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Experiments of base isolation with full-scale building

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ABSTRACT: The base isolation structure is designed to reduce vibration of buildings by isolating buildings from the ground. Though its principle and mechanism are extremely simple, it is useful anti-earthquake structure

In Japan about 60 buildings having the base isolation structure have been built and are in use now. Various base isolation devices have been developed, and many experiments have been reported.

However, there are few experiments on full-scale real buildings. There are only few reports relating to the reliability and applicability of whole base isolation structure system including the upper framing, and validity of designed values.

Using the base isolated building (2-storied reinforced concrete apartment) built in October, 1989, we have examined the basic vibration characteristics of base isolated structure, and conducted the proving experiments (static loading experiment, free vibration experiment, and excited vibration experiment), using the jacks set in the underground pit of building in order to ascertain the validity of designed values and the reliability of system. After that, we have conducted the earthquake and strong wind observations, using the earthquake meters installed in the base isolated building, ground, and adjacent building of conventional structure system for the purpose of clarifying the effect of base isolation structure.

The result of these experiments and observations verify high reliability of the base isolation structure and show the favorable effect against earthquake. The obtained results are reported in this paper.

1. INTRODUCTION

In order to prove the reliability, safety and living comfort of base isolation structure we have conducted the experiment using the full-scale building for 4 months. For the purpose of examining the basic vibration characteristics of base isolated building and verifying the validity of design values and the reliability of base isolation device we have executed measurement of building weight, static force experiment, microtremors measurement, excited vibration experiment, and free vibration experiment. So as to evaluate the behavior of building under the influence of earthquake, to prove the base isolation effect, and to ascertain the safety, we have been conducting the earthquake observation also during the period of proving experiment. We measured vibration also under the influence of strong wind which is considered as an external disturbance in addition to earthquake.

This report discusses the results of static load experiment, free vibration experiment, and earthquake and strong wind observations, which were executed in order to reveal the restoring force characteristics of base isolation layer in case of significant deformation of base isolated building, to check the relation to the element test, and to examine the conformity to restoring force characteristics adopted for designing.

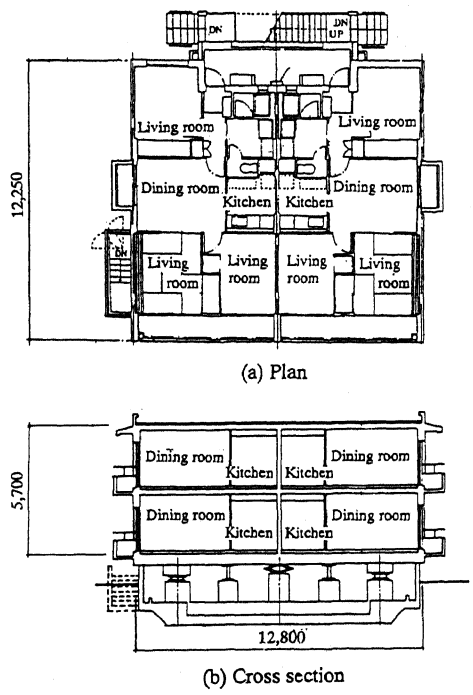


Fig.1 Outline of building

2. OUTLINE OF MODEL BUILDING

2.1 Upper structure

The base isolated building used for the experiment is 2 storied reinforced concrete apartment house with 2-apartments on each floor. The plan and cross section are shown in Fig. 1.

2.2 Base isolation system

We used the laminated natural rubber as isolator, and two different types of damper, namely steel bar damper and lead damper. 4 sets of isolator and damper were used. In order to prevent torsion they were arranged to align with the center of gravity of building. Fig. 2 shows the shape of each base isolation device and the relation between load and deformation. Table 1 shows the constants of each base isolation device which have been used for designing.

Our experiments were classified into 3 groups by the composition of isolators as follows.

(1) Only laminated rubber:

The building is supported only by the laminated rubber so as to clarify the vibration characteristics in damper-less state.

