# THREE DIMENSIONAL SHAKING TABLE TESTS ON SEISMIC BEHAVIOR OF ISOLATORS FOR HOUSES

by

Masanori IIBA[1], Mitsumasa MIDORIKAWA[2], Hiroyuki YAMANOUCHI[3] and Bujar MYSLIMAJ[4]

## ABSTRACT

Lessons learned from the Hyogo-ken Nanbu Earthquake of January 17, 1995 and the good performance of seismically isolated structures during this destructive 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 information about the experimental data-processing progress are presented.

**KEY WORDS :** 3-dimensional
Shaking Table
Isolators
Houses

## 1. 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. Over 5,000 people were killed due to building collapse resulting from the severe shaking. The earthquake was one of the most devastating and costly natural disasters in recent history considering (a) the number of buildings destroyed, (b) the number of people killed and injured, (c) the size of the affected area and (d) the variability, extent and severity of 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.

In this paper, results of 3-dimensional shaking table tests on recently developed base-isolation systems for houses are presented.

1) Head, Structural Dynamics Division, Structural Engineering Department, Building Research Institute, Ministry of Construction, Tsukuba-shi, Ibaraki-ken, 305-0802, Japan
2) Director, IISEE, Building Research Institute, Ministry of Construction, Tsukuba-shi, Ibaraki-ken, 305-0802, Japan
3) Director, Codes and Evaluation Research Center, Building Research Institute, Ministry of Construction, Tsukuba-shi, Ibaraki-ken, 305-0802, Japan
4) JSPS Research Fellow, Institute of Engineering Mechanics and Systems, University of Tsukuba, Tsukuba-shi, Ibaraki-ken, 305-8573, Japan

These tests were conducted primarily 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.

## 2. DEVELOPMENT AND POPULARIZATION OF BASE ISOLATION SYSTEMS FOR HOUSES

As in the case of Northridge earthquake of January 17, 1994, during Kobe earthquake as well seismically-isolated structures performed quite well. That was clearly noticed from the observed earthquake response of two base-isolated buildings constructed in Kobe city[1]. In a 6 story steel-encased reinforced concrete base-isolated structure the ratio of maximum acceleration response of first and sixth floor to that of the foundation were 0.35 and 0.34 respectively, demonstrating thus the great effectiveness of base isolation in reducing the acceleration response of structures and consequently the seismic forces acting on them.

The good performance of base-isolated structures during the Kobe earthquake caused a prompt increase in construction of base-isolated buildings [2]. The number of this kind of buildings designed and constructed by the end of 1995 was almost equal to the total number of base-isolated buildings constructed during the period 1985-1994. The year 1996 marked a record. The number of base-isolated structures designed and constructed during this year was more than twice of that reported for the year 1995.

However, base-isolated residential housing is not yet popular in Japan [3,4]. Several factors account for this[4].

### a) Relatively Small Weight of Residences

As it is well known, the fundamental principle applied to seismically-isolated structures is the elongation of the natural period in order to reduce the acceleration response and consequently the earthquake forces acting to the structure. This can be achieved either by increasing the weight of the structure or by decreasing its stiffness. The latter is widely applied in mid-rise buildings because of its effectiveness in achieving the goal. Due to the large weight of mid-rise buildings, a slight decrease of the stiffness caused by the installation of laminated rubber bearings at the base of the building structure easily produce considerable period elongation. But this cannot be done so easily in case of light residences. To compensate for their relatively light weight, rather flexible laminated rubber bearings need to be used. In doing so, special attention must be paid to avoid buckling, otherwise other types of isolators (such as sliding or rolling) need to be developed to deal properly with this problem.

### b) Habitability During Strong Winds

In case of low, light-weight residences, the impact of earthquake and wind forces have comparable importance on this type of structures. Therefore, besides the reduction of acceleration response through the installation of isolators at the base of the building structure, proper measures need to be taken in order to assure the habitability and comfort during strong winds or typhoons.

### c) First Floor and Foundation Reinforcement

In common residential construction (without base-isolation), the weight of building is transferred to the foundation through sills, which are directly laid on the continuous foundation (Fig. 1a). In case of base-isolated residences (Fig. 1b) an additional horizontal frame of girders is needed to carry the weight of the building and transfer it to the foundation through the isolators. Therefore, individual foundation under each isolator, mat foundation or reinforcement of the ordinary continuous foundation is required. This, together with the reinforcement of the first floor, requires extra labor and materials, and consequently lead to additional cost.

### d) Cost Performance

Cost performance remains a very important issue. The total cost of base isolation system for residences (isolators plus the reinforcement of the first floor and the foundation) is considerable. Isolator makers and house builders estimate it to be roughly 1/5 - 1/4 of the total cost of ordinary residences without base isolation. Therefore, further efforts are needed to reduce the cost of base isolation systems, including standardization of isolators and simplification of building configuration.

In order to achieve the target 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.

## 3. 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 Fig. 2.

Rather flexible laminated rubber bearing is used in case of isolator type W (Fig. 2) 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 higher equivalent damping 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 uses a simpler and more compact mechanism : the friction between two spherical surfaces and a sliding cylinder (Fig. 2). 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.

## 4. 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.

### 4.1 Shaking table simulation capabilities

Tests were performed on a large-scale three-dimensional shaking table recently installed at the Public Work Research Institute of Ministry of Construction [5]. 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. In order to give a clearer image about the simulation capabilities of this shaking table, its specifications are shown in Table 1 [5].

