Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Base isolation system for houses

Kenji Hagio, Koji Kitazawa & Ichiro Nagashima
Taisei Corporation, Yokohama, Japan

ABSTRACT : The static and dynamic characteristics of a base isolation system for houses were investigated by the lateral loading test and forced vibration test of a test house to verify the design value. Then effect of base isolation system was evaluated by the earthquake motion measurement of the test house and earthquake response analyses under strong earthquake motions. It confirmed that the base isolation system works efficiently to reduce the earthquake response acceleration.

1 INTRODUCTION

To keep daily life more safe and comfortable a base isolation system for house was developed. A test house was built on sliding type isolators to verify the static and dynamic characteristics of the isolation system and to measure their performance in earthquake.

2 TEST HOUSE

The test house has two stories of precast reinforced concrete panels and a pent house at the third floor with wooden roof. Twenty one isolators were set between the foundation base mat and reinforced concrete beams of the first floor cast in site (Figure 1).

The isolator comprises an elastic slide bearing of laminated rubber and steel with Poly-tetra-fluro-etherene plate at the bottom, a polished stainless slide plate and a horizontal spring of chroloprene rubber (Figure 2). The elastic slide bearings support whole weight of the house 210 tf. They cut the propagation of earthquake motion into the house as a result of sliding when response shear force of house exceeds the frictional force. The horizontal spring works so as to suppress the displacement of house.

These isolators reduce response acceleration of house nearly equal to $\mu \cdot g$ (μ : frictional coefficient of slide bearing, g : acceleration of gravity).

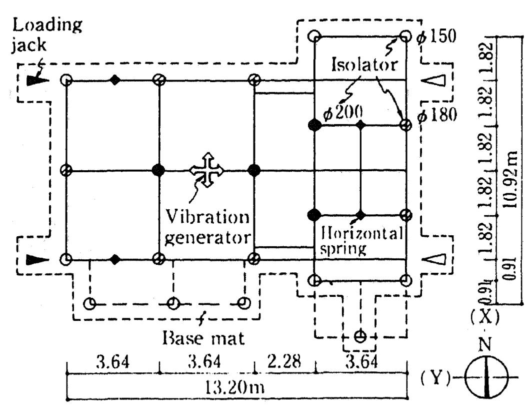

Figure 1 Plan of first floor

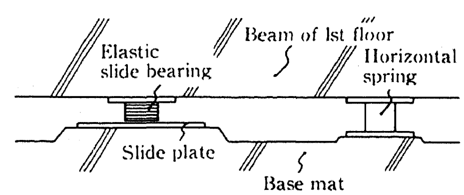

Figure 2 Base isolation system

3 STATIC LOADING TEST

The restoring force characteristics and frictional coefficient of isolator were tested by lateral loading to the house with oil jacks (Figure 1). The cyclic loading was controlled by load until the sliding occurred and thereafter by displacement in some steps up to ±80mm. The relative displacement was measured between the base mat and the first floor. The loading was repeated four cycles till the hysteresis loop turned into stable. The relationship of restoring force and displacement in forth cycle is shown in Figure 3. The stiffness and the frictional coefficient of isolator were evaluated

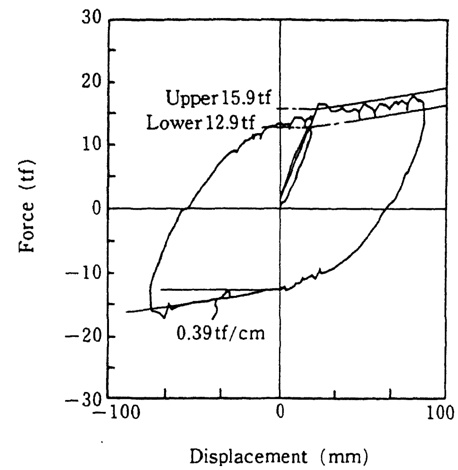

Figure 3 Restoring force and displacement (4 th cycle of static loading test)

Table 1 Total stiffness of elastic slide-bearing & horizontal spring

Displacement (Shear strain)*1	Total stiffness (tf/cm)*2				
	1 st cycle	2 nd cycle	3 rd cycle	4th cycle	Average
1 cm (26%)	8.27	8.63	8.04	7.78	8.20
1.5 cm (38%)	7.94	7.57	7.70	7.32	7.63
2 cm (51%)	7.53	6.73	6.97	7.04	7.07
Design value 8.03					

*1 Shear strain of elastic slide bearing ϕ180
*2 Linear approximation

depending on these relationships.

