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COMPARISONS BETWEEN EARTHQUAKE RESPONSE CHARACTERISTICS OF BASE-ISOLATED AND ORDINARY BUILDINGS

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SUMMARY

For the purpose of investigating the general properties and effectiveness of a base-isolated building in direct comparison with a traditional building, full-sized model test was conducted in a yard of Tohoku University in Sendai. Two test buildings, base-isolated and ordinary founded, were constructed side by side on an identical soil condition. After conducting a static loading test and a forced vibration test, the buildings were employed for earthquake observation. Thirty earthquakes were recorded during the observation term from June 1,1986 to July 20,1987. The maximum acceleration at the roof of buildings was 272gal for the ordinary building and 42.2gal for the base-isolated building respectively.

INTRODUCTION

In the modern base-isolation system, the combination of spring and damping elements has been widely used. As to the spring element, the steel laminated rubber bearing is used in general, because it has superior characteristics such as low horizontal stiffness, high vertical stiffness and large loading capacity. As for the damping element, various devices have been proposed and applied to actual buildings. The test building was designed to be able to set up those various kinds of damping device.

In the first step of the serial tests, the combination of laminated rubber bearings and cylindrical oil dampers was used for the base-isolation system. The oil damper provides certain advantages since it has a reliable damping effect for not only large amplitude of motion but also small amplitude of motion. This paper refers to the test results and their analyses of the system using laminated rubber bearings and cylindrical oil dampers.

DESCRIPTION OF TEST BUILDINGS AND BASE-ISOLATION SYSTEM

Two test buildings, base-isolated and ordinary founded, were constructed side by side on a relatively hard loam layer with gravel whose shear wave velocity is 310m/s. The buildings were full-sized three-story reinforced concrete structure, the dimensions and construction method of the superstructures being exactly the same for both buildings.

Fig.1 shows a general view of the test buildings. The building on the right is the base-isolated building. The plan and elevation of the test buildings are shown in Fig.2, in which the installation of rubber bearings and oil dampers are indicated. The base-isolation system was consisted of six rubber bearings and twelve oil dampers.

The dimensions of rubber bearing are shown in Fig.3. It has eighteen layers of 6.7mm-thick rubber and seventeen 3.0mm-thick steel plates. The horizontal stiffness is 618~650kg/cm, and the vertical stiffness is $5.18\sim6.54\times10^5$kg/cm. The two types of oil damper, type A and B, were installed. The damping coefficient is 27kg·s/cm for type A and 125kg·s/cm for type B. The cross section of oil damper B is shown in Fig.4.

SITE EXPERIMENTS

The static loading test and the forced vibration test were carried out at the site soon after the completion of test buildings.

Static Loading Test The static horizontal load was applied to the lower part of the base-isolated building using jacks. The load-displacement relation of the system is shown in Fig.5 for large displacement up to ±170mm. The equivalent stiffness and damping ratio obtained from the hysteresis curves are shown in Table 1 for a large(±170mm) and a small(±30mm) displacements respectively.

Dynamic Loading Test The forced vibration test was carried out for both buildings. A vibration exciter installed at the center of roof slab applied sinusoidal forces horizontally to the building in one direction. The test was performed for the base-isolated building under two conditions, with and without oil dampers, so as to make clear the dynamic properties of rubber bearings alone and the effect of oil dampers. The natural frequencies and damping ratios thus experimentally obtained are summarized in Table 2.

The natural frequencies of the ordinary building were 3.63Hz for X(transversal)-direction and 4.39Hz for Y(longitudinal)-direction. The corresponding frequencies of the base-isolated building with oil dampers were 0.722Hz for X-direction and 0.731Hz for Y-direction when the peak amplitude was 2.3mm at the roof of the building. The damping ratios of the base-isolated building were 16% for X-direction and 15% for Y-direction which were about ten times larger than those for the ordinary building. The oil dampers produced about 13% increment of the damping effect.

