The LRB (Ref. 4,5,6,7) was formed by laminating 20 layers of rubber with thickness of 5 mm and 19 steel plates with thickness of 2 mm, and the lead plug with diameter of 35 mm was pressed into at the center hole of the bearing. The HDR (Ref. 8) is composed of special rubber which is distinguished by damping characteristic from regular linear rubber. Therefore, the rubber itself would work as an energy dissipator as well as an isolator without any unique mechanism such as the lead plug, when it is subjected to shear deformation. The HDR was formed by vulcanizing 31 layers of the rubber with thickness of 2 mm, each layer of which was laminated between two steel plates with thickness of 0.6 mm. Both bearings are simple and compact as Menshin bearings for bridges so that they are very likely to be used in Menshin bridges.

Specific scale rule was not taken into consideration when the dimension of the model was decided, and the model was assumed as a small prototype. When the deck is supported by a fixed bearing at one end with the other end being supported by roller bearing, the fundamental natural period is about 1 sec. The stiffness of the Menshin bearings was designed to make the fundamental natural period about 2 sec, two times of regular one, so that the Menshin system performs effectively.

Excitation by sinusoidal motions and earthquake ground motions was made. Frequency as well as intensity was varied in the sinusoidal excitation to study the natural period of the model. Two ground motions which were recorded on the ground near the Kaihoku bridge during the Miyagi-ken-oki earthquake (M7.4) of 1978 and on the Hachiro-gata bank during the Nihon-kai-chubu earthquake (M7.7) of 1983 were used for the excitation. They are hereafter designated as a Kaihoku record and a Hachiro-gata record, respectively. The time of the Hachiro-gata record was reduced one half of the original. The intensity of the records was varied. **Fig. 1** shows the response acceleration spectrum ratio (acceleration response/peak input acceleration) of the two records.

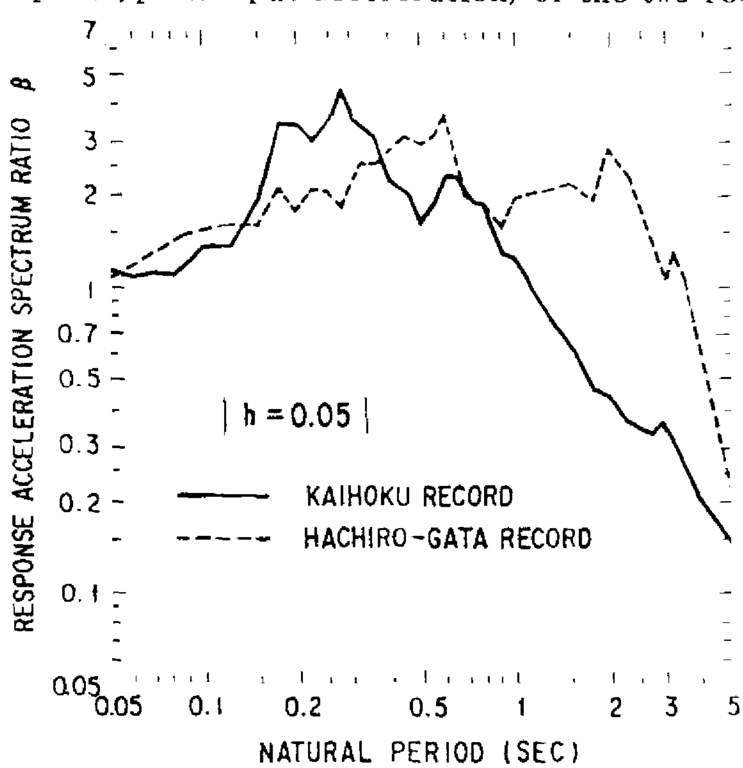


Fig.1 Response Acceleration Spectrum Ratio

Sinusoidal Excitation **Figs. 2** and **3** show the resonance curve of acceleration and displacement. The fundamental natural frequency varied from 1.62 Hz to 0.67 Hz for the LRB model and from 1.95 Hz to 0.95 Hz for the HDR model by increasing the input acceleration from 0.01 g to 0.04 g. This clearly shows the shear-strain dependence of the stiffness of LRB and HDR. The fundamental natural frequency of the model supported by regular fix and roller bearings does not depend on the input acceleration.

