COMPARISON OF SEISMIC RESPONSE BETWEEN BRIDGE WITH SLIDING-TYPE BASE-ISOLATION SYSTEM AND THAT WITH LAMINATED RUBBER BEARING

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SUMMARY

Comparison of dynamic characteristics between bridge with sliding-type base-isolation system and that with laminated rubber bearing under earthquake motion has been made. 4-span continuous steel box girder elevated bridge with lead laminated rubber bearings which is located on Bay-area Line of Hanshin Express Highway is selected as the subject of study because its dynamic responses under Kobe Earthquake were measured actually. Four kinds of laminated rubber bearings whose physical properties are different are taken into account in this study. Several types of earthquake motions such as Kobe Earthquake, Pacoima Earthquake, Taft Earthquake, and so on whose amplitude is appropriately changed are used as input earthquake motions. The result shows that from the point of view of reduction of girder acceleration, sliding-type base-isolation system is more effective than laminated rubber bearing in case that stronger earthquake attacks the bridge although the relative displacement between superstructure and substructure is considerably large. It has also been revealed that any significant difference is not recognized between these two types of base-isolation systems in case that the relatively weak earthquake occurs.

INTRODUCTION

After Kobe Earthquake, base-isolation system has been positively equipped in the elevated bridges in order to reduce the earthquake effect on their substructure. As the typical types of base-isolation systems which can be set up in bridge structures, laminated rubber bearing [Skinner, Robinson and McVerry, 1993] and sliding-type bearing [Okamoto et al., 1995a] have been proposed. In case that the laminated rubber bearings are equipped in the elevated bridges, the natural period of superstructure becomes longer under the action of laminated rubber and the earthquake energy is absorbed by the action of non-linear shear hysteresis of lead plug. And this type of bearing has already been used in practice in some countries. On the other hand, the advantageous points of sliding-type bearing are as follows; that is, 1) the response of bridge decreases as a result of large energy dissipation through the sliding bearing and this leads to the considerable reduction of shear force acting on the top of pier; 2) the resonant excitation is unlikely to occur because of the large energy dissipation of the sliding system. Unfortunately, the sliding-type bearing has not been adopted practically yet because of its uneasy maintenance of sliding surface, occurrence of large relative displacement or residual one between bridge deck and pier, and indispensability of stopper. However, it may be important to compare the seismic characteristics between these two types of base-isolation systems from the point of view of seismic capacity of bridges.

The purpose of this study is to make a comparison of dynamic characteristics between bridge with sliding-type base-isolation system and that with laminated rubber bearing under earthquake motion. 4-span continuous steel box girder elevated bridge is selected as the subject of study. The maximum values of deck acceleration, shear force acting on the top of pier, relative displacement and residual displacement between deck and pier, and pier acceleration under several types of strong earthquake motions are obtained through time-history analysis. Then, by comparing these values, it is discussed which type of bearing is more effective

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1. ANALYTICAL MODEL AND ANALYTICAL METHOD

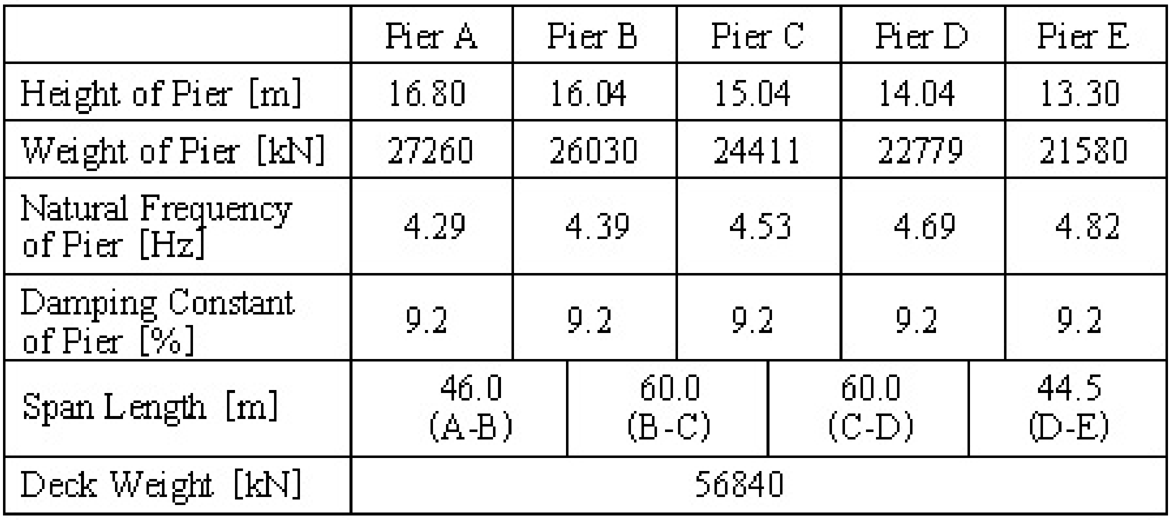
4-span continuous steel box girder elevated bridge with lead laminated rubber bearings which is located on Bay-area Line of Hanshin Express Highway is selected as the subject of study because its dynamic responses under Kobe Earthquake were measured actually. Its bridge length and width are 211.5 meter and 21.94 meter, respectively. The substructure of this bridge is composed of T-shaped concrete pier and pile foundation. Lead laminated rubber bearings are equipped on the intermediate three piers and pivot-roller bearings are set up on both end piers. The dimension and physical properties of bridges adopted in the time history analysis are indicated in Table 1.

