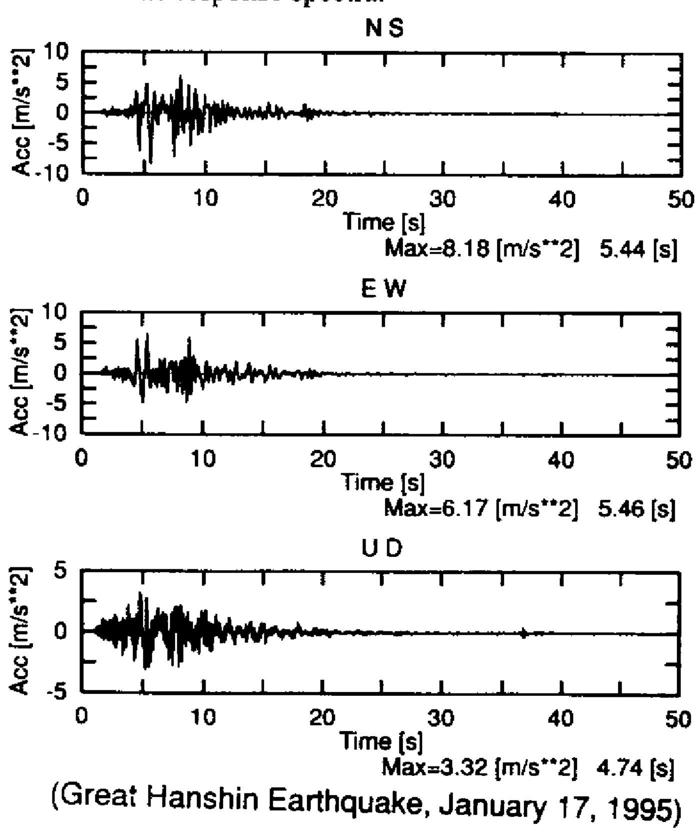

Figure 15. Ground accelerations at the Kobe Marine Observatory

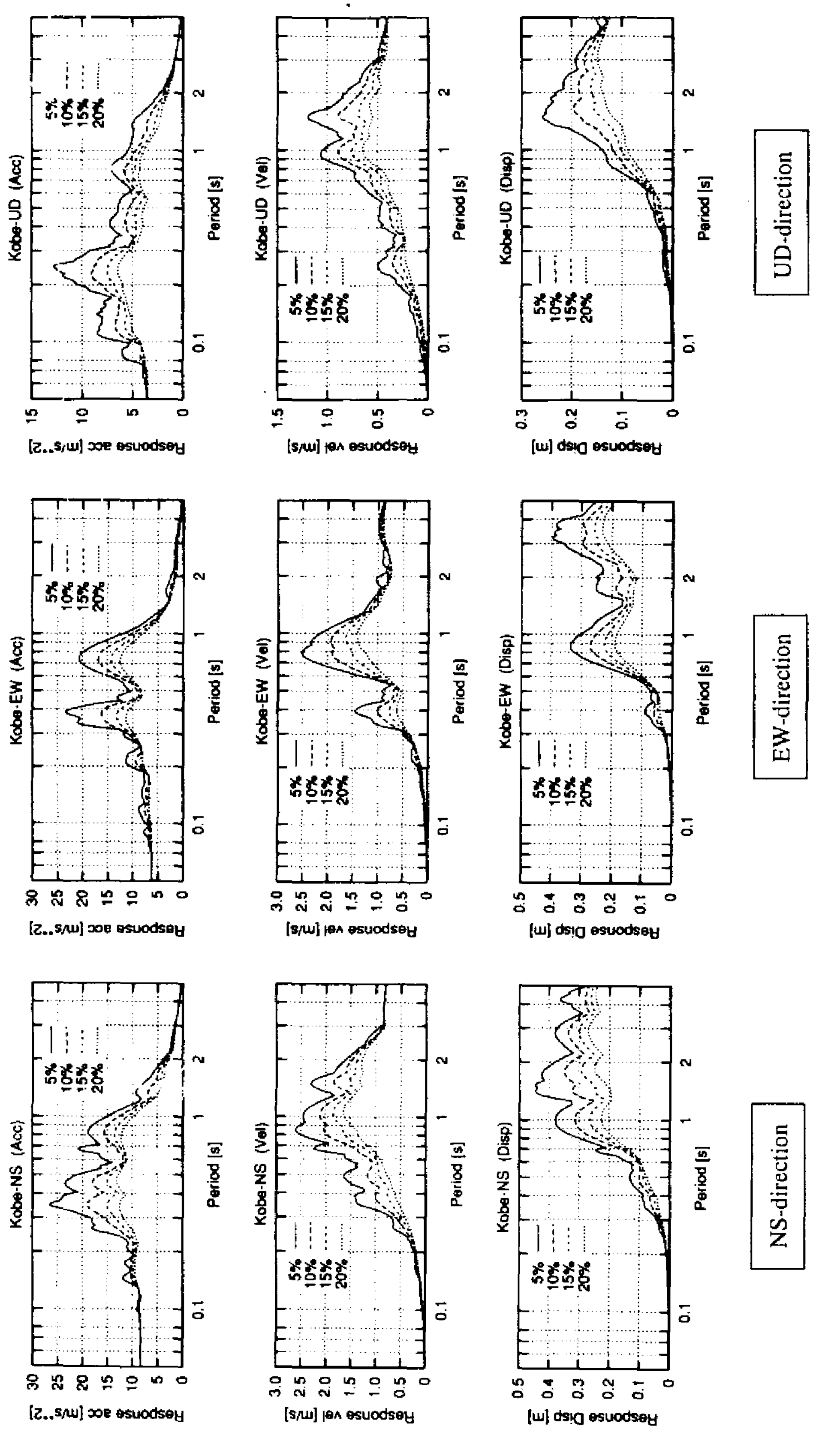

Figure 16. Response spectra of ground accelerations at the Kobe Marine Observatory

However, base-isolated structures are usually non-linear systems which can be expressed by bi-linear single-degree-of-freedom systems. Figure 17 shows the maximum response accelerations, velocities and displacements of the bi-linear systems subjected to the NS- and EW-components of the Kobe Marine Observatory ground motion. Normal base-isolated structures have isolation periods (T_2) of 2 to 3 sec and yielding coefficients (B) of 0.05 to 0.1. The response accelerations of such base-isolated structures would be reduced to 1/5 to 1/2 of the ground acceleration in the KS-direction (8.18 m/s^2), and 1/5 to 1/3 of that in the EW-direction (6.17 m/s^2). The response displacements would be 0.24 to 0.37 m in the NS-direction, and 0.13 to 0.19 m in the EW-direction. From these estimated values, it is concluded that the normal base-isolated buildings would show good isolation performance even if they had been in the most severely damaged areas.