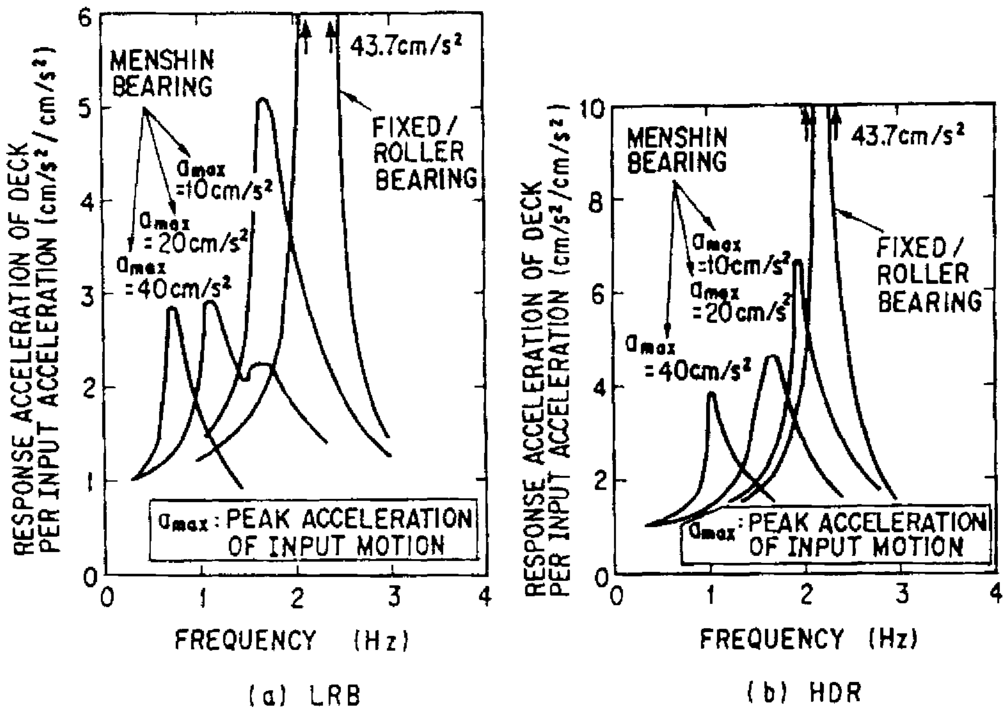


Fig.2 Amplification of Resonance Acceleration Curve

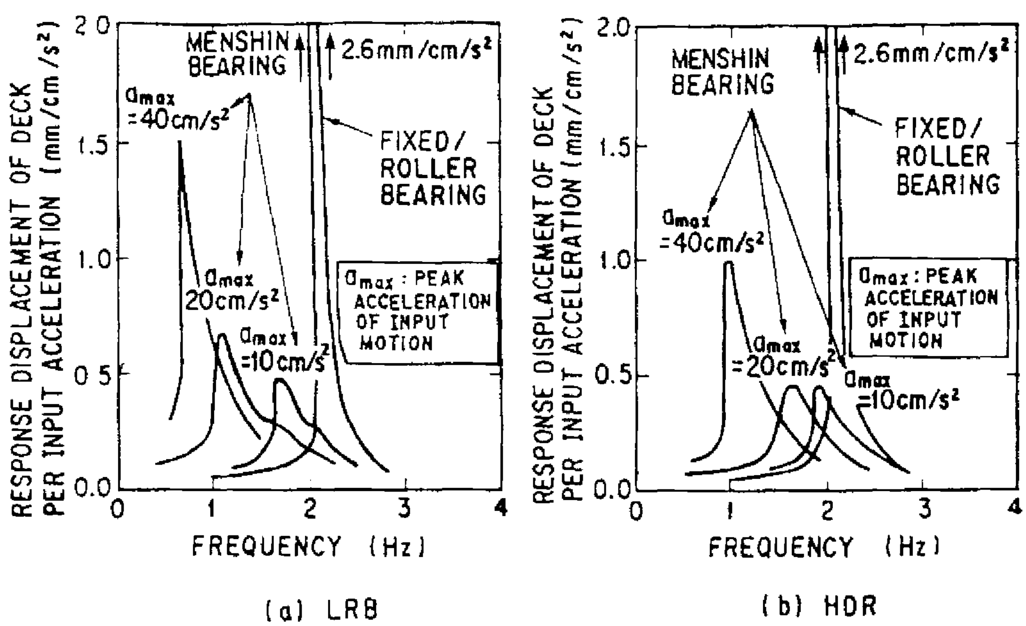


Fig.3 Amplification of Resonance Displacement Curve

Table 1 shows damping ratio by the half-power method with use of the resonance curves. The damping ratio is about 2 % for the model supported by the regular fix and roller bearings, and about 11 % and 9 % for the model supported by the LRB and the HDR, respectively, when subjected to the sinusoidal excitation with peak input acceleration of 0.04 g. It means that an increase of the damping ratio of 9 % and 5 % was made by adopting the LRB and the HDR, respectively.

Table 1 Equivalent Viscous Damping Ratio by Half-Power Method

BEARING \ INPUT INTENSITY	10 (cm/s^2)	20 (cm/s^2)	30 (cm/s^2)
L R B	0.08	0.092	0.113
H D R	0.064	0.087	0.092
FIXED/MOVABLE BEARING	0.02		

The hysteresis loops of shear force vs. shear deformation of the bearings are shown in **Fig. 4**. The hysteresis loops of the LRB look bilinear shape, especially in small amplitude, while the HDR is featured by the spindle-like shape. The lead plug of the LRB, which gives high initial stiffness, produces the bilinear shape. On the other hand, the HDR does not create high stiffness in small deformation and does not form the bilinear shape.