In the time history analysis, the above described 4-span continuous bridge is modeled as spring-mass-dash pot structural system. Four kinds of laminated rubber bearings whose physical properties are different are taken into account here. Table 2 shows the physical properties of four kinds of laminated rubber bearings (refer Fig. 1). In this table, the physical property of lead laminated rubber bearing is the same as the one actually equipped in the bridge on Bay-area Line of Hanshin Express Highway. The values with respect to other three laminated rubbers are obtained from the laboratory tests.

Fig. 2 illustrates the schematic diagram of analytical model in case that the sliding-type base-isolation system is equipped on the three intermediate piers. As for the friction coefficient of sliding-type bearing, the same value as adopted in Dr. Okamoto’s research [Okamoto et al., 1995b] is considered here. On the other hand, the property of restoring force of rubber device used in sliding-type bearing will be discussed later in Paragraph 4.2.

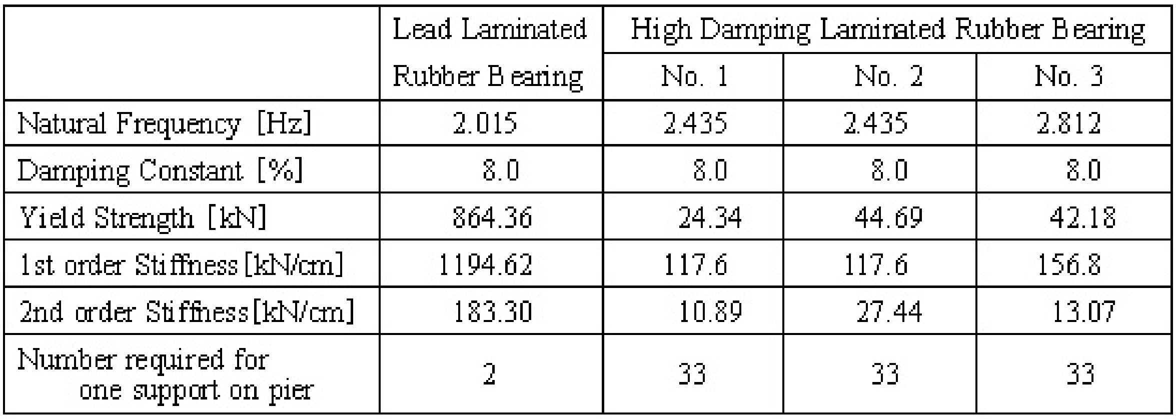
In the time history analysis, Newmark's β -Method (β =1/6) is adopted in numerical integration.

Table 1: Dimension and physical properties with respect to analytical Model



	Pier A	Pier B	Pier C	Pier D	Pier E
Height of Pier [m]	16.80	16.04	15.04	14.04	13.30
Weight of Pier [kN]	27260	26030	24411	22779	21580
Natural Frequency of Pier [Hz]	4.29	4.39	4.53	4.69	4.82
Damping Constant of Pier [%]	9.2	9.2	9.2	9.2	9.2
Span Length [m]	46.0 (A-B)	60.0 (B-C)	60.0 (C-D)	44.5 (D-E)	
Deck Weight [kN]	56840				

Table 2: Physical properties of laminated rubber bearing.