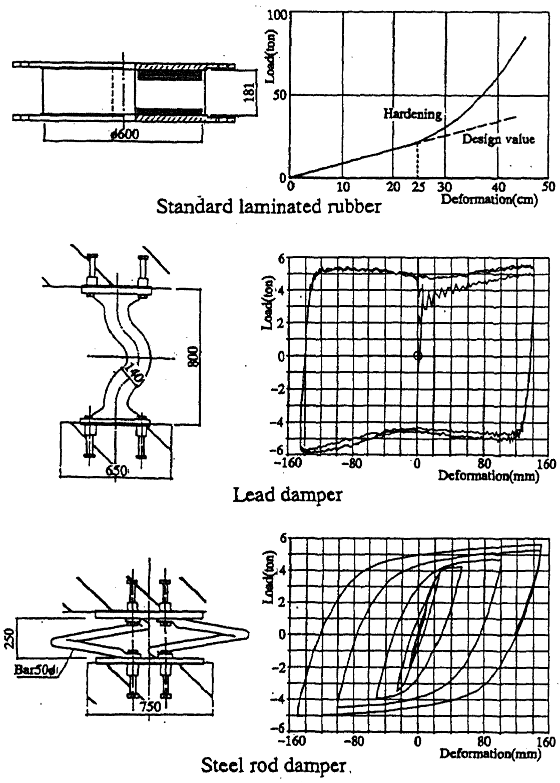


Fig.2 Shape of base isolation device and Relation between load and deformation of base isolation system

Table 1 Constants of base isolation device

Device		Stiffness	Yield Strength
Laminated rubber		K_1 = 0.75 t/cm	---
Steel rod damper		K_1 = 2.00 t/cm K_2 = 0	Qy = 6.0 t
Lead damper	Level I	K_1 = 14.0 t/cm K_2 = 0	Qy = 3.5 t
	Level II or above	K_1 = 20.0 t/cm K_2 = 0	Qy = 5.0 t

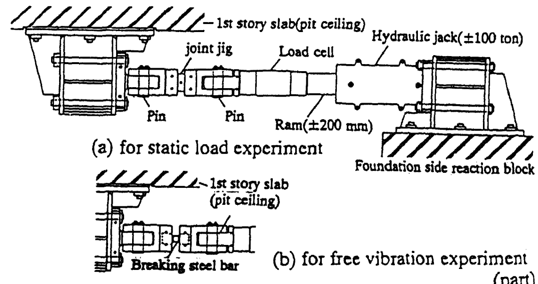


Fig.3 Loading equipment

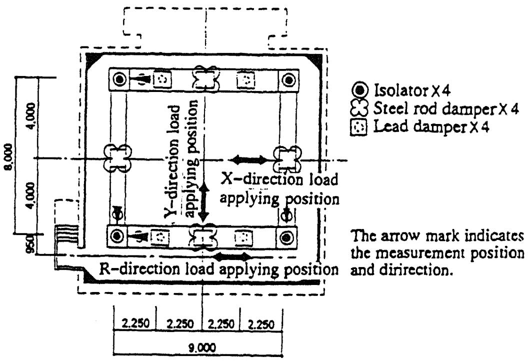


Fig.4 Loading position and method

(2) Laminated rubber + steel bar damper:

The lead damper is removed so as to clarify the effect of lead damper.

(3) Laminated rubber + steel bar damper + lead damper:

Building in completed state

Each experiment was conducted, basically, in two orthogonal directions (X - East-West, Y - South-North) of building and also in the torsion direction (R direction).

3. STATIC LOAD EXPERIMENT, AND FREE VIBRATION EXPERIMENT

3.1 Outline

In the static load experiment the loading device shown in Fig. 3 was installed between the foundation and the 1st story slab, and the upper structure was moved horizontally to cause the horizontal deformation in base isolation layer.

The load was applied in the 3 places, in the 3 directions, as shown in Fig. 4. For measurement of horizontal displacement, we used the ultrasonic relative displacement meter. For measurement of horizontal load, we used the load cell mounted on the hydraulic jack. Basically, the 3-cycle repetition load was applied to give the displacement up to 3, 5, and 10 cm. Maximum deformation given was 15 cm. The average loading speed was about 1 mm/sec.