Figs. 5 and **6** show the dependency of the equivalent stiffness and the equivalent damping ratio on the deformation acquired from the sinusoidal excitation tests. The equivalent stiffness is defined as gradient of a line connecting the two points at the maximum and minimum displacement of a hysteresis loop, and the equivalent damping ratio is defined as a value proportional to the ratio of damping energy loss per cycle to strain energy stored at maximum displacement as shown in **Fig. 7**. An empirical equation for the equivalent stiffness k_e was obtained as shown in **Fig. 5**. Though the equivalent damping ratio is scattered, compared with the equivalent stiffness k_e, the damping ratio h_e may be considered 0.16 for the LRB and 0.13 for HDR in the range of the shear deformation from 1 to 50 mm.

The equivalent stiffness and the equivalent damping ratio from the cyclic shear loading tests of the bearing alone, which were conducted prior to the shaking table tests, are also shown in **Figs. 5** and **6** for comparison. In the cyclic shear loading tests, alternating shear deformation was repeatedly applied to the bearings under constant vertical force corresponding to the dead weight of the deck. The equivalent stiffness and equivalent damping ratio estimated from the sinusoidal excitation tests are in good agreement with the result of the cyclic shear loading tests of the bearing alone so that it can be deduced that the test method, a shaking table test or a cyclic shear loading test, does not affect the equivalent stiffness and the equivalent damping ratio of a Menshin bearing.

