Study on a Sliding Type Base Isolation System as a Fail Safe Device

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ABSTRACT

High damping rubber (HDR) sliding bearing has a stable dynamic property by sliding for large response displacement. Therefore they were effective even for extra-strong ground motions over design level as a fail safe device.

The performance was confirmed by shaking table test and the response behavior were simulated well by analysis using poly-linear model.

1 INTRODUCTION

It is important to assure the safety of a base isolated building even for extra-strong ground motions in the case that the building is required especially high earthquake resistant capability. High damping rubber sliding bearing is one of the base isolation devices to satisfy this demand.

This device is composed of laminated high damping rubber (HDR) with PTFE plate attached at its bottom. Under weak and moderate earthquake motion high-damping rubber deforms to absorb the vibration energy and to reduce the response. Under extra-strong ground motions, it slides on bearing plate and does not transmit shear force more than friction force to a superstructure. Therefore it has a stable dynamic property for extra-strong ground motions that is a function of a fail safe device.

Tri-axial shaking table test and simulation analyses were conducted to confirm the performance of the system.

2 OUTLINE OF TESTS

2.1 Test specimen

Test specimen is a rigid body mounted on four HDR sliding bearings shown in Fig.1. Four horizontal springs are also attached to reduce the sliding displacement. The model size is 3×2.25m in plan and the total weight is 8ton. HDR sliding bearings are composed of laminated HDR with PTFE plate attached at its bottom. They are set on the bearing plates made of stainless steel. Horzontal springs are made of HDR.

The contact pressure is about 60kg/cm^2 . The natural period of the specimen is 0.67sec at 100% shear strain of HDR. The scale law of time is 1/2.5, so that the natural period of the prototype structure is 1.68sec. Coefficient of friction is about 0.15. The diameter of the sliding bearings is 6.5cm and the total thickness of rubber is 1.2cm.

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2.2 Method of Experiment

The test specimen was excited by tri-axial shaking talbe with sinusoidal motions and scaled earthquake motions.

At first, sinusoidal uni-axial excitation was used to see the fundamental dynamic property of HDR sliding bearings, that is, equivalent shear stiffness and damping ratio that depended on reaponse displacement. And then, to confirm the behavior of the system subjected to strong ground motion, uni-axial and tri-axial earthquake excitations were conducted. The earthquake waves were EL CENTRO 1940, HACHINOHE 1968 and artificial wave, in which longer period components were dominant. Maximum amplitudes of input waves were varied as 10cm/s, 20cm/s of seismic design level and 36cm/s of over design level. The time axis was compressed by 1/2.5 under the scale law, so that the maximum velocity for prototype structure corresponded to 25cm/s, 50cm/s and 90cm/s each other.

2.3 Results of Experiment

Dynamic property of HDR sliding bearings

Examples of hysteresis loop of HDR sliding bearings for sinusoidal motions are shown in Fig.2 and the equivalent shear stiffness and damping ratio for each response displacement are shown in Table.1 and Fig.3.

Before sliding the dynamic property of HDR sliding bearings is that of HDR. The equivalent shear stiffness depended on shear strain and it decreased from small strain. The equivalent damping ratio was almost constant of 11∼13%.

HDR sliding bearings began to slide at shear strain level over 200% (displacement is 2.4cm) shown in Fig 2 (a). After sliding the equivalent stiffness decreased gradually and the equivalent damping ratio increased as the response displacement became large. The value was 15.1% at 2.64cm (r_{eq} =220%) and 29.2% at 7.22cm (r_{eq}=600%). r_{eq} is defined here as ratio of respone displacement to total thickness of rubber. The hysteresis loop was very stable even at 7.22cm and the energy absorption was large.

Dynamic behavior under earthquake motions.

The maximum response values of acceleration and displacement of rigid body under several earthquake motions are shown in Table.2 and the maximum shear force and displacement are shown in Fig.4.

The response acceleration of rigid body was reduced to 1/1.7, 1/2.0 of input acceleration when maximum velocities of EL CENTRO NS were 3cm/s, 10cm/s. At the level of maximum velocity 20cm/s, HDR sliding bearings did not slide for one wave and slided a little for five waves. The response acceleration was reduced to 1/1.1∼1/2.7 for six waves. And the maximum displacement was 3.4cm (r_{eq}=280%).

At the level of maximum velocity 36cm/s, which was over design level, HDR sliding bearings slided and response acceleration increased only a litte. The maximum response displacement was 7.1cm (r_{eq}=600%), which correspond to 44.4cm of prototype displacement and not excessive for design. And the hysteresis loop was stable at this large displacement.