In the free vibration experiment the breaking steel bar was fitted to the center of jack used for the static load experiment as shown in Fig. 3 (b). Free vibration was generated as a result of breaking of steel bar by moving horizontally the upper structure. The seismographs located on the 1st story and rooftop were used in addition to relative displacement meter which was used for the static load experiment. In order to determine the weight of upper structure of the building, we measured the weight of building in advance by jacking it up before the experiment. The weight of building was 638.9 tons.

3.2 Result of static load experiment

The load vs. deformation characteristics in the Y direction which were obtained in the experiment are shown in Fig. 5 for each configuration of base isolation system. The solid lines in the figure represent the measured data, the broken lines represent element test (static) data, and the alternate long and short dash lines represent the design restoring force.

The displacement plotted on the abscissa is average relative displacement of both ends of 1st story slab of building whereas the ordinate represents the applied load. In the case where only the laminated rubber was used, the behavior was linear in the range of displacement of up to 50 mm or so, but at displacement of more than 50 mm slight nonlinear behavior was observed. This is the same trend with that observed in the element test where only the laminated rubber was used. The measured stiffness of laminated rubber was 3.20 tons/cm, which is intermediate value between design rigidity and rigidity determined in the element test. In the case where the steel bar damper was used, the relation between load and deformation represents the feature of steel bar damper, namely spindle shape. In the case where the steel bar and lead dampers were used, the hysteresis area was increased owing to the effect of lead damper. In case of repeated loading with amplitude of 100 mm, the stable loop was obtained. The experimental data coincide well with the restoring characteristics obtained from the data of the static element test conducted for each base isolation system. Table 2 shows the list of initial stiffness. The similar results were observed also in the experiment in the X directi.