EARTHQUAKE OBSERVATION AND ITS ANALYSIS

Accelerograph Setup Eleven accelerographs were installed in the base rock, near the surface of the surrounding ground, the base slab of the base-isolated building, the first floors and roofs of both buildings as shown in Fig.6. Totally, twenty-seven components, twenty horizontal and seven vertical, were involved in the accelerograph setup.

Earthquakes Observed The earthquake observation started in May 1986. Thirty earthquakes were recorded from June 1,1986 to July 20,1987, which involved three Ⅳ, ten Ⅲ, nine II and eight I on the seismic intensity scale by JMA (Japan Meteorological Agency). The maximum acceleration recorded on the ground surface was 91.3gal at the point No.1 near the cliff, and the corresponding peak accelerations at the roof of building were 272gal for the ordinary building and 42.2gal for the base-isolated building.

Distribution of peak accelerations As an example, the peak accelerations of all components during the earthquake of February 6,1987 (magnitude:6.7, epicentral distance:168km, forcal depth:31km) are shown in Fig.7. This was one of the most powerful earthquakes recoded during the observation term. The peak accelerations at the roof of the base-isolated building were 35.8gal for X-direction and 31.8gal for Y-direction, which were from 1/5.7 to 1/4.9 of the values at the roof of the ordinary building. Similarly, significant reductions of the peak accelerations were measured between the base-isolated and ordinary buildings during other earthquakes. The time historical records of the earthquake at the five major points, the ground surface near the building, the first floors and the roofs of both buildings, are shown in Fig.8 for X-direction and Y-direction respectively.

Amplification Factor of Building The amplification factor (AF) of building is defined as follows in this paper.

$$AF = \frac{\text{maximum acceleration at the roof of building}}{\text{maximum acceleration at the ground surface near building}}$$

AF was calculated with the thirty earthquakes for two horizontal components. Fig.9 shows the plotting of the AF values for X and Y directions. The mean values of AF of the ordinary building are 5.95 for X-direction and 3.08 for Y-direction. While the mean values of the base-isolated building are 0.99 for X-direction and 0.89 for Y-direction. It was found that the amplification factor of the base-isolated building was almost 1.0 or a little less than 1.0 on an average, i.e., the base-isolated building does not amplify the input ground motion, and thus, the level of building response was nearly equal or a little less than the level of input ground motion. On the other hand, the ordinary building amplified the input ground motion by three to six times. Therefore the earthquake response of the base-isolated building is about 1/6 to 1/3 of that of the ordinary building on an average.

A large scattering of the plots appears in Fig. 9. This is due to the differences in the predominant frequencies of input ground motion and the natural frequencies of the building. The predominant frequencies of input ground motion appeared from 2.5 to 5.0Hz for the thirty earthquakes.

Analysis of Observed Motions Fourier spectra of the ground motion and the earthquake responses at the base slab, first floor and the roof of the base-isolated building during the earthquake of February 6,1987 are shown in Fig.10. Fig.11 shows the mode shapes of the base-isolated building obtained from band pass filtering technique. Followings can be seen from the figures.

(1) Earthquake motions at the base slab and the ground surface have almost the same amplitude.

(2) Earthquake motions at the first floor and the roof are almost the same, i.e., the building vibrates as a rigid body without rocking motions.

(3) The predominant frequency of the ground motion appears at 2.5Hz. The natural frequency of the building appears at 0.7Hz for the first mode and at 7.0Hz for the second mode.

Simulation Analysis The base-isolated building was idealized into a lumped mass system as shown in Fig.12. Because the elasticity of oil in the dampers provides additional stiffness during very small amplitude, the stiffness of the base-isolation system was represented by a bi-linear spring as shown in Fig.13, which was determined from the forced vibration test.

The earthquake motions obtained at the base slab were applied to the above model. Fig.14 shows the comparisons of simulated motion and observed record at the roof of building for X and Y directions. The motions of first mode are practically in good agreement with each other. However, the actual records involves much high frequencies which can not be well realized in the simulated motions. The high frequencies appeared in the observed records seems to be resulted not from higher modes of building but from the friction at the mechanical joint or other portions of oil dampers.