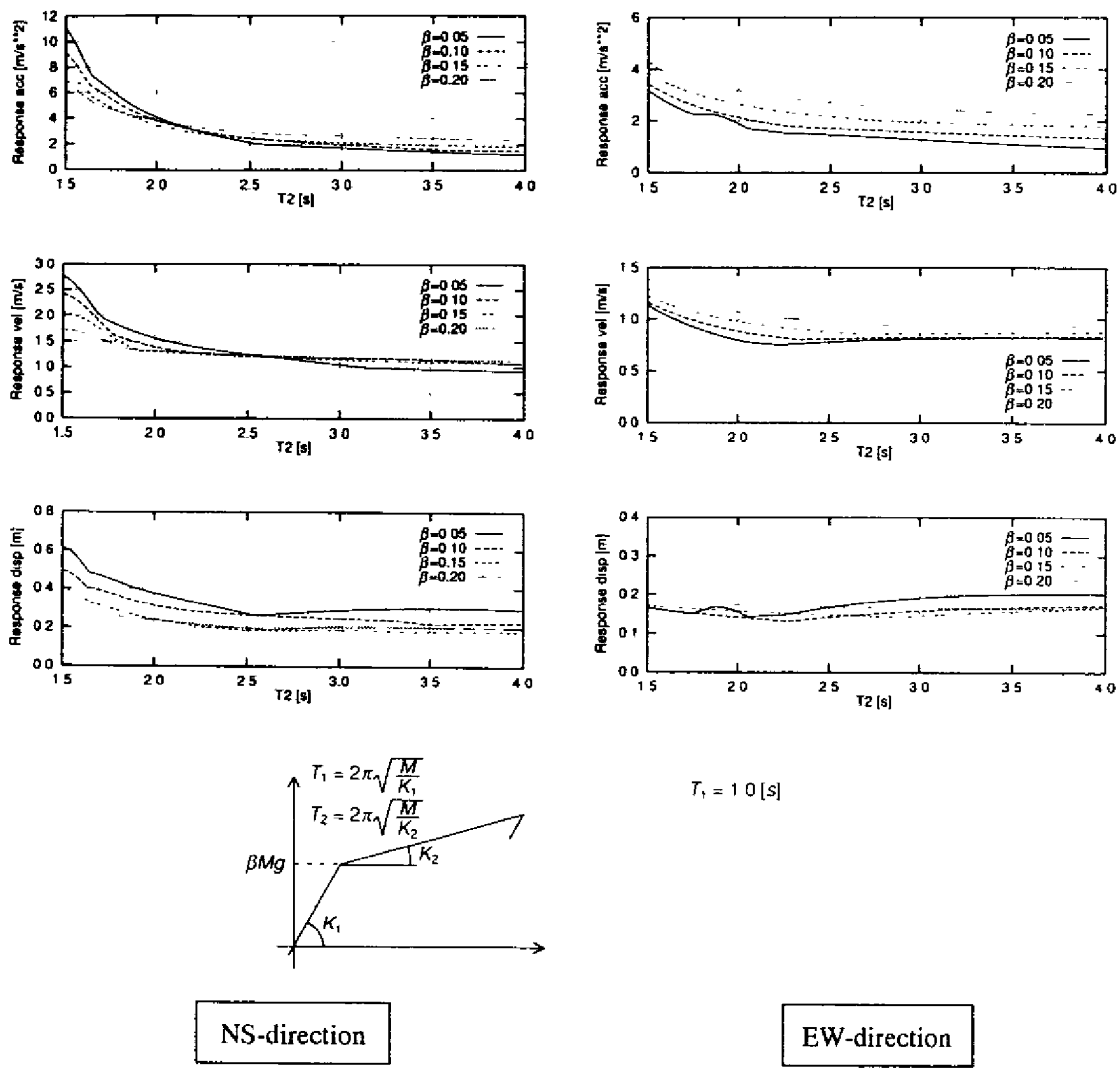

Figure 17. Estimated responses of base-isolated buildings to ground accelerations at the Kobe Marine Observatory

5. PROGRESS OF APPLICATIONS AFTER THE EARTHQUALKE

The success of the base-isolated buildings in the Hanshin-Awaji earthquake convinced structural engineers and architects of effectiveness of seismic isolation. Since the earthquake, construction of base-isolated buildings has explosively progressed. Figure 18 shows change in annual numbers of the licenses for construction of base-isolated buildings from 1985 to 1996. The number of the licenses began to drastically increase from September 1995, and the annual number in 1996 reached 207, while the total number during 10 years before the earthquake was 79. However, it is predicted that the annual numbers in 1997 and 1998 will be 200 or so, which means that the explosive progress after the earthquake is now over. It is expected that steady progress of the applications will continue.

