

RESPONSE CHARACTERISTICS OF BASE-ISOLATED STRUCTURE WITH SILICONE RUBBER BEARINGS

S. Hayashi¹, H. Watanabe¹, Y. Nakamura¹, T. Yoshizawa² and T. Nakamura³

¹Shimizu Corporation, Tokyo, Japan
²Bridgestone Corporation, Tokyo, Japan
³Shin-Etsu Chemical Industry Co. Ltd., Tokyo, Japan

1.INTRODUCTION

More than sixty base-isolated buildings have been built in Japan. A number of base-isolation systems were considered in our research, which was intended to establish the effectiveness of base-isolation systems. We conducted research on silicone rubber bearings. Generally, silicone rubber is durable and its characteristics are not dependent on the temperature within the relevant design range.

The first part of the report covers material and elements testing. After the bearings were installed in the building, we performed forced vibration tests in both the horizontal and vertical directions. These test results form the next section. After several experiments, we carried out earthquake observations. We report on the effectiveness of the system in reducing response acceleration during a small displacement. This system was installed in the building in March 1992.

2.CHARACTERISTICS of SILICONE RUBBER and SILICONE RUBBER BEARINGS

2.1 Material

The fundamental characteristics of the rubber are shown in Table 1. The 25% modulus of the silicone rubber is somewhat low compared to that of the high damping rubbers. It is nearly equal to that of natural rubber, however, the tensile strength of the silicone rubber is low compared to other rubbers. Silicone rubber is equal to the natural rubber in the ultimate elongation.

Certain tests were performed on the silicone rubber material. Fig. 1 shows the shear modulus and the tanδ as a function of temperature. Tanδ is a factor related to damping. The shear modulus and the tanδ of the silicone rubber material are not dependent on the temperature within the relevant design range.

We performed several aging tests to investigate the durability of silicone rubber. Table 2 shows the results. The aging test simulated sixty years of natural aging. The variations in stiffness was +17% and that in ultimate elongation was -7%. Tensile strength remained nearly unchanged.

2.2 Bearing (Scale model)

We used a scale model to test the fun-

Table 1 Material characteristics of rubber

Material	Hardness (JIS A)	25% Modulus (kgf/cm ²)	Ultimate Elongation (%)	Tensile Strength (kgf/cm ²)
Natural Rubber	40±5	3.4±1.0	≥500	≥200
High Damping Rubber (Low Modulus Type)	50±5	4.7±1.0	≥800	≥150
High Damping Rubber (High Modulus Type)	60±5	12.0±2.0	≥650	≥100
Silicone Rubber	45±5	4.0±1.0	≥500	≥90

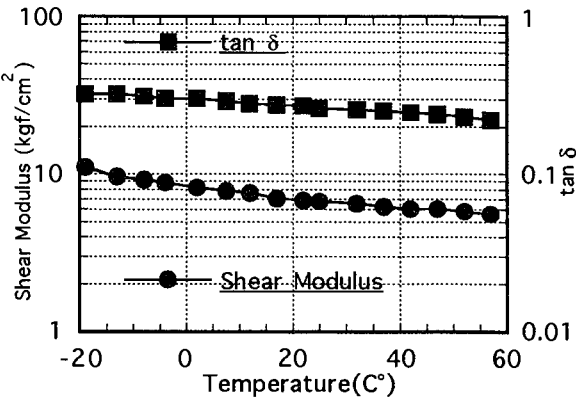


Fig. 1 Dependence on temperature of material

damental characteristics of the silicone rubber bearing.

Fig. 2 shows the influence of vertical stress on the hysteresis characteristics of the silicone rubber bearing. The experiment was performed by varying the vertical stress. As it increases, the loop area expands and the equivalent damping ratio tends to increase. This tendency was evident at small displacements. However, there was almost no change in the shear modulus.

Fig. 3 shows the influence of loading speed on the shear modulus and the equivalent damping ratio of the silicone rubber bearings. The experiment was performed in which the loading speeds were altered. The shear modulus of the silicone rubber bearings did not respond to changes in the vibration frequency within the relevant design range. The damping ratio was influenced by frequency changes.

To investigate the durability of the silicone rubber bearing further, we performed another aging test.

Table 3 shows the results of the aging test. The variation in horizontal stiffness was about +20% and that for the damping ratio was -10%~+20%.