CONCLUSIONS

(1) The base-isolation system consisting of the laminated rubber bearings and the oil dampers was proved to be very effective in reducing the acceleration response of the building during small or medium earthquakes.

(2) The acceleration amplitude of the base-isolated building is about from 1/6 to 1/3 of that of the ordinary building on an average.

(3) The principal mode of the base-isolated building can be simulated satisfactorily by a simple lumped mass system.

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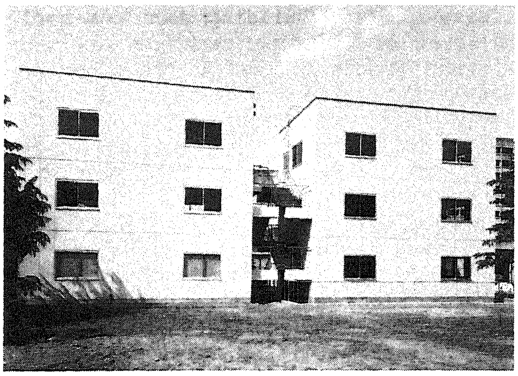


Fig.1 General View of Test Buildings

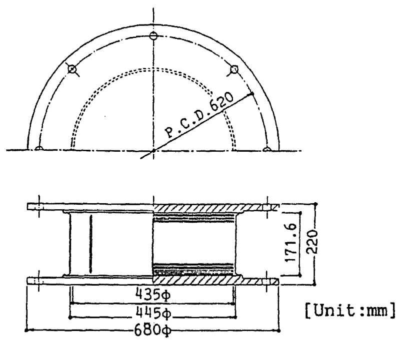


Fig.3 Rubber Bearing

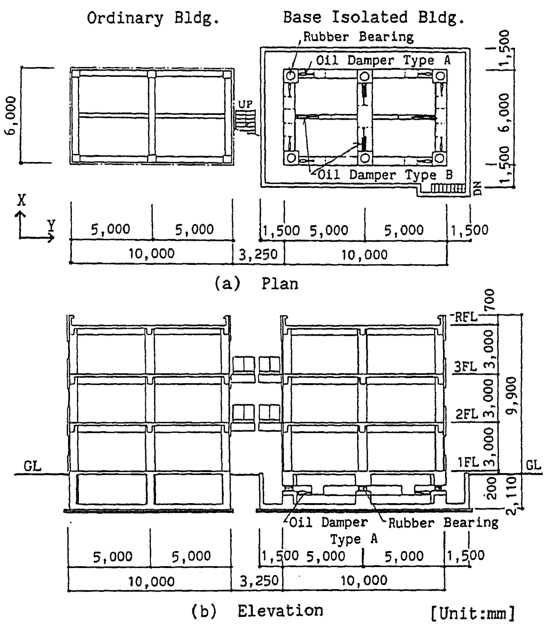


Fig.2 Plan and Elevation of Test Buildings

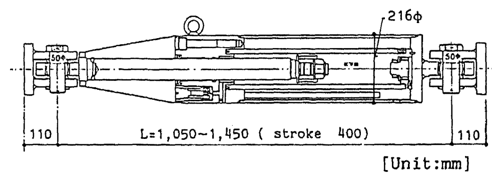


Fig.4 Oil Damper (Type B)

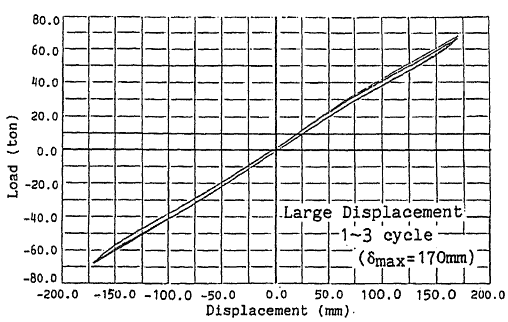


Fig.5 Load-displacement Relation of Base-isolated System

Table 1 Equivalent Stiffness and Damping Ratio

Displacement (cm)	Equi. stiffness (t/cm)	Equi. damping (%)
3.0	3.83	1.24
17.0	4.33	1.67