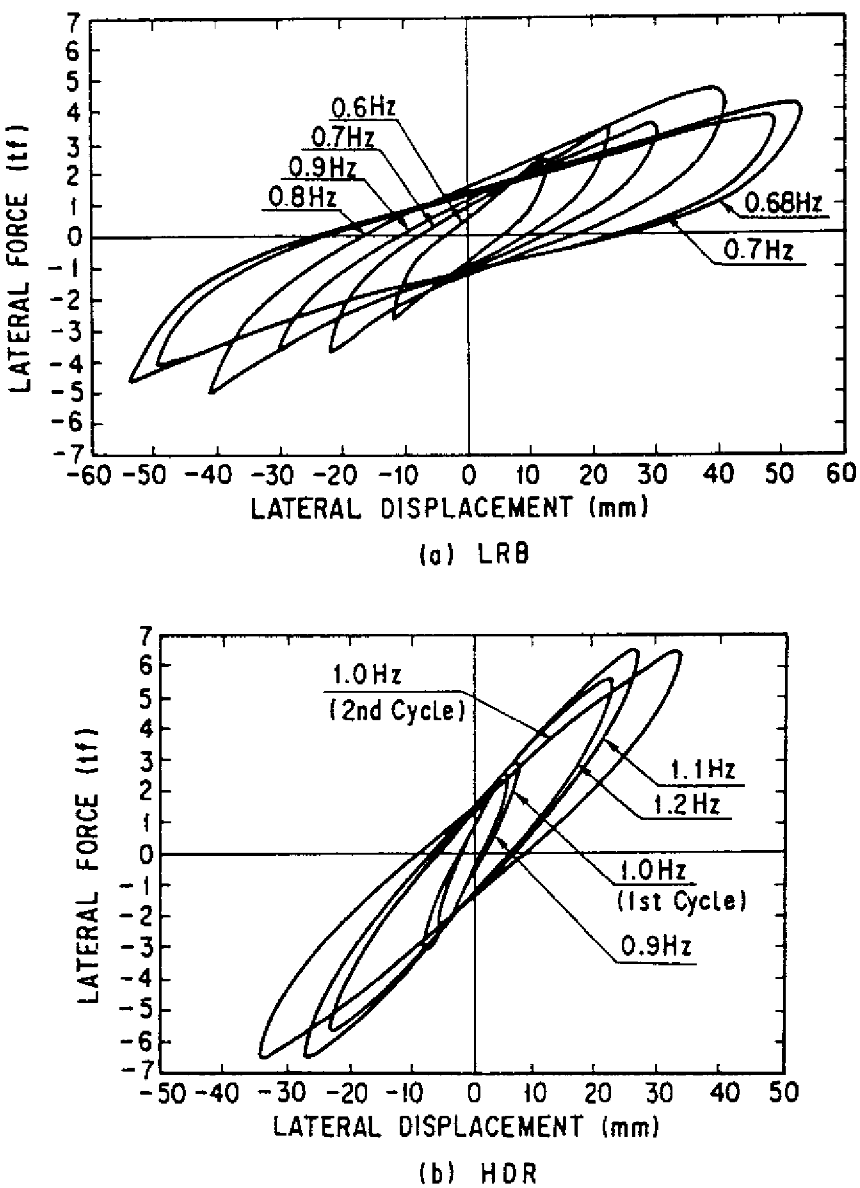


Fig.4 Hysteresis of Lateral Force vs. Lateral Displacement

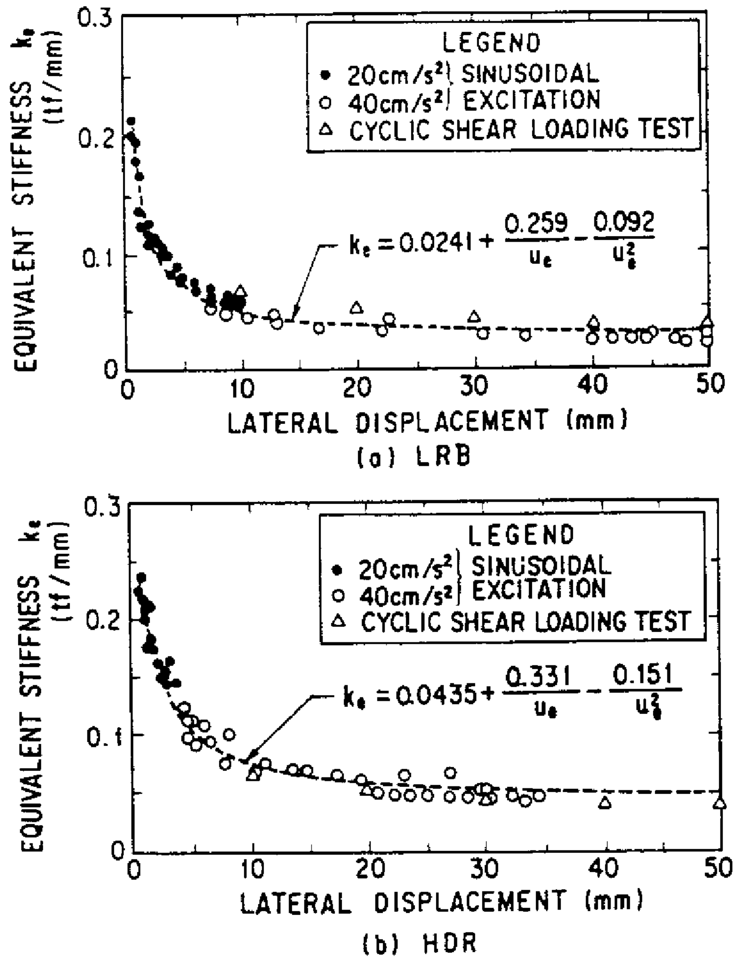


Fig.5 Equivalent Stiffness