Total stiffness of elastic slide bearings and horizontal springs were evaluated from the initial modulus of hysteresis curve. Table 1 shows total stiffness in the displacement of 1 cm, 1.5 cm and 2 cm before sliding occurs. These displacements correspond to following shear strain of elastic slide bearings, 26 %, 38 % and 51 %. The total stiffness tends to decrease as the strain level increase.Consequently the stiffness of isolator was 88 % of design value at maximum strain level before sliding occurs. The stiffness in the strain level 26 % agrees well to the design value 8.03 tf/cm. The relationship of stiffness and shear strain is shown in Figure 4, where the result of forced vibration test and earthquake measurement are plotted. The relationship shows the stiffness decreases hyperbolically depending on the increase of shear strain.

The stiffness of horizontal springs were evaluated from the slope of hysteresis curve after slide occurs. Table 2 shows the result. The stiffness of horizontal spring agrees well to design value 0.41 tf/cm.

The frictional coefficient of elastic slide bearings were calculated as a ratio of friction load to the whole weight of house 210 tf. The friction load were obtained from the total stiffness of isolators in the strain level 51 % and the stiffness of horizontal springs as shown in Figure 3. Table 3 shows the result. It seems that the upper value of frictional coefficient corresponds to the dynamic coefficient of friction for the speed of oil jacks as 0.25 kine and the lower one corresponds to the least value of the dynamic coefficient of friction. The coefficient of friction in the first cycle are comparatively large, however, it decrease and turns into stable in the third and four cycle. The coefficient of friction vary from 0.061 to 0.087. These value satisfy the design value from 0.05 to 0.15, which is specified considering the deviation depended on the velocity of slide.

Table 2 Stiffness of horizontal spring (tf/cm)

	Test result		Design value
	1 st cycle	4th cycle	
Horizontal spring	0.45	0.39	0.41

Table 3 Coefficient of friction

	1 st cycle	2 nd cycle	3 rd cycle	4 th cycle
Upper value	0.087	0.081	0.076	0.076
Lower value	0.073	0.070	0.063	0.061
Design value 0.05~0.15				

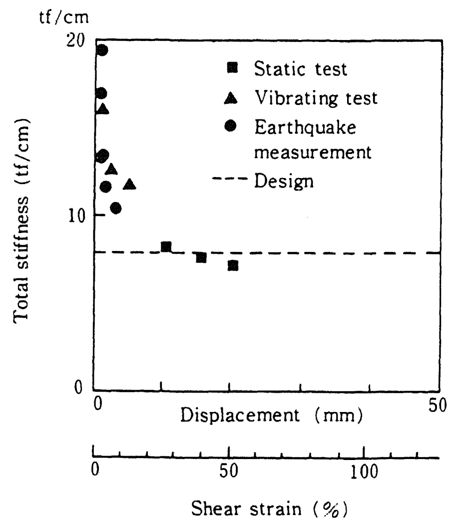

Figure 4 Dependence of total stiffness on strain level

4 FORCED VIBRATION TEST

The dynamic properties of the base isolated house were investigated by the forced vibration test. A vibration

