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RESPONSE OF A 25-STORY SRC RESIDENTIAL BUILDING DURING THE HYOGO-KEN NANBU EARTHQUAKE

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ABSTRACT

The Hyogo-Ken Nanbu Earthquake hit one of the most densely populated urban area of Japan on the morning of January 17, 1995, resulting in a major disaster in Japan. This paper describes strong motion of the earthquake recorded at a 25-story SRC residential building and simulation analyses of the building using the recorded motion. The building is located in one of the most devastated area, where suffered from strong earthquake motion scaled at seismic intensity scale 7 by the Japan Meteorological Agency. Though some of non-structural members of the building was damaged, the principal structure of the building survived without any substantial damage. The peak acceleration reached 315 cm/sec^2 at the basement floor, and 635 cm/sec^2 at the 24th floor of the building, though some of the record was over-scaled at measurement instruments. The behavior of the building structure during the earthquake was investigated using a nonlinear lumped-mass model that was used for structural design. The recorded motion at the basement was used as input motion to the model. The responses at upper floors were compared with the recorded motion to show the validity of the design model and the design criteria for earthquake resistant design.

KEYWORDS

earthquake observation; strong motion; steel encased reinforced concrete; high rise building; ambient vibration; random decrement technique; lumped mass model; nonlinear response analysis;

INTRODUCTION

The Hyogo-Ken Nanbu Earthquake hit one of the most densely populated urban area of Japan on the morning of January 17, 1995, resulting in a major disaster in Japan. (Architectural Institute of Japan, 1995, EERI, 1995) The magnitude of the earthquake is estimated as 7.2 by the JMA (Japan Meteorological Agency). The death toll from the earthquake exceeded 5,500, which is the second worst record in this century in Japan after the Great Kanto Earthquake in 1923. More than 150,000 buildings and houses were totally or partially destroyed during intense motion of the earthquake and subsequent fire to the earthquake.

The Shin-Nagata Urban Complex of the Housing and Urban Development Corporation is located in one of the most devastated area, where suffered from strong earthquake motion scaled at seismic intensity scale 7 by the JMA. The seismic intensity scale 7 is described as 'very disastrous' motions that involve demolition of houses by more than 30%, intense landslides and large fissures in the ground.

Seismometers installed in the building successfully recorded the strong motion of the earthquake, which was considered to be extremely precious from the technical point of view. Using these records, analyses

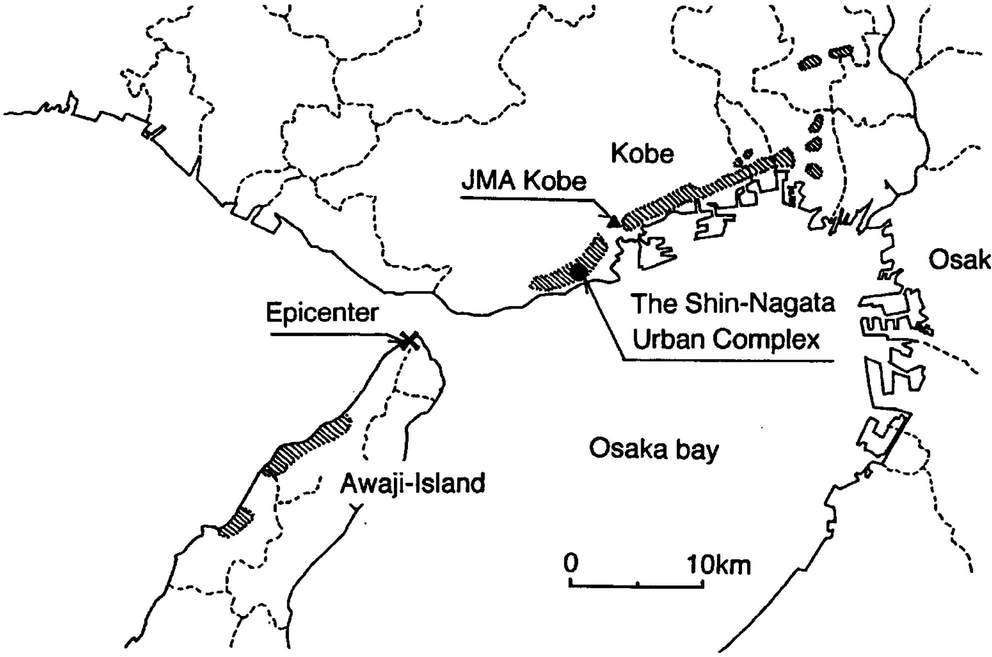

Fig.1 Geographic location of the epicenter and the building with the area of seismic intensity scale 7

and simulation of the earthquake records were done to investigate how the building did behave and survive during the strong motion with only minor non-structural damages.