	Lead Laminated Rubber Bearing	High Damping Laminated Rubber Bearing		
		No. 1	No. 2	No. 3
Natural Frequency [Hz]	2.015	2.435	2.435	2.812
Damping Constant [%]	8.0	8.0	8.0	8.0
Yield Strength [kN]	864.36	24.34	44.69	42.18
1st order Stiffness [kN/cm]	1194.62	117.6	117.6	156.8
2nd order Stiffness [kN/cm]	183.30	10.89	27.44	13.07
Number required for one support on pier	2	33	33	33

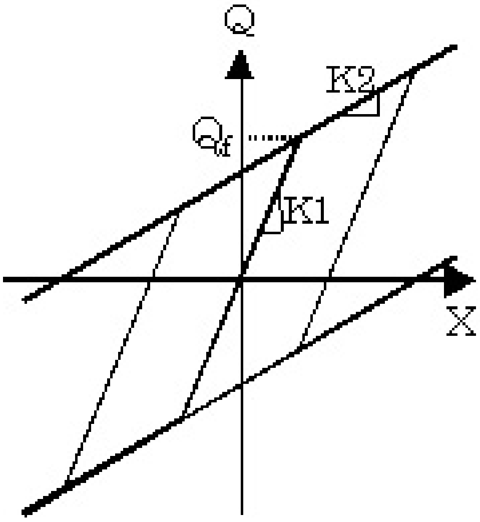


Fig. 1: Relation between shear displacement and restoring force of laminated rubber bearing
X: shear displacement, Q: restoring force, K1: 1st order stiffness
K2: 2nd order stiffness, Q_f: yield strengt.

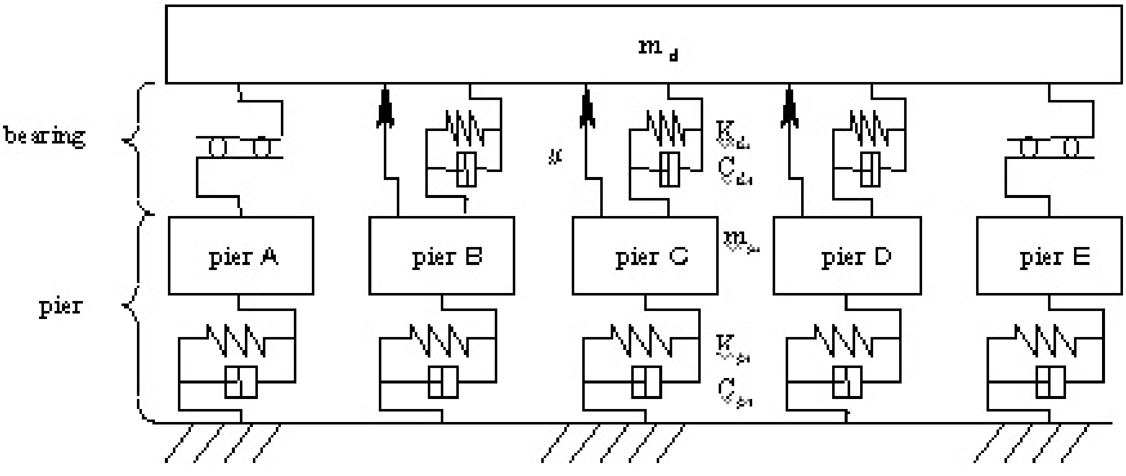


Fig. 2: Spring-mass-dash pot analytical model for 4-span continuous bridge with sliding-type bearings
m_d: mass of deck, m_{pi}: mass of pier, k_{di}: spring constant of rubber device,
k_{pi}: spring constant of pier, c_{di}: damping constant of rubber device, c_{pi}: damping constant of pier,
μ : friction coefficient of sliding-type bearing

2. INPUT EARTQUAKE MOTION

Several types of earthquake motions such as Kobe Earthquake, Pacoima Earthquake, Miyagi Earthquake, Taft Earthquake, and Hachinohe Earthquake whose amplitude is appropriately changed are used as input earthquake motions. Fig. 3 expresses the relation between maximum acceleration amplitude and predominant period obtained from several well-known earthquake records described above. From Fig. 3, three levels of maximum acceleration amplitude that are the function of predominant period are assumed to be given by three lines as follows; Level-High : upper dotted line; Level-Medium : solid line; Level-Low : lower dotted line.

