UTILITIES/INDUSTRIES JOINT STUDY ON SEISMIC ISOLATION SYSTEMS FOR LWR (PART II) OBSERVED BEHAVIORS OF BASE-ISOLATED GENERAL BUILDINGS UNDER REAL EARTHQUAKES

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This paper describes the observed behavior of base-isolated buildings under real earthquake conditions. These buildings were constructed by five construction companies participating in the Joint Study on Seismic Isolation Systems for light-water reactors (LWRs). All the buildings are medium- or low-height buildings of reinforced-concrete structures with combinations of laminated rubber bearings or sliding bearings and various damping devices.

Introduction

In recent years in Japan, base-isolated buildings have been rapidly gaining attention and at present (June 1989), more than 20 such buildings have been completed. Research and development concerning base-isolated buildings has been carried out among construction companies and rubber manufacturers since 1983. At first, most of these buildings were their own office buildings or research facility buildings, but recently there has been an increasing number of orders from general clients.

This paper gives outlines of structures, base-isolation systems, and observed earthquake records of base-isolated buildings constructed by five construction companies participating in the "Joint Study on Seismic Isolation Systems for LWRs" to contribute to the study on application of base-isolation system to LWR plants.

Outline of Base-Isolated Buildings and Observed Earthquakes

A list of the base-isolated buildings described in this paper is given in Table I. All of the buildings are medium- or low-height buildings of reinforced-concrete construction with combinations of laminated rubber bearings or sliding bearing and various damping elements adopted as base-isolation systems. The aseismic designs were made by dynamic analyses with natural periods set at 1.2 to 3.0 s at large deformations.

These buildings are all equipped with instruments for measuring vibrations due to earthquakes and strong winds, with basic experiments such as forced vibration tests already conducted, while numerous observation records of small- or medium-scale earthquakes have been obtained.

Representative earthquakes observed at the individual buildings are listed in Table II, while the epicenter and building locations are shown in Fig. 1. These buildings are all situated in eastern Japan, comparatively high in seismicity, and a number of earthquakes of magnitudes 5 to 6 have been observed. It has been verified through comparisons with conventional non-base-isolated buildings that these base-isolation systems are effective.

The outlines of the individual buildings and their base-isolation systems and representative earthquake observation results are described below.

Tohoku University Test Buildings

1. Building Outline

This base-isolated test building was constructed on the campus of Tohoku University in 1986 for the purpose of joint research between Tohoku University and Shimizu Corporation to gather the verification data on base-isolated structures, and stands next to a non-base-isolated building having a completely identical superstructure to directly ascertain the effects of base isolation. The superstructure, as shown in Fig. 2, is of three-story reinforced-concrete construction with exterior walls finished using ALC panels, the total weight being ~255 ton. The base-isolated building has its superstructure supported by six laminated rubber bearings.

2. Base Isolation System

At the beginning, a combination of natural rubber bearings and oil dampers was adopted, and after having made observations for a given period, the system was switched to high-damping rubber bearings and observations were resumed. The outlines of the base-isolation devices are shown in Figs. 3 and 4. The high-damping rubber bearings had exactly the same configurations as the natural rubber bearings with only the rubber material being different.

The primary natural frequency of the base-isolated building was ~0.61 Hz in the case of the natural rubber bearings plus oil dampers and ~0.58 Hz in the case of the high-damping rubber bearings (calculated from equivalent stiffness at horizontal displacement of 10 cm), with equivalent damping factors set at ~15% for both cases.

3. *Earthquake Observation Results*

Earthquake observations were started from June 1986 and a total of more than 50 earthquakes have been recorded since then. Representative records for the different systems are described below.

The results obtained for the Fukushima-Ken-Oki Earthquake of February 6, 1987 are shown in Fig. 5 as observation records obtained with laminated rubber bearings plus oil dampers. With the building of conventional construction, a maximum acceleration in excess of 200 gal was recorded at the top of the building, whereas it was ~40 gal with the base-isolated building, and there was an acceleration reduction effect of ~1/6 to 1/5. The floor response spectrum was also greatly reduced in short-period components, and it was verified that the system was activated effectively.