1. RECORDED EARTHQUAKE MOTION

1.1 Outline of the Building

The epicenter of the earthquake was near the northern end of the Awaji Island, where is about 15 kilometers apart from the location of the building in which motion of the earthquake was recorded. Fig.1 shows the geographic location of the epicenter and the building together with the area for seismic intensity scale 7 by the JMA.

The building is a 25 story steel encased reinforced concrete (SRC) building with three underground stories. The height of the building is 82 meters and it has 65 meters by 84 meters building area. The floors lower than the 4th floor of the building has been used as a department store and community center and the upper floors as apartment house for rent since the building was constructed about twenty years ago. Fig.2 shows the outline of the elevation view of the building.

Principal structure of the building survived the strong motion without any substantial damage, although some of non-structural members, such as non-structural beams and walls of the building mostly in the north-south direction, are damaged during the earthquake. The damages of non-structural members of the building were repaired in order to restore good-quality of the building and amenity for residents.

1.2 Recorded Earthquake Motion

Earthquake observation has been continued at the building since it was constructed. The locations of the seismometers are shown in the Fig.2. Five seismometers, two in the basement, one in the fifth floor and two in the 24th floor, are installed. Each seismometer measures three components in direction; north-south, east-west and up-down, which is noted as NS, EW and UD after this.

Although the seismometers installed in the building were ones of fairly old type, which used optical film to record the motion, three out of five seismometers successfully recorded the motion of the earthquake. However, some of the record was over-scaled at measurement instruments, since such a large acceleration had not been expected in this region of Japan. Consuming much time and labor, digitized data were obtained from the records on the optical film, which could be used subsequent analyses and simulations.

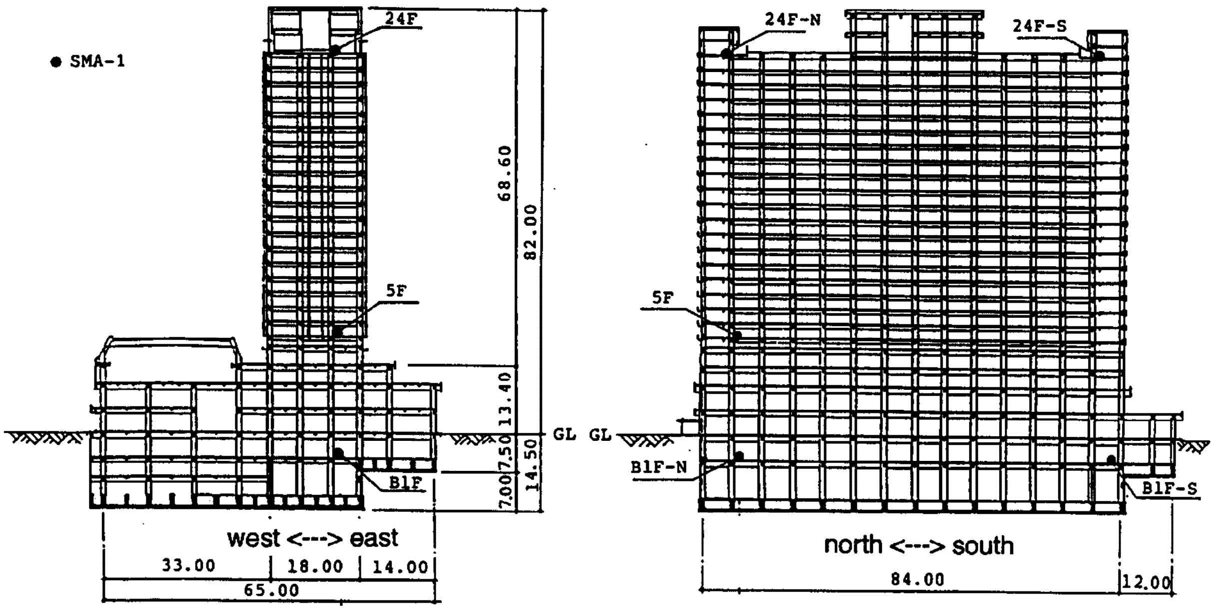

Fig.2 Elevation view of the building and locations of seismometers

Time History of the Recorded Motion The observed records showed peak acceleration as large as 315 cm/sec^2 at the basement floor, and 635 cm/sec^2 at the 24th floor of the building in NS component. All of NS components in three floors were over-scaled, while only the record at the 24th floor was over-scaled in EW component and none of UD components was over-scaled.