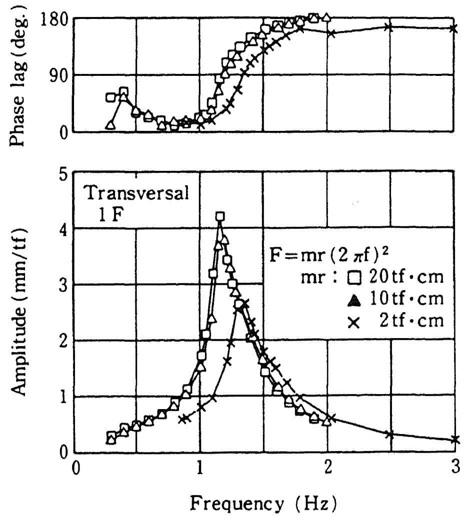

Figure 5 Resonance curve

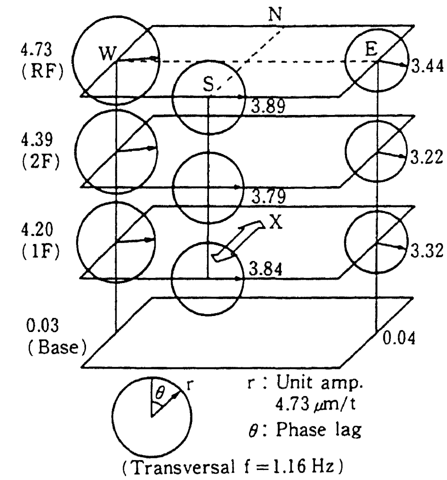

Figure 6 Resonance mode

Table 4 Result of forced vibration test

Direc toin	Un:balance moment of generator (tf·cm)	Shear*1 strain (%)	Resonanse frequency (Hz)	Stiffness (tf·cm)	Damping factor (%)	
					From amp*2	From phase*3
X	20	10.5	1.16	11.8	8	7
	10	5.1	1.20	12.5	9	9
	2	0.9	1.35	16.0	9	9
Design		–	0.96	8.03	–	–

*1 Shear strain of elastic slide bearing ϕ180

*2 Applied $1/\sqrt{2}$ method to amplitude spectra

*3 Caliculated from inclination of phase spectra

Table 5 Damping factor

Method \ Result	Shear strain of isolator (%)	Damping factor (%)
Vibration test	0.90~10.5	7~9
Eearthquake measurement	0.33~6.74	7.1~10

generator was set on the first floor as shown in Figure 1. The frequency range of vibrating was from 0.3 Hz to 15 Hz. The power of generator was adjusted three level by changing the unbalance moment as 20 tf · cm, 10 tf · cm and 2 tf · cm. The motion of house and base mat were measured by the seismometer of displacement-type. The resonance curve of displacement at the first floor of the house is shown in Figure 5. The resonance frequency , the vibrating mode of house and the damping factor were investigated by resonance curves.

Table 5 shows the result of forced vibration test. The stiffness and shear strain were calculated from the measured resonant frequency and displacement. The resonance frequency tends to shift toward low frequency in case of the higher power level of vibrating. These tendency can be explained by the dependency of stiffness on shear strain of isolator as shown in Figure 4. The resonance mode is shown in Figure 6. The amplitude of house at each floor are almost same, so it seems that the house vibrates like a rigid body.

Table 5 shows the damping factor obtained from resonance curves of the vibration test and result of earthquake measurement. The damping factor in earthquake was obtained by approximating the transfer function measured in the earthquake with the single freedom model of house. The damping factor are almost same as 7 % to 9 % and did not depend on the method of calculation or shear strain level of isolator.

5 EARTHQUAKE MEASUREMENT

The behavior of isolated house and effect of isolation was investigated by the simultaneous earthquake motion measurement of the isolated test house and another non-isolated house, size and structure of which are similar to the test house. Many earthquake motion were recorded, however the measured earthquake records are so small that the bearing did not slide. The maximum value of horizontal acceleration at the ground surface was 35 Gal.