Next, as an observation record with the high-damping rubber bearings, the results obtained in the Fukushima-Ken-Oki Earthquake of October 4, 1987 are shown in Fig. 6. With this system also, the maximum response acceleration of the base-isolated building was similarly reduced to ~1/5 compared with the non-base-isolated building.

Both of the earthquakes were of medium scale, and the deformations of the base-isolation devices were held to small ranges, but it is expected that with the high-damping rubber bearings greater base-isolation effects would be demonstrated in larger scale earthquakes.

4. *Remarks*

This building was constructed with the objective being verification tests of base-isolated construction, and it is possible for various base isolation systems to be installed and their effects verified through earthquake observations. At present, basic experiments and earthquake observations have been completed for two types of base-isolation systems. Experiments on new base-isolation systems will continue into the future, and much is expected of the research results.

Funabashi Chikuyuryo Dormitory

1. Building Outline

The base-isolation system applied in this building is composed of laminated rubber bearings and viscous dampers. The dormitory is shown in Fig. 7.1 (RC 3F, total floor space: 1530 m^2, building weight: 2,479 ton). The primary natural period is 2.1 s.

2. Base Isolation System

Layout of devices is shown in Fig. 7. Here, we have two types of rubber bearings which can support 200 and 150 ton. In Fig. 7.2, a 200-ton rubber bearing is cut to show its structure. Both types of rubber bearings are designed to make their natural frequency 0.5 Hz in horizontal direction and 18 Hz in vertical direction when they support 200 or 150 ton of weight, respectively. The maximum horizontal relative displacement is 30 cm.

A cross section of the damper is shown in Fig. 7.3. The damping force is provided by the shear deformation of the viscous fluid between the upper plate attached to superstructure and the base plate attached to basement. Here, the equivalent damping factor is 8% (the characteristics of the damper are nonlinear). Lateral deformation capacity is 30 cm which is equal to that of rubber bearings.

3. Earthquake Observation Results

In this building, 15 accelerometers (horizontal: 9, vertical: 6) have been installed to observe earthquakes. We have been observing earthquakes since April 1987, when construction was completed. In the earthquakes we observed to date, the base isolation system reduced the maximum acceleration level at the first floor to less than half the level of input.

Figures 8 and 9 show the wave records and spectra of two typical earthquakes observed on December 17, 1987 and March 18, 1988. In both earthquakes, we realize that the large acceleration level at the basement is effectively reduced at the roof. The wave at the roof contains natural frequency of the isolation system. In spectra, we can see that the inputs over 1 Hz are reduced by the isolation system.

4. Remark

From earthquake observations, the base-isolation system using laminated rubber bearings and viscous dampers has appeared to have good "Isolation Ability." Using simulation analysis, we are planning to study the structure in more detail.

Ohbayashi High-Tech R&D Center

1. Building Outline

This building is the laboratory which was constructed in 1986 in the field of the technical research institute of Ohbayashi Corporation in Kiyose-city of Tokyo. The outline of the building, a five-story reinforced-concrete structure, is shown in Fig. 10. The total height is 21.85 m, the total area is 1628 m^2 and the total weight is about 3000 tons. Designed base shear coefficient of longitudinal (x) direction is 0.15 which is 3/4 of the Japanese seismic code.

2. Base-Isolation System

The base-isolation system consists of 14 natural rubber bearings and 96 special steel bar dampers, as shown in Fig. 11. A steel bar is a cantilever type supported with three spherical bearings. The horizontal yielding deflection is about 3 cm. As for the mechanical property of a base-isolation system for large displacement, natural period in horizontal direction is 3.0 s, natural period in vertical direction is 0.067 s (15 Hz), equivalent viscous damping ratio based on the hysteretic loop area is 10%, and allowable horizontal displacement is about 40 cm.

