CHARACTERISTICS OF SEISMICALLY ISOLATED BUILDING

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SUMMARY

It is well known that installation of seismic isolation bearing effectively improves seismic-resistance of building during earthquake. The CTI Fukuoka Building adopted seismic isolation bearing to withstand major tremor similar to the recent Hyogo-ken Nanbu Earthquake due to possible slippage of the dislocation near the area. The object of this study is to examine the seismic behavior of the building as well as to verify the characteristics of seismic isolation bearing based on the performed static loading and excitation tests.

The building is a seven-floor structure consists of ordinary reinforced concrete (Y-direction) and earthquake-resisting (X-direction) rigid frame walls. Seismic isolation bearings are installed at the foundation. The building was shook at the base in two directions perpendicular to the walls using hydraulic jacks to produce damped free vibration. Devices for measuring displacement are placed in the first, fourth and top floors to determined the seismic characteristics of the structure. Results reveal that the building behaves as rigid body in X-direction with natural frequency of 1 Hz and damped vibration propagates at approximately five-second interval, which show high seismic isolation effect. On the other hand, high frequency vibrations of about 4 Hz and over were observed in Y-direction. This is due to the difference of rigidity in the two directions, where stiffness is greater in X-direction. Also, the natural frequency obtained from the test is significantly smaller than the designed value, since the latter corresponds to large displacements during earthquake. Displacement modes show rocking and three-dimensional vibrations in Y-direction. Moreover, damping constant in the first vibration mode varies according to displacement of bearing within the range of approximately 0.1 to 0.14, thus satisfying sufficient condition for seismic isolation bearing.

Based on the excitation test results, the building exhibits the necessary seismic characteristics as designed, although its behavior during earthquake was not possible to estimate since shear strain of seismic isolation bearing was very small.

INTRODUCTION

In recent years, It is well known that application of seismic isolation bearings on foundation effectively improves seismic-resistance of buildings under earthquake. Nevertheless in the past, the installation of seismic isolation bearings had just been limited in few important structures or buildings owing to the cost of construction.

On the records observed in Hyougoken-nanbu earthquake (1995. January.17), it is evident that the bearings withstand well to major tremors. For the reasons mentioned above, in recent years the seismic isolation bearings have spread even to various buildings.

In this construction, in view of the location near a dislocation area where slippage may possibly occur, seismic isolation bearings were adopted to withstand strong earthquake similar to Hyougoken-nanbu earthquake.

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When finishing the building, in order to examine the seismic behavior as well as to verity the characteristics, static loading and excitation tests were made by using hydraulic jacks. In this paper the results of the tests are described and discussed.