### 4.2 Experimental setups and instrumentation

Two experimental setups were used during shaking table tests. The one shown in Fig. 3 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 experimental setup shown in Fig. 4 was used for investigating the seismic performance of a full-scale, two-story base-isolated house model. In Fig. 5 is shown schematically how the experimental setup presented previously in Fig. 4 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 for each of the experimental setup shown in Fig. 3 and Fig. 4, was monitored through 50 and 74 channels, respectively. As it is shown both in Fig. 3 and Fig. 4, accelerometers (strain-gauge type), velocity transducers (servo type) and displacement transducers (servo type, reel type, and laser type) were installed on the specimens.

### 4.3 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 specimens ( see Figs. 3 and 4 ) 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.

### 4.4 Tests series

Series of tests conducted for each type of isolator are summarized in Table 2. The O 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.

## 5. RESULTS OF THE TESTS AND DISCUSSION

Results presented hereafter will mainly cover the aspects mentioned previously in section 1. Nevertheless, it is important to mention here that all experimental results obtained from three-dimensional shaking table tests confirmed the beneficial effect of isolators in reducing the acceleration response of base-isolated system. As an illustration, in Fig. 6 are shown the input motion in the Y direction (a) and the corresponding acceleration response wave of base-isolated system (b), for the isolator type U. A remarkable reduction of the acceleration response can be easily noticed.

### 5.1 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.

For convenience, the isolator type T, U and W are referred to in the following results. They are considered as representative types for rolling system, sliding system and rubber bearing system, respectively.

In Fig. 7 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. Comparing first graphs shown in Figs. 7 a) and 7 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 (Fig. 7 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.

In order to examine further the effect of vertical component of input motion on the acceleration and displacement response of base-isolation system, peak horizontal acceleration response - peak vertical input acceleration and peak horizontal displacement response - peak vertical input acceleration relationships are drawn in Fig. 8 and Fig. 9, respectively. Peak horizontal acceleration response and peak horizontal displacement response values referred to the vertical axes of Figs. 8 and 9, represent the composed peak response values of acceleration and displacement. Peak vertical input acceleration values referred to the horizontal axes of Figs. 8 and 9, represent the maximum acceleration observed in the vertical component of input motions applied to the shaking table in case of bi-directional (XY) and three-directional (XYZ,XYZ2) Kobe JMA excitations, adjusted to a peak ground velocity of 50cm/s. Looking first at the results shown in Fig. 8, it can be noticed that for the isolator type U and W the increase of vertical input acceleration is associated with a slight increase of horizontal acceleration response. For the isolator type T the same tendency appears to be valid up to a certain level of vertical input acceleration, after that, at a doubled level of vertical input acceleration, the horizontal acceleration response drops slightly. In case of horizontal displacement response (Fig. 9), the increase of vertical input acceleration either doesn't affect at all the displacement response in the horizontal direction (isolator type W) or is associated with a slight drop at a doubled level of vertical input acceleration (isolator type T and U).

### 5.2 Effect of mass eccentricity

Based on the experimental setup shown previously in Fig. 5, series of tests were conducted (see Table 2) with the purpose of investigating the effect of mass eccentricity on the response of different base-isolation systems. During these tests, El Centro 1940 and Kobe JMA input motions were adjusted to two intensity levels : 25cm/s and 50cm/s.

In Fig. 10 are shown compared the displacement response waves for two extreme cases of weight distribution in the system : balanced weight (ECC0) and unbalanced weight Case 2 (ECC2). Here again, previously mentioned representative types for rolling system, sliding system and rubber bearing system are considered. The first thing which can be noticed from these results is that, for the three types of isolators, the ECC0 response waves are almost similar with those corresponding to the ECC2 case. In addition, in case of unbalanced weight (ECC2) the peak displacement response of the heavier side is larger than that of the lighter side. This can be also noticed from the results shown in Fig. 11, where the horizontal axis is referred to the gravity center location or mass eccentricity ratio, while the vertical one to the maximum displacement response. Larger values of peak displacement response have resulted for the heavier side compared to the lighter one. Furthermore, as the mass eccentricity increases the difference between the maximum responses of the heavier and lighter side becomes larger, particularly for laminated rubber bearing type and rolling type of isolator. Finally, in order to see the effect of mass eccentricity on the torsional response of the base-isolation system, the maximum torsional angle(MTA) is plotted against mass eccentricity ratio (Fig. 12). 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.

### 5.3 Effectiveness of displacement control device

An important issue in dealing with base-isolated systems is the displacement control. Certainly, the base-isolation reduces remarkably the acceleration response, but on the other hand it leads to a larger displacement response, which must be kept within the allowable limits determined in accordance with the mechanical characteristics of isolators.

In this section, results obtained from shaking table tests on a base-isolation system (see isolator type W in Fig. 2) additionally equipped with a displacement control device (DCD) are presented. A schematic drawing of DCD is shown in Fig. 13. As it can be noticed from this figure, the contact between the outer cover and the rubber bumper is expected to happen when the displacement response of the base isolation system reaches 150mm. For displacement response values larger than 150mm the isolation-system and DCD will interact together, demonstrating thus the dynamic characteristics of the combined system as a whole, i.e. isolators+DCD. In order to examine the behavior of the combined system at different levels of input motion intensity, three-directional Kobe JMA input motion was adjusted to the following intensity levels : 50, 60, 70, 80 and 90cm/s. For each input level, maximum acceleration and displacement response values in a two-dimensional plan were determined and by making use of respective maximum input acceleration (observed during the tests) the graphs shown in Figs. 14 and 15 could be drawn. For comparison reasons, analytically simulated results for the case of base-isolation system without DCD are also shown. Results presented in both figures indicate that the base-isolation system starts to interact with DCD at the input motion intensity levels higher than 70cm/s (respectively 794gal of maximum input acceleration). At the input motion level of 80cm/s (respectively 936gal), DCD has effectively restraint the displacement response up to an amount of 6mm, without any sudden increase in the acceleration response (Figs. 14 and 15). At the input motion level of 90cm/s (respectively 1089gal), a sharp increase in the acceleration response is observed (Fig. 14), while the displacement response is restraint nearly 12mm (Fig. 15). What was mentioned above for the sharp increase in the acceleration response can be clearly noticed from the acceleration-displacement response relation shown in Fig. 16.