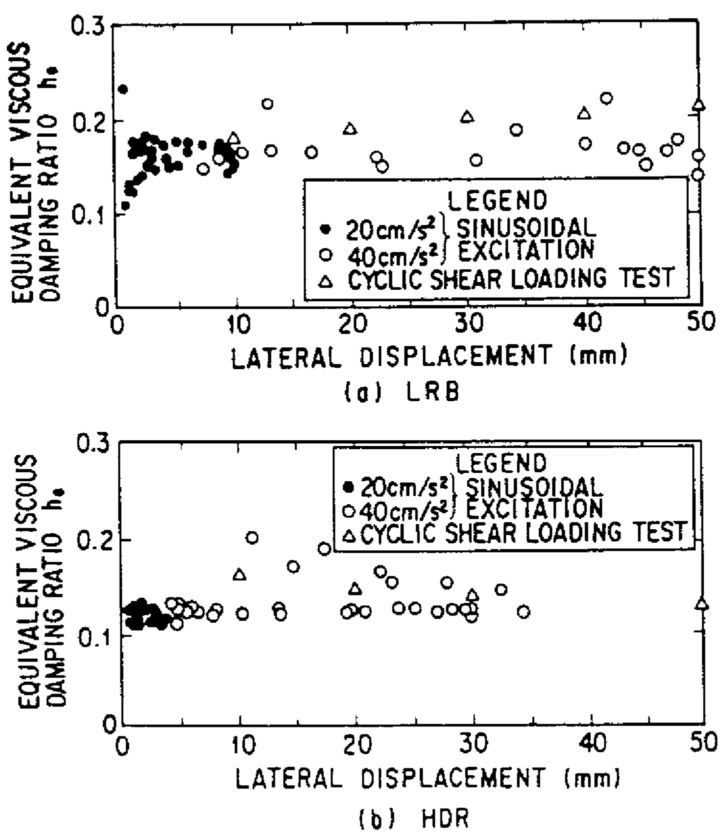


Fig.6 Equivalent Viscous Damping Ratio

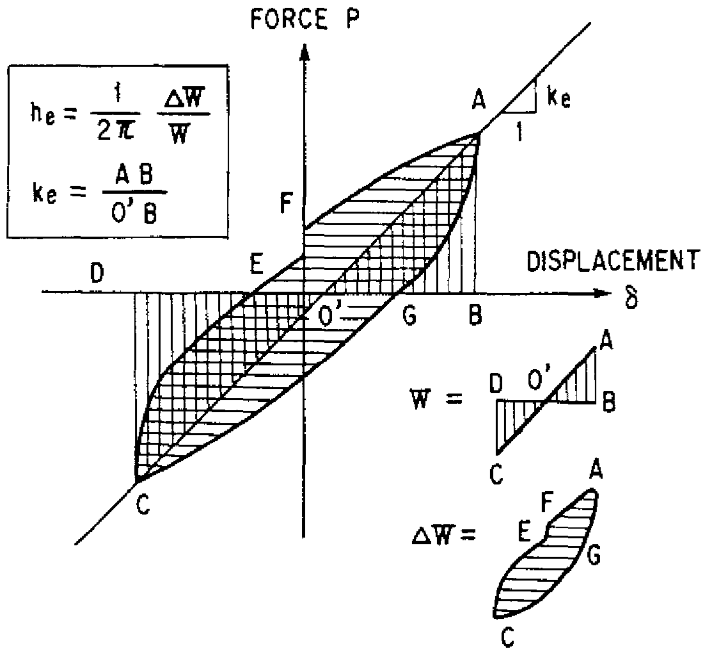


Fig.7 Definition of Equivalent Stiffness k_e and Equivalent Viscous Damping Ratio h_e

