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SHAKING TABLE TESTS ON PERFORMANCE OF ISOLATORS FOR HOUSES SUBJECTED TO THREE DIMENSIONAL EARTHQUAKE MOTIONS

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SUMMARY

Lessons learned from Kobe earthquake and the good performance of seismically isolated structures during this earthquake have persuaded structural engineers, isolator makers and housing construction companies to undertake a cooperative research project to investigate the possibility of introducing seismically isolated structures in Japan's private housing sector. Verification of isolators and base-isolated houses behavior under 3-directional recorded earthquake ground motions has been one of the most important objectives of the project. In order to realize that, 3-dimensional shaking table tests on different types of base isolation systems and on a full-scale, two-story base-isolated house model were conducted. In this paper, characteristics of the newly-developed isolators, the outline of the tests and the latest results obtained from the experimental data-processing are presented.

INTRODUCTION

The January 17, 1995 Hyogo-ken Nanbu earthquake, informally called the Kobe earthquake, severely hit one of the most congested urban cities of Japan, unfortunately located near the fault rupture area. It was one of the worst disasters in the second half of this century, almost commensurate with the great Kanto earthquake which Japan experienced in the first half of this century. The earthquake produced severe building damage. Scientists and engineers involved in earthquake-related disciplines have been shocked by the damage, deaths and injuries that resulted from this earthquake. As a result, important questions have been raised about earthquake preparedness, disaster response, seismic design, upgrading of earthquake-resistant structures and introduction of new technologies which can assure high safety levels against destructive earthquakes [Yamanouchi H. et al., 1997; Iiba et al., 1998].

The high concentration of damage in conventionally built residences and the good performance of seismically isolated structures during this destructive earthquake [BCJ, 1995] have persuaded structural engineers, earthquake engineering researchers, isolator makers and housing construction companies to undertake a cooperative research project to investigate the possibility of extending further the seismically isolated structures in Japan's private housing sector as well. In order to achieve the required performance for the isolators and base-isolated residences, isolators' makers have been focusing on the development of new types of devices which are presented in the following section.

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FUNDAMENTAL CHARACTERISTICS OF NEWLY-DEVELOPED ISOLATORS

Seven new types of isolators, designated here as R, S, T, U, W V and X, were developed by different makers. Based on the fundamental concepts used for developing each of them, they can be grouped in three systems :

a) - Rubber bearing system : W
b) - Sliding system : S, U
c) - Rolling system : R, T, V, X

Fundamental characteristics of each isolator are shown summarized in figure 1. Rather flexible laminated rubber bearing is used in case of isolator type W and in order to prevent buckling phenomena the outer diameter is increased by designing a hollow in the center. Furthermore, in order to achieve a relatively high equivalent damping coefficient oil dampers are added to the system. The two isolators belonging to the sliding system, S and U, are principally designed to absorb the energy through friction, but their mechanical realizations are different. While the former uses the friction between flat surfaces as well as high damping rubber to achieve the desired characteristics, the latter, known as friction pendulum system, uses a simpler and more compact mechanism : the friction between two spherical surfaces and a sliding cylinder. In case of isolators belonging to the rolling system, the R and T types are designed on the basis of a combination between ball bearing and high damping laminated rubber, providing an equivalent damping coefficient of 26.9% and 20%, respectively. The isolator V is based on a combination of ball bearing with a spherical surface. Although the isolator type X belongs to the rolling system, the concept used to develop it is different from the isolators R, T and V. In order to achieve its target performance in terms of restoring force characteristic and equivalent damping, curved rail is used in combination with friction resisting shafts and wheels.

OUTLINE OF 3-DIMENSIONAL SHAKING TABLE TESTS

Verification of isolators and base-isolated houses behavior under recorded earthquake ground motions has been one of the most important objectives of the project. In order to realize that, 3-dimensional shaking table tests on different types of base isolation systems and on a full-scale, two-story base-isolated house model were conducted. Tests were performed on a large-scale three-dimensional shaking table recently installed at the Public Work Research Institute of Ministry of Construction [PWRI, 1997]. This shaking table is specially designed for simulating earthquake ground motions of the same intensity as those ones recorded during the Northridge Earthquake of January 17, 1994 or Kobe Earthquake of January 17, 1995.

