Two stoppers which prevent excessive relative displacement between the deck and the columns were provided with the top of the each column as shown in **Photo 5**. A rubber was placed on the stopper to lessen the impact force of collision. Although the gap space of the stopper at both columns was adjusted to equalize each other as much as possible, it is noted that collision did not always take place simultaneously at each stopper.

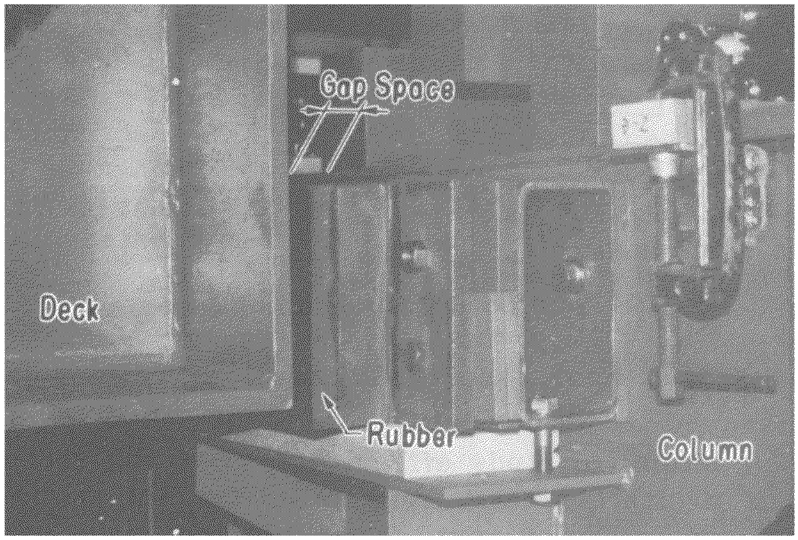


Photo 5 Stopper

Excitation was made either in longitudinal direction or in longitudinal and vertical direction. The horizontal and vertical components of the Kaihoku record and the Hachiro-gata record were used for the excitation. Ratio of acceleration intensity between horizontal and vertical components was assumed the same with the original records.

Effect of Collision and Vertical Excitation **Fig. 10** shows the response of the model when the stoppers are not provided, and **Fig. 11** shows the response when the stoppers with the gap space of 2 cm each were provided. Collisions, which took place when the stoppers of 2 cm gap was provided, developed greater acceleration at the deck and the columns.

Fig. 12 shows the hysteresis loops of the LRB for the tests shown in **Figs. 10** and **11**. Since the shear force computed by multiplying the acceleration developed at the deck by the mass of the deck is presented in **Fig. 12**, it should be noted that the shear force represents the total force transmitted to the columns through only the bearings when not colliding, and through both bearings and stoppers when colliding. The shear force jumped up significantly due to the collision.

Figs. 13 and **14** show the peak input acceleration vs. the peak deck response. It is seen in **Figs. 13** and **14** that when the collision did not take place at the stoppers, the response displacement and acceleration of the deck are almost proportioned to the input acceleration. However, when the collision took place at the stoppers, the displacement of the deck is controlled by the stoppers within a little bit more than the gap space as shown in **Fig. 13 (b)**. The acceleration of the deck is raised by the collision as shown in **Fig. 14 (b)**. For example, the acceleration amounts to 0.69 g and 0.83 g for the gap of 3 cm and 2 cm, respectively, contrasted to 0.59 g without stoppers, under the excitation

