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BASE-ISOLATION SYSTEM WITH HYBRID LEAD RUBBER BEARINGS

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ABSTRACT
Multi-layer rubber bearings with several kinds of damper are commonly used in base-isolated buildings. Systems with such devices are mainly designed for seismic safety against strong earthquake excitations, so the performance in weak earthquakes is not always sufficient from the view point of habitabilities. In order to get good seismic performances both in weak and strong earthquakes, new isolator device named HLRB have been developed. The mechanical properties of HLRB, the seismic responses of a HLRB building and an application of HLRB system to an existing base-isolated building are presented.

1. INTRODUCTION
In Japan, over sixty base-isolated buildings with multi-layer rubber bearings have been constructed since 1982[1]. The authors have already developed base isolation systems with two kinds of rubber bearings, which have been applied to three buildings. From field seismic observation results of these buildings, some informations have been obtained. Two important informations are as follows. The first is that the performances of all buildings in moderate earthquake excitations were satisfactory. The second is that the performances in weak earthquakes were not always sufficient, especially in case that the ratio of natural period of the building to that of the ground is nearly unity. The performance in weak earthquakes is concerned to "habitability", and the habitability is estimated by floor acceleration.

The authors have developed a new isolator that gives good habitabilities in weak earthquakes and also seismic safety[2] in strong earthquakes. The new isolator is named "HLRB[3]".

In this paper, the mechanical properties of HLRB and its parts obtained from several experiments, the results of seismic response analysis comparing HLRB with LRB building, and an application of this system to an existing base-isolated building are presented.

2. DESCRIPTION OF HLRB
HLRB means hybrid lead rubber bearing. Fig.1 shows a vertical section view of HLRB. This isolator is vertically composed of a Lead rubber bearing (LRB) and a rubber bearing with a stopper (SRB). The lateral stiffness of

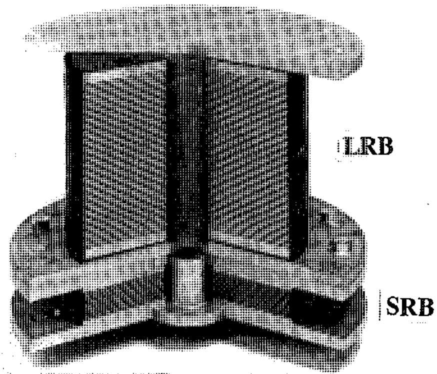


Fig.1 Vertical Section View of HLRB

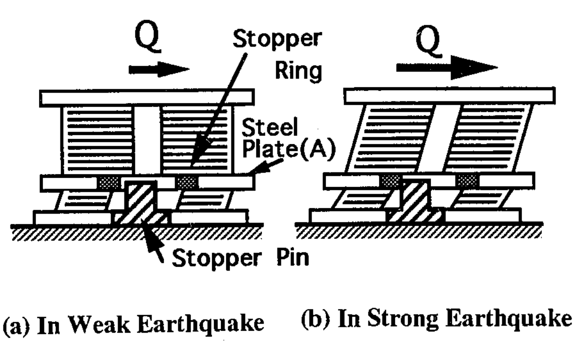


Fig.2 Mechanical Action of HLRB

the rubber bearing of SRB is designed to be lower than that of LRB. The mechanical actions of HLRB in earthquakes are shown in Fig.2(a)and(b). SRB mainly works in weak earthquakes and LRB in strong earthquakes.The stopper is arranged in a center hole of SRB, and is composed of a steel pin and a ring that is made of glass fiber reinforced plastic(GFRP) and set closely in a steel plate (A) shown in Fig.2. There is clearance between the pin and the GFRP ring. This clearance controls the range that SRB mainly works. The GFRP ring absorbs the impact energy which is generated in collision of pin and ring. The role of the stopper is to restrict lateral displacement of SRB within acceptable level and to transmit shearing force to LRB in strong earthquakes.

The main dimensions of a HLRB that is used in this study are as follows. The design diameter is 450 mm. The thickness of natural rubber layer is 4 mm. The number of the rubber layer of LRB and SRB is 44 and 9 respectively. The thickness of steel layer is 3mm and 4mm, respectively. The diameter of lead plug is 90 mm.