### 5.4 Seismic performance of a base-isolated house model

Based on the experimental setup shown previously in Fig. 4, two series of tests on a full-scale, two-story non- and base-isolated house model were conducted (see Table 2) with the purpose of investigating the effect of base isolation on the response of superstructure.

In Fig. 17 are shown summarized peak acceleration responses for the non-isolated house model and the base-isolated one due to El Centro 1940 (a) and Kobe JMA (b) input motions, adjusted to a peak ground velocity of 50cm/s. In both cases, a remarkable effect of base-isolation in reducing the acceleration response of superstructure can be noticed.

## 6. CONCLUDING REMARKS

Three-dimensional shaking table tests on recently developed base-isolation systems for houses and on a full-scale, two-story base-isolated house model were conducted. These tests were primarily conducted with the purpose of investigating the effect of bi-directional and vertical earthquake motions on characteristics of isolators, the effect of mass eccentricity, the effectiveness of displacement control device and the seismic performance of a base-isolated house model. The most relevant observations made in the previous section are summarized as follows :

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. As the mass eccentricity increases the difference between the maximum response of the heavier and lighter side of the system becomes larger, particularly for laminated rubber bearing type and rolling type of isolator. The maximum torsional angle response increases with the increasing mass eccentricity, being this tendency relatively stronger for the rolling type of isolators.

3. Displacement control device (DCD) could effectively restrain the displacement response up to an input motion intensity level of 80cm/s. At a higher level of input motion intensity, a sudden increase in the acceleration response was observed, suggesting thus that in the design of DCD-s the effect of input motion intensity should be carefully treated.

4. Two series of tests on a full-scale, two-story non- and base-isolated house model demonstrated clearly the remarkable effect of base-isolation in reducing the acceleration response of superstructure.

## 7. ACKNOWLEDGMENTS

The authors would like to express their sincere thanks to all the members of the committee on "Development of seismically isolated houses", the chairman of which is Mr. Shoichi Yamaguchi, president of Tokyo Kenchiku Structural Engineers, for providing data and valuable suggestions related to this study. In addition, the kind assistance of Dr. Keiichi Tamura and Mr. Takuo Azuma, respectively Head and Research Engineer of the Ground Vibration Division at the Earthquake Disaster Prevention Research Center of Public Work Research Institute in Tsukuba, in operating the large-scale three-dimensional shaking table is greatly appreciated.

## 8. REFERENCES

[1] The Building Center of Japan : Base-isolated buildings - Technical development and earthquake motion observation records, Part 2, June 1995 (in Japanese).
[2] Kitagawa Y. : Future view of base-isolated buildings in Japan, The Kenchiku Gijutsu, March 1999, pp. 116-117 (in Japanese).
[3] Yamanouchi H., Midorikawa M. and Iiba M. : Research and development on base-isolation technologies for houses - A survey on the performance based evaluation of base-isolated houses and shaking table tests on model houses, Kenchiku Kenkyu Shiryo, No. 89, March 1997 (in Japanese).
[4] Iiba M. et al. : Research on performance of base-isolated house, Proceedings of the Second World Conference on Structural Control, Kyoto, Japan, June 1998, Volume 2, pp. 1119-1126.
[5] Public Work Research Institute : Large-scale three-dimensional shaking table, Public Work Research Institute, Ministry of Construction, 1997.

**Table 1** Specifications of shaking table used

| Item | Specifications |
|---|---|
| Table size | 8m x 8m |
| Loading Capacity | Rated 100tf<br>Max. 300tf |
| Maximum displacement | Horizontal ±60cm<br>Vertical ±30cm |
| Maximum velocity | Horizontal ±200cm/s<br>Vertical ±100cm/s |
| Maximum acceleration* | Horizontal ±2G<br>Vertical ±1G |
| Exciting frequency | DC～50Hz |

* For 100tf loading.

**Table 2** 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

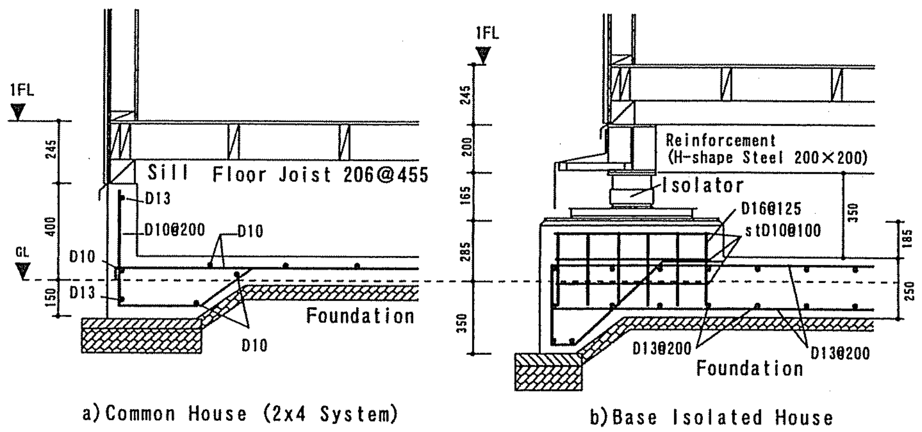
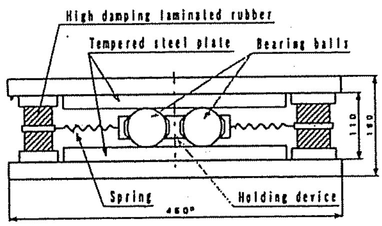