Experimental Setups and Instrumentation

Two experimental setups were used during shaking table tests. The one shown in figure 2 was used for testing different types of base-isolation systems under one-, two- and three-directional earthquake excitations, providing thus the experimental data base necessary for the investigation of the effect of bi-directional and vertical earthquake motions on characteristics of isolators, the effect of mass eccentricity and the effectiveness of the displacement control device. The other one, quite similar with the experimental setup shown in figure 2, was used for investigating the seismic performance of a full-scale, two-story base-isolated house model. In figure 3 is shown schematically how the experimental setup presented previously in figure 2 was rearranged in order to create various conditions of mass/weight distribution in the system, i.e. balanced weight (top), unbalanced weight Case 1 (middle) and unbalanced weight Case 2 (bottom).

The input-output of the experimental setup shown in figure 2 was monitored through 50 channels. As it is shown in figure 2, accelerometers (strain-gauge type), velocity transducers (servo type) and displacement transducers (servo type, reel type, and laser type) were installed on the specimens.

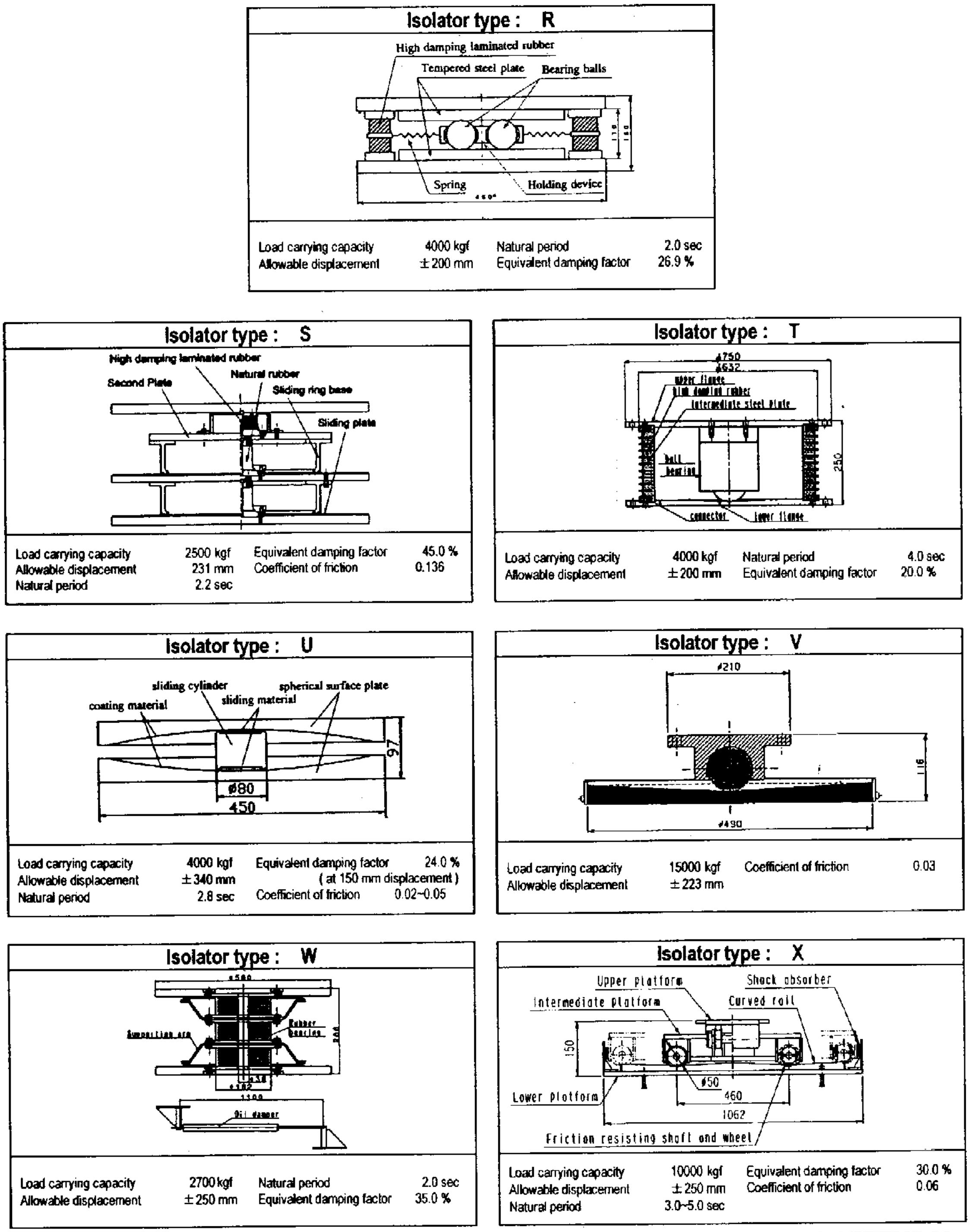


Figure 1: Fundamental characteristics of newly-developed isolators

Earthquake Input Motions Used