3. MECHANICAL PROPERTY

3.1 STOPPER

Fig.3 shows a contact state of pin and ring. The pin is subjected to bending and shearing force, on the other hand the ring is subjected to contact compression. The dimension of the stopper is designed by Herz equation[4]. Fig.4 shows the relationship between shearing force and displacement from the beginning of contact. The maximum force that acts on the stopper in strong earthquakes is determined by the seismic response analysis which will be shown later. Below the maximum force , the stopper shows nearly linear and elastic hysteretic behaviors.

3.2 SRB and LRB

SRB is composed of a rubber bearing and a stopper, so its hysteretic behavior is modeled by a tri-linear type as shown in Fig.5. This model is made up by the hysteresis of the stopper and the rubber bearing obtained from experiments. The analytical model of SRB is composed of a linear characteristics of the rubber bearing and a higher stiffness property of the stopper.

LRB is composed of a rubber bearing and a lead plug, and has dowel pin joints at both ends. Its hysteresis loop is modeled as shown in Fig.6.

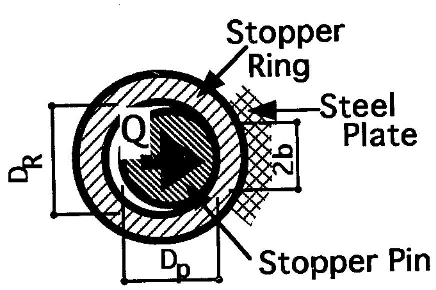


Fig.3 Contact State of Pin and Ring

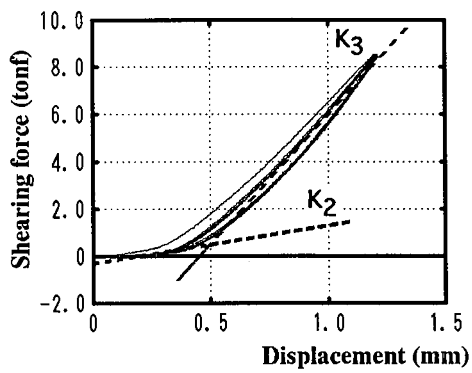


Fig.4 Hysteresis Loop of Stopper after Contact

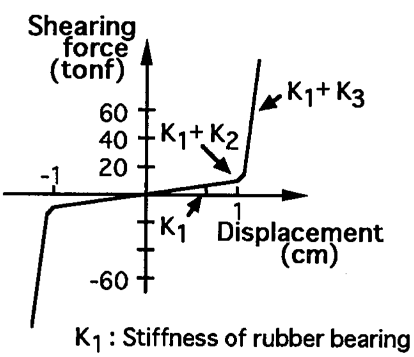


Fig.5 Hysteretic Model of SRB

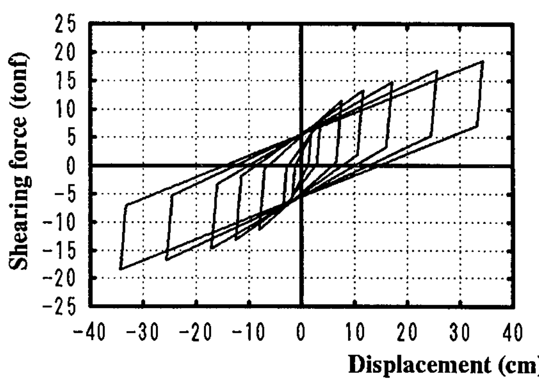


Fig.6 Hysteresis Loop Model of LRB

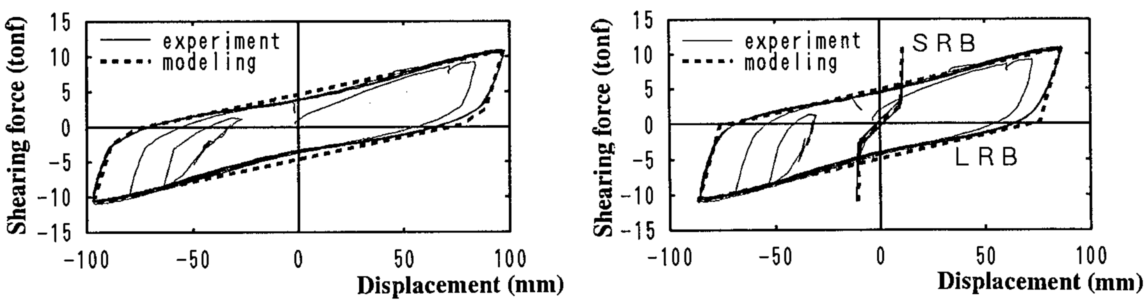
3.3 HLRB

The lateral stiffness of HLRB can be simulated by an analytical model that connects LRB and SRB in series. The hysteresis loops of HLRB and its two parts(LRB and SRB) obtained from experiments are shown in Fig.7 (a) and (b) with the analytical model. The results of analytical models are well agreed with the experimental results. The variation of the lateral stiffness of HLRB and LRB under various displacement, are shown in Fig.8. The lateral stiffness of