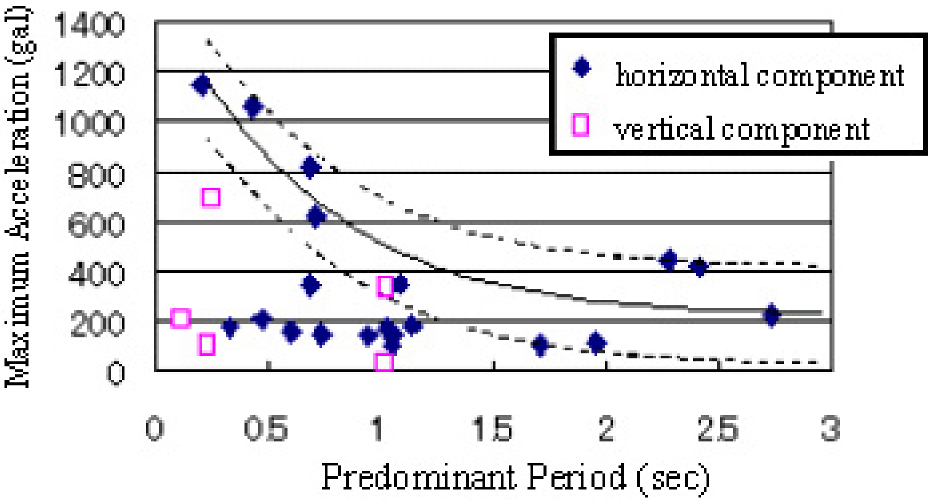


Fig. 3: Predominant period vs. Maximum acceleration amplitude of earthquake motions

Table 3: Maximum values of acceleration amplitude of input earthquake motions

	Predominant Period [sec]	Observed Max. Acceleration [gal]	Assumed Maximum Acceleration		
			Level-High	Level-Medium	Level-Low
Pacoima (S16E)	0.21	1147.3	1200	1100	900
Taft (S69E)	0.33	175.8	1100	900	700
Kobe (NS)	0.69	818.0	900	700	500
Miyagi (NS)	1.06	137.6	500	300	100
Hachinohe (NS)	2.73	225.0	400	200	100

Table 3 shows the maximum value of acceleration amplitude of input earthquake motions and their predominant period. In this study, totally 15 kinds of earthquake motions listed in Table 3 are adopted as input earthquake motion.

3. RESULTS OF TIME HISTORY ANALYSIS AND DISCUSSION

3.1 Comparison of Maximum Response values among Four Types of Laminated Rubber Bearings

Fig. 4(a) shows the relation between maximum acceleration amplitude of input earthquake motion and maximum absolute acceleration of bridge deck. From this figure, the response of laminated rubber bearing No. 2 is considerably larger than other bearings if the acceleration amplitude is greater than 0.4G. And this tendency is more remarkable as the increase of input acceleration amplitude. Though not shown in figures or tables, the results with respect to the shear force acting on the top of pier show the same tendency as the deck acceleration.

The relation between maximum acceleration amplitude of input earthquake motion and maximum relative displacement between deck and pier is illustrated in Fig. 4(b). From this figure, the following facts are found.

1) The relative displacement increases linearly as the increase of input acceleration amplitude.
2) Any significant difference can not be recognized among four kinds of laminated rubber bearings.

Summarizing the results described so far, lead laminated rubber bearing and laminated rubber No. 3 are selected for the comparison of seismic effectiveness with the sliding-type base-isolation bearing.

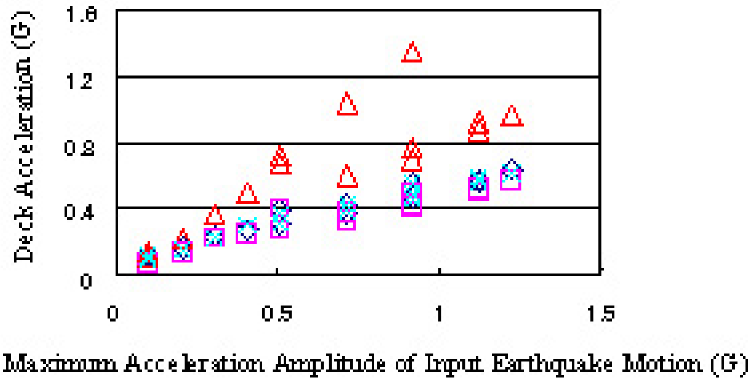


Fig. 4(a): Acceleration of pier vs. Maximum acceleration amplitude of input earthquake motion
(◇ lead laminated ☐ No. 1 △ No. 2 × No. 3)