2.3 Bearing (Real scale)

Fig. 4 shows the dimensions of the bearing used in this test. The bearing consisted of 24 layers with a thickness of 6.5-mm and a diameter of 600mm, 23 steel plates with a thickness of 3.1mm, top and bottom flange plates with thickness of 29.6-mm.

Table 4 shows the design values of this bearing. The equivalent horizontal stiffness for a displacement of 10 cm is 663.7 kgf/cm (horizontal frequency is 0.3Hz), and the equivalent hysteresis damping ratio is 0.12.

Before installing the rubber bearings under the building, a static loading test was performed at the laboratory.

A horizontal loading test was carried out under a constant vertical load of 110 tf. The horizontal stiffness and the equivalent damping ratio at each displacement are shown in Fig. 5.

In this displacement range, the horizontal stiffness of the silicone rubber bearing is linear. The values are almost equal to the design values. And the equivalent damping ratio is higher than 15% at displacements under 20cm and 13% at displacement of 30cm in the second cycle. This value is higher than the design value.

Table 2 Material characteristics by aging tests

		Initial Value	Value after Aging Test	Ratio of Variation
Stiffness	kgf/cm ²	8.9	10.4	+17%
Tensile Strength	kgf/cm ²	103	106	+3%
Ultimate Elongation	%	680	630	-7%

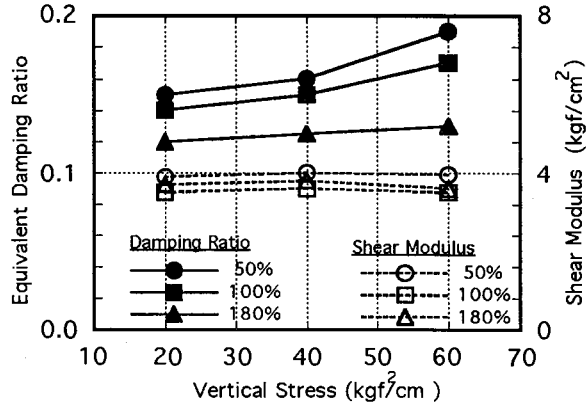


Fig. 2 Dependence on vertical stress of bearing characteristics

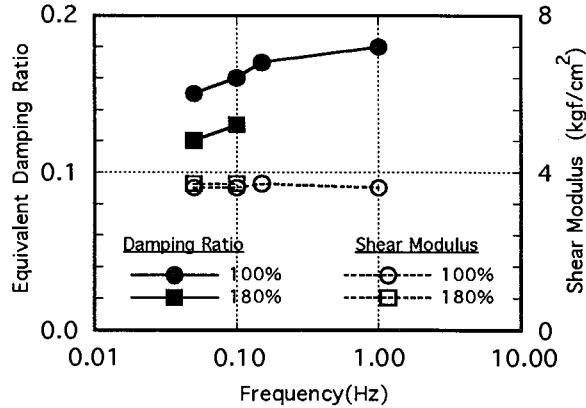


Fig. 3 Dependence on frequency of bearing characteristics

Table 3 Bearing characteristics by aging tests

Aging Tests	Horizontal Stiffness	Damping Ratio
Ordinary states	+20%	-10% ~ +20%
Vertical stress dependency	+13%	-9%
Frequency dependency	0%	+2% ~ 5%
Cyclic dependency	same as the initial state	same as the initial state

3.BUILDING

The building with the silicone rubber bearings is located in Matsuida, Gunma Prefecture, Japan. It is a two story reinforced concrete structure which was completed in March 1992. A general view of the building is shown in Fig. 6.

The building is used as a guard house and PBX (Private Branch Exchange) for the factory. The building is 8.4m by 8.4m, and the total combined area is about 142m². Total weight of the building is 392tf.

Four bearings were installed. This building was founded on a gravel layer with clay, which has a shear wave velocity of 370m/sec. Construction of the base-isolated building with the silicone rubber bearings had been authorized by the Minister of Construction in Japan.

4.SITE EXPERIMENT

In order to investigate the basic properties of the building, forced vibration tests were carried out immediately after installation of the silicone rubber bearings.