3. Earthquake Observation Results

Fourteen earthquake records which are larger than JMA III seismic intensity in Tokyo have been observed since August 1986. From these, the acceleration records of the December 1987 Chiba Toho-Oki Earthquake are described here. The amplification ratio of acceleration and the time history of acceleration are shown in Figs. 12 and 13, respectively. Acceleration records of a non-base-isolated building (three-story reinforced concrete main building of the Institute) are also shown. From these records, peak acceleration at the roof of the High-Tech R&D Center in x-direction became 11 gal against 44 gal of ground acceleration. On the other hand, peak acceleration at the non-base-isolated building was amplified to 59 gal, and therefore the reduction ratio of peak acceleration of base-isolated building-to-non-base-isolated building became about 1/6.

4. Remark

The feasible base-isolation system consisting of natural rubber bearings and special steel bar dampers which can take large energy absorption was developed. Large reduction effect of response peak acceleration could be obtained by earthquake observation. However, further observation should be continued for larger earthquake excitations.

Research Laboratory of Kajima Corporation

1. Building Outline

This building was constructed as an acoustic laboratory building of the Kajima Institute of Construction Technology. The building was designed to have not only the function of reducing acceleration response during a severe earthquake, but also horizontal and vertical isolation from ground micro vibration, for the accurate acoustic testing. The total weight of the building is about 2230 tons. A cross section of the building is shown in Fig. 14, and the arrangement of base-isolation devices is shown in Fig. 15.

2. Base Isolation System

The building is supported by 18 laminated rubber bearings together with 14 steel rod dampers. The laminated rubber bearings used here have much thicker rubber layers than ordinary bearings for earthquake protection only (Fig. 16). The steel rod dampers have reinforced-concrete deformation restrainers which can protect the steel rod from local damage at the fixed end (Fig. 17).

The horizontal natural frequency is 1.25 Hz in elastic condition of the steel damper, and is 0.5 Hz in plastic condition. The yield force of damper corresponds to 5% of the building's weight.

3. Earthquake Observation Results

Earthquake response has been observed since the building was completed on July 30, 1986. To date, 18 earthquakes have been observed. The acceleration time histories and the acceleration response spectra observed on December 17, 1987 are shown in Fig. 18. The maximum acceleration distributions observed during earthquakes on December 17, 1987, March 18, 1988, and August 12, 1988 are shown in Fig. 19.

4. Remark

The maximum response acceleration at the top of the base-isolated building was equal or slightly larger than the maximum ground acceleration. However, the maximum acceleration was observed as one-half to one-third times smaller than that at the top of the adjacent ordinary non-base-isolated building. The response displacement to the earthquake on December 17, 1987 was about 8 mm which did not result in yielding of the steel rods. The larger reduction of response acceleration can be expected for severe earthquakes strong enough to cause the yielding of steel rods.

Research Laboratory of Taisei Corporation

1. Building Outline

This building is a base-isolated four-story reinforced-concrete building with a total floor area of 1173 m^2, a weight of about 2500 tons, and a fundamental period of 1.2 s. The overall dimensions of this building are shown in Fig. 20. A total of eight elastic sliding bearings are installed at the column locations and eight horizontal springs are placed near four building corners.

2. Base-Isolation System

The base-isolation system used for this building consists of elastic sliding bearings, bearing plates (stainless steel), and horizontal springs (cylindrical rubber block), as shown in Fig. 21. The elastic sliding bearing is a laminated rubber bearing with a poly tetra fluoro ethlene (PTFE) plate attached on its bottom surface placed against a bearing plate. The elastic sliding bearing functions by reducing seismic response of a building for weak or moderate earthquakes by the period lengthening effect associated with the elastic deformation of laminated rubber without sliding. For severe earthquakes it functions by sliding the bearing on a stainless-steel plate in which the seismic energy is absorbed with friction, and thus the shear force induced in the building is limited to the friction force as schematically shown in Fig. 22. The coefficient of friction is in the range of 0.05 to 0.15.

3. Earthquake Observation Results

In earthquake observation, an earthquake, whose epicenter was in Chiba, was recorded on August 12, 1988. This earthquake caused no sliding but some elastic deformation of rubber. The waveforms and the maximum acceleration profiles recorded during this earthquake in this building and an adjacent non-base-isolated building are shown in Fig. 23, which shows the effect of this base-isolation system on the building responses.