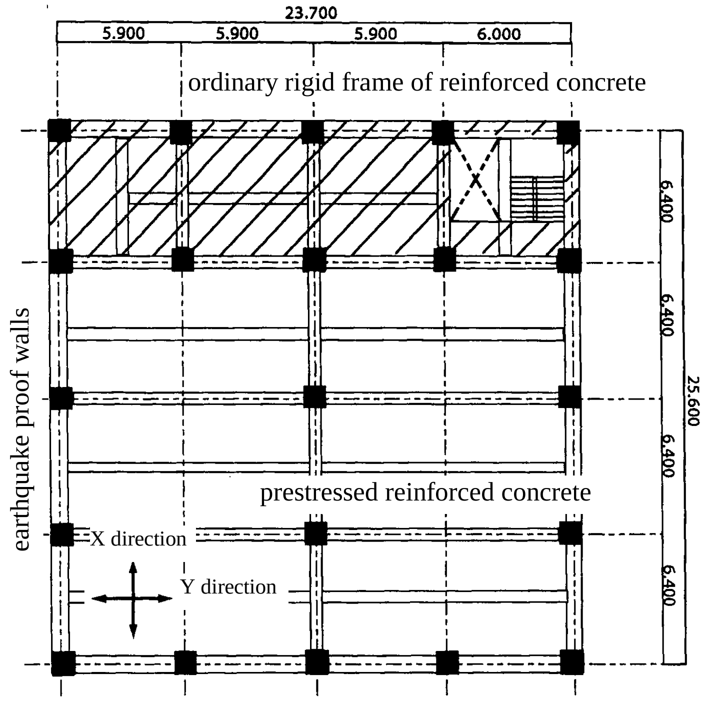

Figure 2.1.1: Building structure

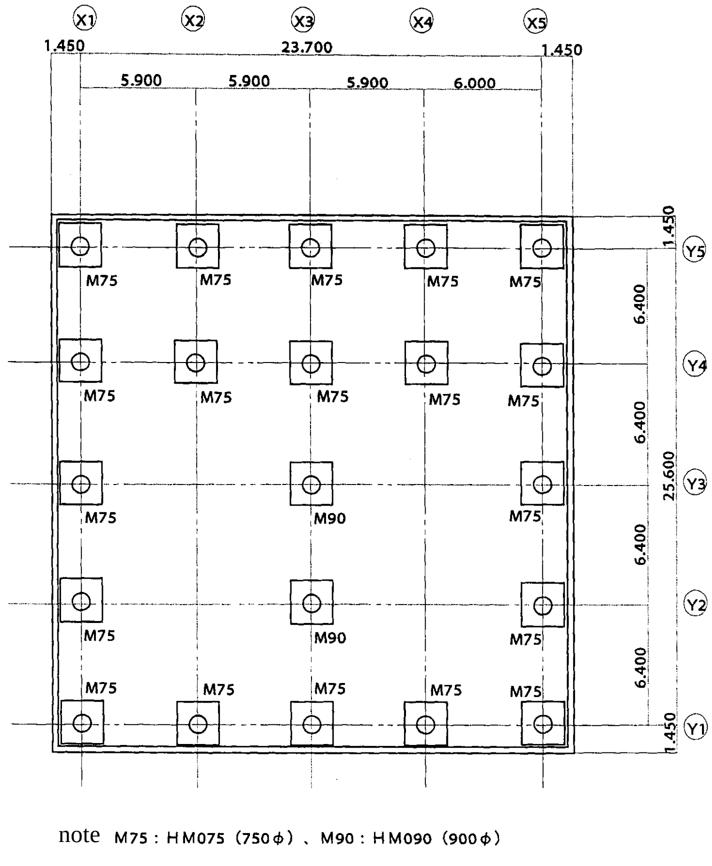

Figure 2.2.1: Allocation of Seismic isolation device

2. BUILDING OUTLINE

The CTI Fukuoka building is a seven-floor structure with height of 28 meters. As shown in Fig.-2.1.1, the building consists of rigid frame with earthquake-proof walls in X-direction and ordinary rigid frame of reinforced concrete for outer wall in Y-direction. Therefore horizontal rigidity for the two directions is different. furthermore on the underground where the seismic isolation bearings are installed, a rainwater tank is set up.

In Fig.-2.2.1 the installation of seismic isolation bearings is shown, which include 19 set of M75 and 2 M90 type bearings as well as 21 rubber ones in total.