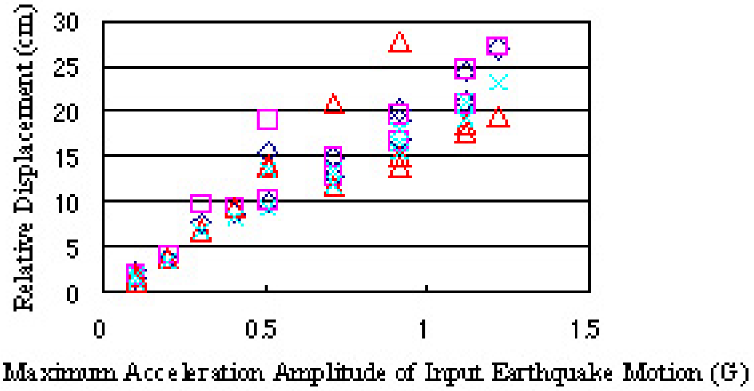


Fig. 4(b): Relative displacement vs. Maximum acceleration amplitude of input earthquake motion
(◇ lead laminated ☐ No. 1 △ No. 2 × No. 3)

3.2 Determination of Property of Rubber Device used in Sliding -type Base-isolation System

The optimal values of physical properties of rubber device used as a stopper in sliding-type base-isolation system are discussed here. The solid line illustrated in Fig. 5 represents the property of restoring force of rubber device adopted in Dr. Okamoto's research [Okamoto et al., 1995b]. However, the rapidly increasing point of restoring force and the stiffness of rubber device should be determined so as to minimize the response under various earthquake motions. Therefore, both values are parametrically changed and the influence of the values of rapidly increasing point of restoring force and stiffness of rubber device on the dynamic response of bridge is investigated in this paragraph.

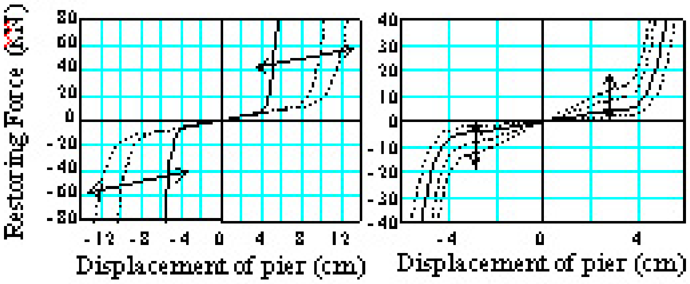


Fig. 5: Change of physical properties of restoring force of rubber device
(left-hand side: Change of rapidly increasing point, right-hand side: Change of stiffness)

Fig. 6 illustrates the relation between the value of rapidly increasing point of restoring force normalized by 3.5 [cm] and the maximum values of dynamic response of deck acceleration, pier acceleration, relative displacement between deck and pier, shear force acting on the top of pier normalized by deck weight, and residual displacement between deck and pier. The lower figure and the upper one of Fig. 6 correspond to the cases that input earthquake motions are Pacoima and Miyagi Earthquake motions, respectively. From these figures, the following facts can be found.

1) Deck acceleration becomes stable when the value of rapidly increasing point becomes greater than 0.2 in case of Miyagi Earthquake and greater than 6.0 in case of Pacoima Earthquake, respectively.
2) Pier acceleration becomes stable when the value of rapidly increasing point becomes greater than 0.1 in case of Miyagi Earthquake and greater than 3.0 in case of Pacoima Earthquake, respectively.
3) Shear force becomes stable when the value of rapidly increasing point becomes greater than 0.2 in case of Miyagi Earthquake and greater than 6.0 in case of Pacoima Earthquake, respectively.
4) In case of Miyagi Earthquake, both relative displacement and residual one between deck and pier are too small to consider the effect of the value of rapidly increasing point on them, although both of them increase rapidly when the value of rapidly increasing point takes the values of less than 0.2.