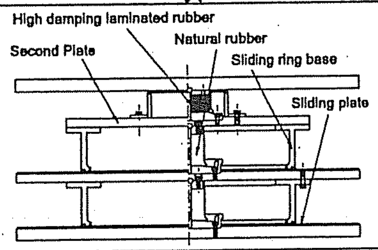

**Fig. 1.** First floor and foundation design for a common house (a) and a base-isolated one (b).

## Isolator type : R



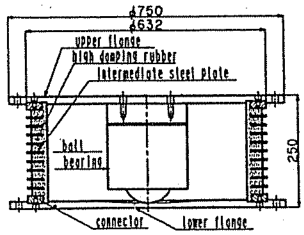

| | | | |
|---|---|---|---|
| Load carrying capacity | 4000 kgf | Natural period | 2.0 sec |
| Allowable displacement | ±200 mm | Equivalent damping factor | 26.9 % |

## Isolator type : S



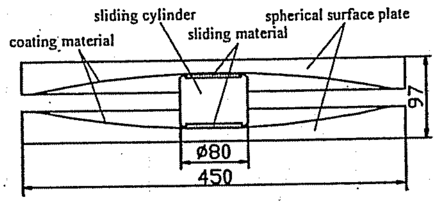

| | | | |
|---|---|---|---|
| Load carrying capacity | 2500 kgf | Equivalent damping factor | 45.0 % |
| Allowable displacement | 231 mm | Coefficient of friction | 0.136 |
| Natural period | 2.2 sec | | |

## Isolator type : T



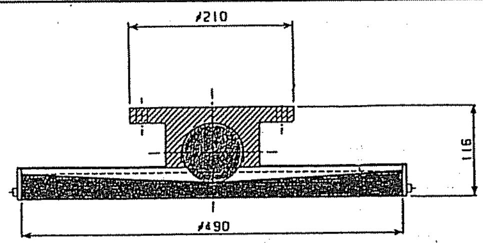

| | | | |
|---|---|---|---|
| Load carrying capacity | 4000 kgf | Natural period | 4.0 sec |
| Allowable displacement | ±200 mm | Equivalent damping factor | 20.0 % |

## Isolator type : U



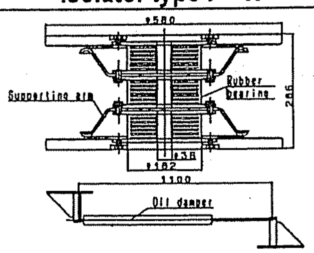

| | | | |
|---|---|---|---|
| Load carrying capacity | 4000 kgf | Equivalent damping factor | 24.0 % |
| Allowable displacement | ±340 mm | ( at 150 mm displacement ) | |
| Natural period | 2.8 sec | Coefficient of friction | 0.02~0.05 |

## Isolator type : V



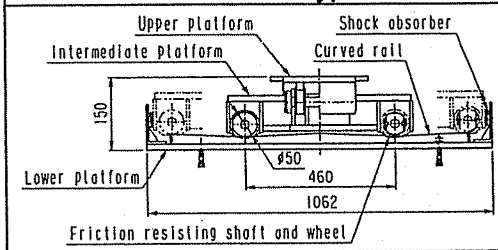

| | | | |
|---|---|---|---|
| Load carrying capacity | 15000 kgf | Coefficient of friction | 0.03 |
| Allowable displacement | ±223 mm | | |

## Isolator type : W




| | | | |
|---|---|---|---|
| Load carrying capacity | 2700kgf | Natural period | 2.0 sec |
| Allowable displacement | ±250 mm | Equivalent damping factor | 35.0 % |

## Isolator type : X




| | | | |
|---|---|---|---|
| Load carrying capacity | 10000 kgf | Equivalent damping factor | 30.0 % |
| Allowable displacement | ±250 mm | Coefficient of friction | 0.06 |
| Natural period | 3.0~5.0 sec | | |