Table 3.1.1: Results of dynamic analysis

			Stage	Direction	Value	Wave
H.D.R	Seismic isolation device	Maximum relative displacement	Ⅱ	X	16.9	Simulated wave
				Y	15.8	Simulated wave
			Ⅲ	X	30.4	PORT ISLAND NS
				Y	28.1	PORT ISLAND NS
		Maximum shear modulus	Ⅱ	X	0.097	Simulated wave
				Y	0.093	Simulated wave
			Ⅲ	X	0.138	PORT ISLAND NS
				Y	0.130	PORT ISLAND NS
	superstructure	Maximum absolute acceleration at top	Ⅱ	X	113.8	Simulated wave
				Y	109.7	Simulated wave
			Ⅲ	X	142.7	Simulated wave
				Y	157.8	TAFT EW
		Maximum shear modulus at bottom	Ⅱ	X	0.097	Simulated wave
				Y	0.096	Simulated wave
			Ⅲ	X	0.137	PORT ISLAND NS
				Y	0.136	PORT ISLAND NS
		Maximum interlaminar angle	Ⅱ	X	1/3290	Simulated wave
				Y	1/547	Simulated wave
			Ⅲ	X	1/2264	PORT ISLAND NS
				Y	1/341	PORT ISLAND NS
Eccentric effects			low effects			
Vertical vibration effects			Seismic response analysis of vertical direction is carried out using the three- dimensional dynamic flame model. The result of analysis are composed wit the rubber plane pressure in horizontal direction, It is performed the case which stage Ⅲ and the marginal study.			
Check for tension			The result of above analysis , in the case of stage Ⅲ, the maximum stress of tensional plane in 10 kgf/cm^2, it is remained in the elastic range. In the case of marginal study, the superstructure keep safety even if it is ignore the H.D.R that is over the admissible tensional plane stress.			

3. DESIGN OF BUILDING

The design is different from general structure design because of the adoption of seismic isolation bearings.

In the case of earthquake, owing to action of seismic isolation bearings the accelerate response decreases, but the relative displacement between foundation and building increase. Moreover dynamic analysis is necessary to investigate building characteristic under earthquake since the shear strain of the seismic isolation bearings behaves nonlinear, The analysis results are given in the Table-3.1.1.

4. TEST

4.1 Excitation test

Because the building is structured with rigid frame with earthquake-proof walls in X-direction and ordinary rigid frame of reinforced concrete for outer wall in Y, the horizontal rigidity is various in the two directions. Therefore exciting directions are determined in two directions, that are X and Y directions as shown as in Fig.-2.1.1.

Taking the view that torsion vibration may occur while building is excited in horizontal, devices for measuring displacement are placed at two sides in a proper location for exciting directions, on the first, forth floor and rooftop of building respectively. By supposing the structure behaves damping free vibration, the seismic characteristics of the building are investigated from the vibration mode recorded on the above-mentioned spots.

A hydraulic jack with bearing capacity of 100 ton is set on the base of the building to generate forced vibration. The building is shocked forcedly by dropping auxiliary piece down as soon as the hydraulic jack finished loading. The seismic characteristics of the structure, that is natural frequency, displacement mode and damping coefficient are examined from the records of the damping free vibration at the same time.

In view that horizontal rigidity depends on displacement, loading conditions are definite to 40,50 and 60 ton in the Y-direction as well as 40,50,60,and 70 ton in the X respectively.

4.2 Static loading test

In the excitation test, loading is increased gradually using the hydraulic jack, the records of the loading and displacement at this time are utilized to examine the static characteristics of the seismic isolation bearings.

5. TEST RESULTS

5.1 Time history

When finishing excitation shocked by the hydraulic jack, the damping free vibrations occur shown in the Figure-5.1.1 and 5.1.2 for X and Y directions respectively. And then to investigate the displacements and the phase difference of vibration, the accelerations observed at the two sides are indicated also. It is found that there are a very little difference in the values between phase and accelerations, it may be caused by the reason that torsion has not appeared.

In the case of X-direction excitation, high order modes of vibrations are observed at the end of loading, and after it the damping vibrations rapidly propagate in approximately five-second interval, the natural frequency turn into damping free vibration with frequency of 1Hz. It shows high seismic isolation effect. Moreover it is clear that the mode shapes are independent on weight of loading. On the other hand, high frequency vibration with about 4 Hz and over are observed in Y-direction and the frequency value increases with loading. It is due to the different rigidity in two directions.