In this way, without or with sliding only a little this system reduced the seismic force under design ground motions. And against over-design strong ground motions the behavior was stable enough to act as a fail safe device.

3 SIMULATION ANALYSIS

3.1 Analytical model

An analytical model is one mass model shown in Fig.5. The dynamic property of

HDR sliding bearings is expressed by poly-linear model. This model is combined by several bi-linear models and one non-linear spring model which has no hysteresis loop. It can fit the equivalent shear stiffness and damping ratio at any displacement to those of experiment.

The equivalent shear stiffness K_{eqj} and damping ratio h_{eqj} at displacement δ_j of poly-linear model are shown by equations (1), (2).

$$K_{eqj} = (\sum_{i=1}^{j} K_i \cdot \delta_i + Q_{NL}(\delta_j))/\delta_j \tag{1}$$

$$h_{eqj} = \frac{1}{4\pi} \frac{W_{eq\cdot j}}{\Delta W_j} \tag{2}$$

$$W_{eqj} = W_{eqj-1} + 4K_{j-1} \cdot \delta_{j-1} \cdot (\delta_j - \delta_{j-1}) \tag{3}$$

$$\Delta W_j = \frac{1}{2} K_{eqj} \cdot \delta_j^2 \tag{4}$$

Q_{NL} : Shear force of non-linear spring model at δ_j

K_{eqj} , W_{eqj} (or h_{eqj}) at δ_j is known by experiment. At first, δ_1 must be decided optionally and K_j is decided in order from K_1 of 1st element bi-linear model by equation (3) Q_{NL} (δ_j) is decided by equation (1) as same. In this case, seven bi-linear models and one non-linear model were used shown in Table 2.

3.2 Results of analysis

The maximum response values of acceleration and displacement of rigid body in the analysis are shown in Table 3 compared with experinental results. The comarison of wave forms and hysteresis loop between analysis and experiment are shown in Fig 6~8.

In case of sinusoidal motion, the wave shape of acceleration in the analysis was unsymmetry after slide occured. Then, amplitude of displacement in the analysis was a little larger than experiment during begining three waves, but became nearly equal there after. Analytical hysteresis loop was almost similar to experimental one except that the coefficient of friction depended on cycle a little. In this way, poli-linear model can be expressed the dynamic property of HDR sliding bearings.

In case of earthquake motions, maximum response values of analysis agreed with those of experiment even in the large response level. Both wave forms of acceleration and displacement of rigid body were well simulated.

CONCLUSION

1) It was confirmed that a system using high damping rubber sliding bearing was effective as a fail safe device against extra-strong ground motions over design level.
2) The response behavior was simulated well by analysis using poly-linear model.

REFERENCES

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Table 1 Equivalent Shear Stiffness and Damping Ratio

Shear Strain of Rubber (Response Displacement) %, (cm)	Equivalent Shear Stiffness (t/cm)	Equivalent Damping Ratio (%)	Period (second)
22 (0.26)	0.97	13.3	0.58
45 (0.54)	0.91	11.5	0.59
105 (1.26)	0.71	10.9	0.67
150 (1.80)	0.65	12.4	0.70
220 (2.64)	0.55 *	15.1 *	0.76
290 (3.45)	0.47 *	19.4 *	0.83
370 (4.42)	0.35 *	24.9 *	0.96
480 (5.79)	0.28 *	28.3 *	1.07
600 (7.22)	0.24 *	29.2 *	1.16
190 (2.3)			

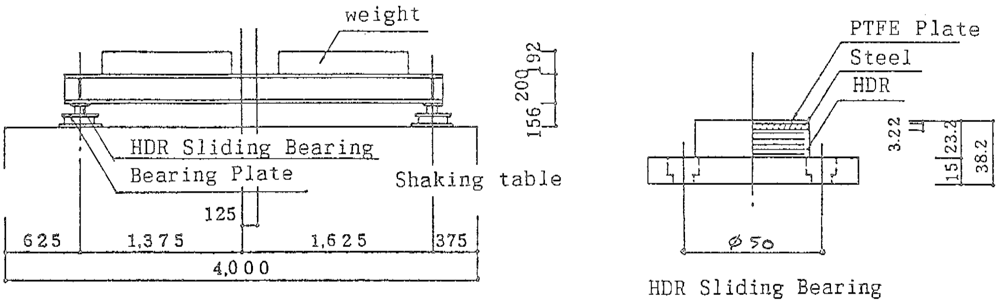
* Sliding occured

Table 2 Constant of Each Bi-Linear Model

Element	Bi-Linear Model		Non-Linear Spring Model
	Displacement δ (Shear Strain)	Stiffness	
1	0.12cm (10%)	0.81 t/cm	0 t/cm
2	0.26 (22)	0.094	-0.086
3	0.54 (45)	0.147	0.097
4	1.26 (105)	0.159	0.111
5	1.80 (150)	0.107	0.146
6	2.64 (220)	0.147	0.151
			0.082