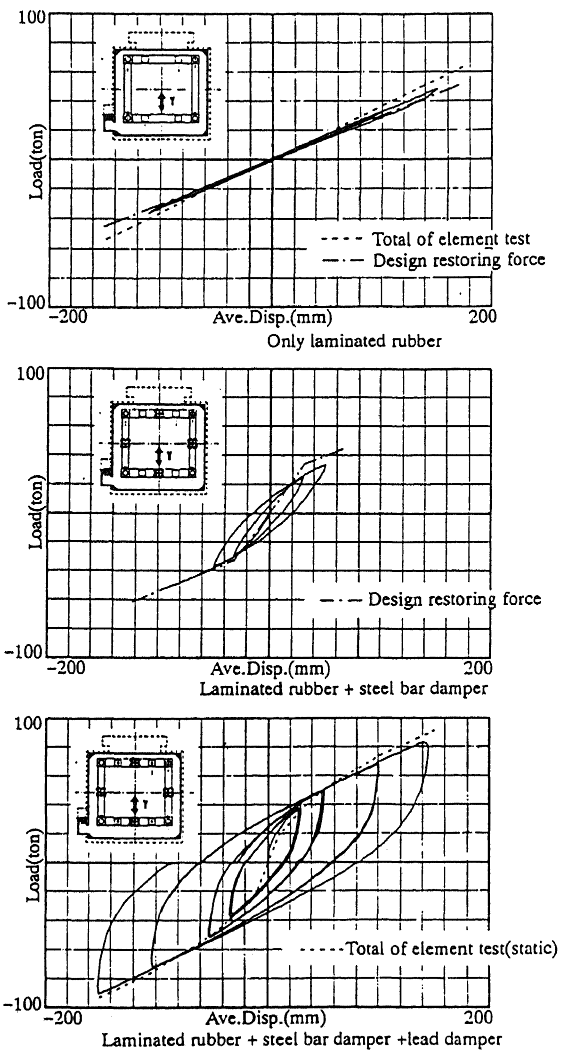


Fig.5 Relation between load and deformation in static load experiment

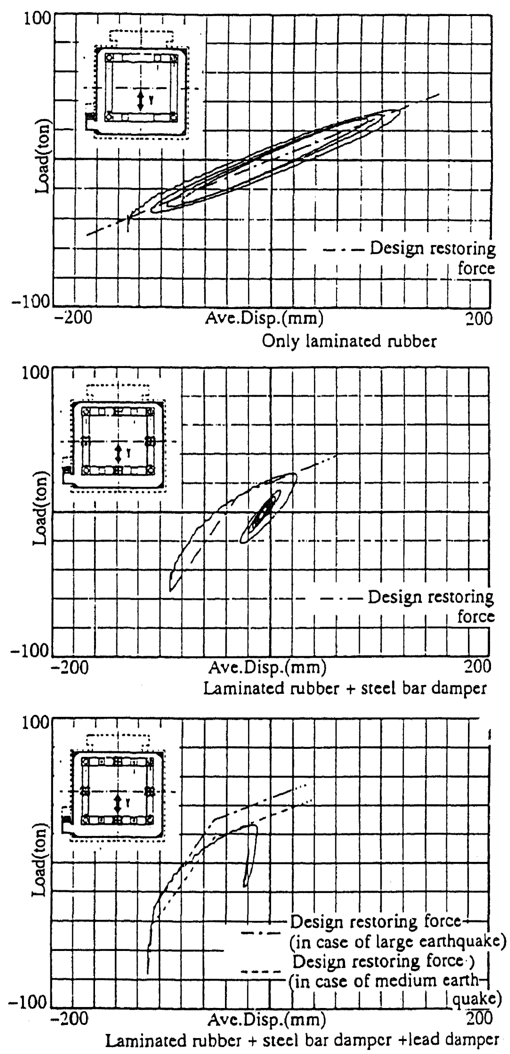


Fig.6 Relation between load and deformation in free vibration experiment

Table 2 List of initial stiffness data

Experiment case	Direction		Measured value (t/cm)	Designed value (t/cm)	Measurement/ Design	Component test (t/cm)	Remarks
Only laminated rubber	Horizontal	X	3.30	3.30	1.10	3.62	In component test δ = 5 cm
		Y	3.25		1.08		
Laminated rubber + steel bar damper	Horizontal	Y	12	11	1.09	–	
Laminated rubber + steel bar damper + lead damper	Horizontal	X	(54)	67	(0.72)	–	Design values for dynamic input 10 kine class.
		Y	(54)		(0.72)		

Notes:
1. Stiffness of each case is of whole base isolation system.
2. The parenthesized measured value of case C are reference data calculated from the natural period.

3.3 Results of free vibration experiment

Figure 6 shows the relation between relative displacement and shearing force of base isolation layer which was calculated from the weight and acceleration of upper structure. The solid line in the figure represents the experimental data whereas the broken line and alternate long and short dash line represent the design restoring force. In the case where only the laminated rubber was used, the experimental data represent the restoring force characteristics indicating the damping factor of 2 to 3% against static design stiffness. In the case where the steel bar damper was used, the experimental data in the half cycle after breakage coincide well with the design restoring force (bi-linear). The stiffness in case of displacement of less than 20 mm coincides well with the initial gradient of design restoring force. In the case where the steel bar and lead dampers were used (initial displacement is 112.9 mm), the damping was remarkable, and there was a shift back to elastic vibration range after about 1 cycle. In this experiment the free vibration was caused by one-direction tension. Therefore residual strain of about 20 mm remained. The experimental data in the range of significant displacement just after breakage of pin resemble the characteristics of design restoring force (tri-linear) peculiar to large earthquake. As the amplitude is reduced, those approach to the characteristics of design restoring force peculiar to medium earthquake.

4. RESULTS OF EARTHQUAKE OBSERVATION AND VIBRATION OBSERVATION IN STRONG WIND

4.1 Outline of observation

Figure 7 shows the location of seismograph meter, relative displacement meter (base isolation layer), pore water pressure gauge, and anemoscope-anemometer. All the 26 elements of acceleration meter (within -3 dB in the range of 0.1 to 30 Hz) were located on the rooftop of base isolated building, its 1st story, and foundation, rooftop of adjacent building of conventional structure system (4-story RC building), and ground. The acceleration meter and relative displacement meter for the base isolated building were located in the position of laminated rubber (plan), including the rooftop measuring points. The ground measuring point was located in the 3 places, namely outside and inside of soil improved area of ground and at the depth of 55 m where Vs = 400 m/s is obtained. The anemoscope-anemometer which we used is arrow vane 3-cup type. It was located at the height of 17 m from the ground on the rooftop of existing building.