4.1 Forced Vibration Test (Horizontal)

In order to investigate the dynamic properties of the building, a forced vibration test was carried out in March 1992. A vibration exciter was installed in the center of the roof slab and applied horizontal sinusoidal forces to the building. Fig. 7 shows the change in the resonance curves of the building along the X axis, based on the eccentric moment of the exciter. The resonant frequency clearly decreases as the loading force increases, i.e. amplitude of horizontal displacement increases. This tendency also holds for ordinary high damping rubber bearings.

The natural frequencies and the damping ratios in both directions as obtained from the experiment are shown in Fig. 8. These values were affected by the amplitude of the vibrations. As horizontal displacement increased, damping ratio increased and natural frequency decreased. The natural frequency was about 0.8Hz (1mm) ~ 0.9Hz (160μm) and the damping ratio was about 8% (160μm) ~ 12.5% (1mm) in both directions. The damping ratio of the silicone rubber bearing exceeds the design value at the displacements over 1mm.

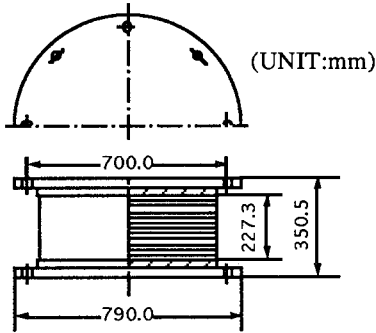


Fig. 4 Dimension of silicone rubber bearing

Table 4 Design value of bearing

Horizontal Stiffness	663.7	(kgf/cm)
Natural Frequency (Horizontal)	0.3	(Hz)
Vertical Stiffness	1170	(tf/cm)
Natural Frequency (Vertical)	12.6	(Hz)
Equivalent Damping Ratio	≥12	(%)

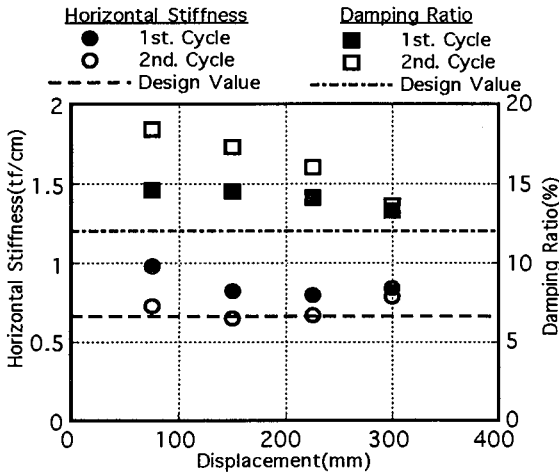


Fig. 5 Horizontal stiffness and Damping ratio by the static loading test

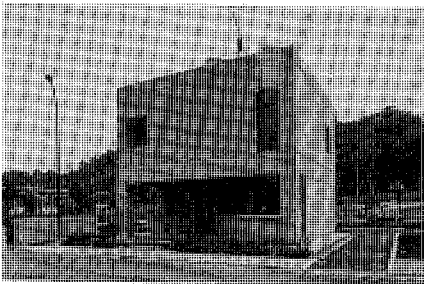


Fig. 6 General view of the building

Fig. 9 shows the results of the natural frequency when the forced vibration test was used on an isolation system with ordinary high damping rubber bearings, lead rubber bearings and the silicone rubber bearings. The natural frequency of the building with the silicone rubber bearings was lower than that of other systems over a small displacement range. The natural frequency of the silicone rubber is 1/3 that of the lead rubber bearing and 1/2 that of the high damping rubber bearing.

Fig. 10 shows the results of the damping ratio when the forced vibration test was used on an isolation system. The damping ratio of the building with the silicone rubber bearing was larger than that of other systems and 1.5 times that of the high damping rubber bearing.

The power spectrum of the micro tremor is shown in Fig.11. The natural frequency is about 1.06Hz.

4.2 Forced Vibration Test (Vertical)

In order to investigate the dynamic properties along the vertical axis of the building, a forced vibration test was carried out in December 1992. A small vibration exciter was installed in the center of the roof slab and applied sinusoidal forces vertically to the building. Force from the exciter was 19.2kgf.

Fig.12 shows the power spectrum of the sum of the response at opposite ends of the first floor and indicates the natural frequency along the vertical axis. The vertical natural frequency of the building with silicone rubber bearings installed is about 14.0Hz. Ordinary systems are over 18Hz.

