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THE STUDY OF BASE ISOLATION SYSTEM FOR ACTUAL USE

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SUMMARY

The authors have been studying a Base Isolation System using laminated rubber bearings and viscous dampers. In April 1987, after preliminary studies, we built a practical base-isolated building. This report describes the design method of a Base Isolation System using laminated rubber bearings and viscous dampers. According to earthquake observation, it appeared that the acceleration was reduced to less than half the level of ground motion at the superstructure. Using the earthquake records, we consider the characteristics of the devices during earthquakes.

INTRODUCTION

Up to now, the energy absorbing devices used in Base Isolation Systems have employed many kinds of dampers based on the plastic deformation of metal. The authors have developed a damper which employs the shear deformation of viscous fluid, and have been studying a Base Isolation System which uses laminated rubber bearings and viscous dampers.

In base isolated structures using this system, the restoring force and damping force are carried by the rubber bearings and the viscous dampers respectively. This makes the design process easier, and results in a system that is effective even under a small level of input. Because of these merits, we are hopeful that we will be able to employ this system not only in buildings for ordinary use but also in precision environmental facilities.

In 1983, we carried out a small-scale model test to confirm the basic characteristics of the system. In 1984, we built a full scale model supporting 500 tons at our laboratory site. We conducted free vibration tests on the full scale model. We also carried out earthquake observations to measure the behavior of the full scale base isolated structure.

The Funabashi Chikuyuryou dormitory, completed in April 1987, was the first building to practically employ this Base Isolation System. In the 18 months since its completion, the building has undergone several earthquakes. In this report, we summarize the design procedure, and examine the "Base Isolation Ability" of the structure through observation records.

DESIGN OF ISOLATION SYSTEM

The Funabashi Chikuyuryou dormitory is shown in Photo.1 and Fig.1 (RC 3F, Total floor space : 1530 m^2, Building weight : 2479 tons). To apply the Base Isolation System to this building, the design was carried out according to the following process.

Rubber Bearings The dimensions of a rubber bearing are decided under the process shown in Fig.2. The conditions for the design of both types of rubber bearings (supporting 150 ton and supporting 200 ton weight) are as follows. Horizontal natural frequency : 0.5Hz, vertical natural frequency : 18Hz, maximum horizontal relative displacement : 30cm, vertical load during an earthquake : twice ordinary state, life-span : 60 years, maximum creep : less than 5% of total rubber thickness during its lifetime. Under these conditions, the local strain of rubber bearings is controlled to under 400%, whereas the failure local strain of rubber is 600%. A pressure under a vertical load is 2,479 tons per 57,218 cm^2 total rubber bearing area. The rubber bearings are laminated with natural rubber and insert plate (steel), but they are surrounded by synthetic rubber to make their lives longer.

In Photo.2 the bearing for a 200-ton weight is cut to show its construction. The thicknesses of the rubber sheets for 200-ton and 150-ton bearings are 6.0mm and 5.8mm respectively. The thickness of the insert plate is 2.2mm for both types. The rubber bearings employed in the Funabashi Chikuyuryou are produced by BRIDGESTONE CORP.

Viscous Dampers The dimensions of a viscous damper are decided under the process shown in Fig.3. The following two conditions are given for design: The maximum horizontal displacement must be controlled to under 30cm, and the life-span must be longer that 60 years. The applied viscous fluid is called SA-P (product of OILES Inc.). The fluid is mainly composed of poly-butene and its viscousity is very high. According to the accelerated aging test, the ozone-proof, water-proof, acid-proof and bacteria-proof characteristics of the viscous fluid were confirmed as being very good. The damping force of the viscous damper is expressed in the following equation.

$$F = 0.42\, e^{-0.043T} A\, (V/d)^{0.59} \tag{1}$$

where F : the damping force (kg), T : the temperature (°C), A : the area of the resistance plate (cm), V : the relative velocity between resistance plate and base plate (cm/sec) and d : the thickness of the fluid (cm). In these parameters which compose eq.(1), the velocity V is calculated in following manner.