Strong ground motions recorded during the El Centro Earthquake of 1940 and Kobe Earthquake of January 17, 1995 (JMA Kobe Station record) were used as input motions at the shaking table. Based on the peak ground velocity value observed in each record, the input earthquake waves were proportionally adjusted to various intensity levels. The following correspondence between the horizontal components of the recorded motions and the geometrical axes of the specimen (see figure 2) was applied : EW→X and NS→Y. In addition, in order to see the effect of vertical component of earthquake ground motion on the restoring force characteristics of different types of isolators, a special case of three-directional earthquake excitation was also considered, where only the vertical component of input motion was doubled.

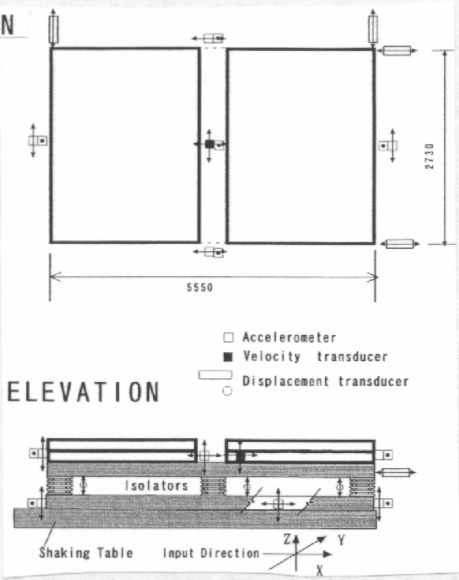


Figure 2: Experimental setup used for testing different types of base-isolation systems

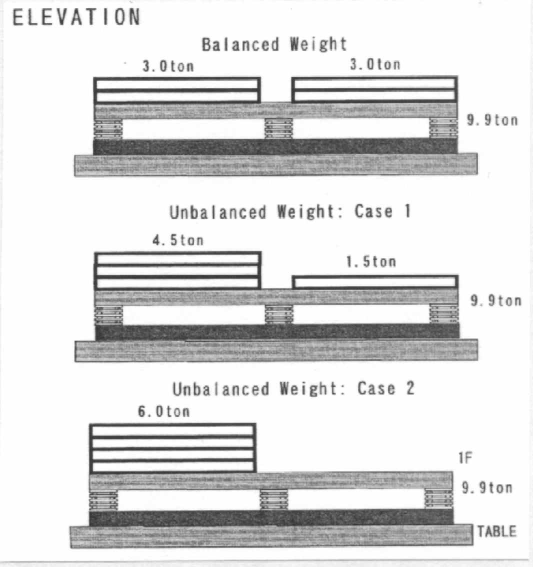


Figure 3: Three patterns of weight distribution in the system

Series of Tests Conducted

Series of tests conducted for each type of isolator are summarized in Table 1. The ○ sign inside the table cells indicates that for the corresponding type of isolator that category of test was conducted. As it can be seen from this table, two- or three-directional tests and the tests related to the various unbalanced weight conditions were conducted for almost all types of isolators, providing thus a basis for comparing the experimental results obtained from different types of base-isolation systems.