The saturated records were interpolated using spline function, which yielded peak acceleration more than 350 cm/sec^2 at the basement and more than 950 cm/sec^2 at the 24th floor in NS component.

Fig.3 and Fig.4 show the time history of the acceleration records at the 24th floor and the basement, respectively. The interpolated records for over-scaled components are shown together. The top panel of each chart shows the NS component of the motion, which is the largest among three measured directions. The second panel and the bottom panel are those in EW component and UD component, respectively. Peak acceleration values at each floor are summarized in the Table 1.

Table 1. Peak acceleration at each floor (cm/sec^2)

	NS component		EW component		UD component	
location	observed	interpolated	observed	interpolated	observed	interpolated
24th floor-S	635	956	302	354	327	not over-scaled
5th floor	379	407	183	not over-scaled	fail to record	
basement-N	315	354	121	not over-scaled	119	not over-scaled

The fact that NS component showed extremely larger acceleration than other two components corresponds to the directivity of the damages of the building. Same directivity of the strong motion was observed at the JMA Kobe Meteorological Observatory, which is located five kilometers northwest to this building. The north-south component at the JMA station recorded 818 cm/sec^2, while east-west component was 617 cm/sec^2.

Frequency Component of the Recorded Motion Fig.5 shows the acceleration response spectra of the recorded motion at the basement for three observed components; NS, EW and UD. It was checked that the interpolation of the saturated data in NS direction did not affect much the response spectrum. From this figure, it can be seen that NS component has three dominant peaks at 0.8 second, 1.2 second and 2