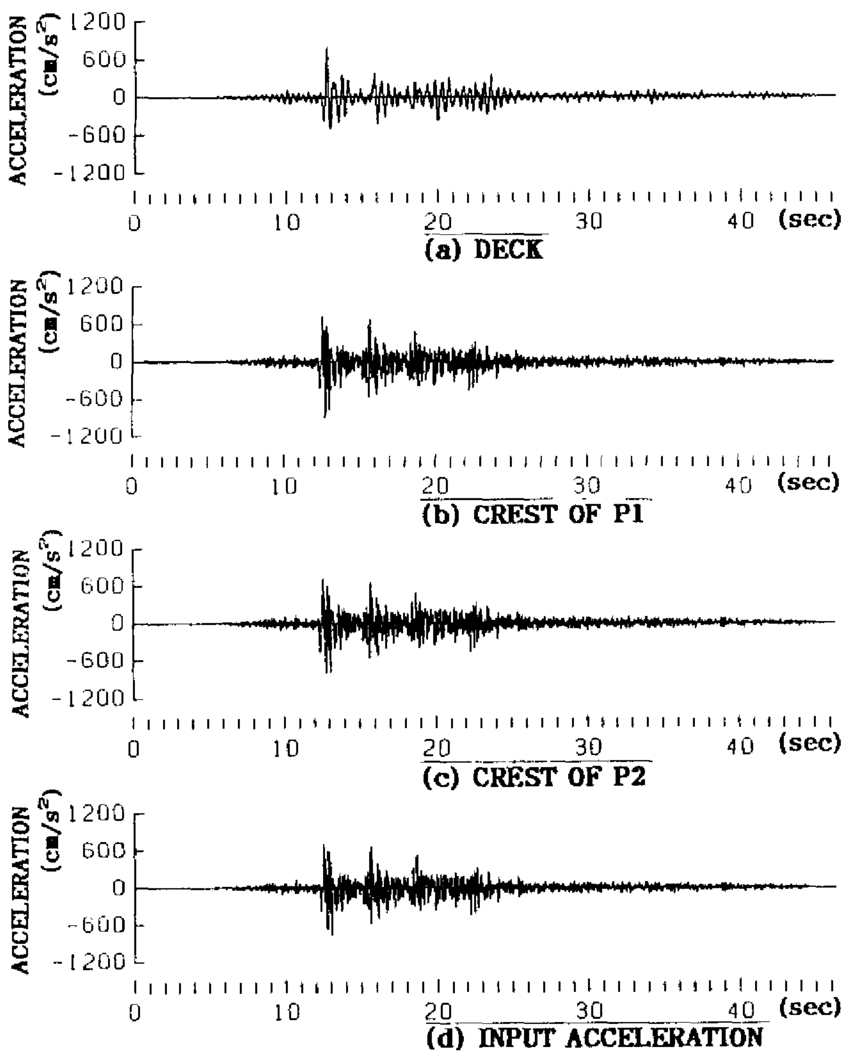


Fig.10 Response When Stopper Is Not Provided

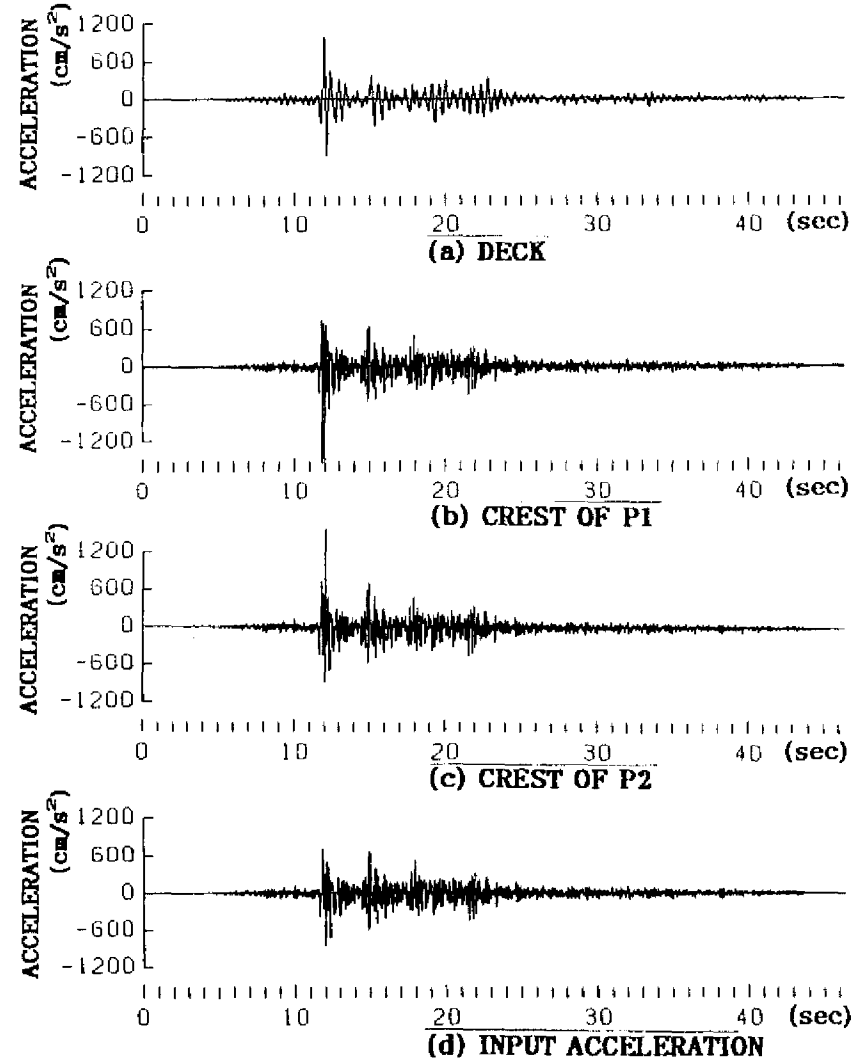


Fig.11 Response When Stopper with 2cm Gap Is Provided

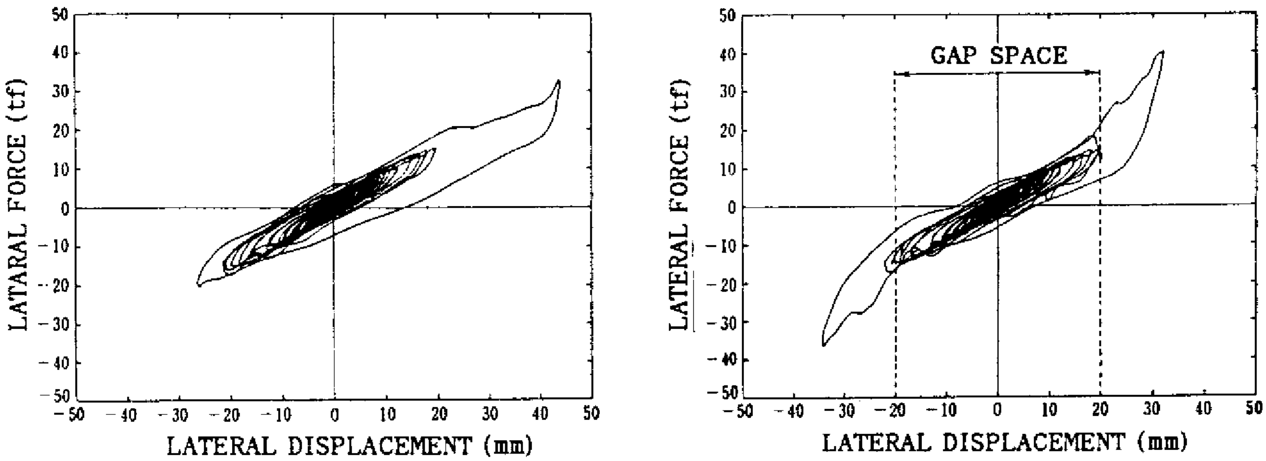


Fig.12 Hysteresis of Lateral Force vs. Lateral Displacement

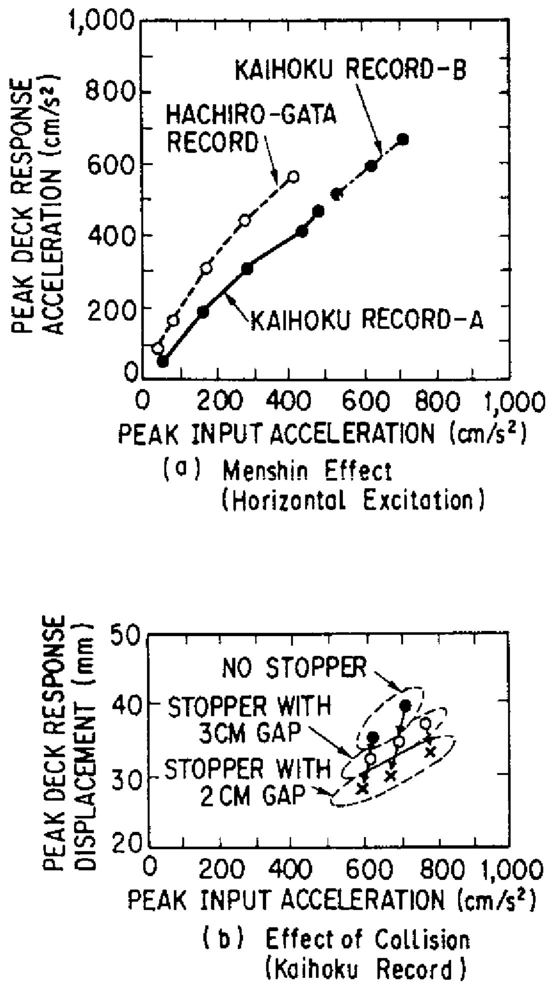


Fig.13 Effect of Stopper for Deck Response Displacement

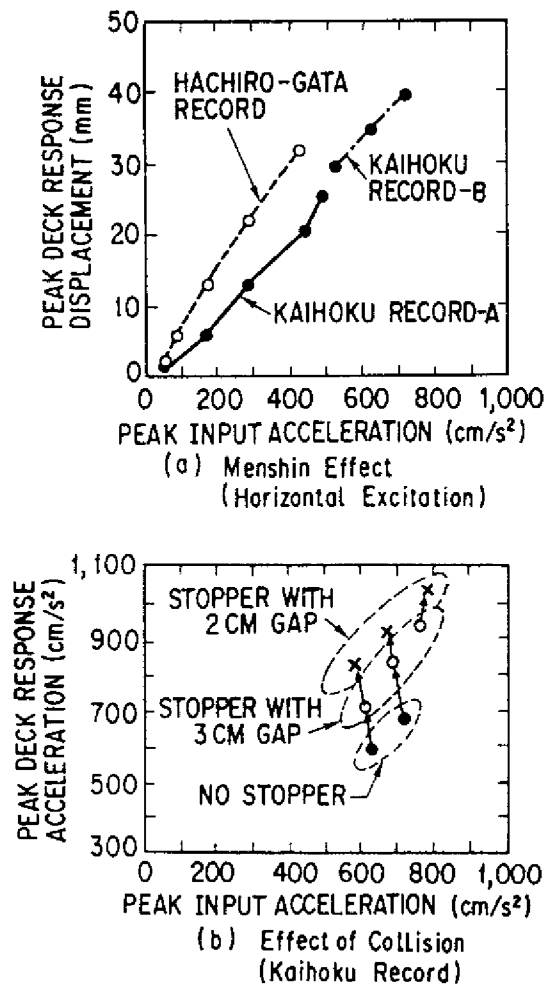
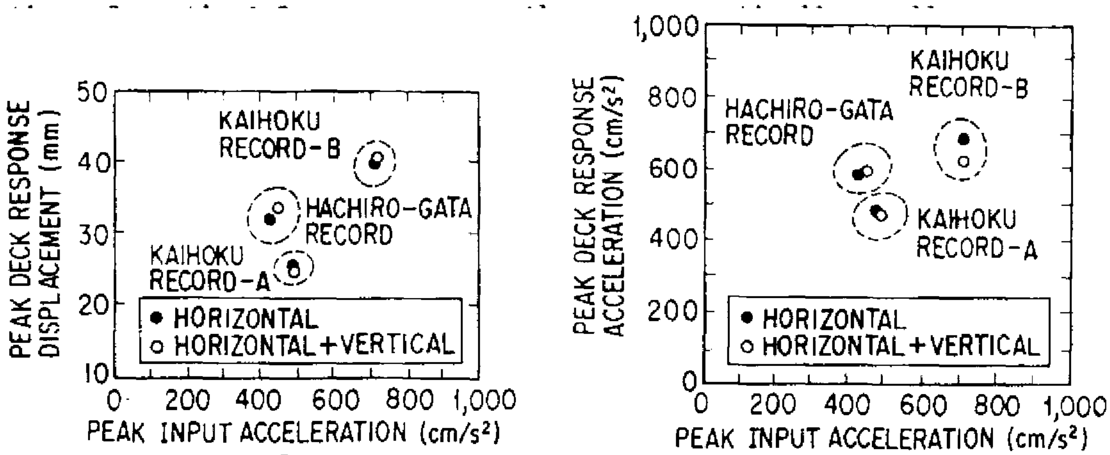