Table 1: Series of tests conducted

Isolator type	**Balanced weight**		**Unbalanced weight**	**Displacement control device**	**Triggering device**
	2 or 3 directional input motion	*Doubled vertical input motion*			
R	○		○	○	
S	○		○	○	
T	○	○	○	○	○
U	○	○	○		
V	○		○	○	
W	○	○	○	○	
X	○[a)]	○		○	
	○[b)]				

[a)] Test on a base-isolated house model ; [b)] Test on a non base-isolated house model

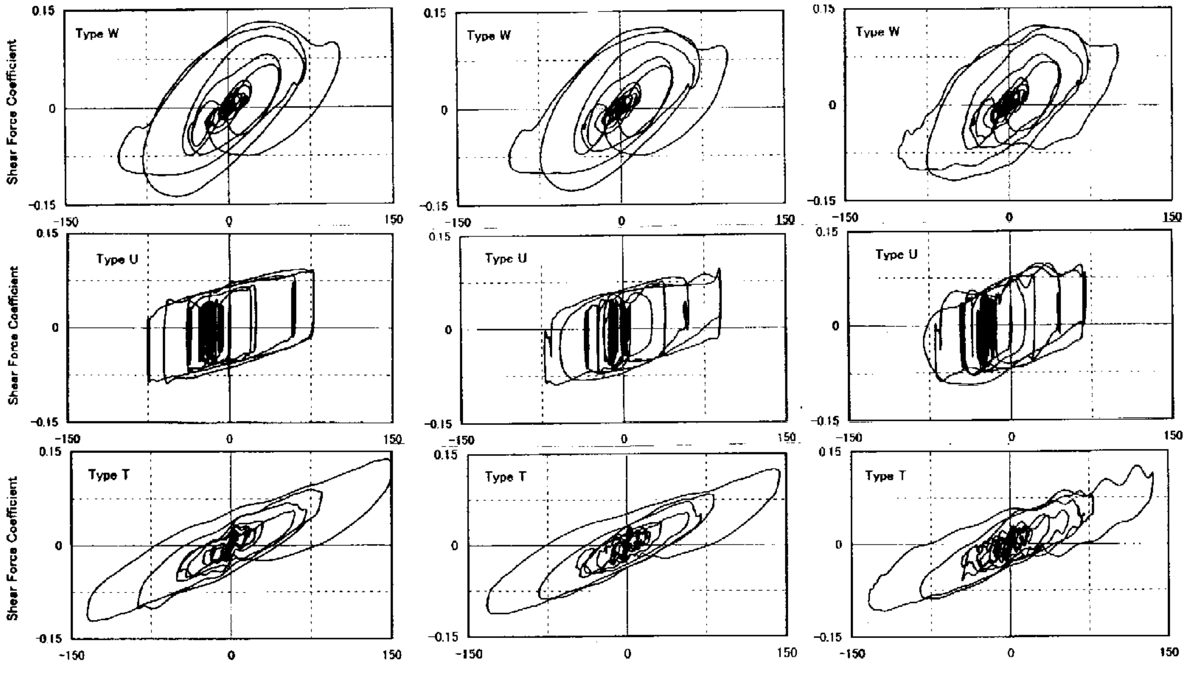
RESULTS OF THE TESTS AND DISCUSSION

A huge experimental database, covering all the series of tests shown above (see Table 1), is already created and gradually is being analyzed with the purpose of investigating a) the effect of bi-directional and vertical earthquake motions on characteristics of isolators, b) the effect of mass eccentricity, c) the displacement control device effectiveness and d) the seismic performance of a base-isolated house model. Results presented hereafter will cover only the main aspects of items a) and b) mentioned above.

Effect of Bi-directional and Vertical Earthquake Input Motion

In order to investigate the effect of bi-directional and vertical earthquake ground motion on dynamic response characteristics of isolators, one-directional (X,Y), bi-directional (XY,YZ) and three-directional (XYZ,XYZ2) earthquake excitations (El Centro 1940, Kobe JMA 1995) were applied as input motions to the shaking table. The above mentioned symbol XYZ2 corresponds to a special case of the three-directional excitation, where the vertical component only was doubled.