4. Remark

The sliding type base isolation system has successfully demonstrated its function of reducing the seismic response of the building for weak earthquakes even without sliding. From now on, it is necessary to continue earthquake observation for severe earthquakes so this isolated system proves to be efficient with sliding.

Conclusions

It can be concluded from the observed earthquake records of the five base-isolated buildings designed and constructed by Japanese construction companies that for medium size earthquakes, magnitude of 5 to 6 (or JMA III), the base isolation systems used in those buildings are all very effective. Furthermore, simulation analyses on the dynamic behavior of each building have been performed to improve analysis methods.

Earthquake observation will be continued to verify the effectiveness of the systems against larger earthquakes, and it is expected that valuable data will be offered in application of base isolation to nuclear power facilities of light-water reactor (LWR) plants, etc.

Table I
List of Base-Isolated Buildings

Building Name	Location	No. of Stories	Total Floor Area	Isolation Devices
(1) Two Full-Sized Test Buildings at Tohoku University	Miyagi	RC3F	417 m^2	Rubber Bearing + Oil Damper/High Damping Rubber Bearing
(2) Funabashi Chikuyu Dormitory	Chiba	RC3F	1173 m^2	R.B. + Viscous Damper
(3) Research Laboratory of Ohbayashi Corp.	Tokyo	RC5F	1628 m^2	R.B. + Steel Bar Damper
(4) Research Laboratory of Kajima Corp.	Tokyo	RC2F	656 m^2	R.B. + Steel Bar Damper
(5) Research Laboratory of Taisei Corp.	Kanagawa	RC4F	1530 m^2	Sliding Bearing + Horizontal Spring

Table II
List of Earthquakes Observed

Date	Epicenter	Magnitude	Depth (km)	Building
Feb. 6, 1987	Fukushima	6.4	18	(1)
Oct. 4, 1987	Fukushima	5.8	51	(1)
Dec. 17, 1987	Chiba	6.7	58	(2)(3)(4)
Mar. 18, 1988	Tokyo	6.0	99	(2)(3)(4)
Aug. 12, 1988	Chiba	5.3	66	(4)(5)