__Ground Motion Excitation__ **Figs. 8** and **9** show how the peak deck response acceleration and displacement increase with the peak input acceleration. The effect of Menshin system can be apparently observed in **Fig. 8**, where the acceleration of the regular bridge amounts to more than two times acceleration of the Menshin bridge under the same input motion.

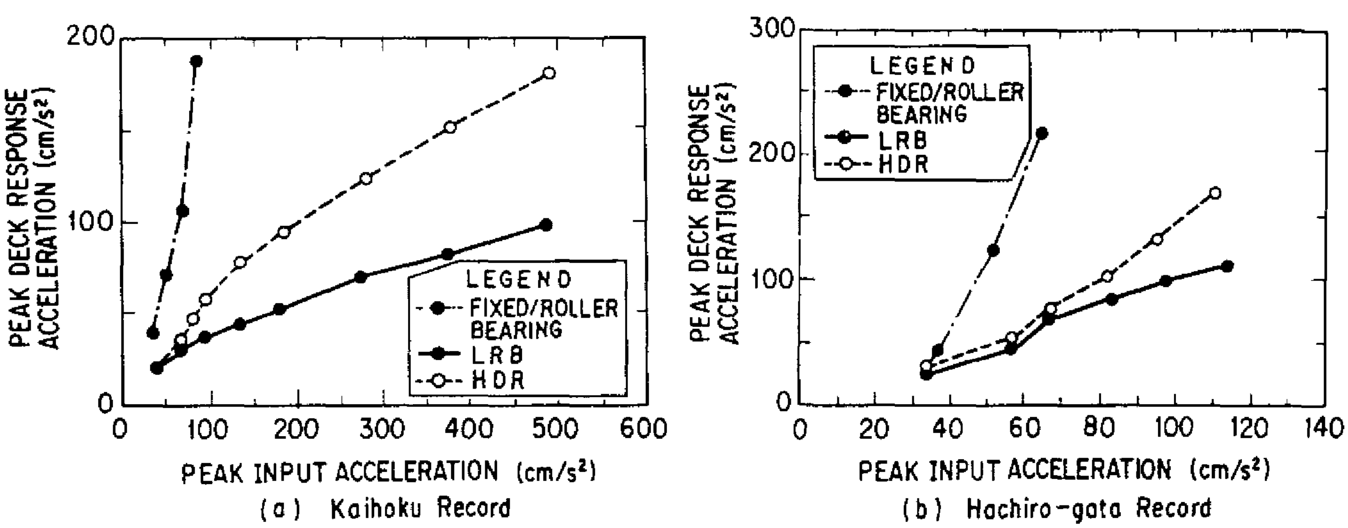
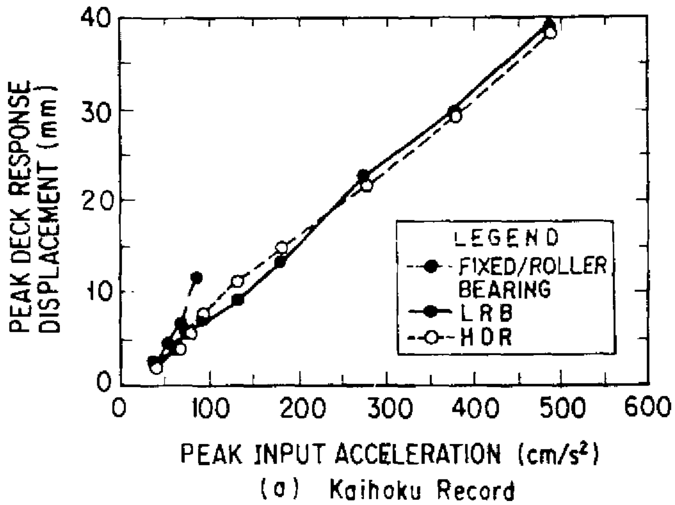