HLRB in range of small displacement are lower enough to increase the natural periods of the building. The variation of the vertical stiffness of HLRB under various shearing strain is shown in Fig.9. The decrease of the effective sectional area with increasing lateral displacement is taken into account in the analytical model.

3.4 CONSIDERATION OF SEISMIC SAFETY

Some additional considerations are necessary in the design of HLRB, to ensure seismic safety. Fig.10 shows an equilibrium of overturning of LRB. The resisting arm of overturning :(B1-δ) should be decrease by δc. Distance δc is the maximum displacement of SRB. Fig.11 shows effective sectional area of rubber bearing caused by lateral displacement. This effective area affects the vertical stiffness as shown in Fig.9 and stability of LRB. Therefore in case of estimation of this area, the maximum displacement(δc) of SRB should be considered.

The stopper is subjected to impact force reaction in strong earthquakes. This impact force is estimated by seismic response analysis which is described later. The maximum impact force is calculated by effective mass of HLRB multiplied by maximum acceleration obtained by seismic analysis.



(a) HLRB (b) LRB and SRB

Fig.7 Hysteresis Loop of HLRB and its Parts

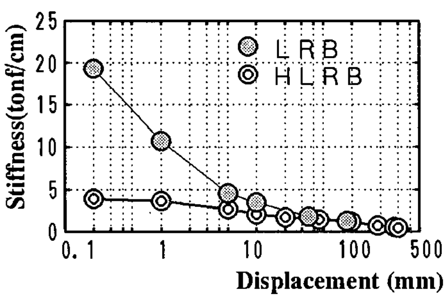


Fig.8 Lateral Stiffness of HLRB and LRB

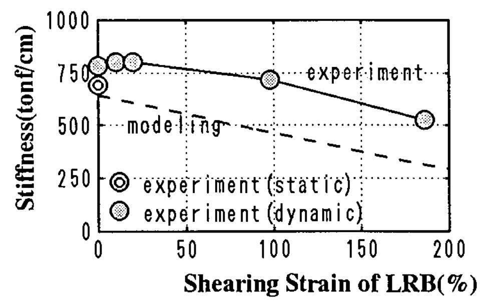


Fig.9 Vertical Stiffness of HLRB

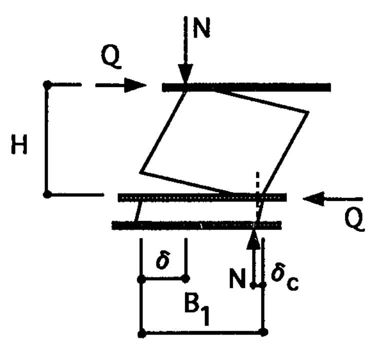


Fig.10 Equilibrium of Overturning

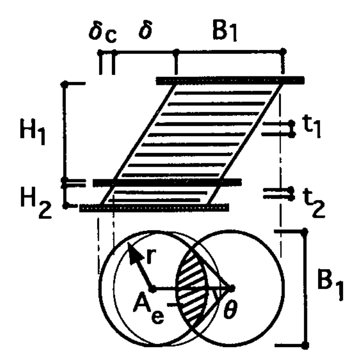


Fig.11 Effective Sectional Area
(hatched region)

4. PRACTICAL APPLICATION

4.1 OBJECTIVE BUILDING

The objective building is an existing three stories base-isolated building with LRBs. Fig.12 shows a section of the building. This building was constructed in 1987 in Technical Research Institute of FUJITA CORPORATION at Yokohama, Japan. This building has a square plan(10.11m x 10.11m) and four columns.