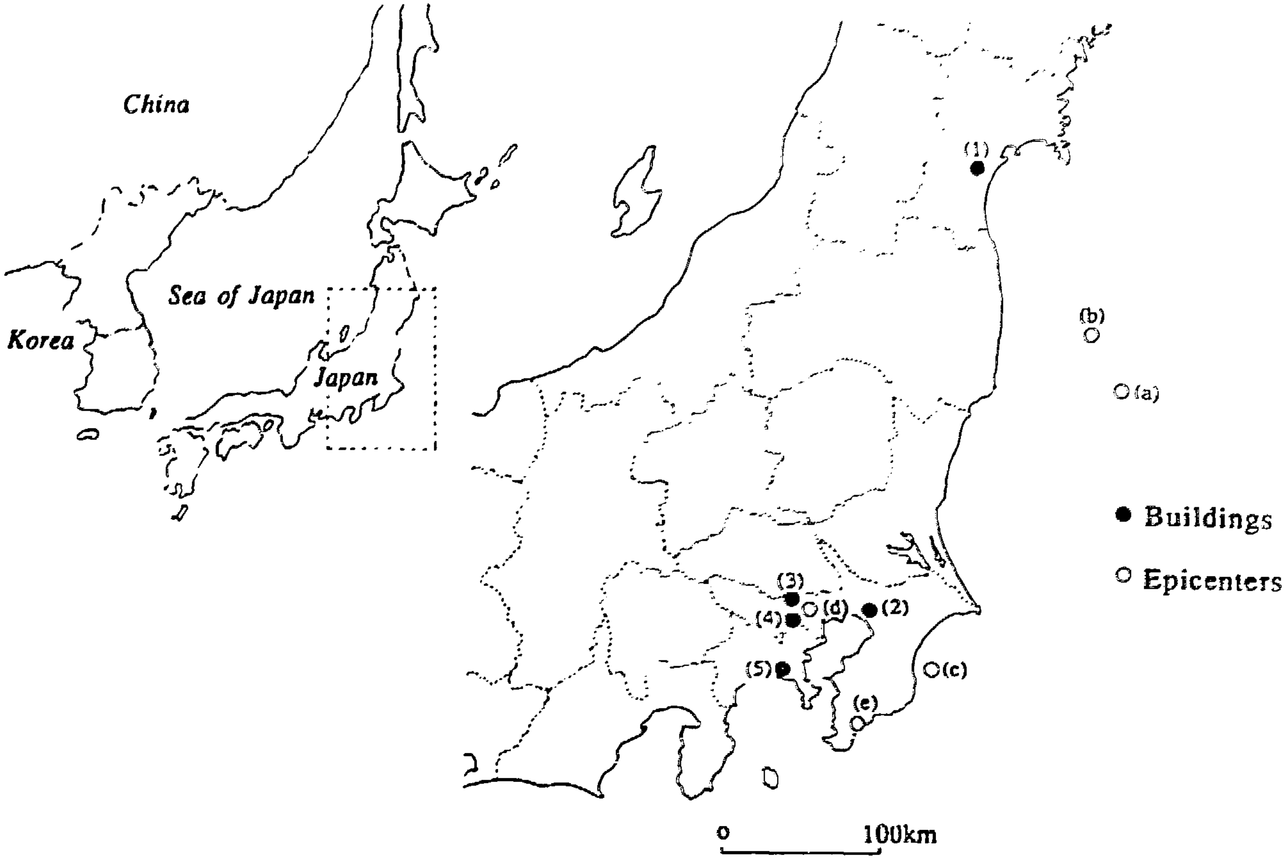


Fig. 1. Location of Buildings and Epicenters

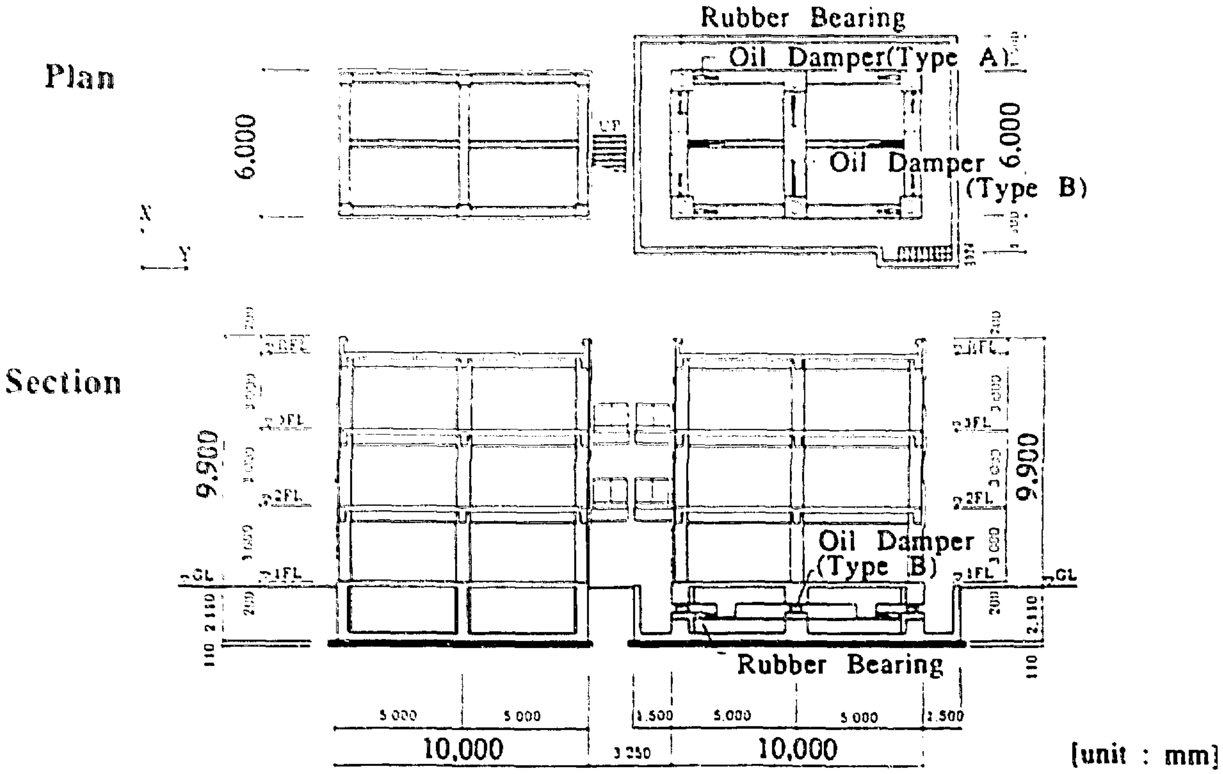


Fig. 2. Plan and Section of Tohoku University Test Buildings