5.2 Fourier spectrum

Under X-direction excitation the Fourier spectrums, corresponding to the damping free vibration shown in Fig.-5.1.1, are indicated in Fig.-5.2.1 which are calculated by FFT way with N=2048, sampling interval Δt=0.01

second. The increment of frequency Δf , indicated x-axis component of the Fourier spectrums, is obtained from the following equation.

$$\Delta f = 1 / (N + \Delta t) = 1 / (2048 \times 0.01) = 0.048 \text{ Hz}$$

In this figure the frequency of 0.98 Hz is predominant, then the second order mode is observed near the value of 5 Hz. And then under Y-direction excitation the Fourier spectrums, corresponding to the damping free vibration shown in Fig.-5.1.2, are indicated in the Fig.-5.2.2. The results reveal that there are a number of peak values which more than the case of x-direction excitation, furthermore various orders are mixed in a mode of vibration.

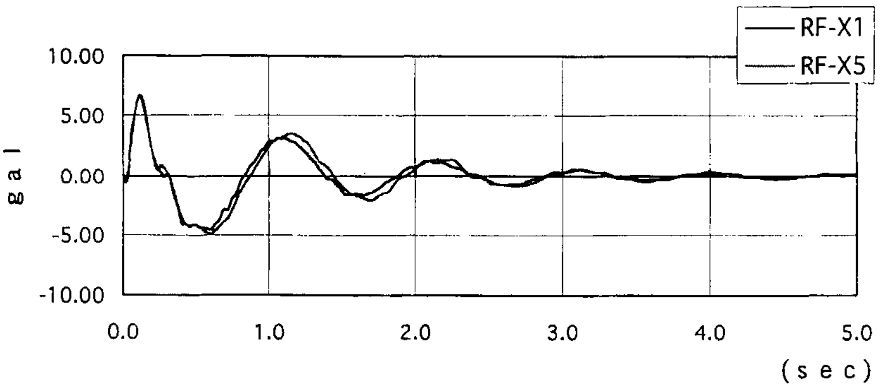

Figure 5.1.1: Time history (X direction, 70t)

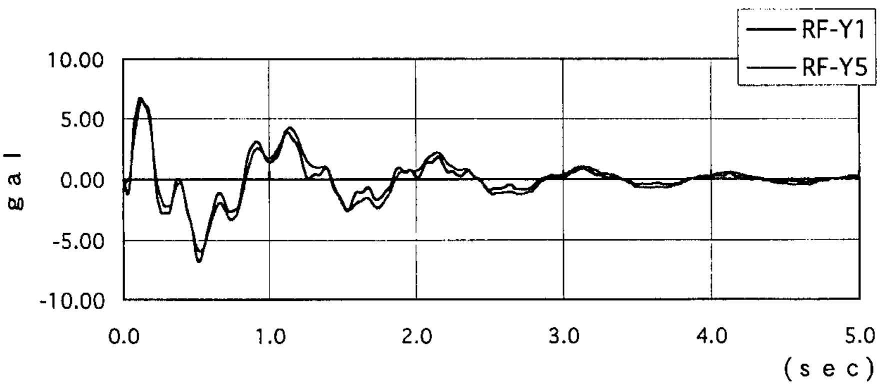

Figure 5.1.2: Time history (Y direction, 60t)

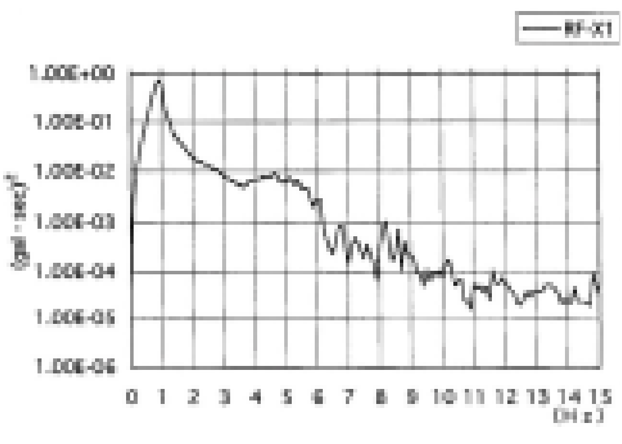

Figure 5.2.1: Fourier spectrum (X direction, 70t)

