Experimental study on the dynamic behavior of the base isolated building

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1. Introduction

As the seismic isolation concept has recently become the center of wide interest with the hope of cost reduction and standardization of structures such as nuclear power plants, a variety of seismic isolation devices have been developed.

In order to apply the seismic isolation devices to an important structure, accumulation of data on the reliability of these devices is essential. Therefore, close experimental studies on linear and nonlinear behavior of a base isolated building constructed by Okumura Corporation at TSUKUBA SCIENCE CITY were conducted. The isolation device consists of laminated elastomeric rubber bearings and steel dampers. The following tests and observation were performed.

(1) Static loading tests on the isolation device element
(2) Static loading tests on the base isolated building
(3) Forced vibration tests on the base isolated building
(4) Free vibration tests on the base isolated building
(5) Microtremer observation of the base isolated building

The observation of earthquake responses of the building has been under way since September in 1986.

This paper describes major test results of the static loading tests, the forced vibration tests and the free vibration tests conducted on the base isolated building. In addition, the results of the observation of microtremors are compared with the above mentioned test results.

2. Outline of the base isolated building and seismic isolation devices

2.1 Base isolated building

Photo. 1 shows a base isolated building. This is a four-story building made of reinforced concrete with dimensions of 15m in width, 20m in length and 14mm in height. The total floor area is 1,330m^2 and the total weight 2,250 tons.

Seismic isolation devices are installed between the base mat and the first floor.

Photo.1 Birds-eye-view of base isolated building

2.2 Seismic isolation devices

The seismic isolation devices consist of laminated elastomeric rubber bearings and the elasto-plastic steel dampers which increase the predominant period and absorb the vibration energy respectively. Fig. 1 shows the laminated elastomeric rubber bearing in detail, consisting of thin natural rubber seets and steel plates. Fig. 2 shows the elasto-plastic dampers in detail consisting of four spiral steel bars. It behaves elastically when it is deformed slightly, and behaves plastically when it is deformed greatly. These seismic isolation devices are installed as shown in Fig. 3.

2.3 Layout of the sensors

Fig. 4 shows the layout of the sensors, which are used for the measurement of acceleration, velocity and displacement of the building in case of the tests.

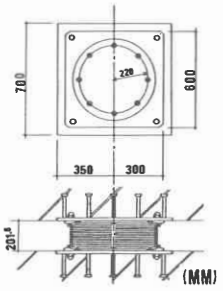

Fig.1 Detail of laminated elastomeric rubber bearing

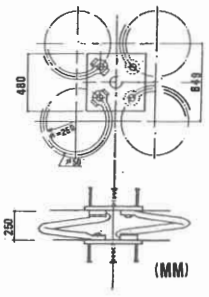

Fig.2 Detail of elasto-plastic damper

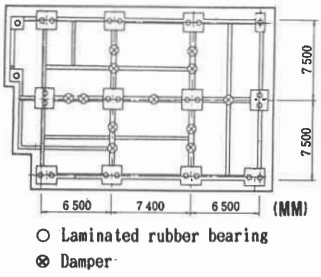

Fig.3 Layout of seismic isolation devices

3. Mechanical characteristics of the isolation devices and the base isolated building.

3.1 Results of static loading tests on the isolation device element

Fig. 5 shows an example of the shear test result for the elastomer under a compression load of 120 tons. The result shows that the elastomer can be considered as linear material up to the displacement of 200mm. The average stiffness of the 25 elastomers used for the base isolated building was 0.82tonf/cm. For the displacement greater than 200mm hardening behavior is observed.

Fig. 6 shows the force-displacement relationship. It should be noted that the characteristics of the restoring force is almost independent of the direction of the external force. The test result shows that the initial stiffness of the damper is 2tonf/cm and the yielding displacement is about 30mm.