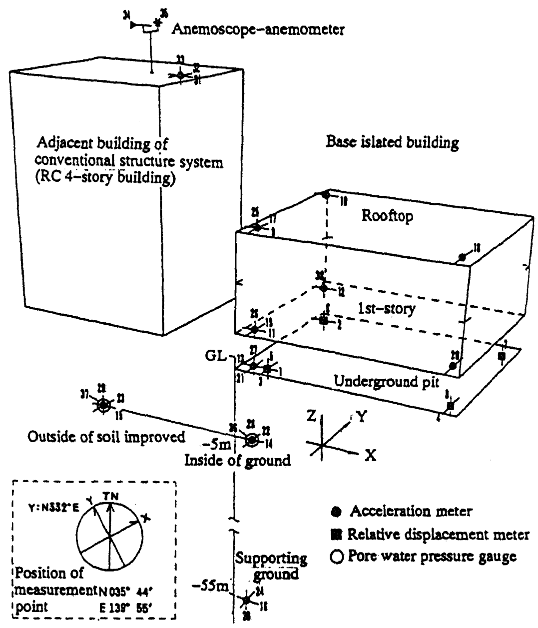


Fig.7 Location of sensors

4.2 Result of observation of earthquake

About 100 earthquake records were obtained by February 2, 1992. Below are shown the earthquake records (14 records) with which the isolation system responded in the range of damper elasticity and the earthquake record with maximum foundation input (lead damper yield occurred).

(1) Earthquake record in the range of damper elasticity

The magnitude of earthquake was M6.5 to 3.8. The epicentral distance was 40 to 140 km. Among all 14 records the largest horizontal acceleration of foundation of base isolated building was about 16.9 cm/s^2, and the maximum horizontal relative displacement of base isolation layer was about 2 mm. Figure

8 shows the observed waves. Figure 9 shows their Fourier spectrum. The data were obtained in the state where two types of damper were used. The primary frequency at the base isolated building was 1.4 Hz (damper is in the elasticity range), and the filter effect was observed at frequency of more than about 2.0 Hz. Figure 10 shows the distribution of maximum acceleration of 14 records, being classified by use/nonuse and combination of dampers. Fig. 10 (a) shows the case where no damper was used. The base isolated building has long primary period (2.2 to 2.3 sec). In all 6 records the maximum acceleration of upper structure is lower than that of foundation. Fig. 10 (c) shows the case where the two types of damper were used. Although the relation between maximum acceleration values of upper structure and foundation is not constant, the maximum acceleration of upper structure is lower than that of foundation if the acceleration of foundation exceeds 10 cm/s^2. The maximum acceleration in the horizontal direction remains almost constant at the 1st story and rooftop, irrespective of whether damper is used or not, which represents well the features of base isolation structure characterized by reduced story drift of upper structure. The maximum acceleration in the vertical direction which is shown in Fig. 10 (d) increases nearly straightly in order of foundation, 1st story and rooftop (natural frequency is about 18 Hz). The maximum acceleration at the rooftop is higher than that observed at the adjacent building of conventional structure system.

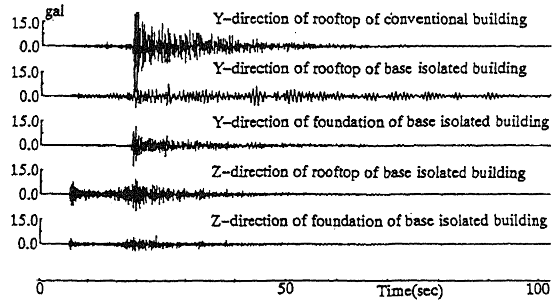


Fig.8 Earthquake acceleration(May 3, 1990)