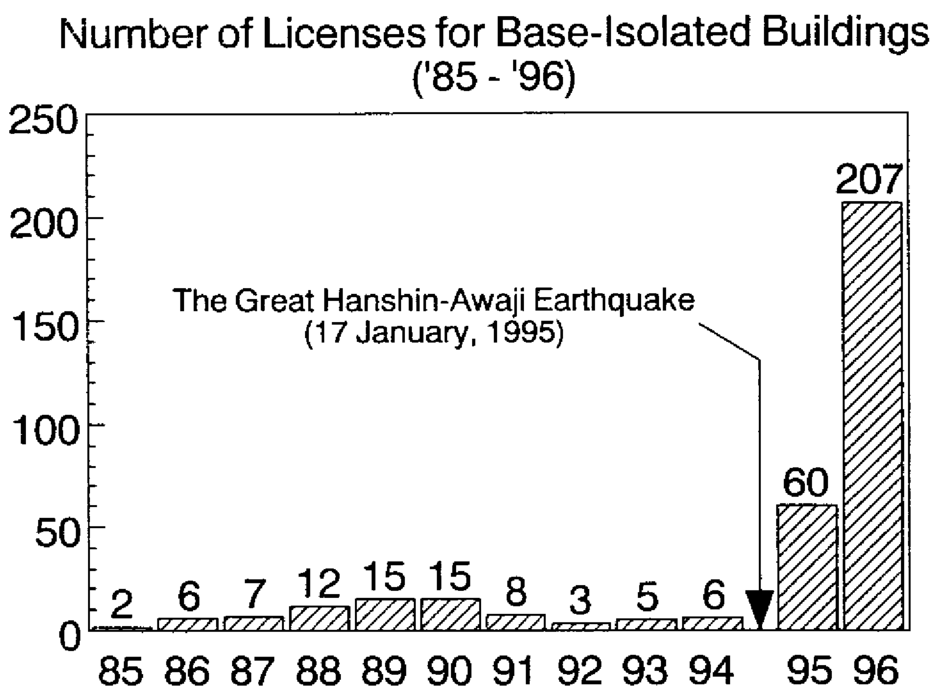

Figure 18. Change in annual numbers of licenses for base-isolated buildings

Figure 19 shows uses of base-isolated buildings before and after the earthquake. Before the earthquake, a large part of base-isolated buildings were constructed for business uses including offices, laboratories and computer centers. After the earthquake also, it is true that many base-isolated buildings are used for the business uses as usual.

The most important change is that a half of base-isolated buildings are used for residential buildings after the earthquake, almost all of which are condominiums. People learned from the earthquake that it is very difficult to repair or reconstruct severely damaged or collapsed condominiums because it is very hard to make a consensus to do it among their habitants and owners having various circumstances. Therefore many people have recognized that condominiums should have very high earthquake-resistance performance by using seismic isolation. This is the reason why base isolation is most applied to residential buildings after the earthquake. Another notable trend is that positive applications of base isolation to hospitals and old people's home have begun. This is also a result from a lesson experienced in the earthquake that hospitals should have superior earthquake-resistance performance to maintain their function even after destructive earthquakes.

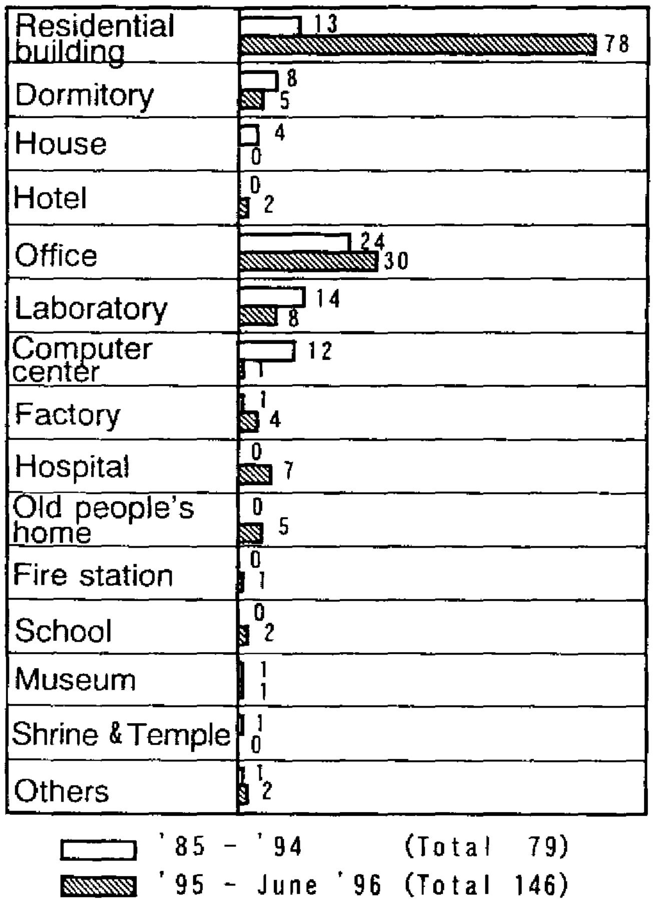

Figure 19. Uses of base-isolated buildings before and after the Great Hanshin-Awaji Earthquake

6. REVISED GUIDELINES FOR SAFETY EVALUATION OF BASE-ISOLATED BUILDINGS

In Japan, aseismic design of all base-isolated buildings must be reviewed by the Building Center of Japan. Guidelines for the safety evaluation were revised after the earthquake.

The revised guidelines require designers to show aseismic performance classes of base- isolated buildings designed by them for design earthquake ground motions of the level-1 and the level-2 which are specified by the designers themselves. The level-1 design earthquakes are defined as ground motions to which the base-isolated building concerned will be probably subjected at least once during its lifetime. The level-2 design earthquakes are defined as the strongest ground motions which occurred or will occur in the site where the base-isolated building concerned is to be built.