**Fig. 2.** Fundamental characteristics of newly-developed isolators.

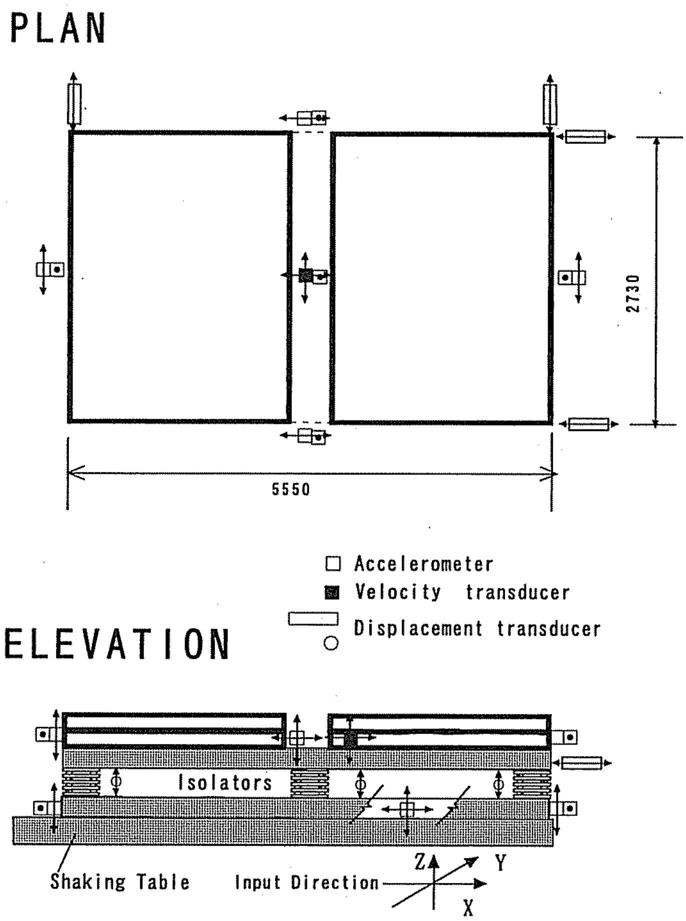



**Fig. 3.** Experimental setup used for testing different types of base-isolation systems.

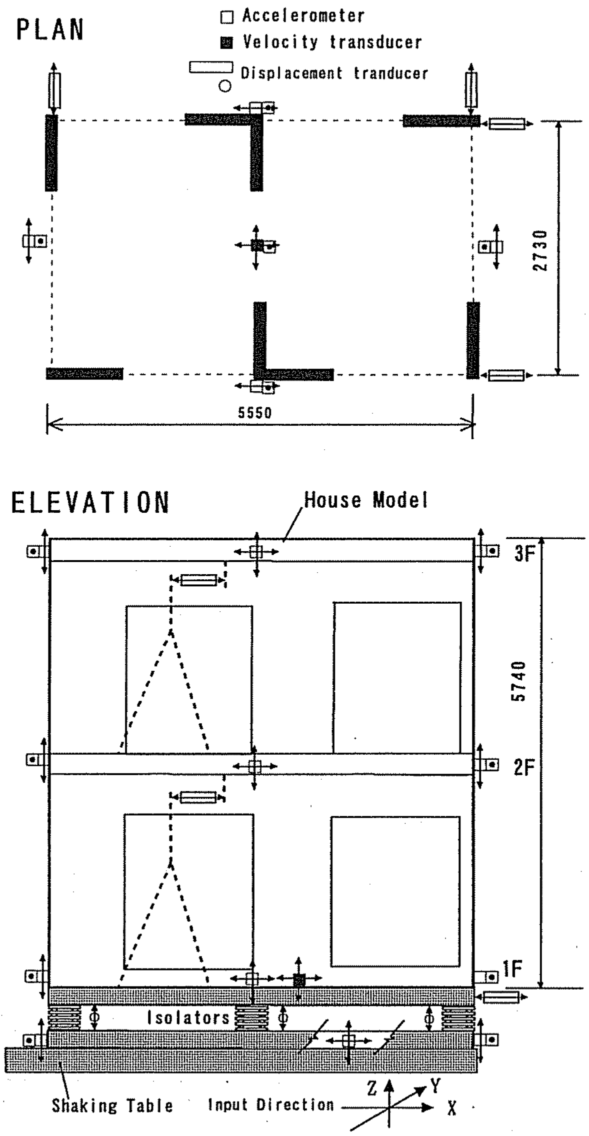



**Fig. 4.** Experimental setup used for testing a base-isolated house model.

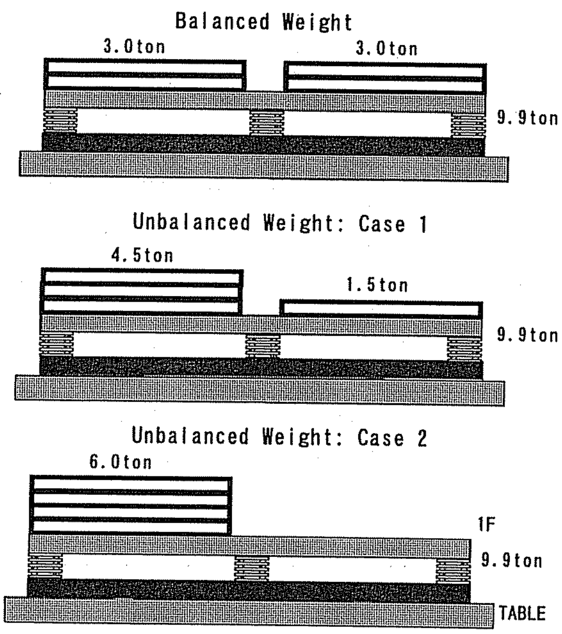