Fig.14 Effect of Stopper for Deck Response Acceleration

of 0.6 g acceleration. This means that the seismic lateral force transmitted to the columns is increased by 1.2 times and 1.4 times for the gap of 3 and 2 cm, respectively, due to the collision.

Fig. 15 shows the effect of vertical excitation in terms of peak deck response. Although some effects of simultaneous excitation which was presumably caused by changes of the equivalent stiffness of the LRB due to



(a) Deck Response Displacement

(b) Deck Response Acceleration

Fig.15 Effect of Vertical Excitation

Deck response when the HDR was adopted is basically analogous to that for the LRB, and so they are not presented here.

ANALYTICAL SIMULATION BY EQUIVALENT LINEAR ANALYSIS

Because the equivalent stiffness and the equivalent damping ratio of Menshin bearing depend on the displacement developed in it as shown in **Figs. 5** and **6**, they have to be evaluated for a specific response displacement ue in the equivalent linear analysis. Therefore the response displacement u_e was assumed to be specified in the form of

$$u_e = c \cdot u_{max} \tag{1}$$

where u_{max} is the peak displacement of the Menshin bearing, and c is a coefficient ($0 \leqq c \leqq 1.0$) representing the intensity of the specific response displacement. The coefficient c was assigned as 0.7 and 1.0. Because the purpose of this study is to clarify the coefficient c, a simplification was introduced in the calculation, i.e., since the peak displacement u_{max} is unknown before the analysis, the iteration of analysis is inevitable in the equivalent linear analysis. However, since the peak displacement obtained from the tests should be the right peak displacement, it was used in **Eq. (1)** instead of the iteration.

Mode damping ratio of the entire bridge model with Menshin bearings was computed by the proportional-to-strain-energy damping computing method (Ref. 9). The method is to estimate the damping ratio for each mode shape of an entire structure as the weighted average of damping ratio of each element with proportion to its strain energy as

$$h_i = \frac{\sum_{j=1}^{n} \phi_{ij}^T \cdot h_j \cdot k_j \cdot \phi_{ij}}{\phi_i^T \cdot K \cdot \phi_i} \tag{2}$$

where h_i is the damping ratio of i-th mode, ϕ_{ij} is an i-th mode vector for j-th structural element, h_j is the damping ratio of j-th element, K_j is the stiffness matrix of j-th element, ϕ_i is i-th mode vector, K is stiffness matrix of the entire structure and n is the number of elements.

The model 1 supported by the LRB was analyzed. **Table 2** shows the fundamental natural period and the mode damping ratio for the fundamental natural mode. Damping ratio of the columns was assumed as 0.2 %, which was estimated from the shaking table test results of the bridge model supported by the regular fix and roller bearings. It is seen in **Table 2** that difference of the fundamental natural period and the mode damping ratio between for c = 0.7 and c = 1.0 is up to only 7 % and 2 % at most, respectively. This means that the fundamental natural period and the mode damping ratio are less sensitive on the coefficient c.

Table 2 Natural Period and Damping Ratio

(a) Natural Period

INPUT MOTION		L R B		H D R	
		c=0.7	c=1.0	c=0.7	c=1.0
KAIHOKU RECORD	A	1.04	1.11	0.84	0.88
	B	1.13	1.18	0.90	0.93
HACHIRO-GATA RECORD	A	1.08	1.14	0.80	0.85
	B	1.15	1.20	0.89	0.92

(b) Viscous Damping Ratio

BEARING	INPUT MOTION		c=0.7	c=1.0
L R B	KAIHOKU RECORD	A	0.149	0.150
		B	0.151	0.152
	HACHIRO-GATA RECORD	A	0.150	0.151
		B	0.152	0.152
H D R	KAIHOKU RECORD	A	0.111	0.112
		B	0.113	0.114
	HACHIRO-GATA RECORD	A	0.109	0.111
		B	0.113	0.114

Fig. 16 compares the predicted and measured deck response acceleration for the Kaihoku record. The predicted response assuming c = 0.7 and c = 1.0 sufficiently assesses the experimental response, and these two values of c do not give meaningful difference on the response. **Table 3** compares the peak response between the predicted and the measured. Although the analysis assuming c = 1.0 gives a little better outcome compared with the analysis assuming c = 0.7, it may be said that the accuracy of both cases are satisfactory enough in practical sense.

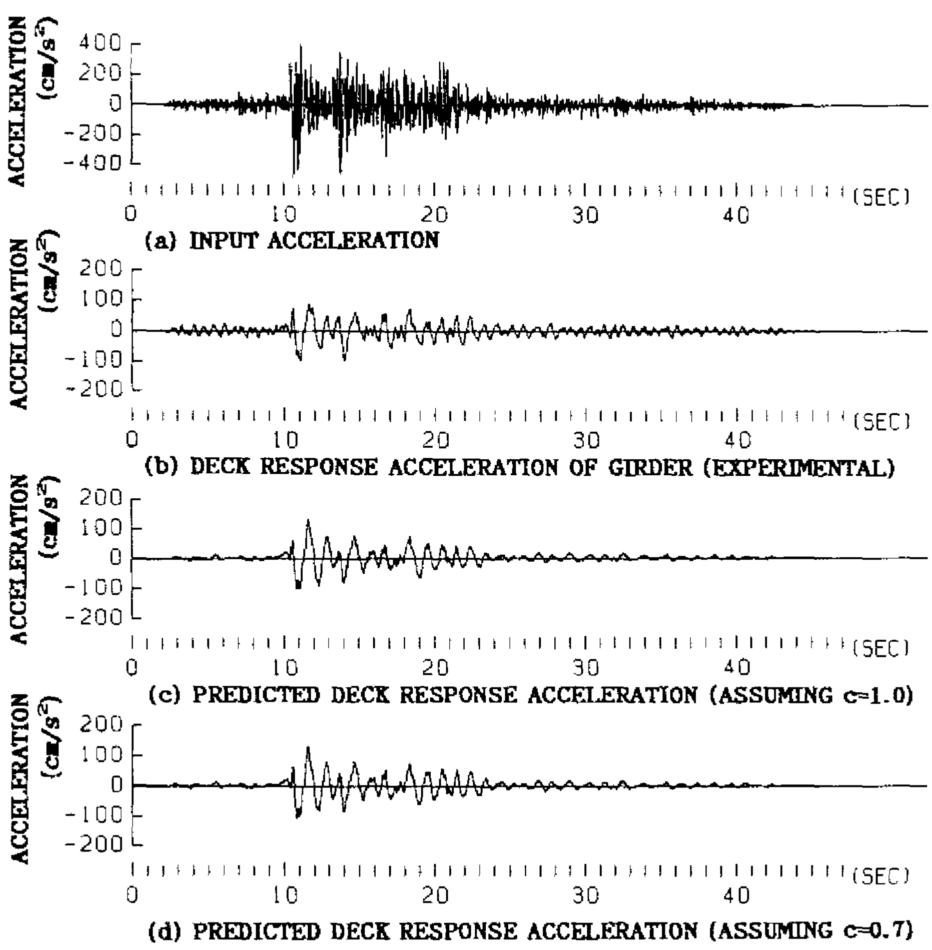


Fig.16 Deck Response Acceleration for Kaihoku Record B

Table 3 Comparison between Experimental and Analytical by Equivalent Linear Analysis