Fig.13 shows the power spectrum of the difference of the response at opposite ends of the first floor. This shows the natural frequency of the rocking vibration, which are 11.8Hz in the X-direction and 12.0Hz in the Y-direction.

The power spectrum of the micro tremor in the vertical direction is shown in Fig.14. The graph indicates the overlap of the vertical vibration and the rocking vibration.

These results demonstrate that the vertical stiffness of the silicone rubber bearing is 1/2 that of the other materials.

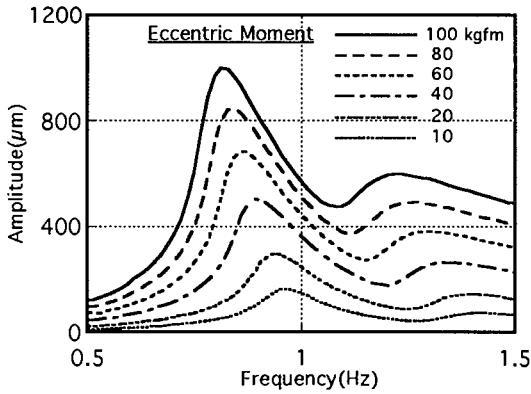


Fig. 7 Resonance curve of different eccentric moment

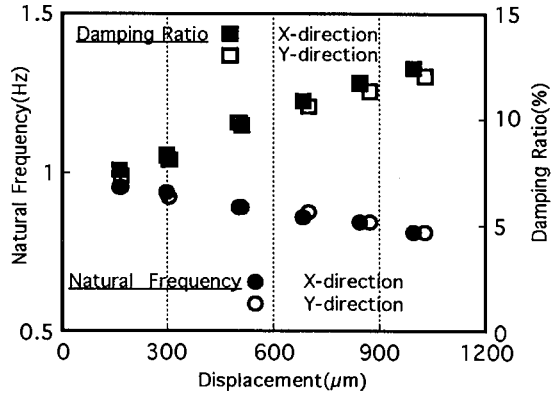


Fig. 8 Damping ratio and natural frequency by the forced vibration test

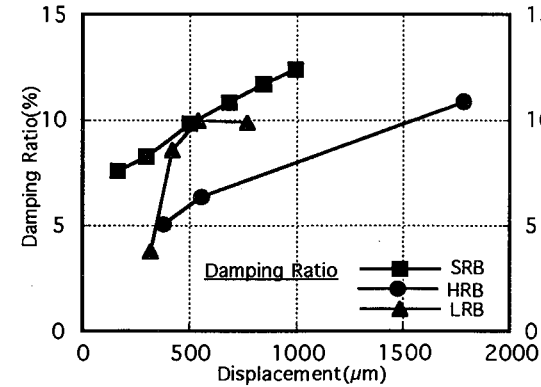


Fig. 9 Damping ratio of several type of bearings by the forced vibration test

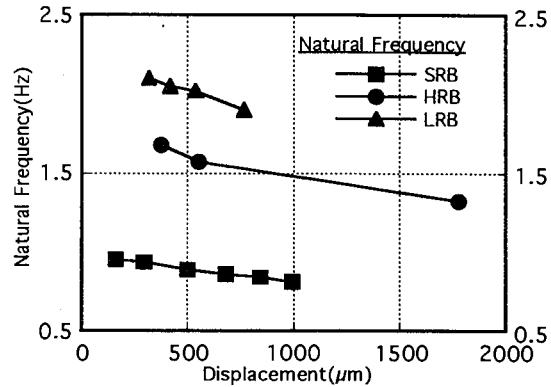


Fig. 10 Natural frequency of several type of bearings by the forced vibration test

5.EARTHQUAKE OBSERVATION

5.1 Accelerometer setup

After the forced vibration test, an earthquake observation was carried out for the building and the surrounding ground to investigate the dynamic behavior of the building during earthquakes. The response of the building to significant earthquake events is automatically recorded.

Acceleration of five points was observed. The accelerometers were placed in the hard soil stratum(GL-20m), on the surface of ground near by (GL-1m), on the base slab of the base-isolated building, and on the first floor and the roof of the building. In all 16 components of earthquake motion were monitored.