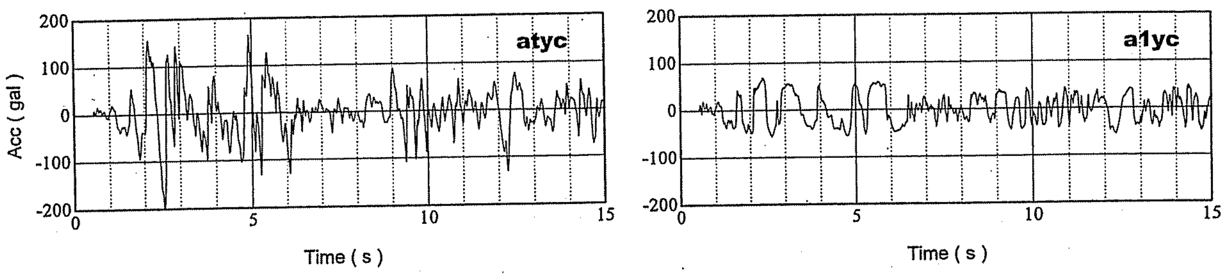
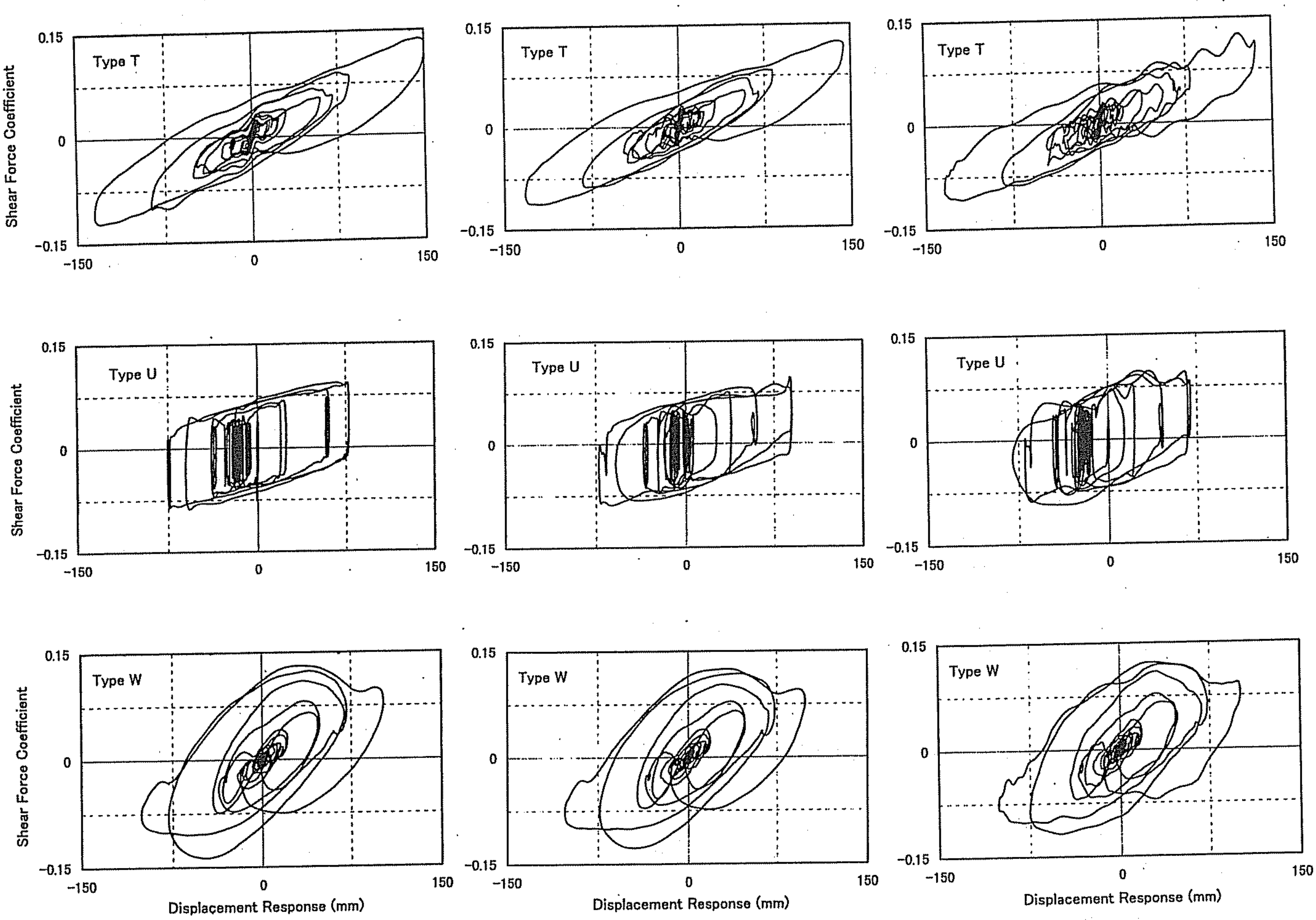



**Fig. 5.** Three patterns of weight distribution in the system.




a) Input motion. b) Acceleration response wave.

**Fig. 6.** Input motion in the Y direction (a) and the corresponding acceleration response wave of base-isolated system (b), for the isolator type U.