In the primary linear response analysis, the effective velocity is calculated in the time span window T (natural period of the structure) giving the desired damping coefficient.

$$Ve = \sqrt{\frac{1}{T}\int_{t_1}^{t_2} v^2\, dt} \qquad (\text{window} : T = t_2 - t_1) \tag{2}$$

Moving t_2 and t_1 throughout the response, the maximum value is chosen as V. In the case of the Funabashi dormitory, V is calculated as 50 cm/sec from the primary linear response analysis, setting the desired damping ratio h=0.08. Also setting the temperature T=15°C (average temperature throughout the year) and the thickness of viscous fluid d=1cm, the area of the resistance plate is calculated using following values.

Building mass	$M = 2.53\text{x}10^3$ kg.sec²/cm
Lateral stiffness	$K = 24940$ kg/cm
Critical damping	$Cc = 2\sqrt{MK} = 15887$ kg.sec/cm
Required damping	$C = hCc \approx 1271$ kg.sec/cm

Required damping force $F = CV = 63548$ kg
Required resistance plate area $A = 28664\ cm^2$

Eight dampers, each having a 34cm radius resistance plate (total area $29053 cm^2$), are distributed as shown in Fig.1. The effect of the temperature difference between winter and summer is also checked. A cross section of the damper is shown in Photo.3.

EARTHQUAKE OBSERVATION RESULTS

In this building, 15 accelerometers have been installed to observe earthquakes. The locations of accelerometers are shown in Fig.1. In Table 1, the maximum observed acceleration values of major earthquakes in Chiba Pref. are shown. The epicenters of these earthquakes are plotted in Fig.4. As can be read in the table, the roof by base ratio of maximum acceleration is 0.4-0.5 for rather small earthquakes whose intensity is smaller than IV (Japan Meteorological Agency scale). But for the earthquakes which had larger intensities, the ratio decreases to 0.2-0.3. Here it is known that the amount of reduction in acceleration is bigger for stronger earthquakes. The roof by first floor ratios of acceleration are almost 1.0-1.2. This fact indicates that the behavior of the superstructure was almost rigid.

Of the seven earthquakes listed in Table 1, the wave records of earthquakes No.1, 6 and 7 in the EW direction are shown in Fig.7. Here, the input wave at the base and the response wave at the roof are compared. The records at the roof contain natural frequency components of the base-isolated structure.

In Fig.9, the Fourier spectra are shown in a comparison of records at the base and records at the roof. From the spectra, most of the acceleration power over 1.0Hz was reduced when it was transferred through the isolation system. In Fig.10, the transfer functions from base to roof are shown. Transfer functions of three earthquakes almost overlap in the frequency range 0Hz through 10Hz. The dominant frequency of the transfer functions is aorund 0.64-0.7Hz. The amplitude is about 2.3-2.5. In earthquakes of this intensity, we couldn't find any difference in the shape of transfer functions caused by maximum acceleration level nor any difference caused by epicenter location.

THE CHARACTERISTICS OF THE SYSTEM'S STIFFNESS

The Base Isolation System installed in the Funabashi Chkuyuryou is desinged to have a natural frequency of 0.5Hz. As can be read in Fig.10, the observed dominant frequency (0.64Hz) was 20% higher than the design. We considered the phenomena as follows.

The Stiffness of The Rubber Bearings The stiffness of the rubber bearings has non-linearity as shown in Fig.5. The design had been carried out using the stiffness (K=24.9 ton/cm) where the shear strain of rubber is 10-40% (about 1.5-7 cm displacement). On the contrary, the relative displacement of earthquake No.6 between the base and the first floor is 1.0 cm in Fig.8 Within a displacement of this level, the stiffness of rubber bearings is calculated Kr=29.6 t/cm in Fig.5 which is 19% higher than the design value.