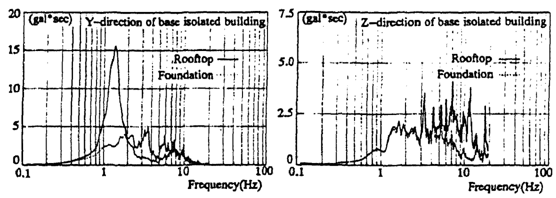
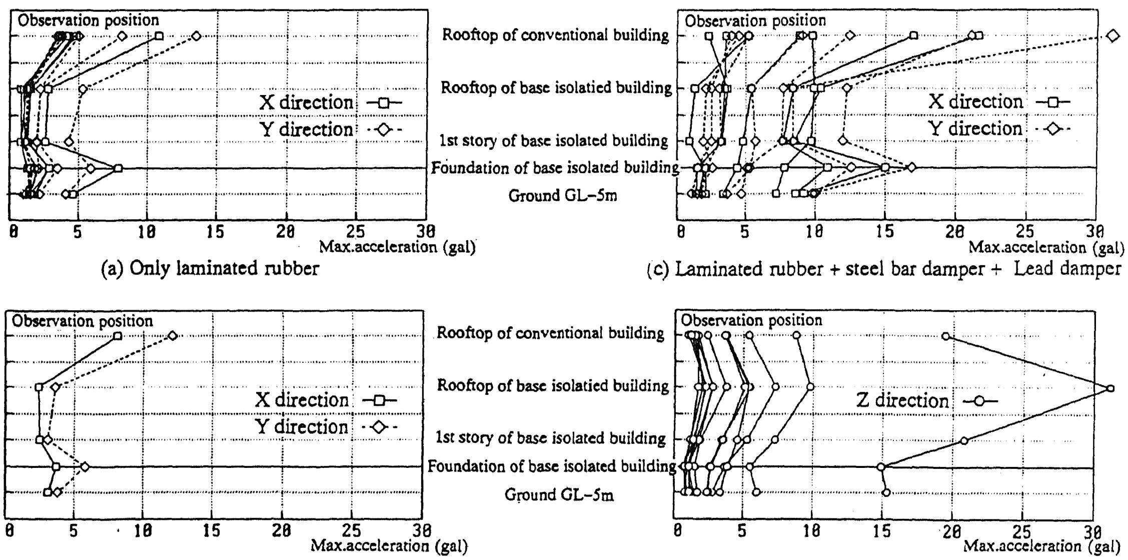


Fig.9 Fourier spectrum



(a) Only laminated rubber

(c) Laminated rubber + steel bar damper + Lead damper

(b) Laminated rubber + steel bar damper

(d) Full combination, Z direction

Fig.10 Distribibution of maximum acceleration
(14 earthquakes recorded from December 1,1988 till May 7,1990)

(2) Earthquake record with maximum foundation input

The recorded earthquake occurred at an epicentral distance of about 60 km from the observation position on February 2, 1992. The intensity of earthquake was M5.9, and the focal depth was 93 km. The horizontal acceleration on the foundation was 80.3 cm/s^2, and the horizontal relative displacement of base isolation layer was max. 7 mm. The designed yield displacement of lead damper was 2.5 mm. The damper is considered to have been yielded. Fig. 11 shows the observed waveform. Figure 12 shows the maximum response acceleration and response magnification at the observation point. In case of earthquake mentioned in item (1), above the response magnification exceeded occasionally 1. In this earthquake with the ground maximum acceleration equal to 80.3 cm/s^2, the maximum acceleration of base isolated building is 22.2 cm/s^2 (1st story) and 22.6 cm/s^2 (2nd story), i.e., about 1/4 of the ground maximum acceleration. As compared to the conventional building the acceleration was reduced to about 1/7. This proves the result stated in item (1) above, showing that the base