5.2 Recorded earthquake data

Several earthquakes were recorded through June 1992. One of the recorded earthquakes is shown below. The highest acceleration of this earthquake on the ground surface was recorded at about 8 Gal. The maximum accelerations of all accelerometers during the earthquake on April 10, 1992 are shown in Fig.15. The maximum accelerations on the roof of the building was 1.70 Gal in the Y direction and 1.30 Gal in the X direction.

The maximum acceleration value of the first floor of the building is reduced 1/3 that of the basement of the building, and 1/5 that of the ground surface. During small earthquakes, the silicone rubber bearings are clearly effective in reducing the response acceleration.

The accelerograms for X direction at several points are shown in Fig.16. The accelerograms recorded in the building showed a longer period of vibration.

The earthquake response at the 1st floor of the building on this earthquake in the X and Y directions imply a fundamental frequency estimated at about 1Hz. Earthquake response in the Z direction is estimated at 12~15Hz. This value was equal to that produced by the forced vibration tests.

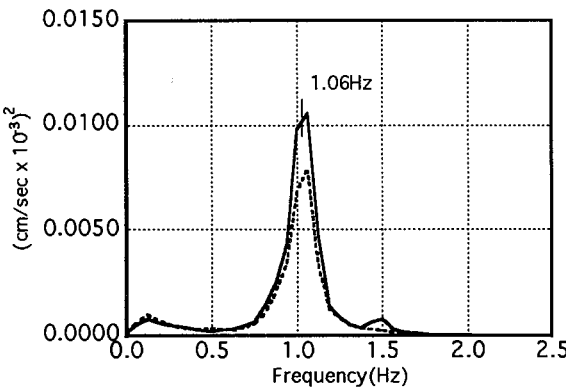


Fig. 11 Power spectrum of the horizontal direction by micro tremor

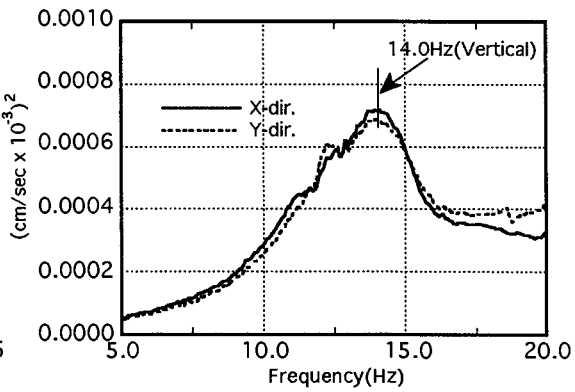


Fig. 12 Power spectrum of the vertical vibration by the forced vibration test

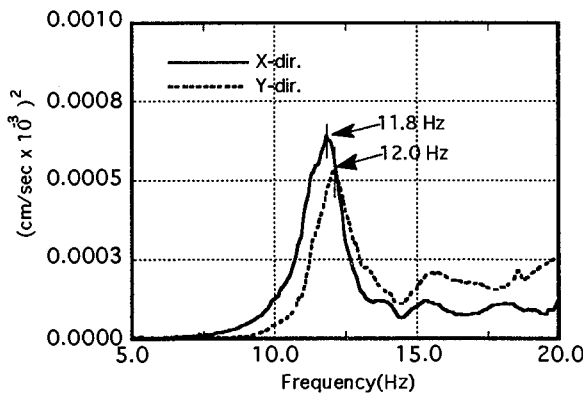


Fig. 13 Power spectrum of the rocking vibration by the forced vibration test

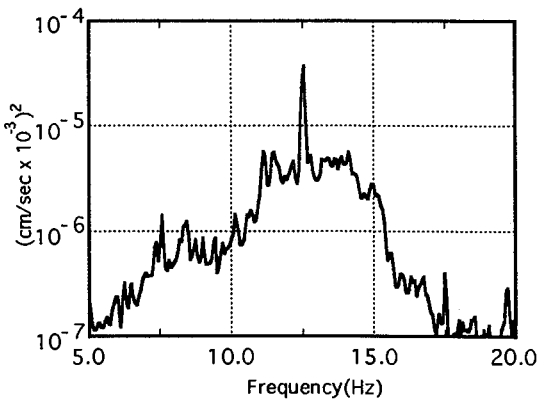


Fig. 14 Power spectrum of the vertical direction by micro tremor

6.CONCLUSION

From the results of the various tests and the earthquake observations, the following conclusions can be made.