Because the natural period of the ground was longer than the natural period of the Base-Isolated building, the performance in weak earthquake excitations, the strength of which is less than 30 cm/sec^2, was not sufficient. Four new SRBs were installed under existing LRBs in order to lengthen the period of the building and to verify the effectiveness of HLRB system.

4.2 SEISMIC RESPONSE ANALYSIS

Before installing, the seismic responses of a HLRB building and a LRB building against several kinds of earthquake excitations were numerically analysed. The analytical model of the building is shown in Fig.13. The analytical results in case of strong earthquakes shows that the responses of the building with HLRB and LRB are almost the same, however in case of weak earthquakes the maximum acceleration response of HLRB building is

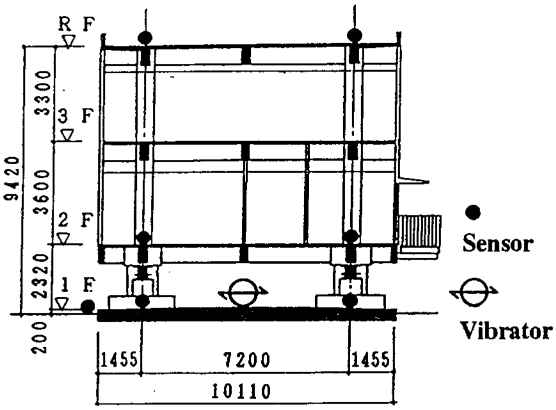


Fig.12 Section of Base-Isolated Building

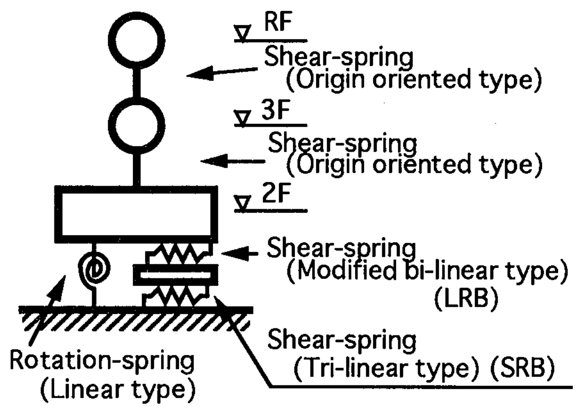
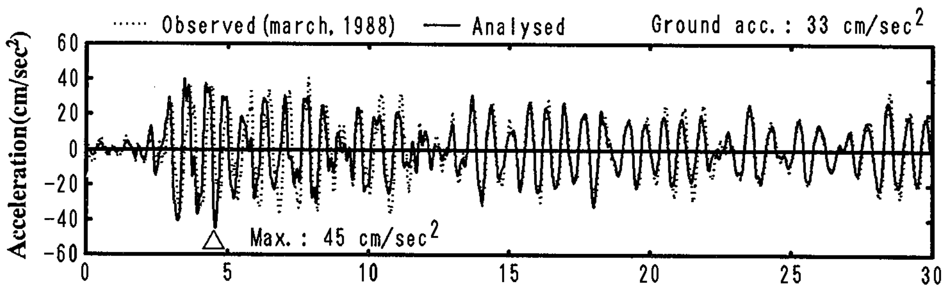
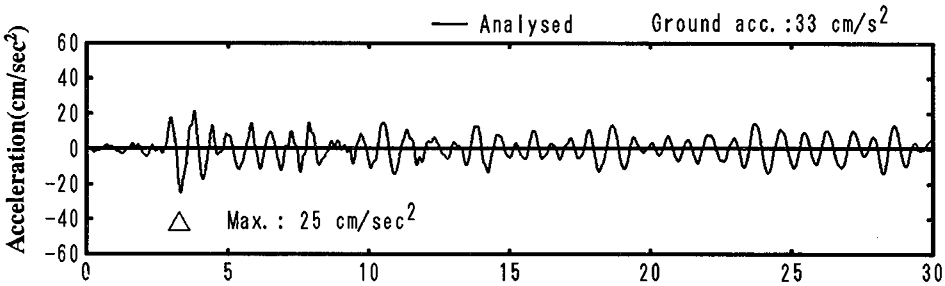