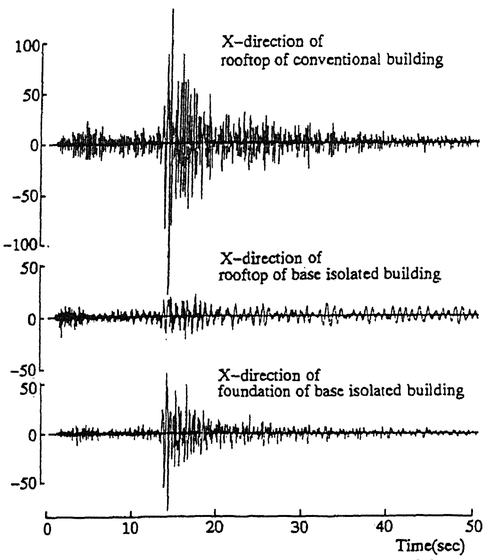
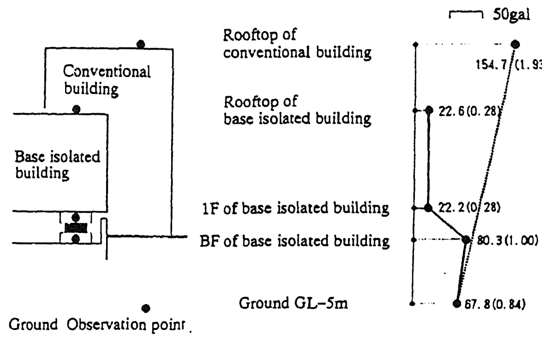


Fig.11 Earthquake acceleration (Feburuary 2, 1992)



(Parenthesized values are response magnification for BF-acceleration.)

Fig.12 Max. response acceleration and response magnification on observation points

4.3 Result of observation of vibration in strong wind

Figure 13 shows the fluctuation of wind speed in strong wind which was observed during the experiment as well as the acceleration waveform of rooftop of base isolated building. Fig. 13 (a) represents the record of Kanto area in the spring's first south wind (the lead damper was not used). Fig. 13 (b) represents the record obtained after the spring's first south wind calmed, which corresponds to microtremors Fig. 13 (c) represent the record in the strong wind similar to the spring's first south wind which blew about one week after the spring's first south wind. Both dampers were used. The main result of observation are shown in Table 3. In the case where the lead damper is not used, the relative displacement of base isolation layer exceeded 1 mm (single amplitude) and could be recognized visually. The comparison of two records obtained in strong wind reveals that the vibration by wind is remarkably reduced by using the lead damper having the high initial stiffness although the maximum wind speed differs a little. isolation effects increases as the magnitude of earthquake increases. The investigation performed after occurrence of earthquake did not reveal any defect in the base isolation system.

5. CONCLUSION

The restoring force characteristics of base isolation system which were obtained in the static load experiment and free vibration experiment coincide roughly with the design restoring force. The base isolation system shows stable behavior even when significant deformation exceeding 150 mm occurred, which has proved the validity of design and the reliability of base isolation system. The earthquakes as intensive as the lead dampers respond in the plastic range have been observed, and the effect of input reduction of earthquake excitation by the base isolation system is verified. We are intending to continue observation so as to accumulate the real response data and to examine the factors affecting the base insulation effects.

Finally, we wish to express our appreciation to Director Yamaguchi at Tokyo Architecture Laboratory who have advised us and our experiment.

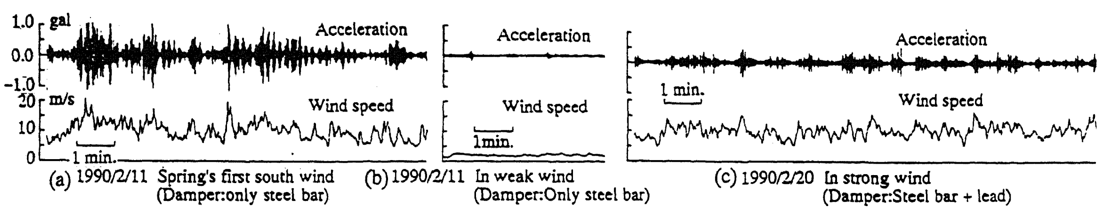


Fig.13 Example of observed wind waves (rooftop Y-direction and wind speed)

Table 3 Main record of wind observation

Date	Climatic state	Wind direction	Max. wind speed	Max. accelelation	Max. displacement	Combination of base isolation devices
1990/2/11	Spring's first south wind	SSW	20.3 m/s	2.3 gal	1.2 mm	Laminated rubber + steel bar damper
1990/2/11	Weak wind	NNW	<3 m/s	<0.1 gal	---	Laminated rubber + steel bar damper
1990/2/20	Strong wind	SSW	17.0 m/s	0.7 gal	0.08 mm	Laminated rubber + steel bar damper + lead damper