Before the earthquake, it was usual to adopt ground motion records adjusted to have a 25 cm/s maximum velocity and a 50 cm/s maximum velocity for the levels-1 and -2 design earthquakes respectively in many areas in Japan, although the levels-1 and -2 earthquakes having maximum velocities of 20 cm/s and 40 cm/s respectively were adopted in Hanshin area where Kobe-City is located. However, ground motions measured in many sites in the earthquake were far stronger than the level-2 earthquakes. Furthermore, it has become apparent that many people expect higher aseismic performance of buildings not only to protect human lives but also to protect properties even in destructive earthquakes. Therefore, the revised guidelines intend that designers freely determine aseismic performance targeted in the base-isolated buildings in consultation with the owners, provided the aseismic performance is higher than the allowable limit as follows:

1. For the level-1 earthquakes, the superstructure and the foundation should be within elastic regions, and the seismic isolation system should be within a stable displacement region. The stable displacement is considered to be about 1/2 of the ultimate displacement of the isolation system within which the rubber bearings can maintain their load-supporting abilities and the dampers can maintain their energy-absorbing functions.
2. For the level-2 earthquakes, the superstructure and the foundation should be within ultimate strength regions, and the seismic isolation system should be within a performance-proved displacement region. The performance-proved displacement is considered to be about 3/4 of the ultimate displacement.

In order to help designers specify the design earthquakes of the levels-1 and -2, the guidelines provide 4 categories of earthquake ground motions. The categories C_1, C_2, C_3 and C_4 are defined by response spectra as shown in Figure 20, and by maximum accelerations, maximum velocities and maximum displacements as shown in Table 1. The designers must specify ground motions which belong to the C_1-category or higher categories than it for the level-1 earthquakes, and those which belong to the C_2-category or higher categories than it for the level -2 earthquakes.

TABLE 1. CATEGORIES OF GROUND MOTIONS DEFINED BY MAXIMUM ACCELERATIONS, VELOCITIES AND DISPLACEMENTS

	Category C_1	Category C_2	Category C_3	Category C_4
A_{max}		400cm/s^2	700cm/s^2	1000cm/s^2
V_{max}	20cm/s	40cm/s	70cm/s	100cm/s
D_{max}		15cm	30cm	60cm