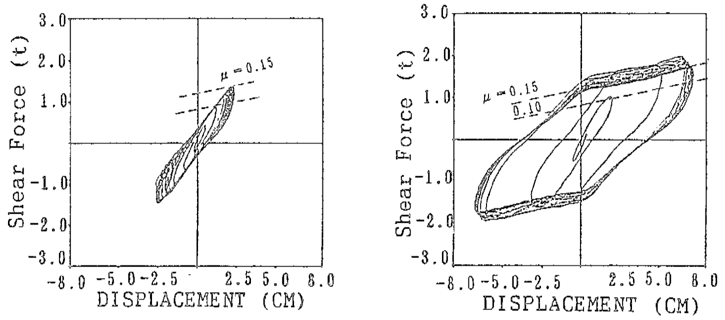
Table 3 Comparison of Maximum Values

Method of Excitation			Input Acceleration	Response Acceleration		Response Displacement	
				Experiment	Analysis	Experiment	Analysis
Sinusoidal Motion	0.5 Hz		100 Gal	111 Gal	135 Gal	1.3 cm	1.8 cm
	1.0		86	188	183	2.9	3.0
	1.0		98	202	191	3.6	3.6
	1.0		182	250	237	7.6	8.1
Earthquake Motion Uni-Direction							
EL CENTRO	NS	3 cm/s	77	45	40	0.3	0.3
		10	259	127	120	1.2	1.5
		20	477	215	193	2.8	3.2
	EW	20	286	233	191	2.9	3.1
Earthquake Motion Tri-Direction							
EL CENTRO	NS	36 cm/s	830	220	246	5.6	7.0
	EW	36	513	286	248	7.0	6.7
HACHINOHE	NS	36	630	218	210	5.4	5.3
	EW	36	477	274	245	7.1	7.4