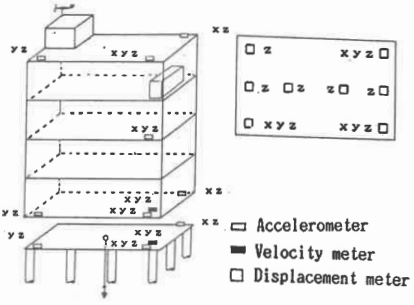

Fig.4 Layout of the sensors

3.2 Results of static loading tests on the base isolated building

Static loading tests were performed by applying the horizontal force to the side of first floor by hydraulic jacks. Fig. 7 shows the force-displacement relationship in case of the building without dampers, that is, the building is supported with elastomers. The stiffness determined from the displacement between 60mm and 90mm was 20.5 tonf/cm, which shows a good agreement with the element test

results. But in the small amplitude region, it is a slightly higher. Fig. 8 shows the force-displacement relationship in case of the building with dampers, that is, both the elastomers and elasto-plastic dampers are installed. The first stiffness corresponding to pre-yielding of elasto-plastic dampers was 45tonf/cm, and the second stiffness corresponding to post-yielding was 24 tonf/cm.
It is concluded that these stiffnesses can be well predicted by the element test results for the elastomer and the damper.

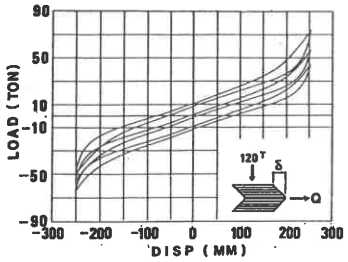

Fig.5 Element test result of laminated elastomeric rubber bearing

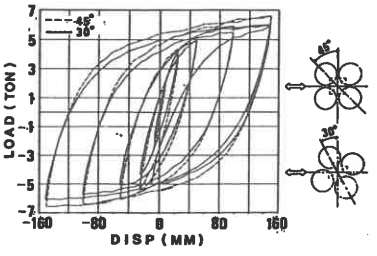

Fig.6 Element test result of elasto-plastic damper

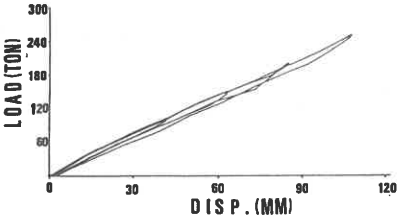

Fig.7 Static loading test result of the building (Without damper)

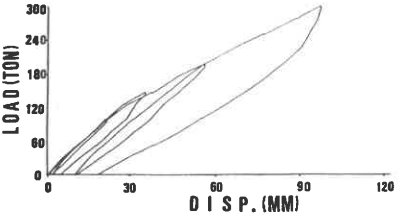

Fig.8 Static loading test result of the building (With dampers)

4. Forced vibration test

The forced vibration tests were carried out to obtain the linear characteristics of the base isolated building.

4.1 Test method

In these tests, exciter mounted on the first floor induced the translational and torsional vibrations. Fig. 9 shows the position of the exciters. In order to examine the effect of the elasto-plastic dampers, a variety of tests were performed for the base isolated building with and without dampers.

4.2 Test results

(1) X-direction excitation

As a typical example of the X-direction excitation, Fig. 10 and Fig. 11 show the frequency response and the vibration mode at the resonance respectively in case of the building with dampers. The velocity frequency response of the first floor, the third floor and the roof per unit excitation force, coincide with each other, showing the typical first mode of the seismically isolated building. The natural frequency was 0.88 Hz and damping ratio was 2.5%.

(2) Y-direction excitation

Fig. 12 shows the frequency response of the roof in case of Y-direction excitation for the building with dampers. The natural frequency was 0.90Hz, showing almost the same value as that of the X-direction excitation. The damping ratio was 2.5%.

(3) Torsional excitation

In this excitation, two natural frequencies corresponding to the translational and the torsional natural frequencies can be found in Fig. 13. It turned out that the torsional natural frequency was 0.80 Hz, which was close to the translational frequency.