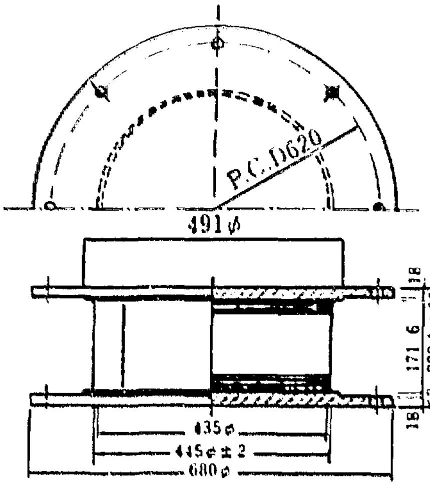


Fig. 3. Dimensions of Laminated Rubber
(High-Damping Rubber)

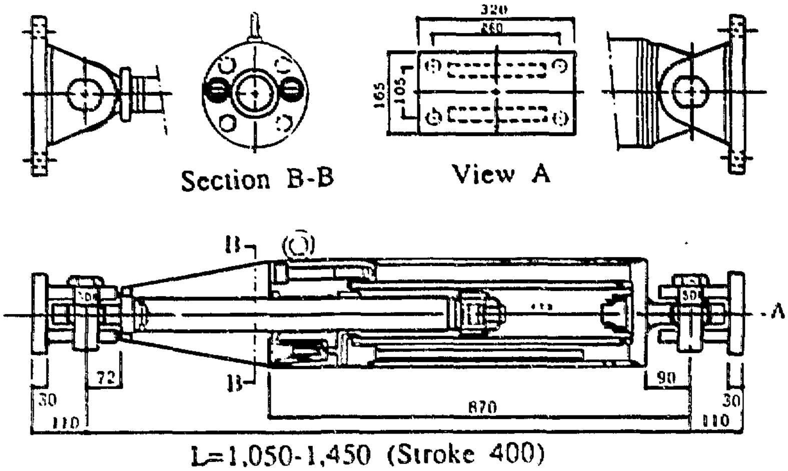
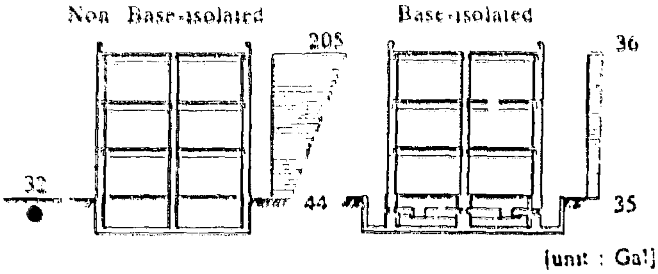
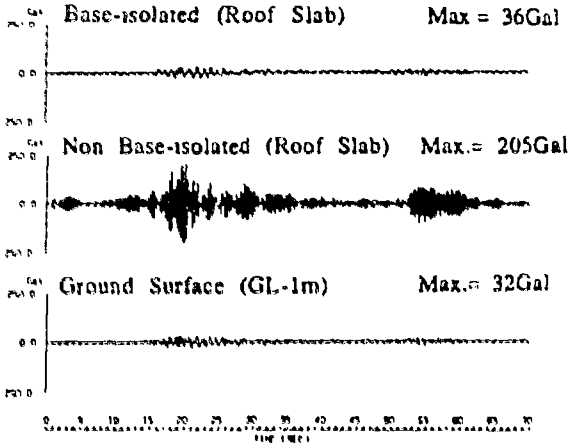