In figure 4 are shown the displacement-shear force coefficient relations of Y-direction, for one-directional (Y) (a), bi-directional (XY) (b) and three-directional (XYZ2) (c) Kobe JMA input motion, adjusted to a peak ground velocity of 50cm/s. For convenience, the isolator type W, U and T are referred to in the following results. They are considered as representative types for rubber bearing system, sliding system and rolling system, respectively. Comparing first graphs shown in figures 4 a) and 4 b), barely any significant difference can be seen between the results obtained by one- and two-directional earthquake excitations. In case of three-directional excitation (figure 4 c)), notches superimposed over the main acceleration response can be easily noticed, demonstrating thus the way the vertical component of input motion is expected to affect the restoring force characteristics of newly-developed base-isolation systems for houses.



a) One-directional (Y) b) Two-directional (XY) c) Three-directional (XYZ2)

Figure 4: Displacement-shear force coefficient relations of Y-direction, for one- (a), two- (b) and three-directional (c) Kobe input motion, adjusted to a peak ground velocity of 50cm/s

In order to examine further the effect of bi-directional and vertical earthquake input motion on the response of base isolation systems having different dynamic characteristics, the following ratios were calculated for each type of isolator used in the system:

a) $\alpha_{x,xy}/\alpha_{x,x}$ and $\alpha_{y,xy}/\alpha_{y,y}$ - where $\alpha_{x,xy}$ is the maximum (i.e. peak) acceleration response in the x direction of the base isolation system subjected to bi-directional input motion xy and $\alpha_{x,x}$ is the maximum acceleration response in the x direction of the base isolation system subjected to one-directional input motion x. Similarly are also defined $\alpha_{y,xy}$ and $\alpha_{y,y}$.

b) $\delta_{x,xy}/\delta_{x,x}$ and $\delta_{y,xy}/\delta_{y,y}$ - are peak displacement related ratios defined in the same way as above mentioned $\alpha_{x,xy}/\alpha_{x,x}$ and $\alpha_{y,xy}/\alpha_{y,y}$.

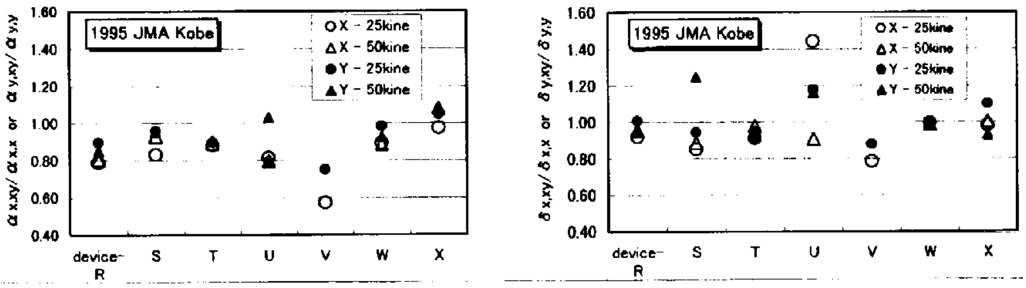
c) $\alpha_{TCM,xy}/\alpha_{M,x+y}$ - where $\alpha_{TCM,xy}$ is the maximum (i.e. peak) acceleration response of the base isolation system subjected to bi-directional input motion xy and $\alpha_{M,x+y}$ is the maximum (i.e. peak) acceleration response of the base isolation system subjected to non-simultaneous one-directional input motions x and y. The square-root-of-sum-of-squares (SRSS) rule was applied for estimating both $\alpha_{TCM,xy}$ and $\alpha_{M,x+y}$, with the only difference that the $\alpha_{TCM,xy}$ value was selected as the largest one resulting from all combinations of time-corresponding values in each direction.

d) $\delta_{TCM,xy}/\delta_{M,x+y}$ - is a displacement related ratio defined and evaluated in the same way as $\alpha_{TCM,xy}/\alpha_{M,x+y}$.

e) $\alpha_{TCM,xyz}/\alpha_{TCM,xy}$ – where $\alpha_{TCM,xyz}$ and $\alpha_{TCM,xy}$ are the maximum (i.e. peak) acceleration response of the base isolation system subjected to three-directional input motion xyz and bi-directional input motions xy, respectively.

f) $\delta_{TCM,xyz}/\delta_{TCM,xy}$ – where $\delta_{TCM,xyz}$ and $\delta_{TCM,xy}$ are displacements related ratio defined and evaluated in the same way as $\alpha_{TCM,xyz}$ and $\alpha_{TCM,xy}$.