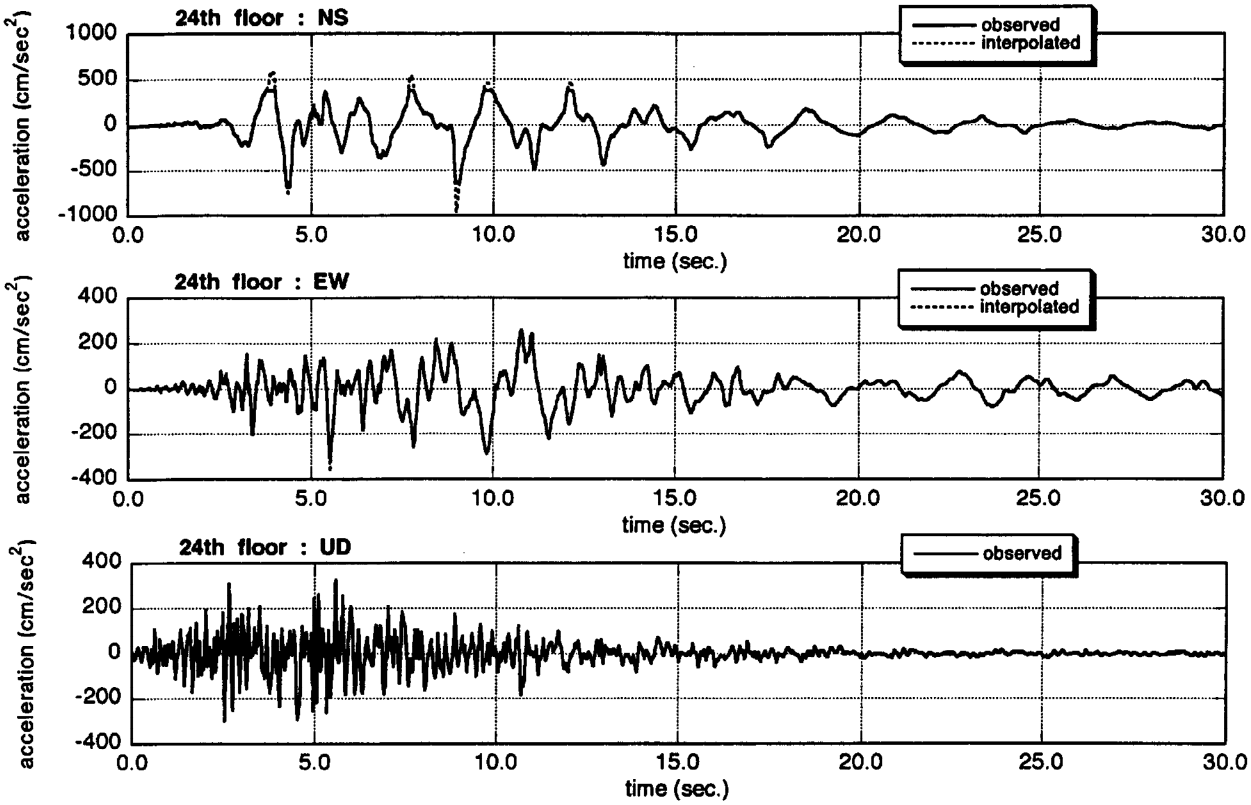

Fig.3 Time history of the acceleration record at the 24th floor

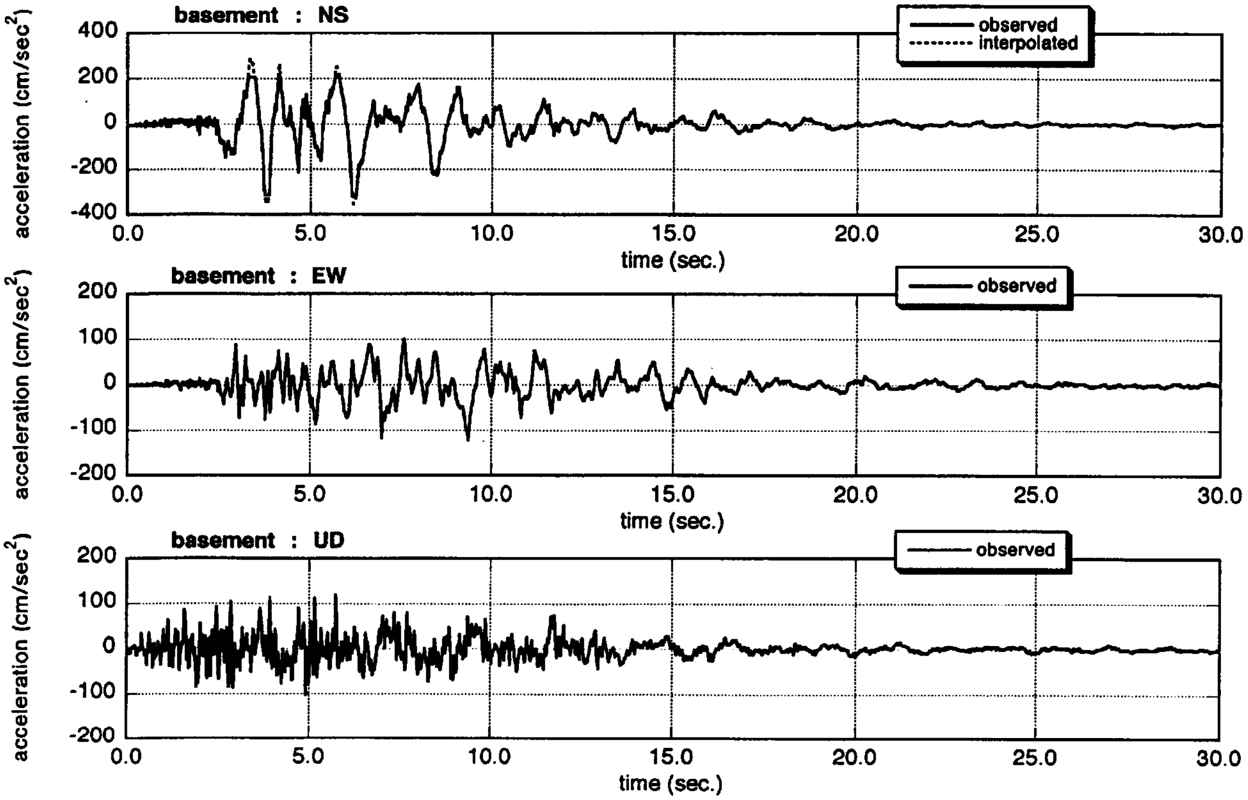

Fig.4 Time history of the acceleration record at the basement

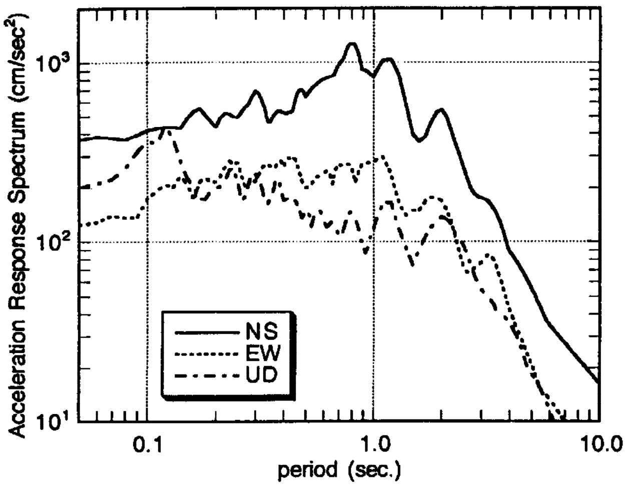

Fig.5 Acceleration response spectrum at the basement

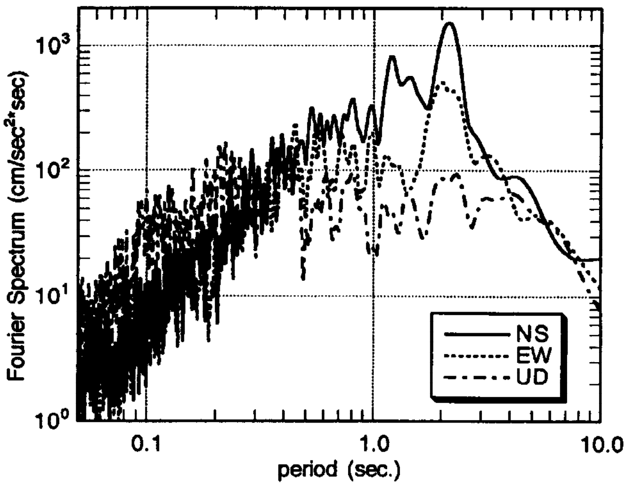

Fig.6 Fourier spectrum at the 24th floor

second, while EW component does not have prominent peaks. The peak acceleration at 0.8 second in NS component exceeds 1000 cm/sec^2, which brings the validity to the interpolated acceleration record at the 24th floor; 956 cm/sec^2. The response in EW component holds lower than 300 cm/sec^2 in the most of period range.

Fig.6 shows the Fourier spectra of the recorded motion at the 24th floor with Hanning window processing. It was checked that the effects of the interpolation of the saturated data were negligible in these frequency analyses. The prominent peak at around 2 second in both NS and EW component seems to be the principal period of the structure under the strong motion. Those natural periods are longer than the period of design model; which are described in the next section, as the design periods are for small amplitudes of motion.

1.3 Dynamic Characteristics of the Building before and after the Repair

The dynamic characteristics of the building were also examined through ambient vibration measurements before and after the repair. The main purpose of the measurements was to investigate the effects of repair on the dynamic characteristics of the building.

Principal natural periods and damping factors of the building in both NS and EW directions before and after the repair were obtained by the Random Decrement method. (Tamura *et al.*, 1995) Table 2 shows the summary of the results of the ambient vibration measurements.

Table 2. principal natural periods and damping factors in ambient vibration measurements

	before repair		after repair		design*
	natural period	damping	natural period	damping	natural period
NS	1.56 sec.	1.5 %	1.26 sec.	1.4 %	1.53 sec.