MENSHIN BEARING	INPUT MOTION		PEAK INPUT ACCELERATION (cm/s²)	EXPERIMENT		SIMULATION			
						c = 0.7		c = 1.0	
				PEAK DECK RESPONSE ACCELERATION (cm/s²)	PEAK DECK RESPONSE DISPLACEMENT (mm)	PEAK DECK RESPONSE ACCELERATION (cm/s²)	PEAK DECK RESPONSE DISPLACEMENT (mm)	PEAK DECK RESPONSE ACCELERATION (cm/s²)	PEAK DECK RESPONSE DISPLACEMENT (mm)
L R B	KAIHOKU RECORD	A	273.2	72.5	21.0	80.2 (1.11)	18.2 (0.87)	80.2 (1.11)	20.6 (0.98)
		B	481.3	101.0	35.8	134.6 (1.33)	36.6 (1.02)	130.4 (1.29)	39.1 (1.09)
	HACHIRO-GATA RECORD	A	85.1	81.7	26.1	120.0 (1.47)	30.4 (1.16)	111.5 (1.36)	31.5 (1.21)
		B	115.6	110.2	41.2	163.7 (1.49)	47.5 (1.15)	151.3 (1.37)	47.9 (1.16)
H D R	KAIHOKU RECORD	A	276.4	124.6	18.6	125.6 (1.01)	17.9 (0.96)	118.6 (0.95)	18.9 (1.02)
		B	484.7	181.9	33.1	190.9 (1.05)	32.2 (0.97)	182.2 (1.00)	33.1 (1.00)
	HACHIRO-GATA RECORD	A	83.1	102.7	14.0	112.5 (1.10)	14.8 (1.06)	113.8 (1.11)	17.0 (1.21)
		B	111.5	170.4	30.4	186.2 (1.09)	31.5 (1.04)	197.3 (1.16)	36.2 (1.19)
AVERAGE OF RATIO						(1.21)	(1.15)	(1.17)	(1.11)

( ) Represents Ratio of Experimental to Analytical

ANALYTICAL SIMULATION BY BILINEAR ANALYTICAL MODEL

An analysis was also made for the model 1 by idealizing the nonlinear hysteretic behavior of the Menshin bearings by a bilinear analytical model. The initial stiffness k_1, post-yield stiffness k_2 and the characteristic load Q are the basic parameters for defining the bilinear model. As shown in **Figs. 17 - 19**, they were estimated from the sinusoidal excitation test results presented in **Fig. 4**. Empirical equations were derived for k_1, k_2 and Q

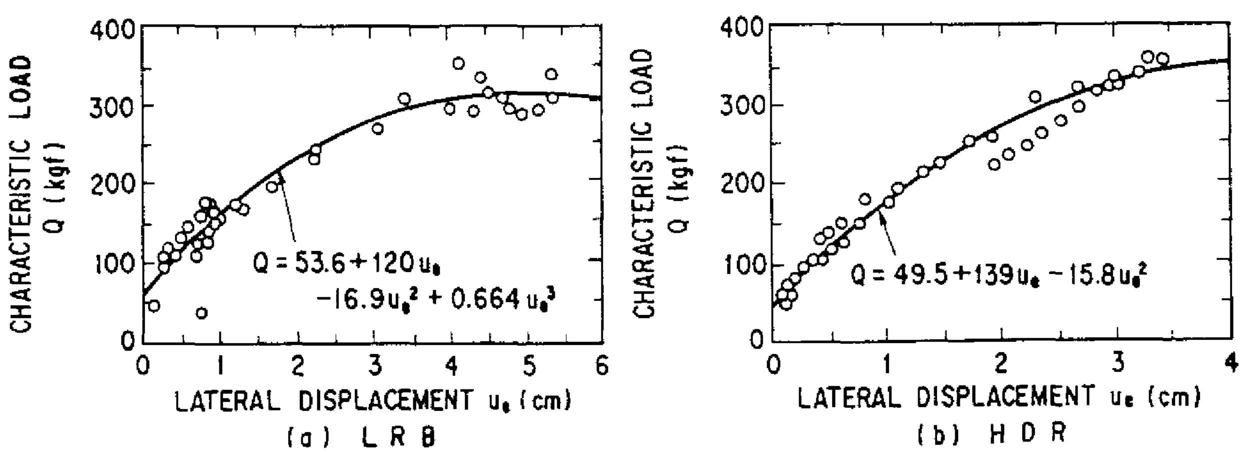
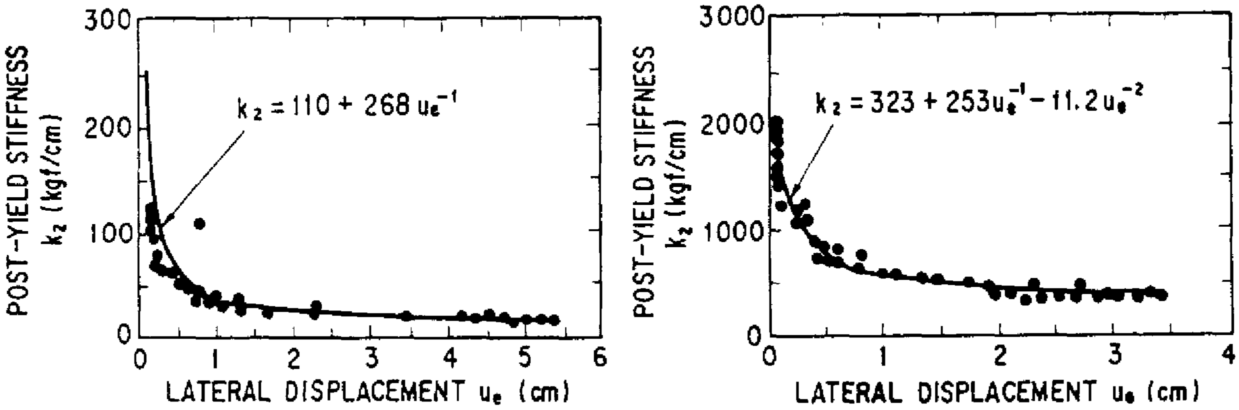
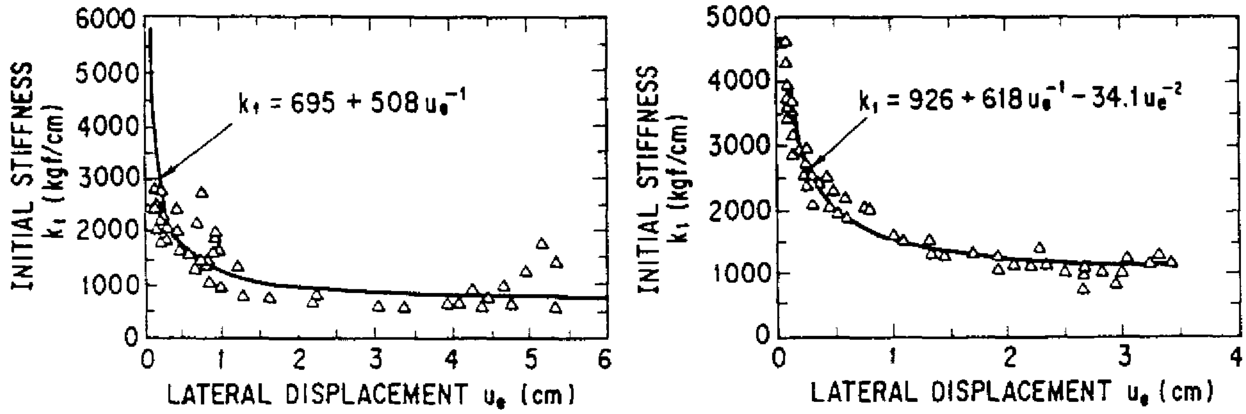