Figure 9 shows the relationships of the horizontal acceleration between the top of the houses and the ground surface. The acceleration of the isolated house was reduced in every case comparing with the non-isolated house. In case that the acceleration at ground surface exceeded 10 Gal, the response acceleration of non-isolated house was more than 60 Gal, on the other hand, that of isolated house was about 10 Gal. It means that the response acceleration of isolated house are

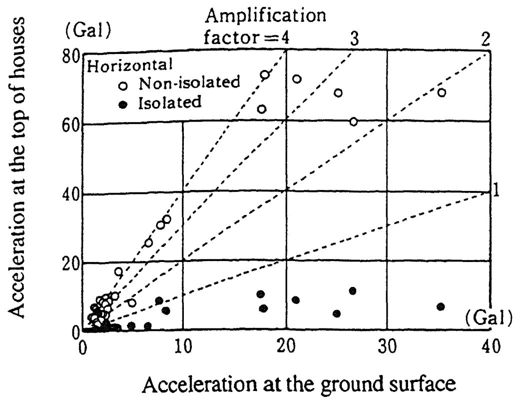

Figure 7 Effect of base-isolation

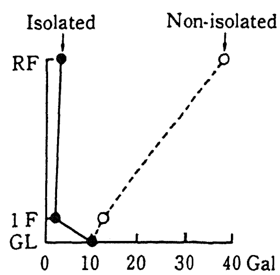

Figure 8 Mode of maximum acceleration

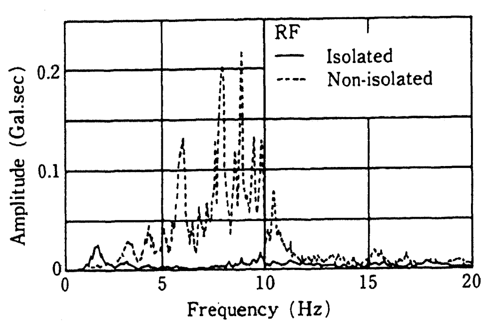

Figure 9 Fourier spectrum

reduced to 1/6 of non-isolated house.

Figure 8 shows mode of maximum response acceleration. The acceleration of the non-isolated house is amplified linearly, but that of non-isolated house is reduced at the first floor and not amplified at upper floor.

Figure 9 shows the spectrum of earthquake motion at the top of houses. The earthquake motion of non-isolated house is dominant in high frequency range, but that of isolated house is suppressed very well. It means that the base isolation system is effective due to the lower natural frequency by isolator even in the small earthquake as the slide does not occur.

6 EARTHQUAKE RESPONSE ANALYSIS

The performance under strong earthquake motion was evaluated by earthquake response analyses. Single freedom system was used as a idealized mathematical model of house. El Centro 1940 NS, Hachinohe 1968 NS were selected as strong earthquake records. Yachiyo 1990 X was also selected as a site record. These acceleration records were scaled as the maximum velocity equal to 50 kine. Bi-linear model is used in the nonlinear response analysis, where design value of stiffness, 0.1 of frictional coefficient and 7 % of damping factor were applied referring the result of test and measurement. Table 6 shows the result.

The maximum response acceleration and displacement were 159 Gal and 138 mm for the input acceleration 342-670 Gal.

Table 6 Response for input level 50 kine

Input \ Response		Isolated	
Wave	Acc. (Gal)	Acc. (Gal)	Disp. (mm)
El Centro	510	141 (0.28)	138
Hachinohe	342	142 (0.42)	114
Yachiyo	670	159	55

( ) Amplification factor

7 CONCLUSION

Through the static and dynamic tests of prototype of house with sliding type base isolation system satisfied the design conditions, and it turned out that base isolation system works efficiently to reduce the earthquake response acceleration. These conclusions are summarized as follows.

1. The restoring force characteristics of base isolation system satisfies the design condition; i.e the frictional coefficient of test was 6.1-8.7 % and within the design specification 5-15 %. Then,isolator are expected to work efficiently.

2. The stiffness of the elastic slide bearing show softening type strain dependency in small strain level as the bearing does not slide. Consequently the stiffness of isolator was 88 % of design value at maximum strain level before sliding occurs.

3. The measured earthquake records are not so strong as the bearings into sliding. However, these results show that the response acceleration of isolated house is reduced 1/6 of non-isolated house due to lower natural frequency by isolators.

4. The response acceleration was less than 159 Gal and sliding displacement did not exceed 138 mm for strong earthquake motion whose maximum velocity are 50 kine.