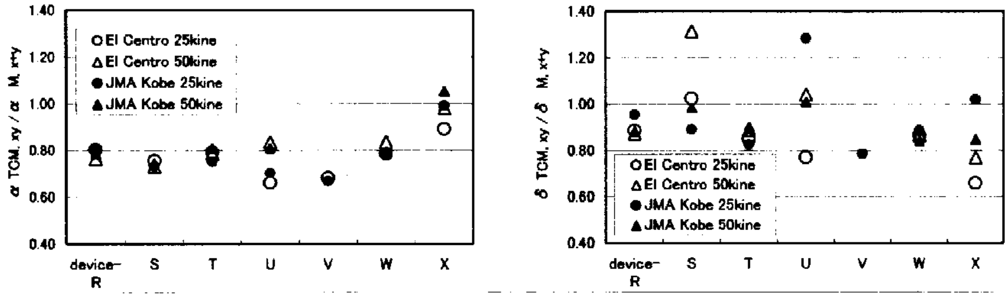
In figures 5 a) and 5 b) are drawn respectively the ratios $\alpha_{x,xy}/\alpha_{x,x}$, $\alpha_{y,xy}/\alpha_{y,y}$ and $\delta_{x,xy}/\delta_{x,x}$, $\delta_{y,xy}/\delta_{y,y}$ for Kobe JMA input motion, adjusted to a peak ground velocity of 25 and 50cm/s. The first thing which can be noticed from these graphs is that in case acceleration response (figure 5 a)), the values of $\alpha_{x,xy}/\alpha_{x,x}$ and $\alpha_{y,xy}/\alpha_{y,y}$ ratios are mostly located within the interval 0.8-1.0. In case of displacement response (figure 5 b)), the values of $\delta_{x,xy}/\delta_{x,x}$ and $\delta_{y,xy}/\delta_{y,y}$ ratios are mostly located within the interval 0.85-1.20. In both graphs the values of the above mentioned ratios for the isolator type W are located very close to 1.0, confirming thus the consistency with the results shown previously in figure 4(compare the first two graphs at the top left of this figure). Nearly the same tendencies of acceleration and displacement response variation were observed for the case of El Centro input motion.



a) Acceleration response ratios b) Displacement response ratios

Figure 5: Variation of acceleration a) and displacement b) for different types of isolators subjected to Kobe JMA input motion, adjusted to a peak ground velocity of 25 and 50cm/s