Fig.17 Characteristic Load



(a) L R B (b) H D R

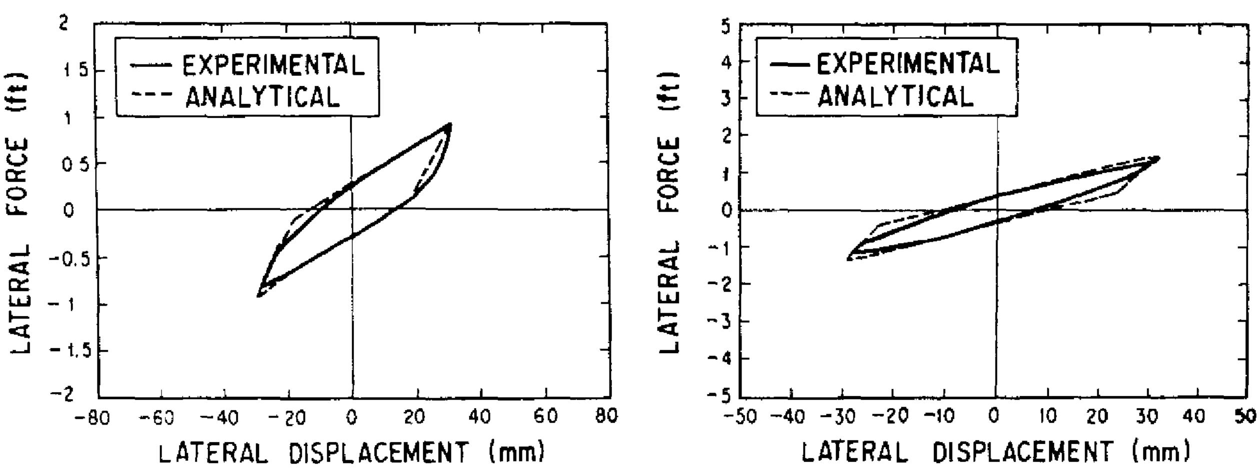
Fig.18 Post-yield Stiffness



(a) L R B (b) H D R

Fig.19 Initial Stiffness

Fig. 20 compares the hysteresis loop thus idealized with the bilinear model and the experimental result. The model remarkably agrees with the experimental loop.



(a) L R B (b) H D R

Fig.20 Analytical Idealization by Bilinear Spring Model

It should be however noted here that because the parameters k_1, k_2 and Q depend on the shear deformation of the Menshin bearings, the idealization with the bilinear model has to be made depending on the shear deformation developed in the Menshin bearings. Because a computer program in which the displacement-independent bilinear model is assumed was used, iteration similar with the equivalent linear analysis was required to determine the most appropriate shear deformation of the Menshin bearings. Therefore, the response displacement of the Menshin bearings ue was assumed as

$$u_e = c_{NL} \cdot u_{max} \tag{3}$$

where c_{NL} is a coefficient ($0 \leqq c_{NL} \leqq 1.0$) and u_{max} is the peak displacement of a Menshin bearing developed during excitation. Although it was anticipated from the preceding analysis by the equivalent linear analysis that the coefficient c_{NL} of 0.7 and 1.0 gives practically small difference, analytical simulation was made assuming these two values for the coefficient c_{NL}. Similar with the equivalent linear analysis, the peak response displacement actually developed in the Menshin bearings during the excitation tests was assigned for u_{max} in **Eq. (3)**, and the iteration was avoided in the analytical simulation.

The same cases studied as in the equivalent linear method were analyzed. To represent energy dissipation at the columns, Rayleigh damping was included. Coefficients of Rayleigh damping were determined so that it gives the mode damping ratio computed by the proportional-to-strain-energy damping computing method for the first and second vibration modes, i.e., h_1 = 0.0 and h_2 =0.02.

Fig. 21 compares the deck response between the analysis and the experiment. The analysis gives good agreement with the experiment, and no significant difference can been observed between c_{NL} = 0.7 and c_{NL} = 1.0. Only slight discrepancy is the decay of the deck response after the main vibration. The tests show faster attenuation than the analysis. This is because the bilinear hysteresis loop of the Menshin bearing was so adjusted to be applicable for the larger shear deformation during the main vibration, and is not fitting for the smaller deformation after that.

Table 4 compares the peak deck response. Defining a ratio of the predicted and experimental peak deck response, the ratio ranges from 0.9 to 1.1 for c_{NL} = 1.0, while it scatters widely for c_{NL} = 0.7. Based on such evaluation, c_{NL} is proposed to be assigned 1.0.