EW	1.67 sec.	0.9 %	1.59 sec.	1.0 %	1.61 sec.

* design model that is described in the section 2.1

In the table, it is clear that the repair work affected the natural period of the building in NS component, in which direction the repair was done. The principal natural period in NS component decreased by 20 percent after the repair, which was equivalent to 50 percent increase of stiffness of the structure. In EW direction, the decrease of natural period was fairly smaller than that of NS direction. As for the damping factors, there seems no clear difference between before and after the repair.

Notice that the natural period before the repair in NS direction was close to that of the design model. This correspondence of the natural period can be explained by the fact that non-structural members, which were damaged during the earthquake, were not considered in the design model. Also notice that the natural period after the repair was close to that of the design model in EW direction, where no major non-structural members existed to affect the structural stiffness.

2. SIMULATION ANALYSES OF THE RECORDED MOTION

2.1 The Lumped Mass Model

The behavior of the building during the earthquake was investigated using a nonlinear lumped-mass model that was used for structural design. The design model for the building was a lumped mass model with 26 masses and tri-linear restoring force characteristics. The model was made on the stories above the ground and was fixed at the base. Columns and major beams were taken into account in designing the model, while small beams and non-structural walls were neglected. The damping was set to 3 percent for the first mode as internal viscous damping.

Natural periods of the design model are shown in the Table 2 in the previous section.

2.2 Nonlinear Response Simulation

Nonlinear response analyses were carried out using the design model. The input to the model was the observed motion at the basement of the building. Simulation was carried out for 20 second time intervals of the records in NS and EW directions independently.