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

**Fig. 7.** 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.

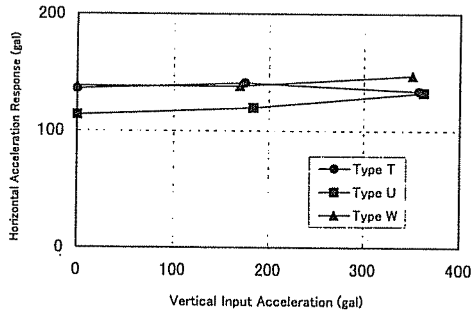



**Fig. 8.** The relation between peak horizontal acceleration response and peak vertical input acceleration.

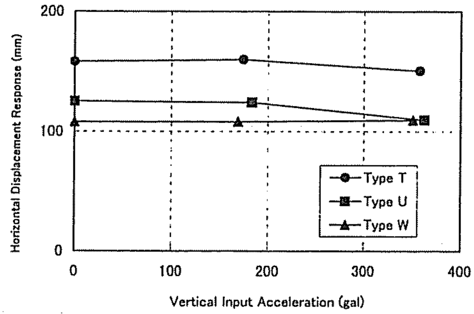



**Fig. 9.** The relation between peak horizontal displacement response and peak vertical input acceleration.

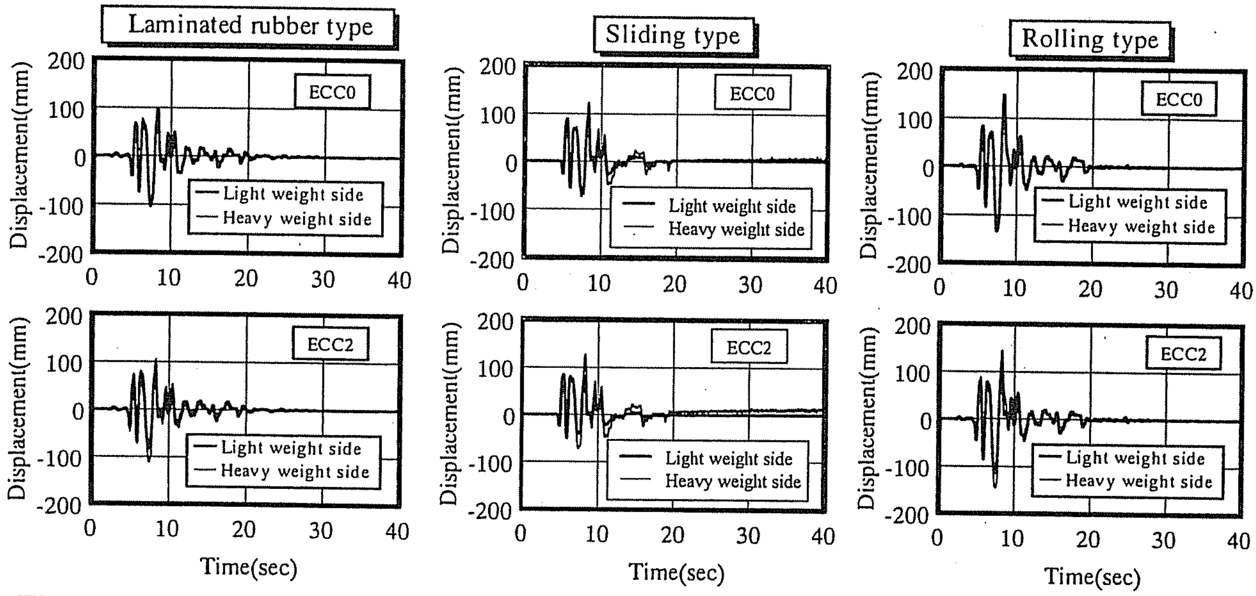



**Fig. 10.** Displacement response waves for two extreme cases of weight distribution in the system.

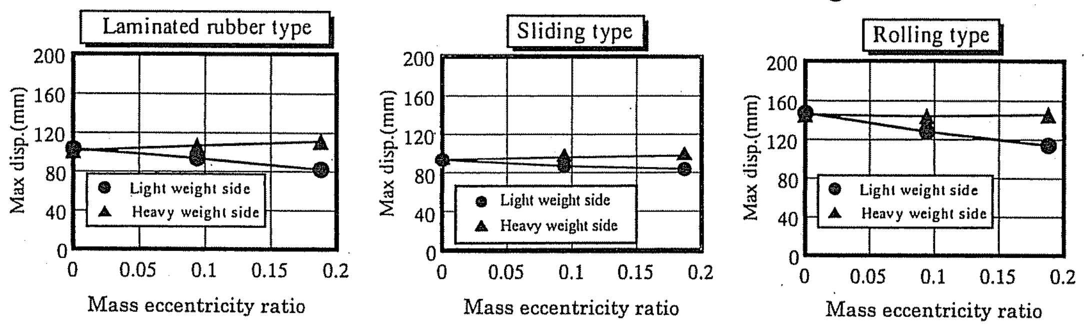



**Fig. 11.** Maximum displacement response versus mass eccentricity ratio.

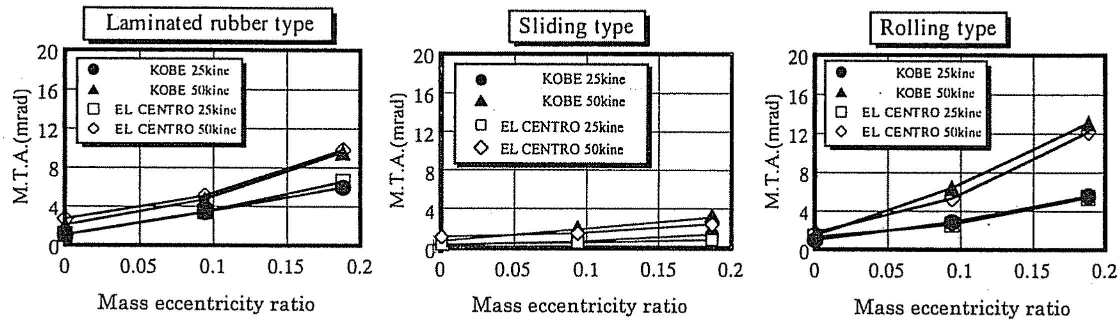