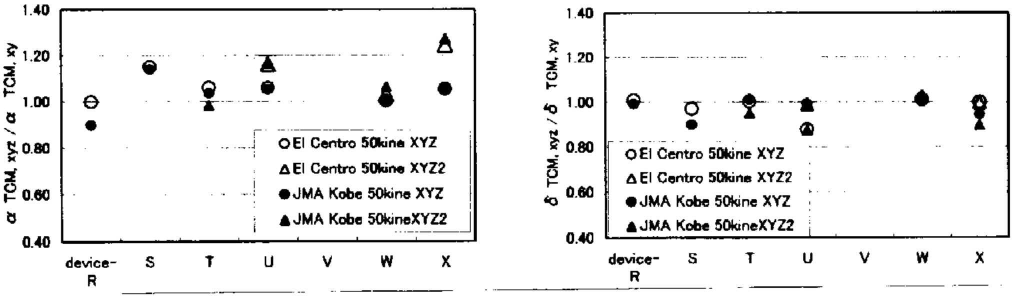
In figures 6 a) and 6 b) are drawn respectively the ratios $\alpha_{TCM,xy}/\alpha_{M,x+y}$ and $\delta_{TCM,xy}/\delta_{M,x+y}$ for El Centro and Kobe JMA input motions, adjusted to a peak ground velocity of 25 and 50cm/s. In case of acceleration response (figure 6 a)), the values of $\alpha_{TCM,xy}/\alpha_{M,x+y}$ ratios for all types of isolators are mostly located within the interval 0.7-0.9, indicating thus that the evaluation of peak acceleration response of the base-isolated system subjected to bi-directional input motion xy on the basis of peak acceleration response due to non-simultaneous one-directional input motions x and y (i.e. $\alpha_{M,x+y}$) will be on the safe side. In case of displacement response (figure 6 b)), the values of $\delta_{TCM,xy}/\delta_{M,x+y}$ ratios for all types of isolators are scattered within a wider interval, exhibiting thus not a clear tendency for all types of isolators like in the case of acceleration. Eventhough, it seems that for the isolator types R, T, V, W and X, $\delta_{M,x+y}$ could provide a more reliable estimation of the peak response due to bi-directional excitation. For sliding type of isolators (S and U), the values of $\delta_{TCM,xy}/\delta_{M,x+y}$ ratios have resulted to be close to 1 or even higher (see figure 6 b)), associated with a larger fluctuation as well.



a) Acceleration response ratios b) Displacement response ratios

Figure 6: Variation of acceleration a) and displacement b) for different types of isolators subjected to El Centro and Kobe JMA input motions, adjusted to a peak ground velocity of 25 and 50cm/s

Finally, in figures 7 a) and 7 b) are drawn respectively the ratios $\alpha_{TCM,xyz}/\alpha_{TCM,xy}$ and $\delta_{TCM,xyz}/\delta_{TCM,xy}$ for El Centro and Kobe JMA three-directional input motions (XYZ,XYZ2), adjusted to a peak ground velocity of 50cm/s. In case of acceleration response (figure 7 a)), the values of $\alpha_{TCM,xyz}/\alpha_{TCM,xy}$ ratios for all types of isolators are scattered within the interval 0.9-1.27, indicating thus that on the average a slight increase of peak horizontal acceleration response due to the vertical input motion should be expected. On the other side, in case of displacement response (figure 7 b)), the values of $\delta_{TCM,xyz}/\delta_{TCM,xy}$ ratios for all types of isolators are scattered within the interval 0.87-1.02, indicating thus that on the average the peak horizontal displacement response either remains unaffected by the vertical input motion or is slightly decreased.



a) Acceleration response ratios b) Displacement response ratios

Figure 7: Variation of acceleration a) and displacement b) for different types of isolators subjected to El Centro and Kobe JMA three-directional input motions (XYZ,XYZ2), adjusted to a peak ground velocity of 50cm/s

Effect of Mass Eccentricity

Based on the experimental setup shown previously in figure 3, series of tests were conducted (see Table 1) with the purpose of investigating the effect of mass eccentricity on the response of different base-isolation systems. El Centro 1940 and Kobe JMA input motions were adjusted to two intensity levels : 25cm/s and 50cm/s.

In figure 8 are shown compared the maximum (i.e. peak) displacement response - mass eccentricity ratio relations for the heavier side (▲) and the lighter one (•). Here again, the previously mentioned representative types for laminated rubber bearing system, sliding system and rolling system are considered. The first thing which can be noticed from these results is that, for the three types of isolators, the maximum displacement response of the lighter side decreases as the mass eccentricity ratio increases, particularly for laminated rubber bearing and rolling type of isolators. As for the maximum displacement response of the heavier side, it seems that the increase of mass eccentricity ratio doesn't affect it at all.