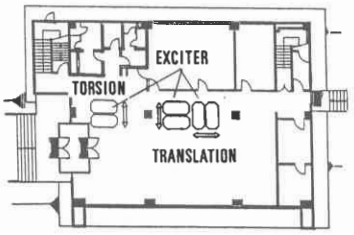

Fig.9 Positions of Exciter

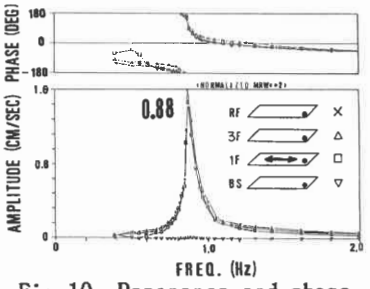

Fig.10 Resonance and phase curve of velocity response in case of X-dir. excitation

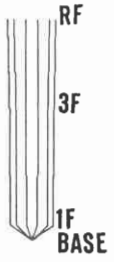

Fig.11 Mode shape at the resonance

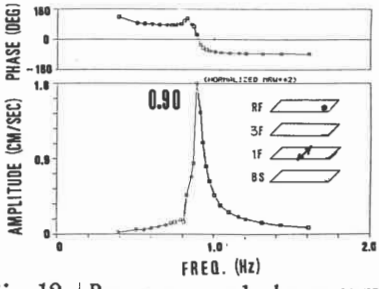

Fig.12 Resonance and phase curve of velocity response in case of Y-dir. excitation

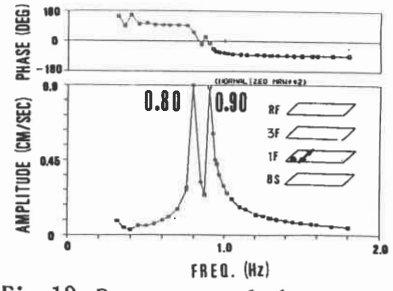

Fig.13 Resonance and phase curve of Y-dir. velocity response in case of torsional excitation

5. Free vibration test

The free vibration tests were carried out to obtain the nonlinear characteristics of the base isolated building.

5.1 Test method

For these tests, a load release device shown in Photo. 2 was developed. It allows to apply relative displacement between the base mat and the first floor and to release it to cause free vibration. Relative displacements of 30mm, 50mm and 100mm were applied.

5.2 Test results

(1) Effect of dampers

Fig. 14 shows the relative displacement response between the base mat and

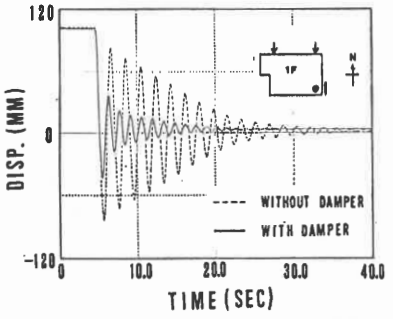

Fig.14 Relative displacement between the base mat and the first floor

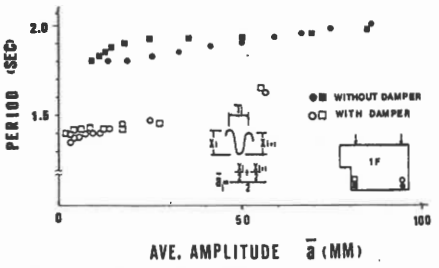

Fig.15 Relationship between amplitude and vibration periods

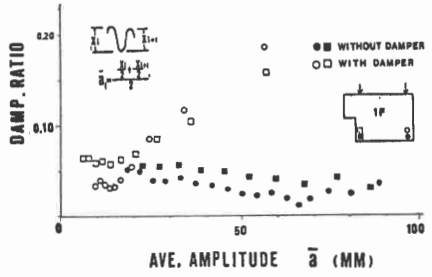

Fig.16 Relationship between amplitude and damping ratios

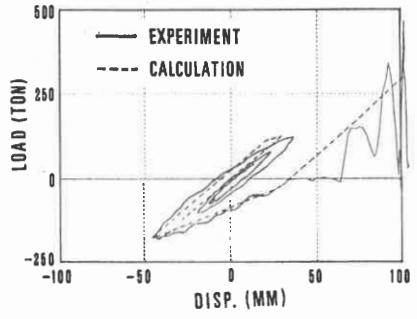

Fig.17 Relationship between restring force and displacement (With dampers)

the first floor in case of a 100 mm initial displacement. The solid line indicates the result for the building with dampers and the dotted line without dampers. It shows that dampers reduce vibration amplitudes sufficiently during a strong earthquake.