**Fig. 12.** Maximum torsional angle response versus mass eccentricity ratio.

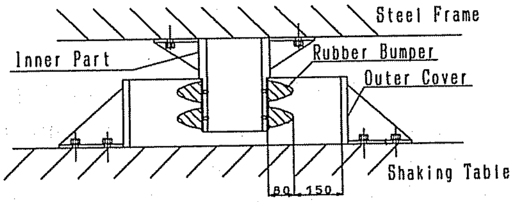



**Fig. 13.** A schematic drawing of DCD.

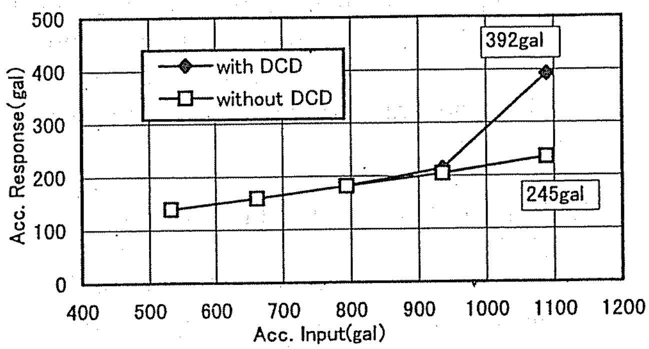



**Fig. 14.** Effect of DCD on acceleration response variation.

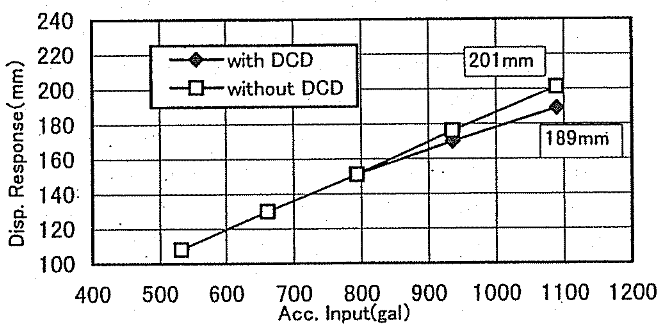



**Fig. 15.** Effect of DCD on displacement response variation.

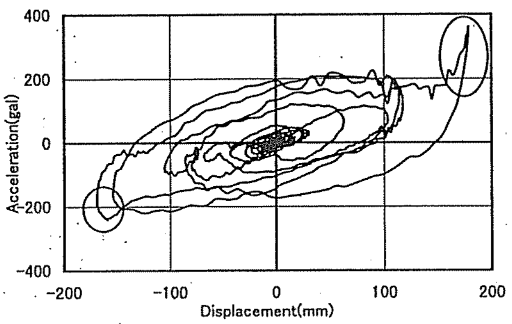
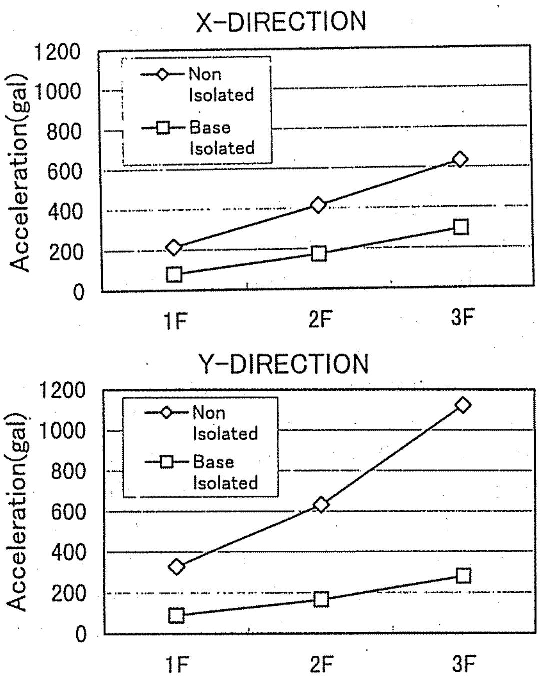
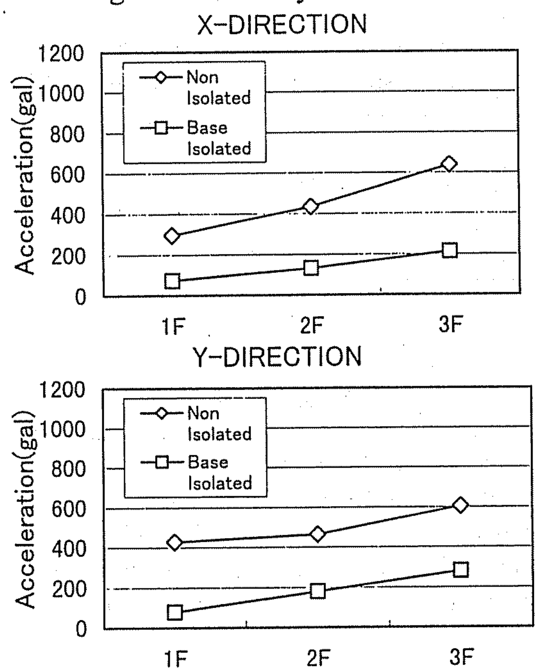



**Fig. 16.** Displacement-acceleration response relation for Kobe JMA 90cm/s.




a) El Centro 1940 adjusted to a peak ground velocity of 50cm/s.




b) Kobe JMA 1995 adjusted to a peak ground velocity of 50cm/s.

**Fig. 17.** Peak acceleration responses for the non base -isolated house model and the base-isolated one.