Table 2 Natural Frequencies and Damping Ratios

Bldg.	Direction	Natural Freq. (Hz)	Damping ratio (%)
Ordinary	X	3.633	1.6
	Y	4.386	1.4
Base-isolated (without damper)	Y	0.737	2.3
Base-isolated (with damper)	X	0.722	16.0
	Y	0.731	15.0

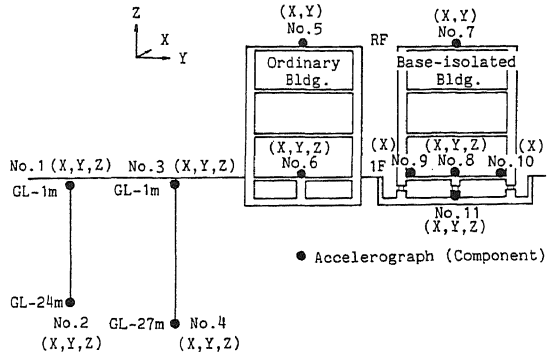


Fig.6 Accelerograph Setup

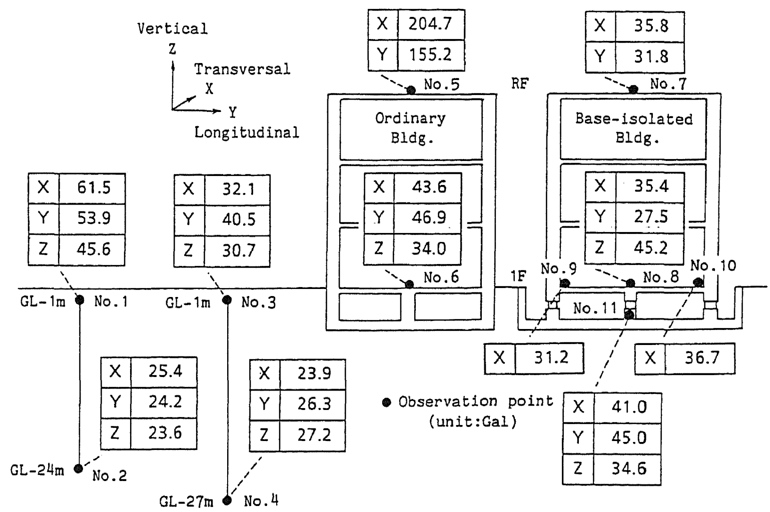


Fig.7 Peak Accelerations Observed during the Earthquake of Feb.6,1987

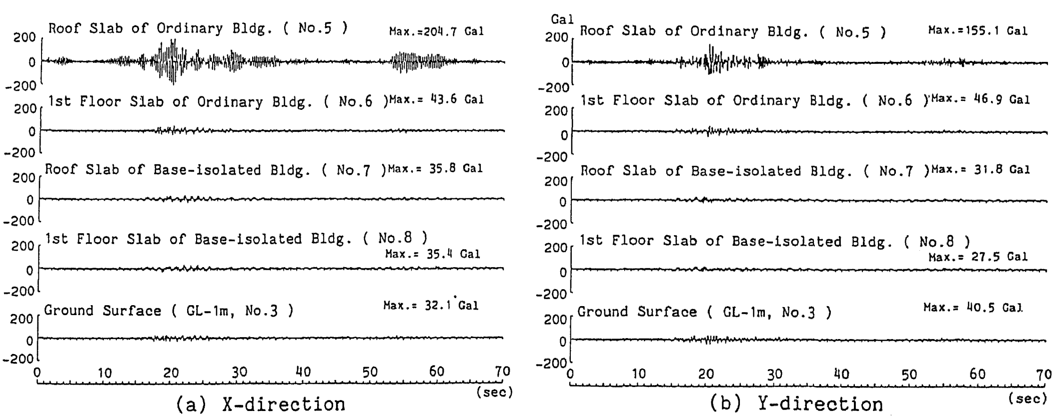


Fig.8 Time-history Records of the Earthquake of Feb.6,1987

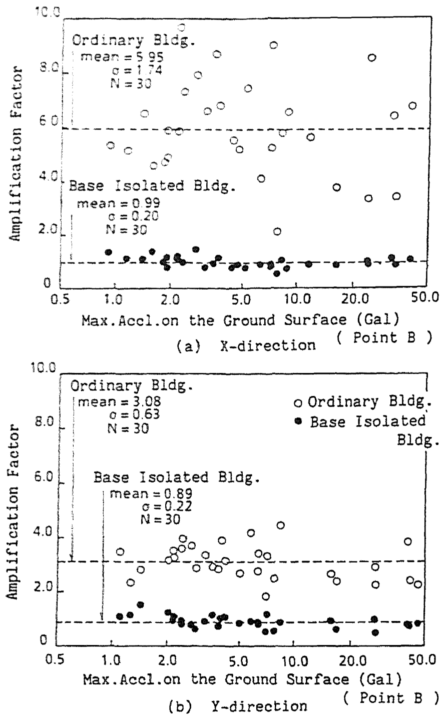