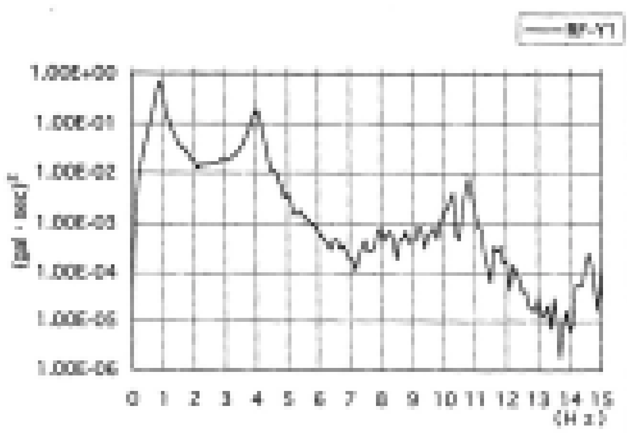

Figure 5.2.2: Fourier spectrum(Y direction, 60t)

5.3 Natural frequency and displacement mode

The natural frequencies in X and Y-directions are obtained, from the predominant frequencies in the above Fourier spectrums, as shown in the Table-5.3.1. For X-direction excitation, with increasing loading, the natural frequencies in X-direction have decreased in a certain extent. This is due to the reason that shear rigidity of the seismic isolation bearings depends on displacement. Comparing the natural frequencies in X-direction, the value of second mode in Y-direction is rather small. Moreover the modes higher than third order have not been appeared, owing to the large horizontal rigidity in this direction. Furthermore the comparison of the natural frequencies between design and test results is indicated also in Table-5.3.1. It is evident that the shear modulus in addition the natural frequencies of design are smaller than the test, since the design is bases on nonlinear deformation assumption.

Table 5.3.1: Natural frequency(Hz)

	Vibration along X direction			Vibration along Y direction		
	Test value	Calculation value		Test value	Calculation value	
γ (%)	2.6	100	150	1.9	100	150
$\Delta \ell$ (mm)	4.26	161	240	3.07	161	240
First degree	0.98	0.376	0.345	0.98	0.371	0.340
Second degree	4.59	3.496	3.497	4.00	2.404	2.392
Third degree		6.711	6.711	10.16 (10.64)	4.785	4.785

γ : shear strain of seismic isolation device, $\Delta \ell$: shear displacement of seismic isolation device

In Fig.-5.3.1 and 5.3.2, the vibration modes in X and Y-directions are shown corresponding to the natural frequencies indicated in Table-5.3.1. Because the horizontal rigidity in X-direction for first mode is smaller than Y, the deformation occurs in X, while the damping free vibration appears in Y-direction. In other hand with damping propagating, the third modes with frequencies of 10.2 Hz and 10.64 Hz reach to same shapes.

For both directions, it is observed that the displacements of building occur in same direction as vibration for first mode but opposite for second. Furthermore the third mode of vibration in Y-direction is observed as well. These are quite agreement with the analysis results shown in Table-5.3.1.

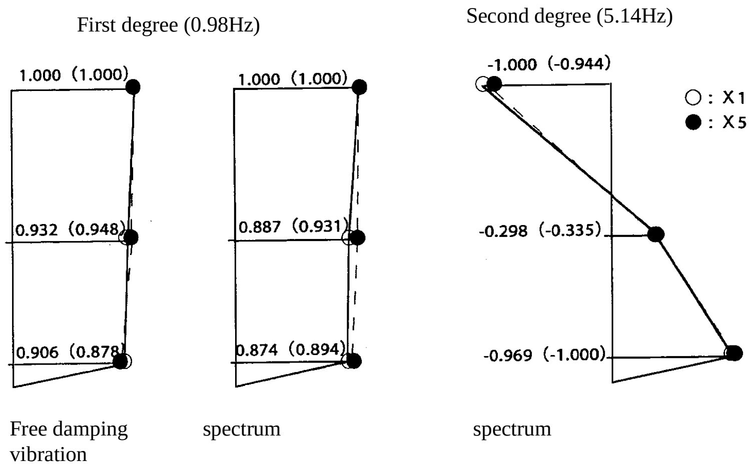

Figure 5.3.1: Deformation mode (X direction)