Simulation for NS direction Fig.7 shows the simulated acceleration responses in NS direction compared with the observed records. The observed records are interpolated ones. The top panel of the chart is for the 24th floor and the bottom panel is for 5th floor. Although peak values are not always corresponding perfectly, there seems fairly well resemblance between the simulation and the observation. Especially, the simulation and the observation at the 5th floor are fairly well corresponding each other except some peaks after 10 seconds.

Fig.8 shows the Fourier spectra of the simulated and the observed motions for NS direction. The left panel is for the 24th floor and the right panel is for the 5th floor. Comparing the simulation and the observation in the charts, notice that discord between them becomes larger in shorter period range; or higher frequency range. This can be attributed to the property of internal viscous damping that is applied to the design model, which becomes larger as frequency becomes higher. Regarding the dominant peaks

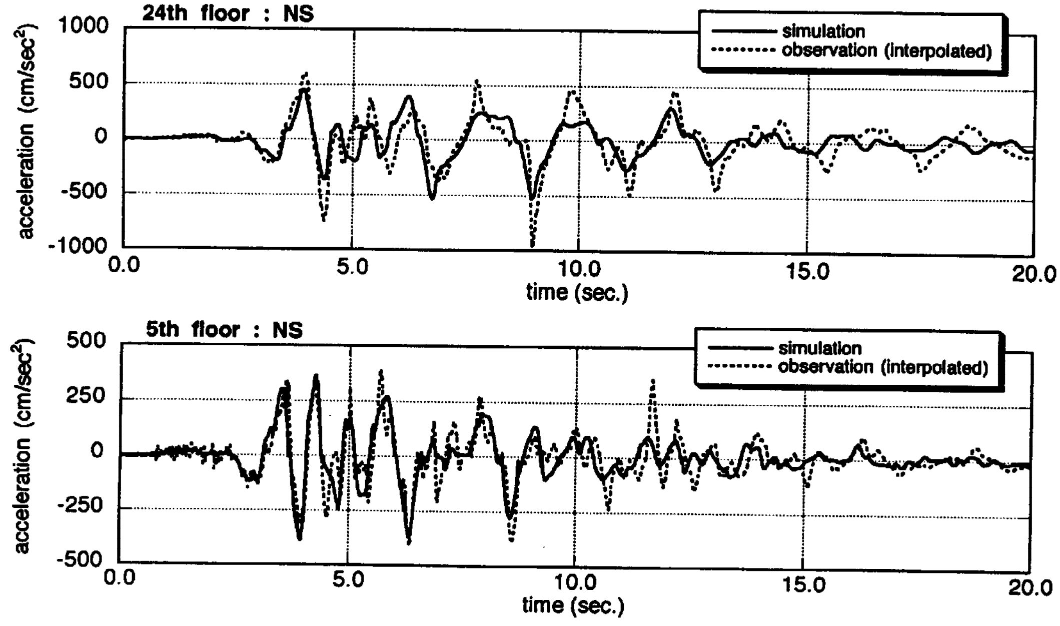

Fig.7 Simulated acceleration response in NS direction

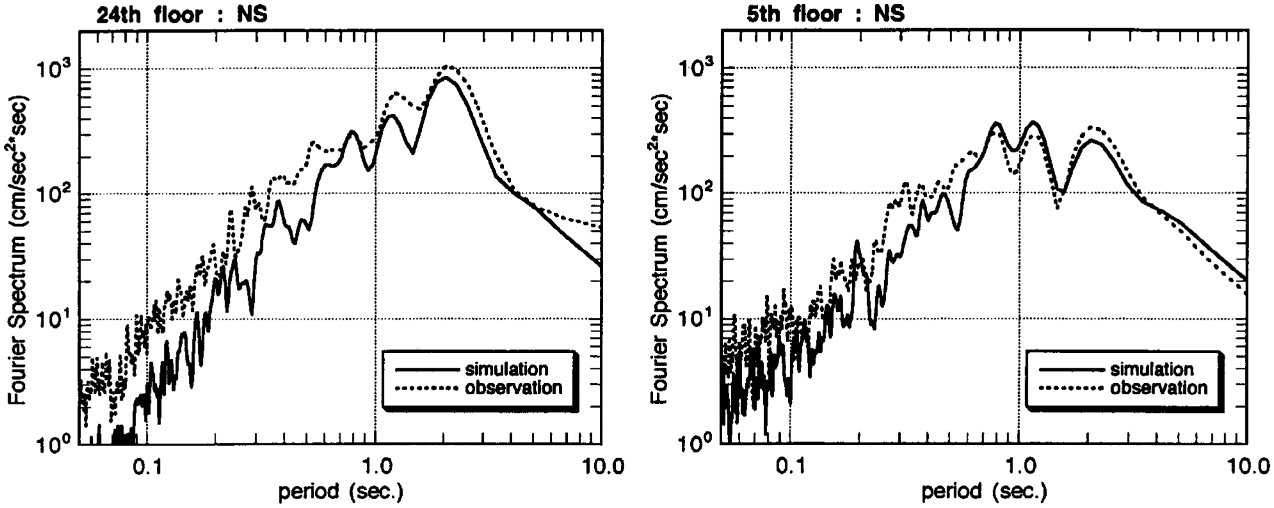

Fig.8 Fourier spectrum of simulated acceleration response in NS direction