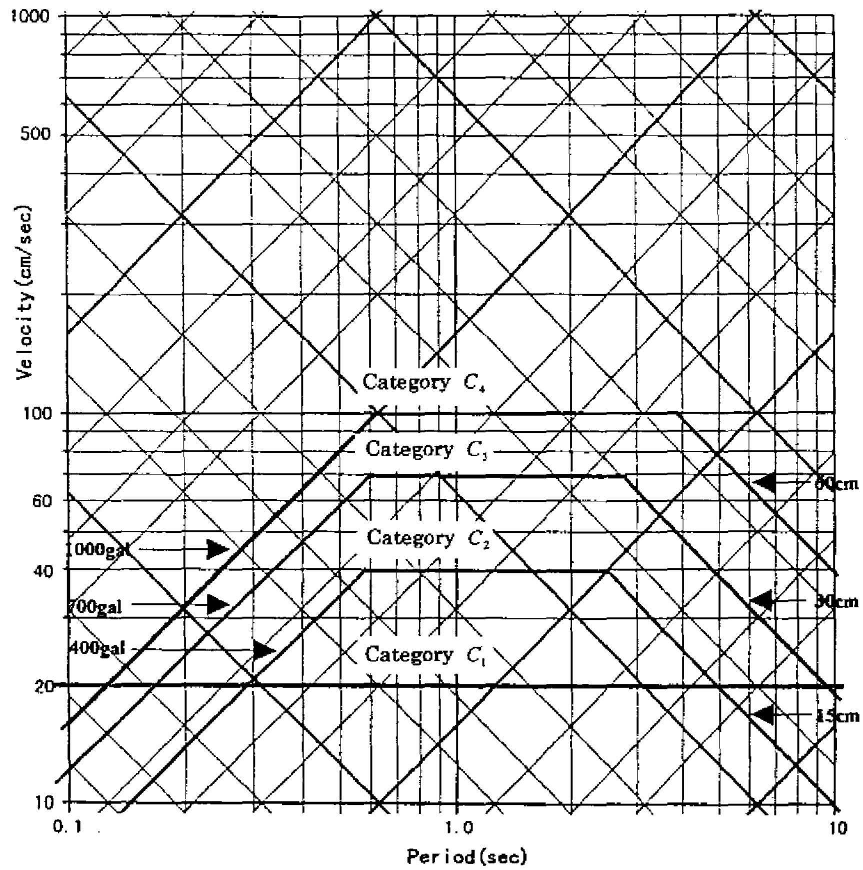

Figure 20. Categories of ground motions defined by response spectra

The guidelines classic structure's response states into 3 states denoted by A, B and C for superstructures, foundations and seismic isolation systems respectively. The states-A, -B and -C of a superstructure or a foundation mean states in which the structure remains within an allowable stress region, an elastic limit region and an ultimate strength region, respectively. The states-A, -B and -C of an isolation system means states in which its displacement remains within the stable displacement region, the performance-proved displacement region and the ultimate displacement region, respectively. Thus the aseismic performance classes of the superstructure, the foundation and the isolation system are evaluated by relating categories of ground motions with response states caused by ground motions of the categories, such as C_1 - A, C_2 - B and so on.

The guidelines require designers to show the aseismic performance classes of the superstructures, the foundations and the seismic isolation systems of the base-isolated buildings for the levels-1 and -2 earthquakes as shown in Tables 2 and 3 for example. As shown in Table 3, ground motions of the safety margin survey level are sometimes added to the safety evaluation when base-isolated buildings have considerable safety margins for the level -2 earthquakes.

TABLE 2. EXAMPLE OF ASEISMIC PERFORMANCE CLASSES (1)

		Level-1	Level-2
Category of ground motion		C_1	C_2
Response state	Superstructure	A	C
	Isolation system	A	B
	Foundation	A	B

TABLE 3. EXAMPLE OF ASEISMIC PERFORMANCE CLASSES (2)

		Level-1	Level-2	Safety margin survey level
Category of ground motion		C_1	C_3	C_4
Response state	Superstructure	A	A	C
	Isolation system	A	A	B
	Foundation	A	A	B

7. CONCLUDING REMARKS

This paper described behavior of two base-isolated buildings in the Hanshin-Awaji earthquake, progress of applications and revised guidelines for safety evaluation of base- isolated buildings, which are summarized as follows:

1. The horizontal ground motion at the base-isolated buildings had a major dominant period of 1.5 sec; nevertheless the isolation performance of the base-isolated computer center was excellent.
2. The isolation performance in the base-isolated laboratory building might be an example in the worst cases possible for the base-isolated buildings; nevertheless the performance was satisfactory.
3. It was shown that the normal base-isolated buildings could perform good isolation even if they had been in more severely damaged areas than the northern area in which the base-isolated buildings were located.
4. The success of the base-isolated buildings in the earthquake led explosive progress of applications of base-isolated buildings. Although the explosive progress is now over, steady progress is expected to continue.
5. After the earthquake, a half of base-isolated buildings are used for residential buildings, although many base-isolated buildings are still used for business uses as usual. Another notable trend is that positive applications to hospitals have begun.
6. In the revised guidelines for the safety evaluation, designers are required to show the aseismic performance classes of the base-isolated buildings for design earthquakes of the level-1, the level-2 and the safety margin survey level if possible which are specified by the designers themselves.

REFERENCES

1. Fujita, T. (1995). "Behavior of Base-Isolated Buildings in the 1995 Great Hanshin Earthquake and Overview of Recent Activities on Seismic Isolation in Japan", *Proceedings of the International Post-SMiRT Conference Seminar on Seismic Isolation, Passive Energy Dissipation and Control of Vibrations of Structures*, Santiago, Chile, 20-39.

2. Fujita, T. (1997). "Progress of Applications, R&D and Design Guidelines for Seismic Isolation of Civil Buildings and Industrial Facilities in Japan", *Proceedings of the International Post-SMiRT Conference Seminar on Seismic Isolation, Passive Energy Dissipation and Active Control of Seismic Vibrations of Structures*, Taormina, Sicily, Italy, 1-23.

3. Kai, M., H. Nishikawa, K. Yasui and K. Izawa (1995). "Response of the Ground and a Building Based on Observed Earthquake Motion Records" (*Part 3, Earthquake Observation and Simulation Analysis of Base-Isolated Building*), Summaries of Technical Papers of Annual Meeting, Architectural Institute of Japan, B-2, pp. 531-532 (in Japanese).

4. Osada, K. and K. Kawata (1995). "Performance of Base-Isolated Building under Southern-Hyogo Pref. Earthquake" (WEST Building of the MPT), *Summaries of Technical Papers of Annual Meeting*, Architectural Institute of Japan, B-2, pp. 631-632 (in Japanese).