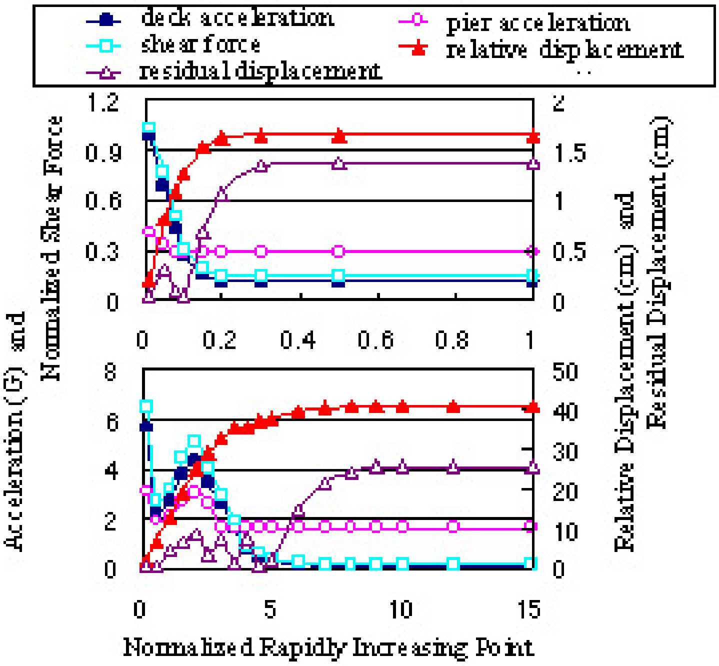


Fig. 6: Maximum values of dynamic response vs. normalized rapidly increasing point (lower figure : Pacoima Earthquake, upper figure : Miyagi Earthquake)

5) Under Pacoima Earthquake motion, both relative displacement and residual one between deck and pier increase rapidly when the value of rapidly increasing point takes the values of less than 7.0 and reach 42[cm] and 25[cm], respectively. These extremely larger displacements may not be acceptable in practice.

These facts indicate that the increase of rapidly increasing point of restoring force causes the larger relative and residual displacements although it leads to the decrease of deck and pier acceleration and shear force acting on the top of pier. Therefore, the optimum value of rapidly increasing point of restoring force may exist between 4.0 and 5.0.

Though not shown in figures or tables, it has been found that the optimal value of stiffness of rubber device is 1.4[kN/cm]. Accordingly, the following values are assumed in the dynamic response analysis of bridge with sliding-type base-isolation system.

rapidly increasing point of restoring force : 14.0[cm] , 17.5[cm], stiffness of rubber device : 1.4[kN/cm]

3.3 Comparison of Seismic Effectiveness between Laminated Rubber Bearing and Sliding-type Bearing

As lead laminated rubber bearing and laminated rubber No.3 are selected as the optimal ones in Paragraph 4.1 and the optimum physical properties of rubber device used in sliding-type bearing in Paragraph 4.2, comparison of seismic effectiveness between both types of bearings is made here.

Figs. 7(a) and (b) show the maximum values of deck acceleration and relative displacements between deck and pier, respectively, under Level-High earthquake motions. The maximum value of deck acceleration is normalized by the corresponding maximum value that is obtained in case that no base-isolation system is equipped in the bridge structure.

From Fig. 7(a), it is recognized that sliding-type bearing is more effective than laminated rubber one from the point of view of the reduction of deck acceleration. The fact that the relative displacement of sliding-type bearing is about 1.3～1.8 times as much as that of laminated rubber one is found from Fig. 7(b).

Though not illustrated in figures or tables, the same investigation were executed under Level-Medium and Level-Low earthquake motions. And subjectively summarizing the facts found in this study, Table 4 may be obtained as the result of comparison of seismic effectiveness between sliding-type and laminated rubber bearings. From Table 4, the following results can be concluded.

1) From the point of view of reduction of girder acceleration, sliding-type base-isolation system is more effective than laminated rubber bearing in case that stronger earthquake attacks the bridge although the relative displacement between deck and pier is considerably large.
2) Significant difference is not recognized between these two types of base-isolation systems in case that the relatively weak earthquake occurs.