The Stiffness in the Viscous Damper If the viscous fluid was an ideal Newton Fluid, it wouldn't have the stiffness essentially. Actually, as shown in Fig.6, the relation between the shear force and the deformation has certain slope Kd. From the experiment using the cylindrical damper model, Kd is expressed in following equation.

$$Kd = 0.047\ A\ (a/d)^{-1}\ (v/d)^{0.7} \tag{3}$$

where A : resistance plate area (cm^2), a : relative displacement between resistance plate and base plate (cm), v : relative velocity between the plates (cm/sec), d : thickness of viscous fluid (cm). Substituting v=8.00cm/sec (according to Fig.8), a= 1.0 , d=1cm, A=3,632×8cm^2 into eq.(3), we obtained Kd=6.0t/cm.

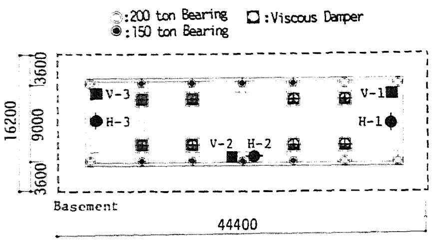
Considering the initial stiffness of the rubber bearings and the stiffness of the viscous fluid, the natural frequency of the building is re-calculated as follows.

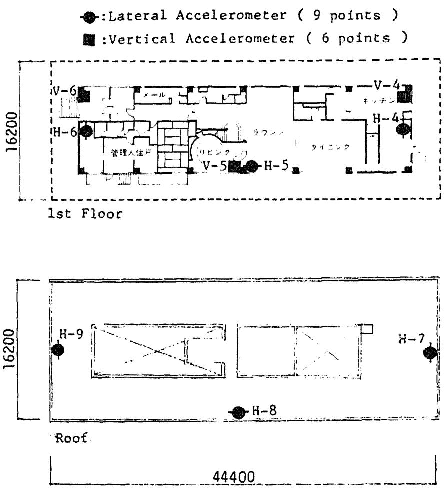
$$1/2\pi\ \sqrt{(Kr+Kd)/M} = 1/2\pi\sqrt{35.6/2.35} = 0.62\text{Hz} \tag{4}$$

This value is almost equal to the observed dominant frequency (0.64Hz).

CONCLUSION

The Funabashi Chikuyuryou, which was designed according to above mentioned design process, appeared to have a good "Base Isolation Ability" from the observed earthquake records. The horizontal acceleration is reduced to less than half the level of that of ground motion. When the input levels were not so large, it was found that the natural frequency of the structure was 20% higher compared with the designed value. It is considered that the initial stiffness of rubber bearings and the stiffness of viscous fluid caused the phenomena. Using the simulation analysis, we are planning to study the structure in more detail.





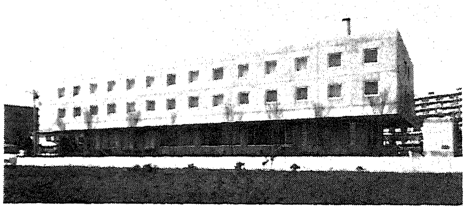


Photo.1 View of the Building.

Fig.1 Location of Accelerometers.

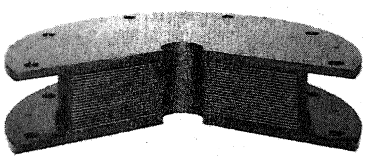


Photo.2 200-ton Rubber Bearing Cut to Show Construction.

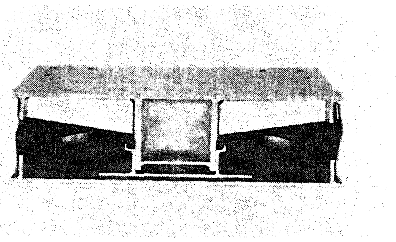


Photo.3 Viscous Damper Cut to Show Construction.