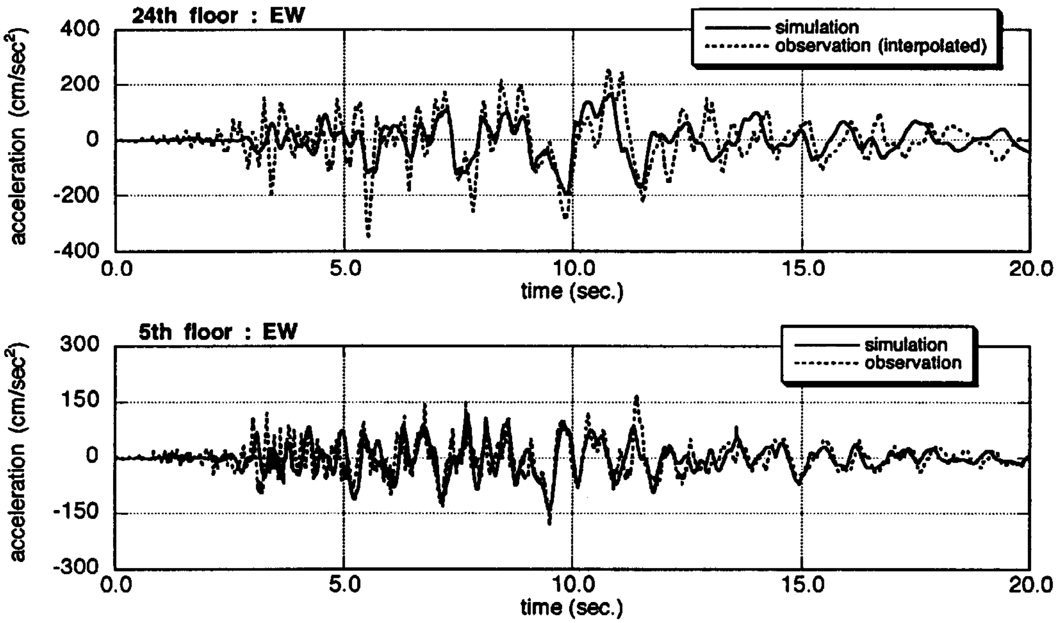

Fig.9 Simulated acceleration response in EW direction

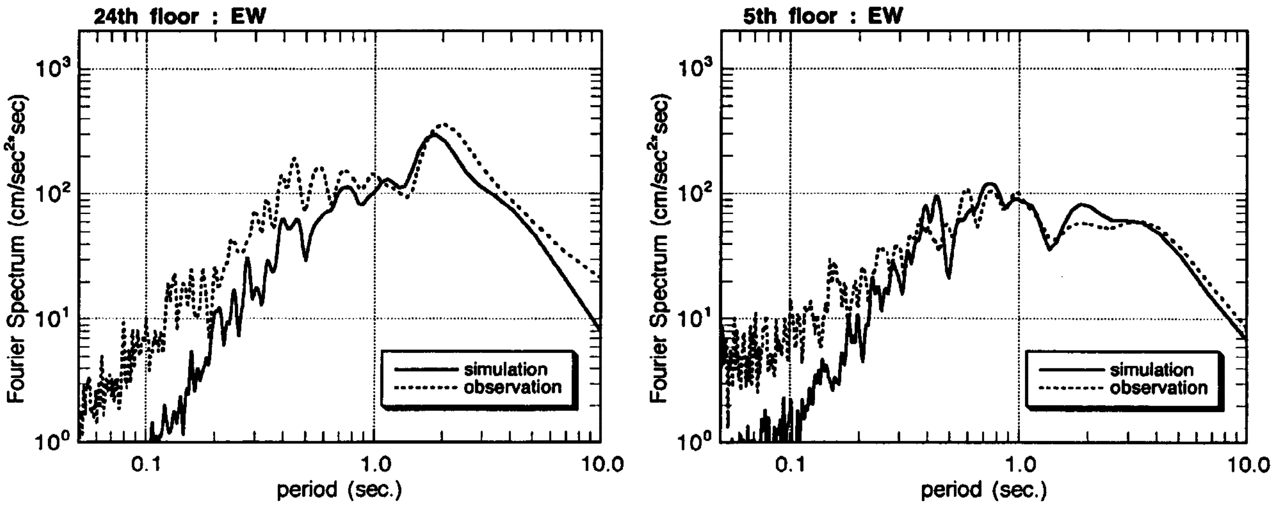

Fig.10 Fourier spectrum of simulated acceleration response in EW direction

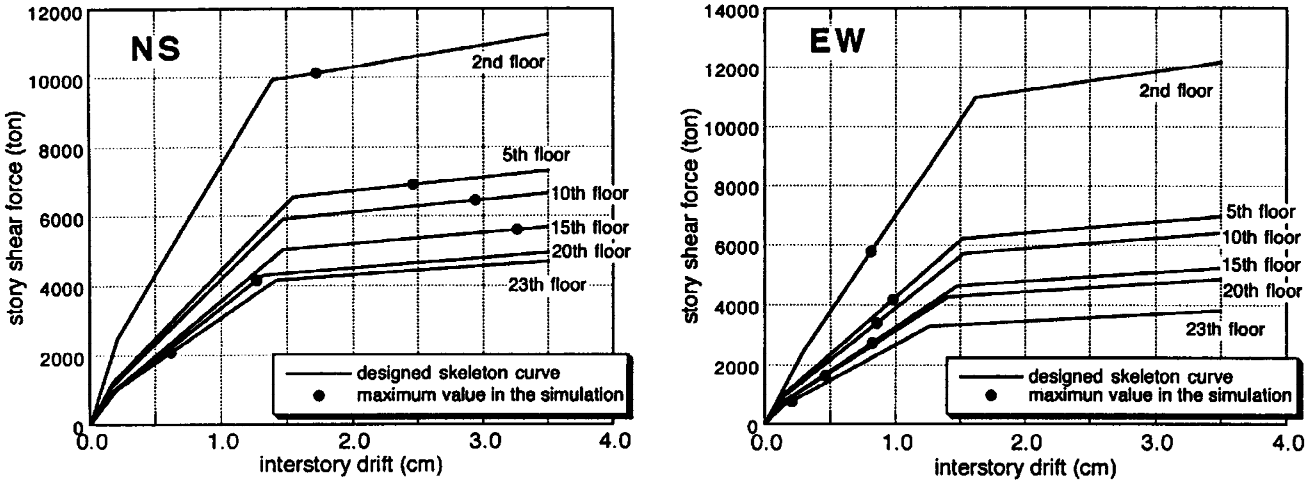

Fig.11 Maximum interstory drift and maximum story shear in the simulation

of the response between 0.8 second and 2 seconds, there are fairly well correspondence between the simulation and the observation.

Simulation for EW direction Fig.9 shows the simulation results in EW direction. Substantial correspondence is observed similarly to NS direction. However, there are some discord at short period peaks. This discord is much obvious in frequency domain, which is shown in Fig.10.

Fig.11 shows maximum interstory drift and maximum story shear force at several floors in the simulation.

That correspondence between the simulation and the observation both in time domain and in frequency domain proves validity of the design model for earthquake resistant design to some extent. However, it is also clear that the model still has certain room for improvement, such as damping characteristics and effects of non-structural members on the restoring force characteristics. Much complicated model such as a three-dimensional frame model will be required for further investigation.

CONCLUSIONS

The followings are the conclusions of this paper.

The strong motion of the Hyogo-Ken Nanbu Earthquake was recorded at a 25-story building, which was located in the area assigned seismic intensity scale 7 by the JMA. North-south component of the strong motion showed extremely large acceleration as much as 956 cm/sec^2 at the 24th floor, which was recovered by interpolation from saturated record.

The dynamic characteristics of the building were examined through ambient vibration measurements before and after the repair of the damaged non-structural members. The effect of the repair work appeared as decrease of the natural period of the building in the mainly damaged direction; north-south.

Through the simulation analyses of the recorded strong motion using the design model of the structure, the validity of the design model for earthquake resistant design is shown. However, the model still has certain room for improvement, such as damping characteristics and effects of non-structural members on the restoring force characteristics.

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