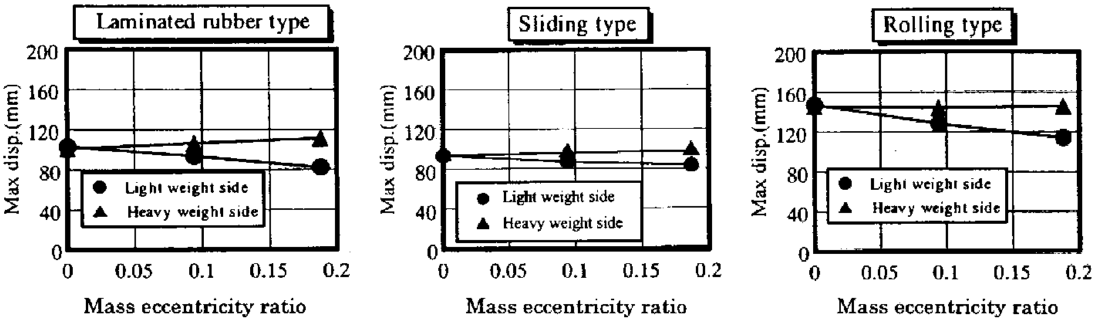


Figure 8: Maximum displacement response versus mass eccentricity ratio

Finally, in order to see the effect of mass eccentricity on the torsional response of the base-isolation system, the maximum (i.e. peak) torsional angle(MTA) is plotted against mass eccentricity ratio (figure 9). From these results it can be noticed that, as the mass eccentricity increases the MTA increases, being this tendency relatively stronger for the rolling type of isolators.

CONCLUDING REMARKS

Three-dimensional shaking table tests on recently developed base-isolation systems for houses were conducted. These tests were primarily conducted with the purpose of investigating the effect of bi-directional and vertical

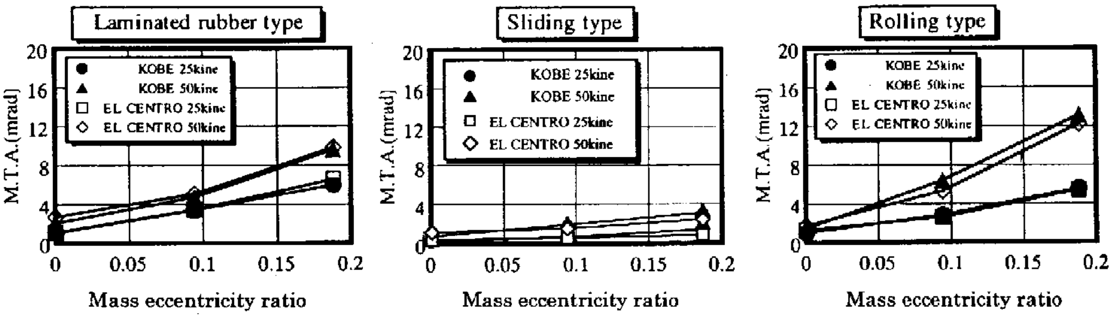


Figure 9: Maximum torsional angle response versus mass eccentricity ratio

earthquake motions on characteristics of isolators, the effect of mass eccentricity and the effectiveness of displacement control device. The most relevant observations made in the previous section are summarized as :

1. No significant difference could be observed between the results obtained by one- and two-directional earthquake excitations. Although dependent on the characteristics of isolators, the effect of vertical motion on horizontal responses is not remarkable.
2. Evaluation of peak horizontal acceleration response for the base-isolation system subjected to bi-directional input motion xy on the basis of peak acceleration response due to non-simultaneous one-directional input motions x and y (i.e. $\alpha_{M,x+y}$) is expected to provide an estimate lying on the safe side. In the same way (i.e. $\delta_{M,x+y}$) can be also evaluated the peak horizontal displacement response of rubber bearing and rolling systems (W and R,T,V,X, respectively). For sliding systems (S and U), it seems that the values of $\delta_{M,x+y}$ could provide an underestimated value for the peak response due to bi-directional excitation.
3. On the average a slight increase of peak horizontal acceleration response due to the vertical input motion should be expected. On the other side, the peak horizontal displacement response either remains unaffected by the vertical input motion or is slightly decreased.
4. The maximum displacement response of the lighter side of the base-isolation system decreases, as the mass eccentricity ratio increases, particularly for laminated rubber bearing and rolling type of isolators. As for the maximum displacement response of the heavier side, it seems that the increase of mass eccentricity ratio doesn't affect it at all. The maximum torsional angle response increases with the increasing mass eccentricity ratio, being this tendency relatively stronger for the rolling type of isolators.

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