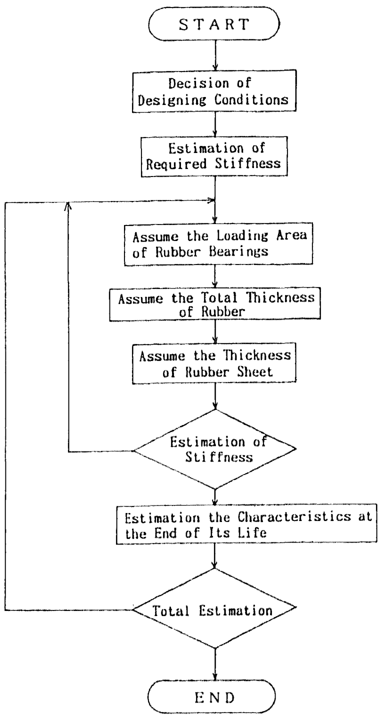


Fig.2 Design Process of Rubber Bearing

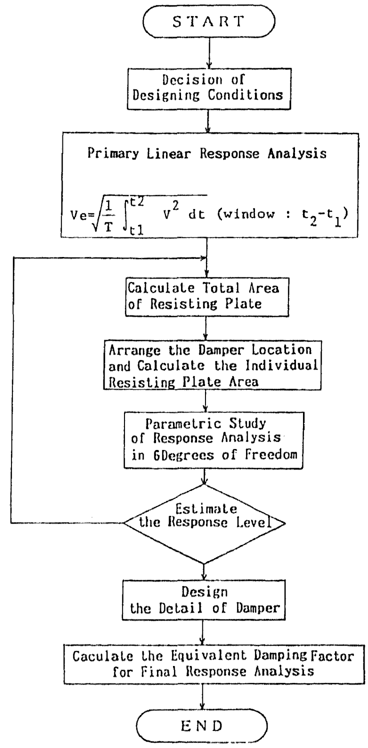


Fig.3 Design Process of Viscous Damper

Table 1 List of Observed Earthquakes. (gal)

No.	Date	Epicenter	Intencity		Base		1st Floor		Roof	
			Tokyo	Chiba	N-S	E-W	N-S	E-W	N-S	E-W
①	87/4/7	Off Fukushima	Ⅳ	Ⅲ	10.8	15.3	6.1	8.6	6.3	9.0
②	4/10	South West Ibaraki	Ⅲ	Ⅲ	12.6	15.6	5.2	2.4	6.2	2.8
③	4/17	North Chiba	Ⅱ	Ⅲ	5.0	5.6	2.4	2.4	2.8	2.4
④	4/23	Off Fukushima	Ⅲ	Ⅲ	8.8	14.0	4.2	4.4	4.0	4.4
⑤	6/16	Central Chiba	Ⅰ	Ⅲ	14.0	18.4	3.2	2.4	3.6	2.4
⑥	12/17	East Off Chiba	Ⅳ	Ⅴ	64.4	86.3	27.0	22.4	23.1	23.3
⑦	88/3/18	East Tokyo	Ⅲ	Ⅳ	50.0	49.9	15.3	8.8	15.8	10.3