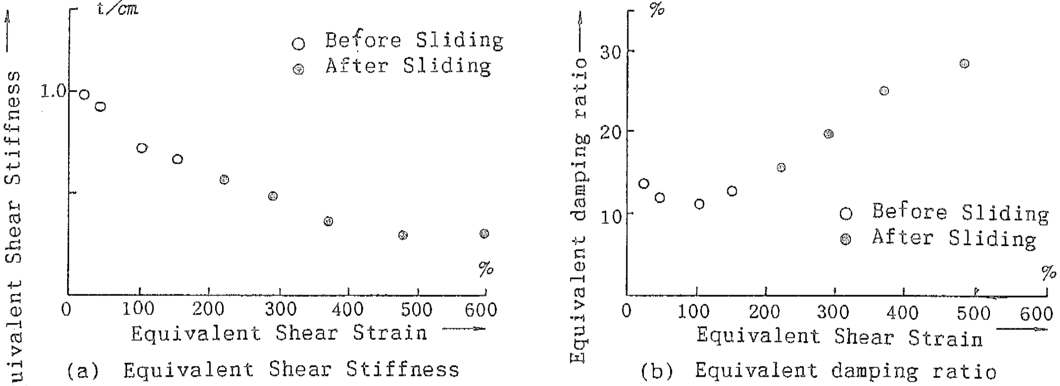
HDR Sliding Bearing

Fig.1 Test Specimen



(a) $r_{eq}=200\%$ (b) $r_{eq}=600\%$

Fig.2 Hysteresis loop



(a) Equivalent Shear Stiffness (b) Equivalent damping ratio

Fig.3 Dynamic Property of HDR Sliding Bearings

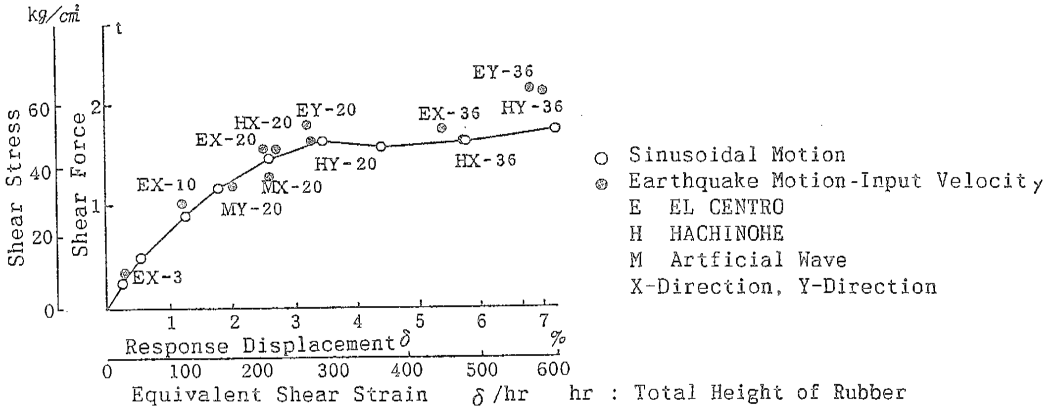
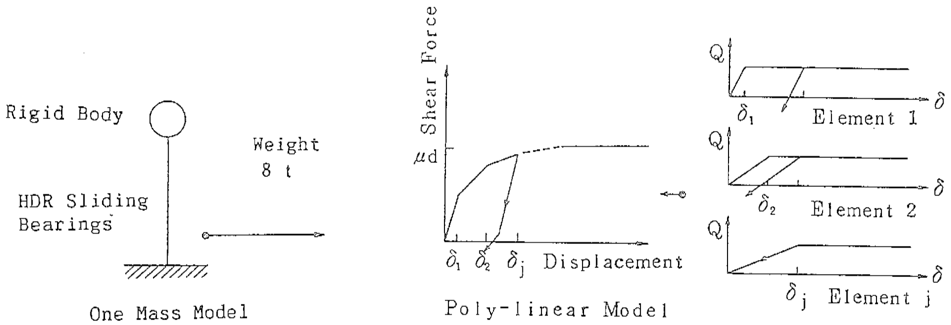


Fig.4 Maximum Response

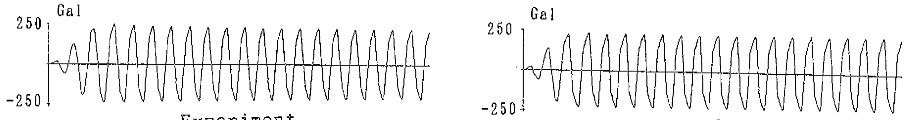


One Mass Model

Poly-linear Model

Fig.5 Analytical Model

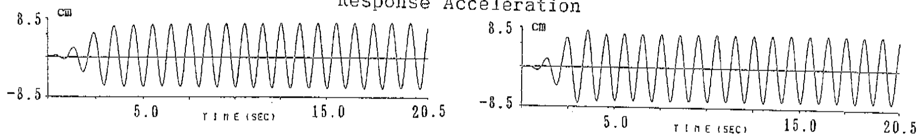
Bi-linear Model



Experiment

Response Acceleration

Analysis

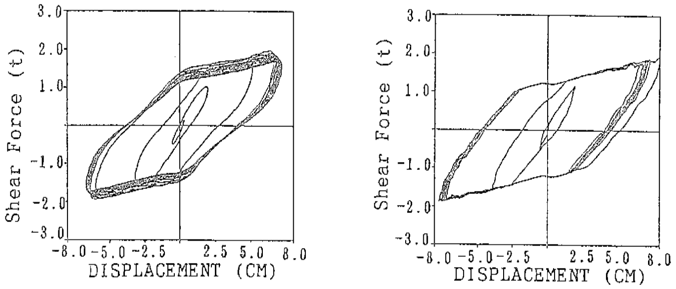


Experiment

Response Displacement

Analysis

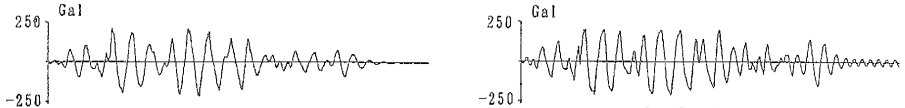
Fig.6 Comparion of wave forms Sinusoidal Motion 1.0Hz 150Gal



Experiment

Analysis

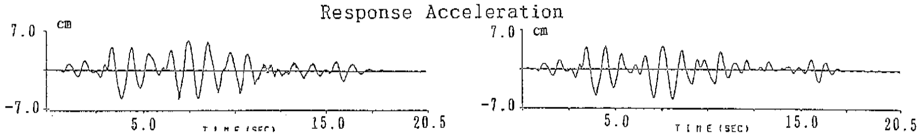
Fig.7 Comparison of Hysteresis Loop Sinusoidal Motion 1.0Hz 150Gal



Experiment

Analysis

Response Acceleration



Experiment

Response Displacement

Analysis

Fig.8 Comparison of wave forms EL CENTRO 1940 NS 36cm/s