Fig.13 Analytical Model of Base-Isolated Building



(a) LRB Building



(b) HLRB Building

Fig.14 Top Floor Seismic Response of LRB and HLRB Building under the same Ground Motion

reduced to one–half compared to that of LRB building, as shown in Fig.14(a) and (b). Fig.14(a) shows the comparison of the observed results and the analytical results of LRB building. Both results are well agreed. The decreased response of HLRB building is caused by the longer period of that building comparing to that of LRB building in region of small displacement of isolators. This is shown in Fig.15, as the relations between equivalent natural period of the base–isolated building and shearing strain of LRB.

4.3 PROCEDURE OF INSTALLING WORK

Procedure of installing new SRBs are shown in Fig.16 (a),(b) and (c). The lifting up construction system was adopted. The lifting up was done,step by step 5mm at a time, until 200mm, as checking the differences of four levels were less than 5mm carefully. Additionally total weight of the building was measured during this work. The design weight is 311 tonf, but the actual weight is about 280 tonf. This result slightly affected the natural period of the building.

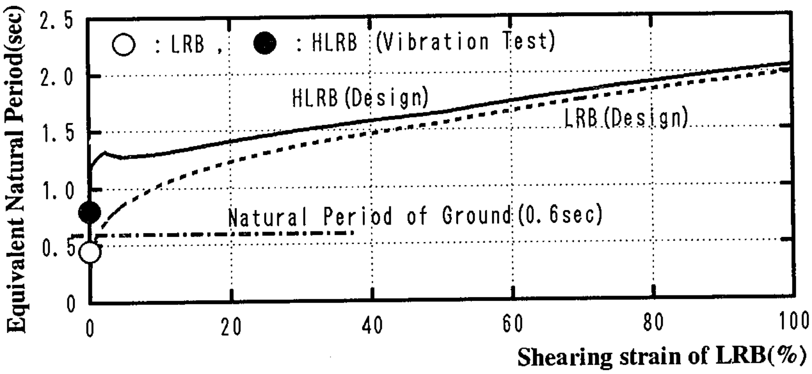


Fig.15 Equivalent Natural Period

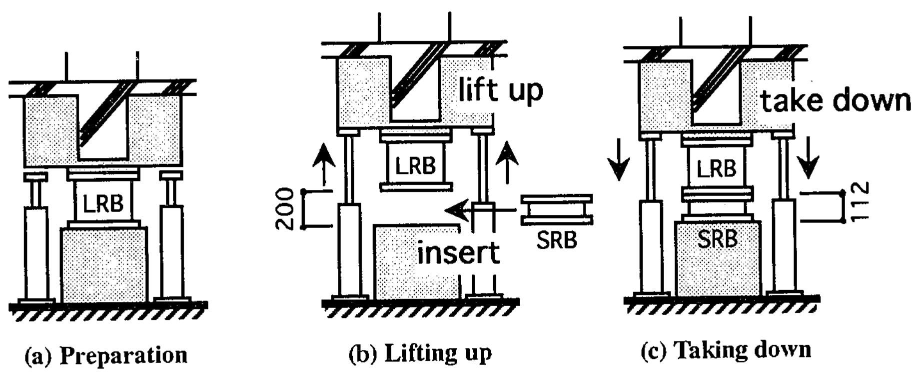


Fig.16 Procedure of Installing Work

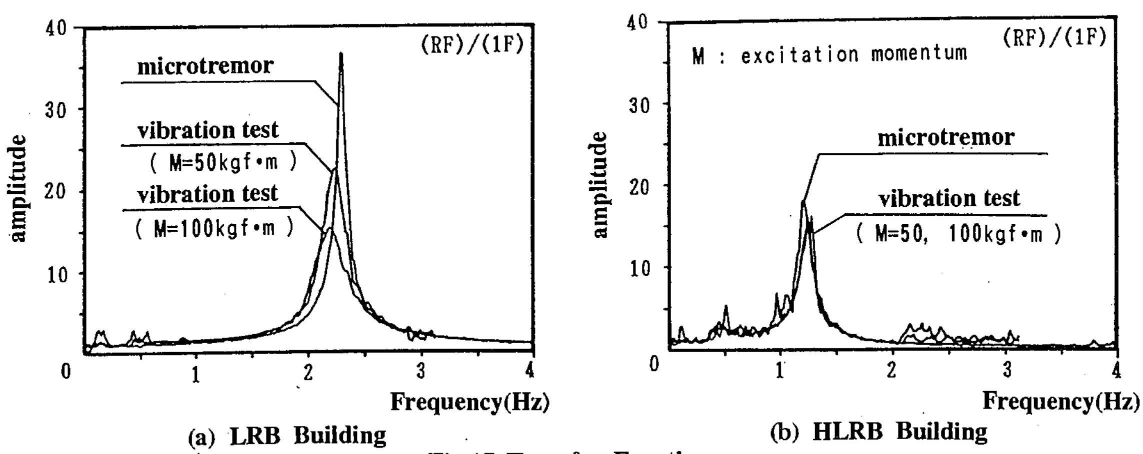


Fig.17 Transfer Function

4.4 VIBRATION TEST AND MICROTREMOR OBSERVATION

Vibration tests and microtremor observations were carried out before/after installing SRBs. The arrangement of vibrator and sensors is shown in Fig.12. The results of the tests are shown in Table 1. At the time that LRB building was constructed, same vibration test was done. Its results is also shown in Table 1. The transfer functions obtained from the vibration tests and microtremor observations are shown in Fig.17(a) and (b).