(2) Vibration periods and damping ratios

Fig. 15 shows the relationship between the average amplitude and the vibration periods, and Fig. 16 shows the relationship between the average amplitude and the damping ratios. For the building without dampers, the vibration periods are almost constant regardless of the change in vibration amplitude. When dampers were attached, the vibration periods are lengthened according to the increase of vibration amplitudes. And the damping ratios are increased due to the hysteretic behavior of steel damper. The maximum damping ratio obtained this tests was about 18 %.

Photo.2 Loading and Releasing device

(3) Restoring force-displacement relationship

Fig. 17 shows the restoring force-displacement relationship obtained by the free vibration test. The dotted line indicates the analytical result based on the element test data described in 3.1. It shows that this relationship is well modelled by the bi-linear model.

6. Summary

Major results are summarized in Table 1 including the results of the micro-tremor observation and the calculation. The followings were clarified through this research.

(1) Frequency response curves for the first floor, the second floor and the roof almost coincided in case of the forced vibration tests, showing the typical first mode of the seismically isolated building.
(2) Damping ratios obtained by the forced vibration tests in case of both with and without dampers were about 2.5 %.
(3) Torsional natural frequencies were found by forced vibration tests to be very close to the translational natural frequencies.
(4) Vibration periods obtained by free vibration tests are lengthened in large deformation region due to the yielding of the dampers.
(5) Elasto-plastic dampers give high-damping due to their hysteretic behavior. The maximum damping ratio obtained by the free vibration tests was about 18 %, which is considered large enough to reduce vibration amplitude sufficiently during a strong earthquake.
(6) Natural frequencies obtained by the microtremor observation were a slightly higher than those from the excitation test, reflecting the characteristics of isolation devices in the range of small vibration amplitudes.
(7) Mechanical characteristics of the base isolated building can be well predicted by the element test results for the elastomer and the damper.

The experimental studies on the base isolated building are summarized as above and it was confirmed that the seismic isolation device consisting of laminated elastomeric rubber bearings and elasto-plastic dampers works well.

Accumulation of data on a lot of earthquake responses is required hereafter for further verification of the performance of the base isolated building.

Table.1 Results of tests and calculation

		Without Damper			With Damper		
		Natural Period (SEC)	Natural Freq. (HZ)	Damp. Ratio (%)	Natural Period (SEC)	Natural Freq. (HZ)	Damp. Ratio (%)
Calculation	X-dir.	2.12	0.47	—	1.45	0.69	—
	Y-dir.	2.11	0.47	—	1.43	0.70	—
	Torsion	2.04	0.49	—	1.75	0.57	—
Microtremor	X-dir.	1.47	0.68	—	1.02	0.98	—
	Y-dir.	1.47	0.68	—	1.02	0.98	—
	Torsion	1.28	0.78	—	1.14	0.88	—
Forced Vibration Test	X-dir.	1.52	0.66	2.64	1.14	0.88	2.38
	Y-dir.	1.52	0.66	2.44	1.11	0.90	2.53
	Torsion	1.39	0.72	—	1.25	0.80	—
Free Vibration Test (Y-dir)	30 mm	1.80	0.56	3.8* 2.6**	1.30	0.77	6.9* 3.1**
	50 mm	1.85	0.54	3.8 2.4	1.37	0.73	10.4 3.9
	100 mm	2.00	0.50	3.2 2.5	1.68	0.59	18.0 8.0

*) 1st Cycle of the Free Vibration
**) 2nd Cycle of the Free Vibration

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