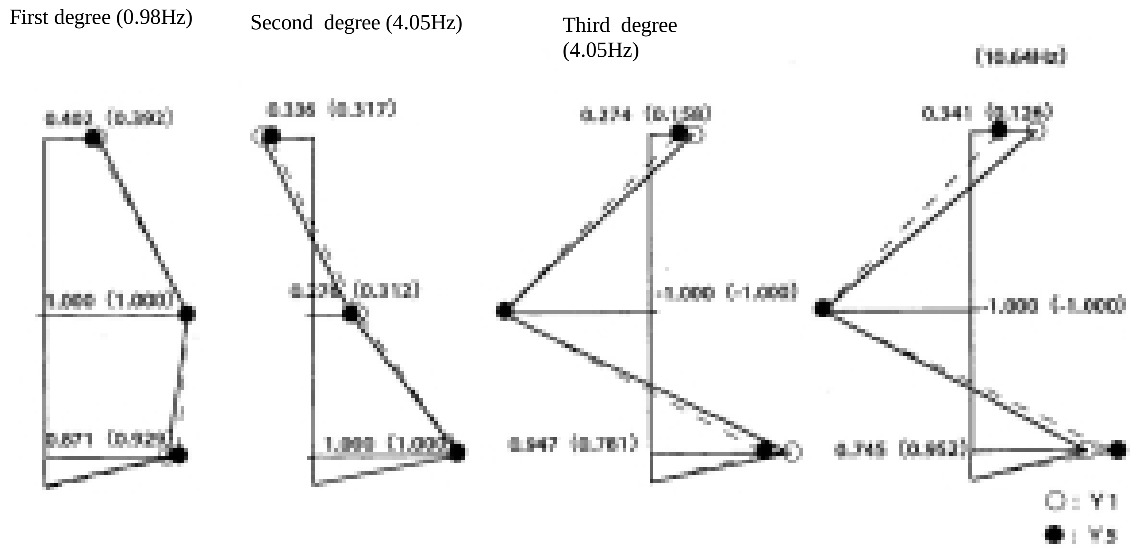

Figure 5.3.2: Deformation mode (Y direction)

5.4 Damping coefficient

Damping coefficient is determined from the mode of damping free vibration. With loading increasing, the damping coefficients get large so that seismic isolation bearing behaves nonlinear. The damping coefficients for first mode depend on displacement with values of 0.1~0.14. Here the bearings with damping rubber show high seismic isolation effect.

5.5 Static loading test

The static characteristics of the seismic isolation bearings are examined by investigating the displacement of foundation that are measured in the process loading to maximum in excitation test. Based on the assumption that the seismic isolation bearings hold same behavior within the limits of this test, it is found that with loading increasing, the displacement has increased such that shear modulus (G) behaves nonlinear

5.6 Characteristics of seismic isolation bearing

In Fig.-5.6.1, the relation of loading to displacement is indicated under static loading test, which is obtained by averaging the values of displacements measured at various points when loading with 70 ton in X and 60 ton in Y-direction respectively. Under static loading, the maximum displacements in horizontal are 4.26 mm and 3.07 mm in X and Y-direction corresponding to loading condition with 70 ton and 60 ton respectively. According to linear shear strain theory, it is evident that with increasing loading, the increments of displacement have increased, and then shear coefficient together with displacement lower in value.