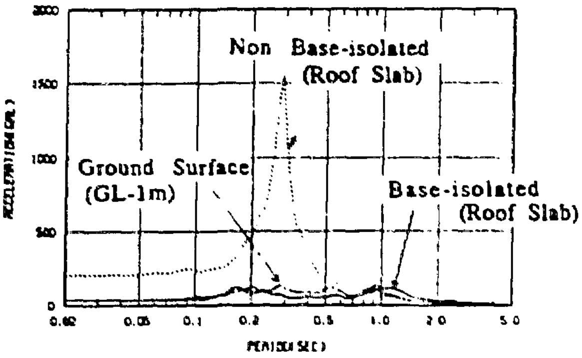
Fig. 4. Oil Damper (Type B)



(a) Max. Acceleration

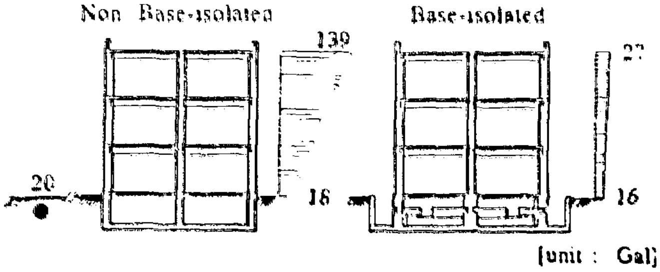


(b) Accelerograms

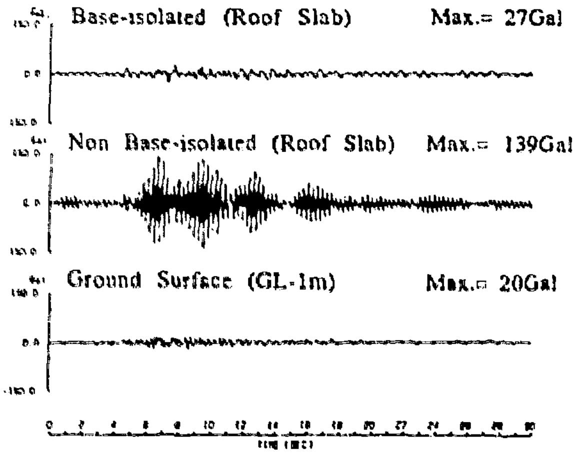


(c) Response Spectra (h=5%)

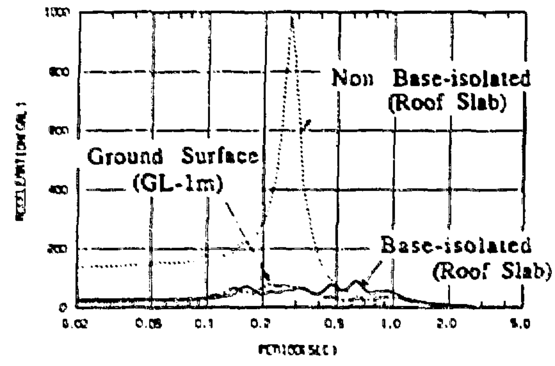
Fig. 5. Observed Records of Oil Damper-Laminated Rubber Bearing (X-direction)



(a) Max. Acceleration



(b) Accelerograms



(c) Response Spectra (h=5%)

Fig. 6. Observed Records of High Damping Rubber Bearing (X-direction)