Fig.8 Peak Deck Response Acceleration



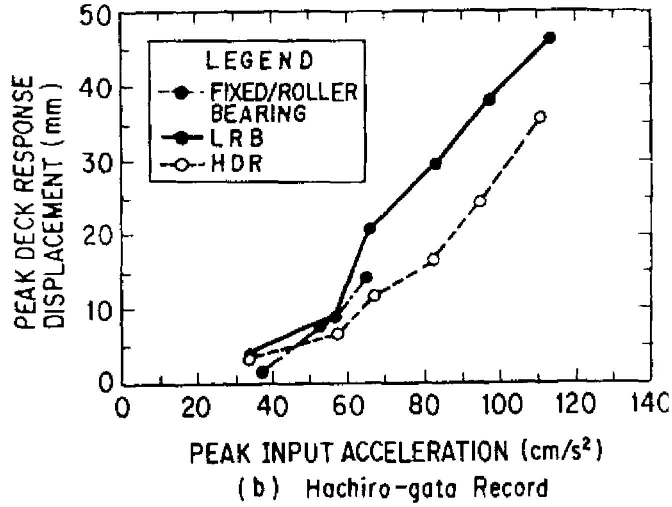


Fig.9 Peak Deck Response Displacement

EFFECT OF STOPPER AND VERTICAL EXCITATION

Tested Model For aiming to study effect of stopper and vertical excitation, another series of excitation tests were made. The columns and the Menshin bearings were replaced with new ones. The column was designed to have higher stiffness than an actual column since a flexible column could soften impact force due to collision developed at a stopper. The Menshin bearings, the lead rubber bearing and the high damping rubber bearing, were designed to make the fundamental natural period of the model about 0.6 sec. **Photo 4** shows the Menshin bridge studied for the effect of stopper and vertical excitation. To distinguish the model with the one presented in **Photo 1**, it is referred as "model 2".

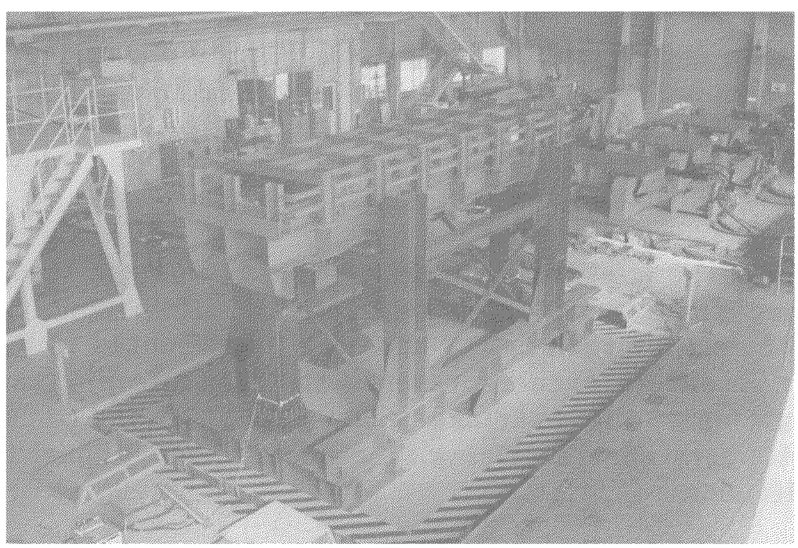


Photo 4 Setup of Shaking Table Test (Model 2)

The LRB was fabricated by vulcanizing 12 layers of rubber with thickness and diameter of 5 mm and 320 mm, respectively. They were laminated with 13 steel plates with thickness of 2 mm. The total thickness of rubber is 60 mm, and the total thickness of the entire bearing after fabrication is 110mm. The diameter of the lead plug is 40 mm. The HDR was fabricated by vulcanizing 16 layers of high damping rubber with thickness of 1.3 mm, and by laminating with steel plates with thickness of 3 mm.