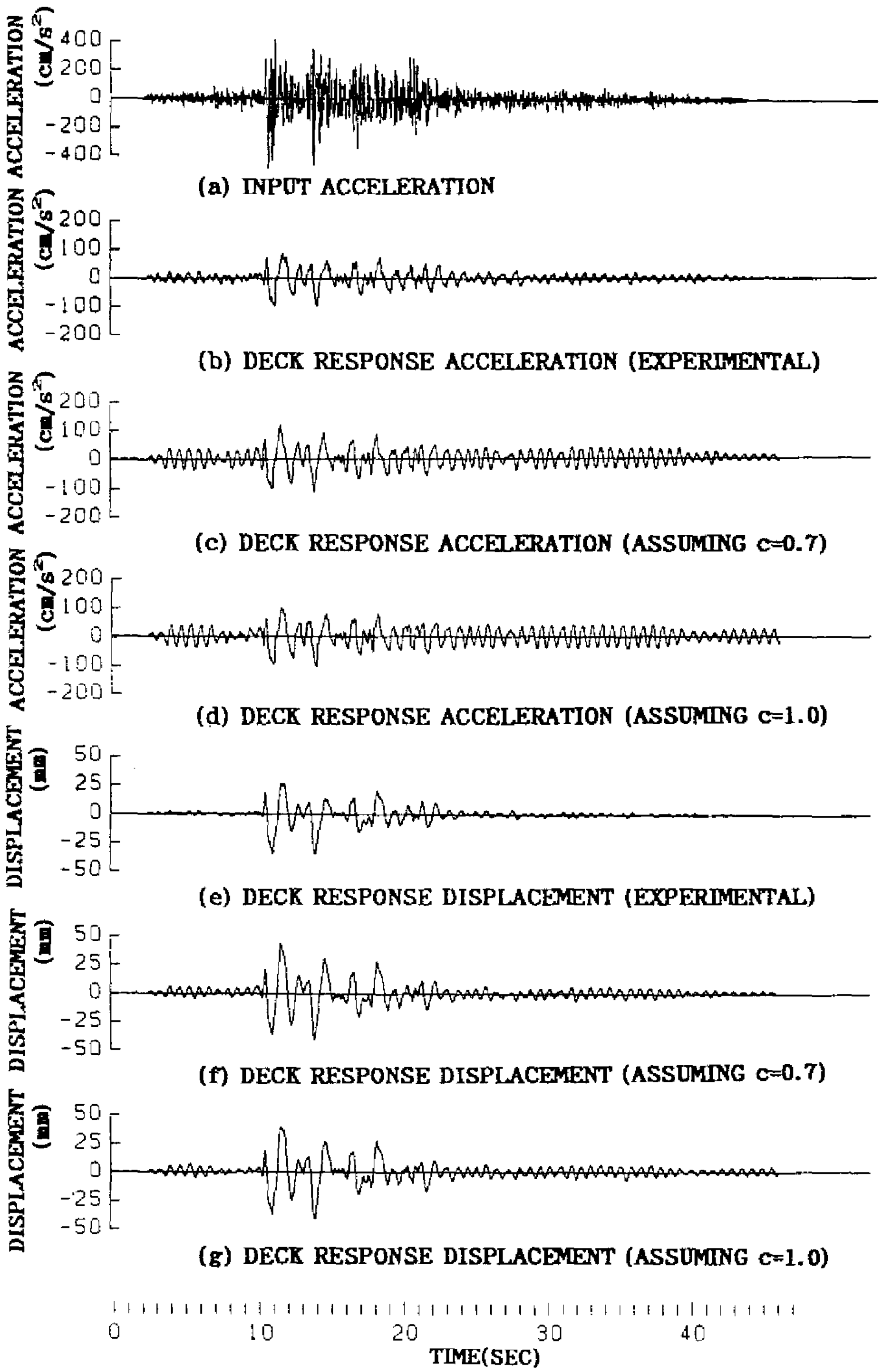


Fig.21 Deck Response for Kaihoku Record B

Table 4 **Comparison between Experimental and Analytical by Nonlinear Analysis**

MENSHIN BEARING	INPUT MOTION		PEAK INPUT ACCELERATION (cm/s^2)	EXPERIMENT		SIMULATION			
						c = 0.7		c = 1.0	
				PEAK DECK RESPONSE ACCELERATION (cm/s^2)	PEAK DECK RESPONSE DISPLACEMENT (mm)	PEAK DECK RESPONSE ACCELERATION (cm/s^2)	PEAK DECK RESPONSE DISPLACEMENT (mm)	PEAK DECK RESPONSE ACCELERATION (cm/s^2)	PEAK DECK RESPONSE DISPLACEMENT (mm)
L R B	KAIHOKU RECORD	A	273.2	72.5	21.0	92.2 (1.27)	25.3 (1.20)	83.6 (1.15)	25.7 (1.22)
		B	481.3	101.0	35.8	118.3 (1.17)	43.4 (1.21)	102.7 (1.02)	40.4 (1.13)
	HACHIRO-GATA RECORD	A	85.1	81.7	26.1	123.7 (1.51)	40.3 (1.54)	97.3 (1.19)	34.1 (1.31)
		B	115.6	110.2	41.6	148.4 (1.35)	60.7 (1.46)	123.0 (1.12)	53.8 (1.29)
H D R	KAIHOKU RECORD	A	276.4	124.6	18.6	128.6 (1.03)	22.1 (1.19)	116.5 (0.93)	20.7 (1.11)
		B	484.7	181.9	33.1	172.3 (0.95)	34.4 (1.04)	156.9 (0.86)	31.7 (0.96)
	HACHIRO-GATA RECORD	A	83.1	102.7	14.0	95.0 (0.93)	15.6 (1.11)	93.6 (0.91)	15.4 (1.10)
		B	111.5	170.4	30.4	189.9 (1.11)	39.3 (1.29)	185.3 (1.09)	39.8 (1.31)
AVERAGE OF RATIO						(1.17)	(1.26)	(1.03)	(1.18)

( ) Represents Ratio of Experimental to Analytical

ANALYTICAL SIMULATION FOR COLLISION

The stopper of Menshin bridges has to be properly modeled in Menshin design since it would cause great impact force to the columns due to collision. As shown in **Fig. 22**, the stopper was idealized as a linear spring functioning only when collision takes place. In the range over the gap space Δ_G of the stopper, a spring with the compression stiffness of the rubber installed on the stopper resists for further compression. Energy dissipation due to collision was disregarded in this idealization (Ref. 10).

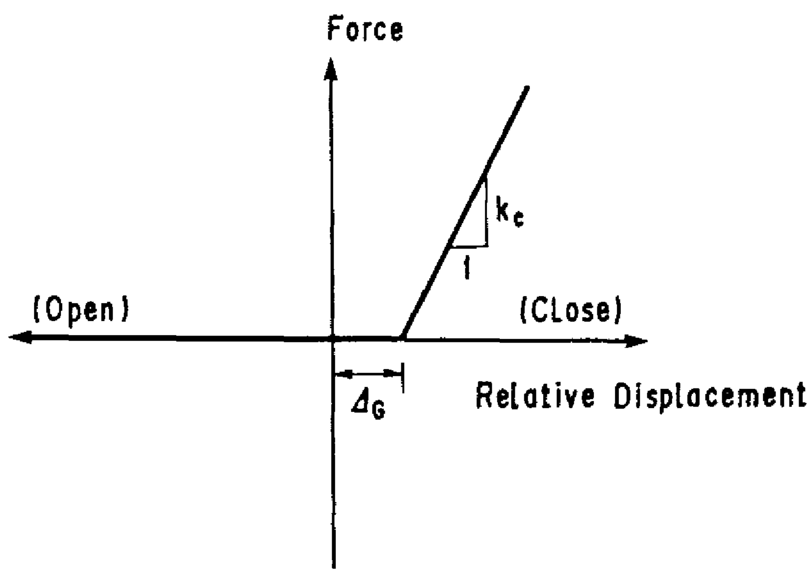


Fig.22 Idealization of Stopper

The width w, height h, thickness t, and young modulus E of the rubber are 40 cm, 20 cm, 7.1 cm and 40.0 kgf/cm^2, respectively, so that the compression stiffness k_c is obtained as

$$\begin{aligned} k_c &= E \times w \times h / t \\ &= 40.0 \times 40 \times 20 / 7.1 \\ &= 4{,}507 \text{ kgf/cm} \end{aligned} \qquad (4)$$

The deck response of the model 2 supported by the LRB was simulated with nonlinear dynamic analysis. The Menshin bearing was modeled as a bilinear model. The initial stiffness, post-yield stiffness and characteristic load of the Menshin bearing were determined by the method proposed in the preceding chapter. The damping of other structural elements than the Menshin bearings is taken into account by Rayleigh damping with the same method as described also in the preceding chapter.

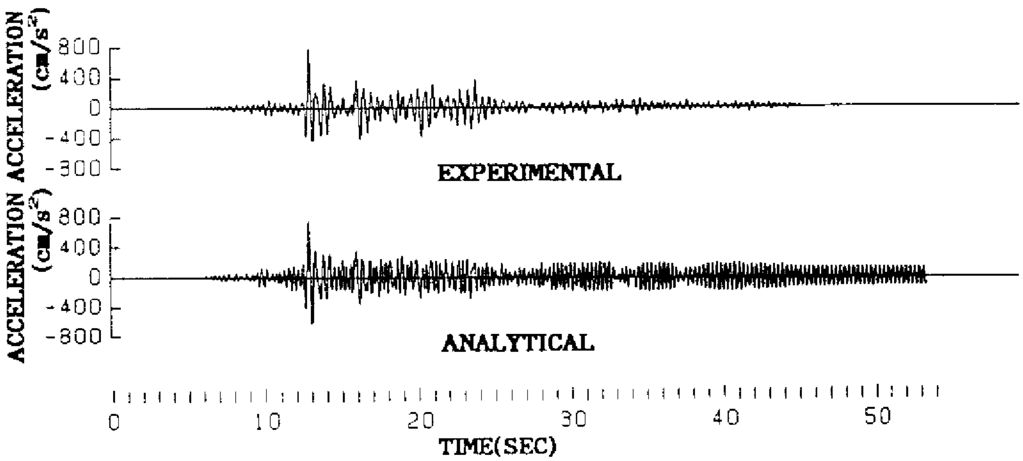
Figs. 23 and **24** compare the deck response acceleration and the response displacement of the bearing between the analysis and the experiments. The analysis can successfully simulate the effect of collision. **Figs. 25, 26** and **27** show the hysteresis loops between the force transmitted to the columns and the relative displacement of the bearing. Sudden increase of the force when collision occurred can be realistically predicted by the analysis, although the effect of strain hardening of rubber can not be simulated in the analysis.