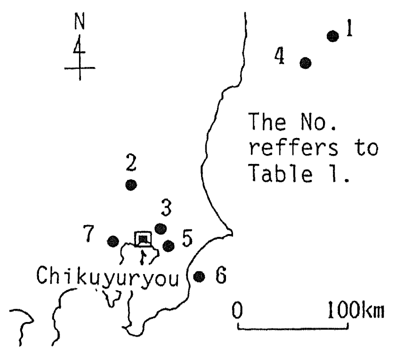


Fig.4 Epicenter Location

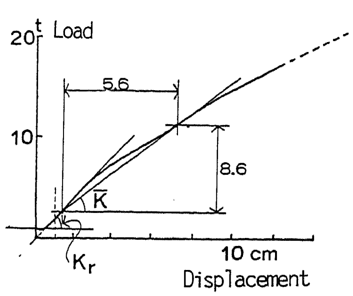


Fig.5 Load-Displacement Relationship of Rubber Bearing

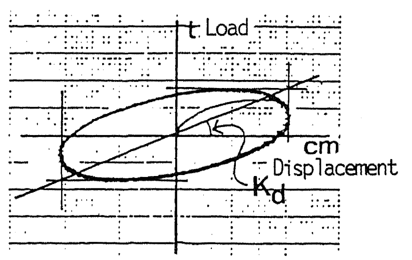


Fig.6 Load-Displacement Relationship of Viscous Damper

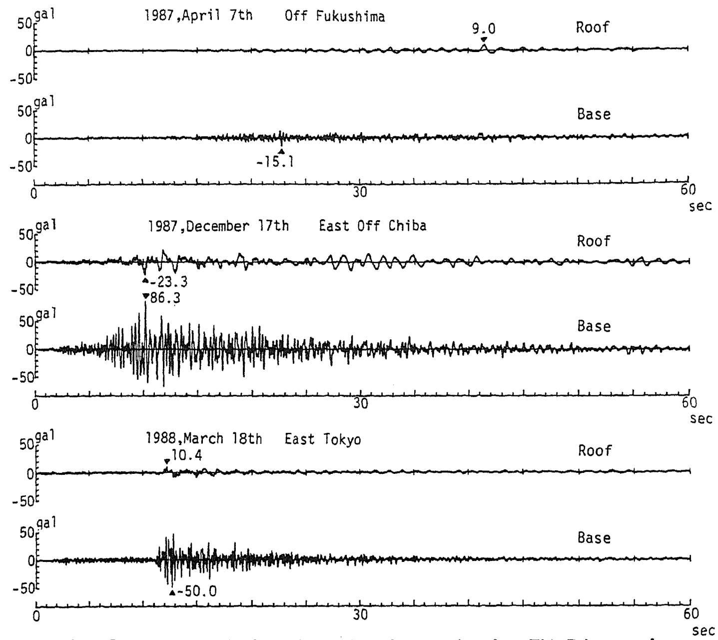


Fig.7 Observed Earthquake Records in EW Direction

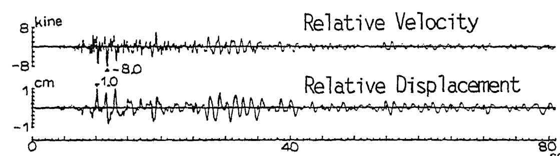


Fig.8 Relative Velocity and Displacemnt between Base and 1st. Floor

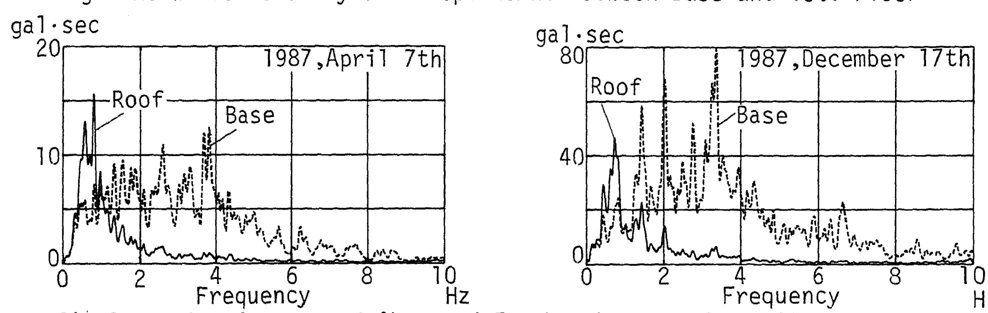


Fig.9 Fourier Spectra of Observed Earthquake Records in EW Direction

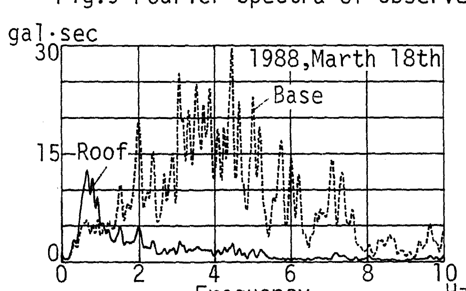


Fig.9 Fourier Spectra.

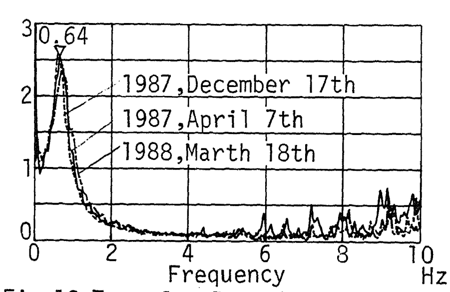


Fig.10 Transfer Functions of Observed Earthquake Records.