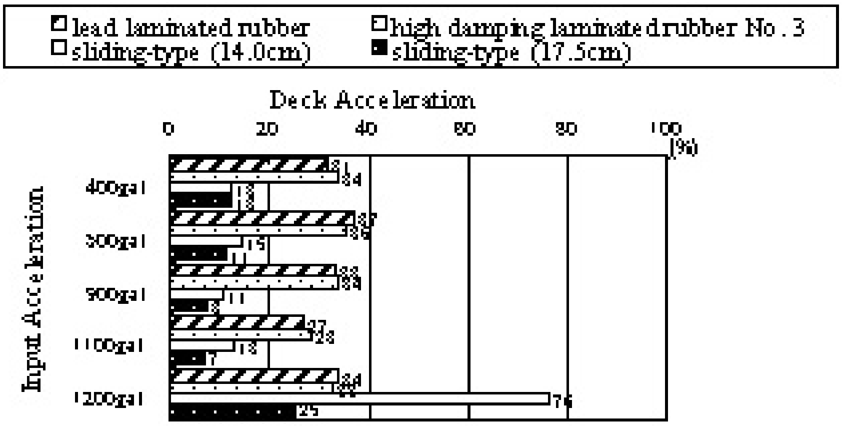


Fig. 7(a): Acceleration of deck vs. Maximum input earthquake acceleration (Level-High)

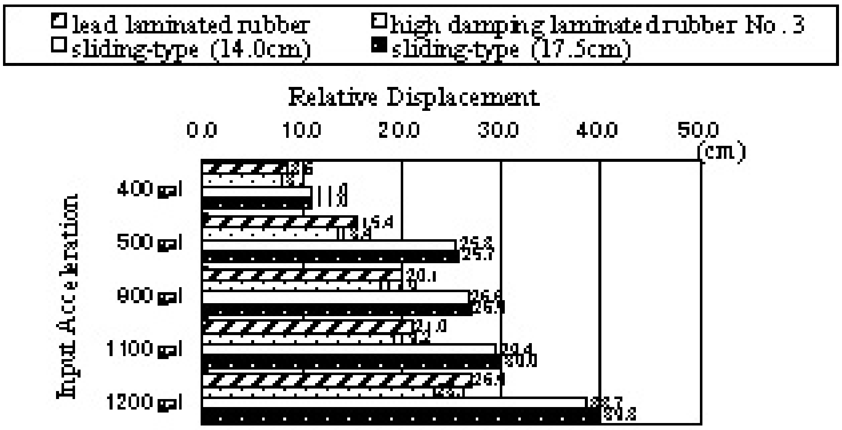


Fig. 7(b): Relative displacement vs. Maximum input earthquake acceleration (Level-High)

Table 4: Comparison of seismic effectiveness between sliding-type and laminated rubber bearings

Predominant of Earthquake Motion [sec]	Assumed Maximum Acceleration					
	Level-High		Level-Medium		Level-Low	
	sliding-type	laminated rubber	sliding-type	laminated rubber	sliding-type	laminated rubber
1.5 ~	◎	×	○	×	△	△
0.5 ~ 1.5	○	×	○	×	○	×
~ 0.5	△	△	△	△	○	×

5. CONCLUDING REMARKS

Comparison of dynamic characteristics between bridge with sliding-type base-isolation system and that with laminated rubber bearing under earthquake motion were made based on the results of time history analysis. As a result, the following conclusions are obtained.

1) From the point of view of reduction of girder acceleration, sliding-type base-isolation system is more effective than laminated rubber bearing in case that stronger earthquake attacks the bridge although the relative displacement between superstructure and substructure is considerably large.
2) Significant difference is not recognized between these two types of base-isolation systems in case that the relatively weak earthquake occurs.

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6. REFERENCES

Okamoto, S., S. Fujii, M.C. Constantinou and P. C. Tsopelas (1995), “Shaking table test of a model bridge with sliding type base isolation system”, *Journal of Structural Mechanics and Earthquake Engineering*, No. 507, pp.167-177, JSCE, Tokyo (in Japanese).

Okamoto, S., Y. Fukasawa, S. Fujii and D. Ozaki (1995b), “Dynamic behavior of a bridge with sliding type base isolation system during earthquake”, *Journal of Structural Mechanics and Earthquake Engineering*, No. 513, pp.191-200, JSCE, Tokyo (in Japanese).

Skinner, R. I., W. H. Robinson and G. H. McVerry (1993), *An Introduction to Seismic Isolation*, John Wiley & Sons, New York.