- (1) The damping ratio of the silicone rubber bearing is a function of horizontal displacement. For displacements under 0.3mm, the damping ratio is 2/3 of the design value. However, the damping ratio exceeds the design value at displacements over 1mm.
- (2) The horizontal stiffness of the silicone rubber bearing is non-linear at very small displacements.
- (3) The damping ratio of the silicone rubber bearing is about twice that of bearings made from other materials at small displacements.
- (4) The horizontal stiffness of the silicone rubber bearing is about 1/3 ~1/2 that of bearings made from other materials at small displacements.
- (5) The vertical natural frequency of the building with the silicone rubber bearing installed is 14.0Hz. This value is quite small compared to that for other bearing systems.
- (6) The amplification factor of a small earthquake of the base-isolated building with silicone rubber bearings, was small.

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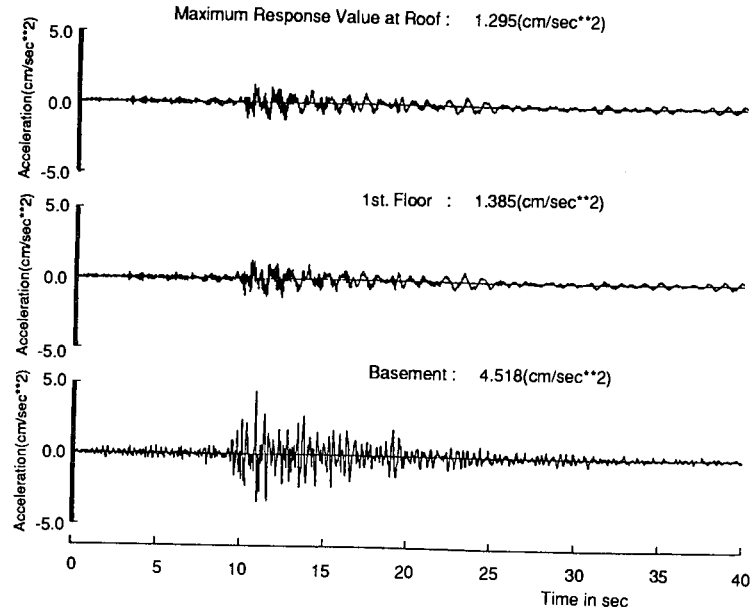


Fig. 16 Time history for X-direction of the earthquake on April 10, 1992

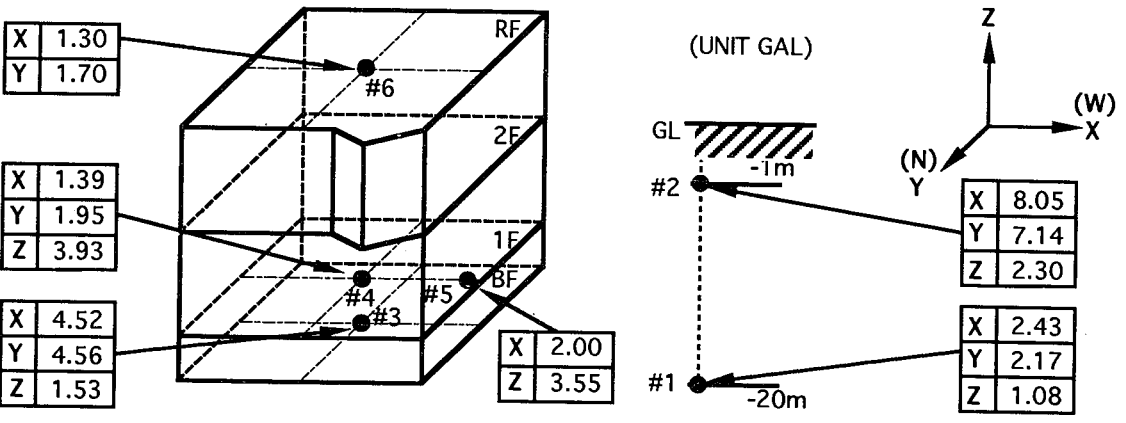


Fig. 15 Maximum acceleration distribution of the earthquake on April 10, 1992