Here, from the maximum displacement of 4.26 mm in X-direction, equivalent shear coefficient (Ke) is determined from the following equation.

$$Ke = Pmax / \Delta l = 70(t) / 0.426(cm) = 164.3 \text{ t/cm}$$

And then the natural frequency for first mode f_1 can be obtained.

$$f1 = 1/2\pi \cdot \sqrt{(g \cdot Ke / W)} = 1/2\pi \cdot \sqrt{(980 \times 164.3 / 6800)} = 0.77\text{Hz}$$

This value is rather smaller than the test. Consequently the equivalent shear coefficient Ke is calculated again corresponding to the natural frequency of test.

$$Ke = (2\pi \cdot f1)2 \cdot W / g = (2\pi \times 0.98)2 \times 6800 / 980 = 274t / cm$$

The above value of Ke is quite close to the one corresponding to the displacement of 1 mm as shown in Fig.-5.6.1. It is why damped vibration propagates quickly in about five-second interval from maximum displacement that the equivalent shear coefficients remain unchanged value, which approximately equal to the one corresponding to the displacement of 1 mm.

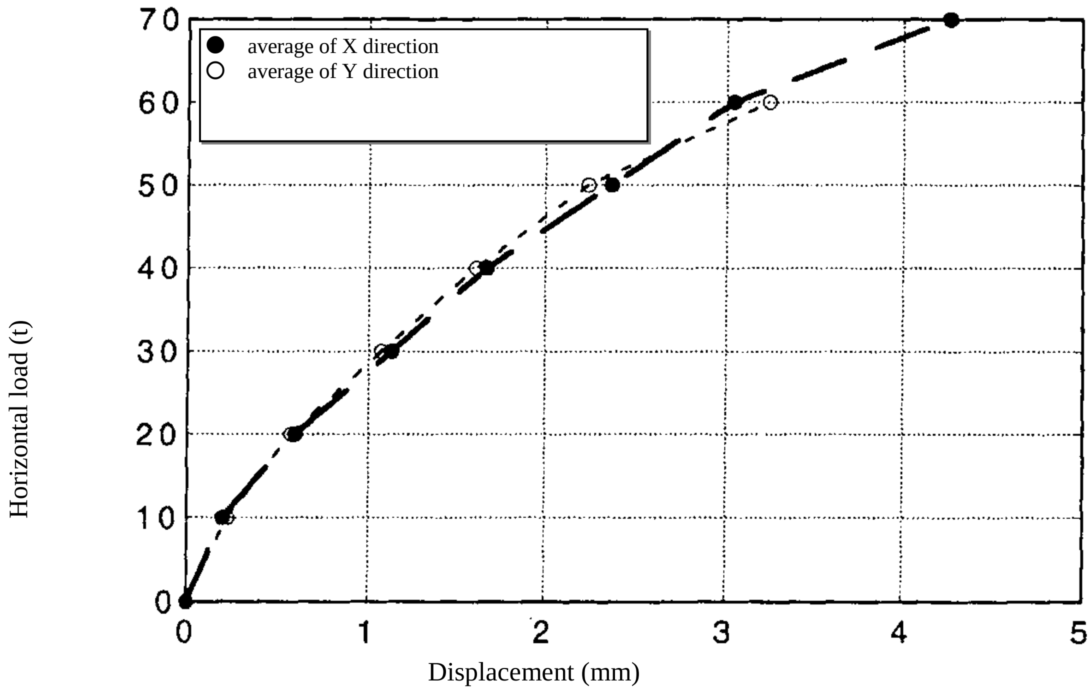

Figure 5.6.1: Load-displacement curve of the seismic isolation bearing

6. CONCLUSIONS

In the present test, based on the assumption of linear shear strain it is proved that the building behaves prescribed seismic characteristics, as designed, although its behavior due to stronger earthquake cannot be estimated from the recently recorded shear strain of the seismic isolation bearing because the values were too small.