Fig.9 Amplification Factors of Test buildings

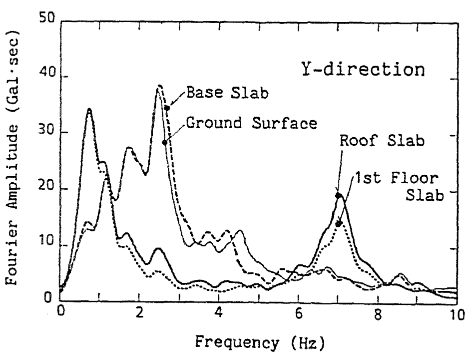
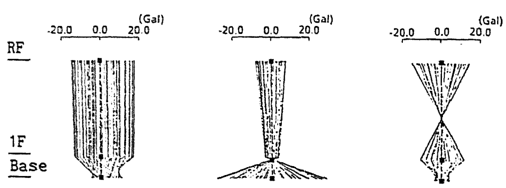


Fig.10 Fourier Spectra of the Earthquake Feb.6,1987



(a) 1st Mode (band=0.25~1.25Hz) (b) Ground Motion (band=2.0~3.0Hz) (c) 2nd Mode (band=6.5~7.5Hz)

Fig.11 Mode Shapes of Base-isolated Building

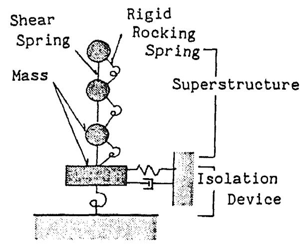


Fig.12 Physical Model

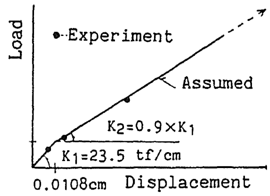


Fig.13 Load-displacement Relation

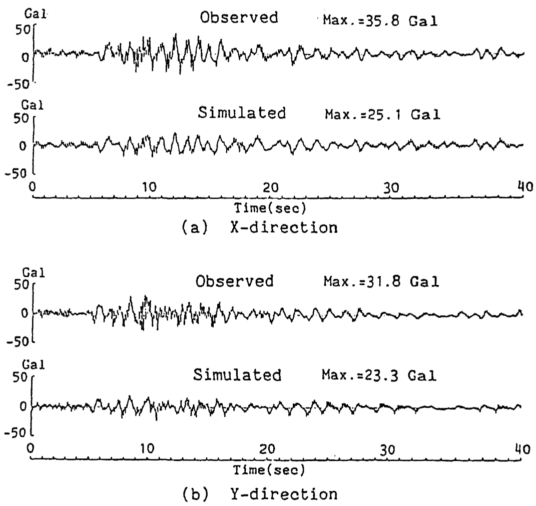


Fig.14 Comparisons of Simulated and Observed Motions