The natural frequency of the building is clearly decreased after the installing work. The natural periods of the building before the work were 0.45 and 0.42 sec. in X and Y direction, respectively. After installing, these were increased to 0.80 and 0.79 sec. These results are plotted in Fig.15. In this figure, natural period of the ground is also indicated. After installing, the natural period of the building became longer than that of the ground in region of small displacement of isolators. The damping factor is slightly decreased from 4.7 and 5.4 to 3.7 and 4.3, in X and Y respectively.

The LRB building shows that the natural period is not changed but the damping factor is increased in five years.

4.5 SEISMIC OBSERVATION

The field seismic observation of the building has been continued for six years. In regard to weak earthquakes, about eighty records were obtained as LRB building and eight records as HLRB building. The observation results show that the maximum acceleration response at top floor of HLRB building is reduced to 73 % of LRB building in case that the strength of earthquake excitations were in the region of 2.5 to 8 cm/s^2 and 82 % in the region of 0 to 2.5 cm/s^2.

4.6 VIBRATION INDUCED BY WIND

As the stiffness of the building is reduced, the vibration induced by wind for one year return period wind velocity(11.4 m/s) is examined from the view point of habitabilities[5]. The calculated maximum acceleration is 1.12 cm/s^2, which is small enough to keep good habitabilities.

Table 1 Result of Vibration Test

Building name	Test date	Direction	Natural period (sec)	Damping factor (%)
LRB Building	May, '87	X Y	0.45 (—) 0.42 (—)	4.2 (-) 3.3 (-)
LRB Building	March, '92	X Y	0.45 (0.44) 0.42 (0.40)	4.7 (1.4) 5.4 (1.6)
HLRB Building	March, '92	X Y	0.80 (0.81) 0.79 (0.81)	3.7 (2.6) 4.3 (-)

Note : Natural period and Damping factor evaluated from the results of Microtremor observations are also shown in parenthesis.

5. CONCLUSION

The new HLRB base-isolation system is introduced with experimental and analytical studies. Through field observation of a building with HLRB system, it can be concluded that this system is effective in reducing building responses to both weak and strong earthquake excitations. Especially, this system can improve habitabilities in weak excitations. Also, the responses of this HLRB building by wind has no problems from the view point of habitabilities.

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