Table 5 compares the peak response of the analysis and the experiment. The accuracy of the analytical prediction expressed in terms of a ratio of the peak predicted response to the peak measured response ranges from 0.92 to 0.95 for the acceleration and from 1.03 to 1.16 for the displacement. They are quite sufficient.

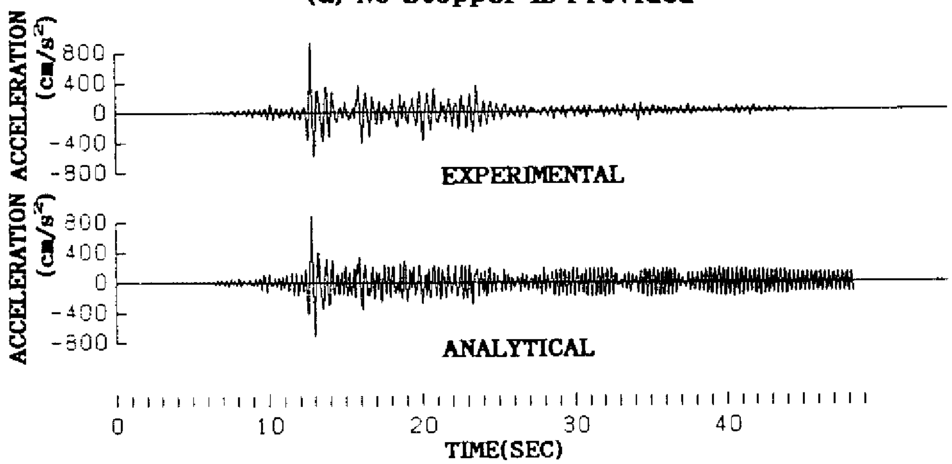
Table 5 Comparison between Experimental Analytical Deck Response

GAP SPACE	PEAK INPUT ACCELERATION (cm/s^2)	EXPERIMENT		SIMULATION	
		PEAK DECK RESPONSE ACCELERATION (cm/s^2)	PEAK DECK RESPONSE DISPLACEMENT (mm)	PEAK DECK RESPONSE ACCELERATION (cm/s^2)	PEAK DECK RESPONSE DISPLACEMENT (mm)
No Stopper	751.6	785.8	43.1	744.7 (0.95)	44.5 (1.03)
3 cm	768.6	937.4	39.1	891.9 (0.95)	44.0 (1.13)
2 cm	787.2	1023.1	35.7	936.8 (0.92)	41.4 (1.16)

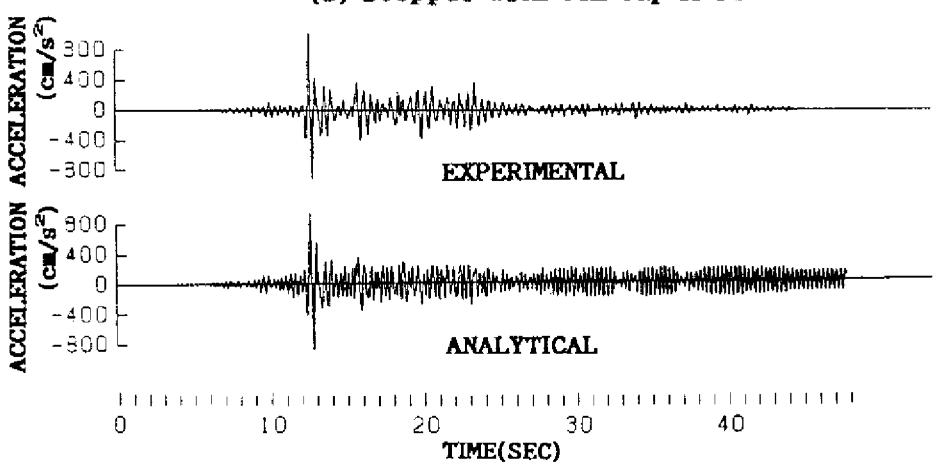
( ) Represents Ratio of Experimental to Analytical



(a) No Stopper is Provided

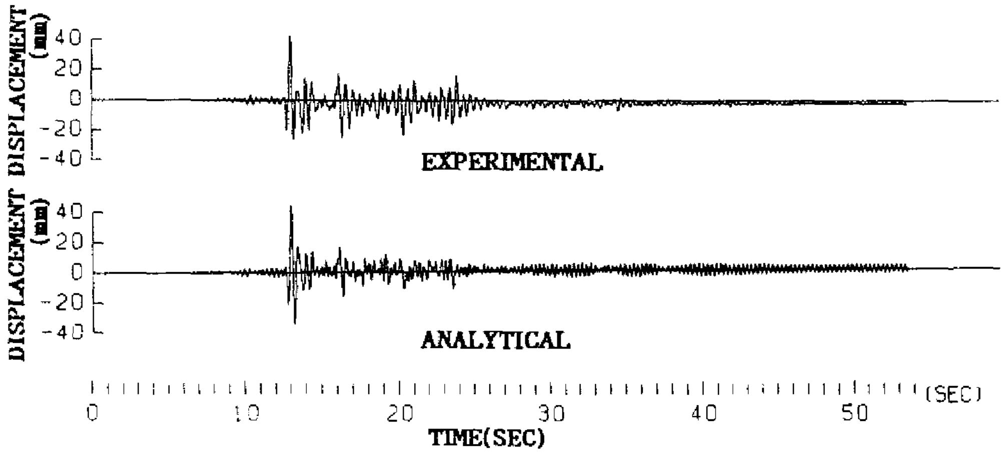


(b) Stopper with 3cm Gap is Provided

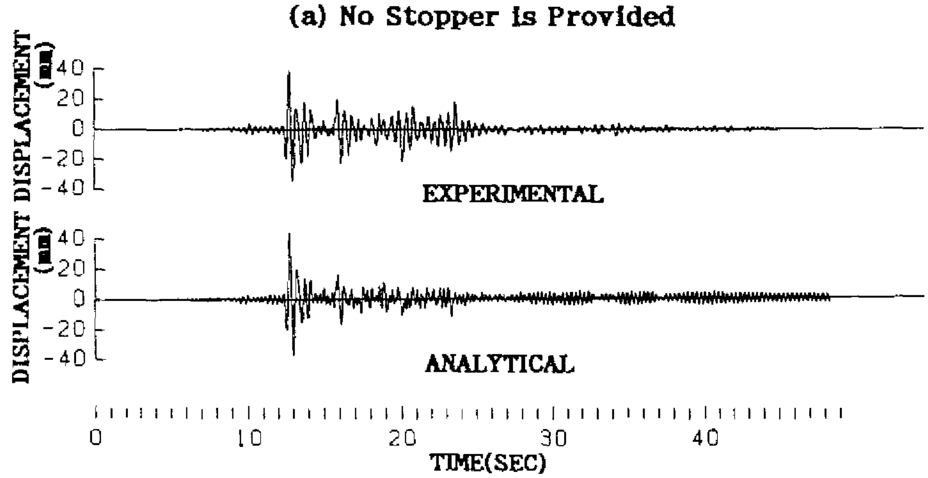


(c) Stopper with 2cm Gap is Provided

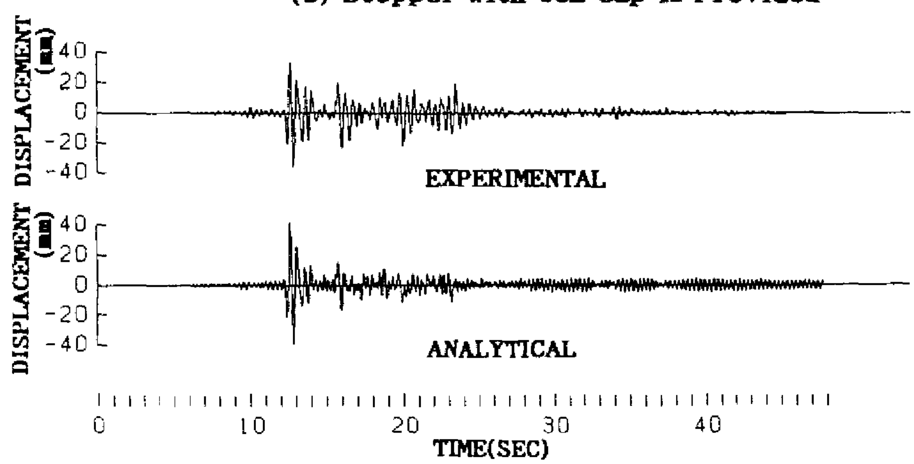
Fig.23 Comparison between Experimental and Analytical Deck Response Acceleration



(a) No Stopper is Provided

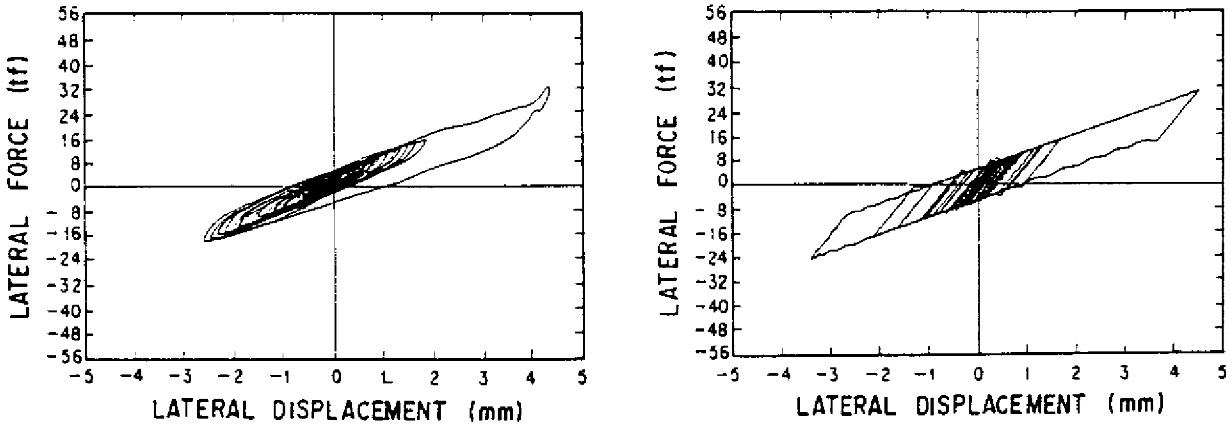


(b) Stopper with 3cm Gap is Provided



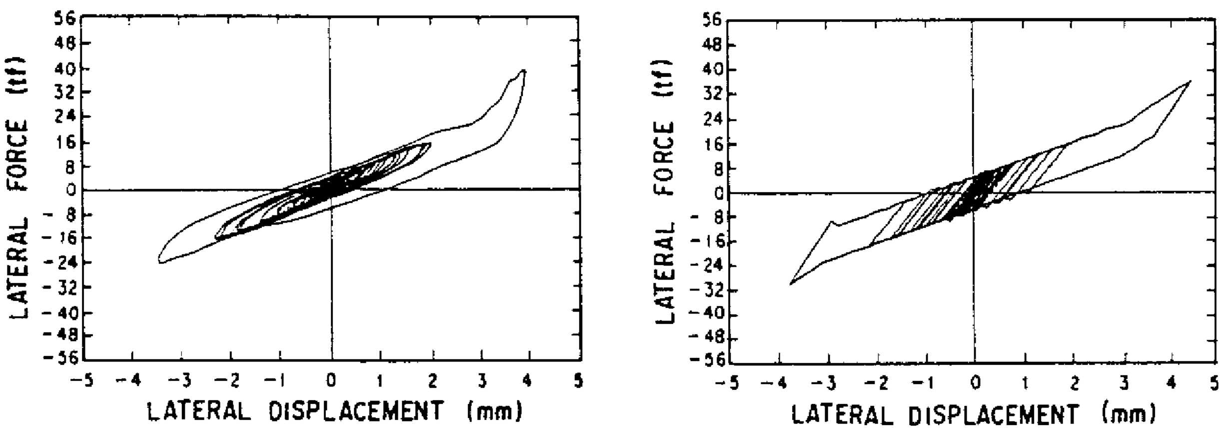
(c) Stopper with 2cm Gap is Provided

Fig.24 Comparison between Experimental and Analytical Deck Response Displacement



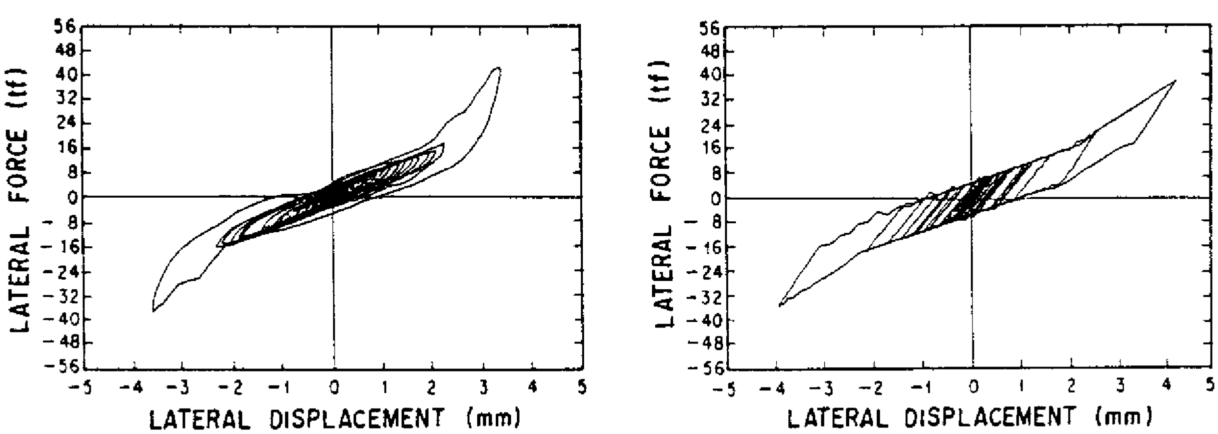
(a) Experimental (b) Analytical

Fig.25 Hysteresis When No Stopper is Provided



(a) Experimental (b) Analytical

Fig.26 Hysteresis When Stopper with 3cm Gap is Provided



(a) Experimental (b) Analytical

Fig.27 Hysteresis When Stopper with 2cm Gap is Provided

CONCLUSIONS

Response characteristics of two Menshin bridges were investigated through a series of shaking table tests. The response data of the model bridges were analyzed by the equivalent linear and bilinear analysis. The following conclusions may be deduced from the result presented herein.

1) The stoppers, which can effectively control the excessive relative displacement between the deck and the column, could develop great impact forces at the columns. Effect of such impact force needs to be considered in the Menshin design. The force and the displacement can be assessed by nonlinear dynamic analysis with the model of stoppers functioning as a linear spring only when the collision occurs.

2) Effect of vertical excitation is less significant to lateral response of the deck.

3) The response of the Menshin bridge can be successfully simulated by the equivalent linear analysis if the equivalent stiffness and the equivalent damping ratio are appropriately assumed in the analysis. The coefficient c in **Eq. (1)** is proposed to be assigned as 1.0 although the difference of the response by assuming c = 0.7 is small.

4) The response of the Menshin bridge can be successfully assessed by idealizing the nonlinear hysteretic behavior of the Menshin bearings with the bilinear model. The coefficient c_{HL} of 1.0 gives better result than c_{HL} of 0.7 to determine the initial stiffness, the post-yield stiffness and the characteristic load of the Menshin bearing.

ACKNOWLEDGEMENT

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