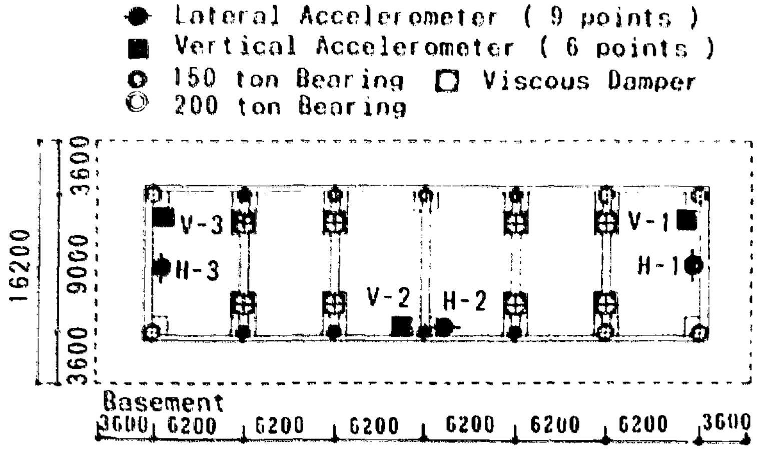


Fig. 7. Layout of Devices

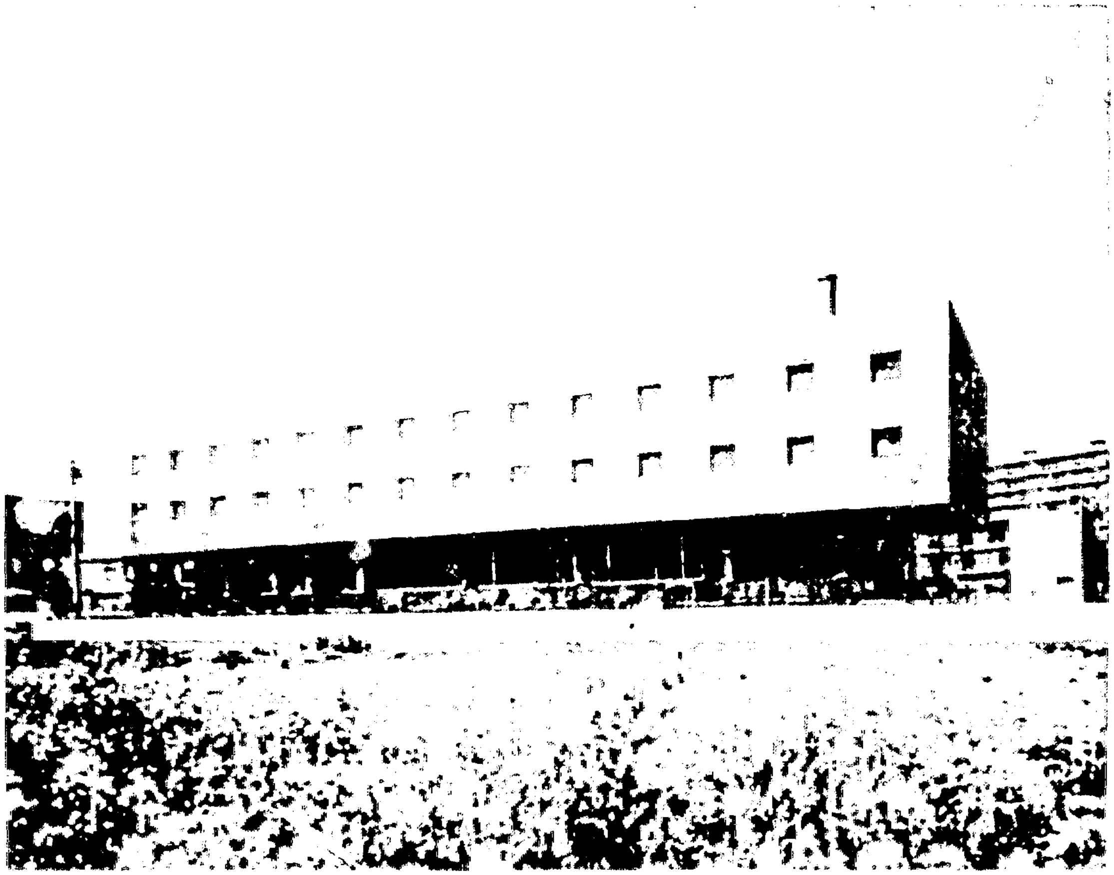


Fig. 7.1. View of Funabashi Chikuyu Dormitory

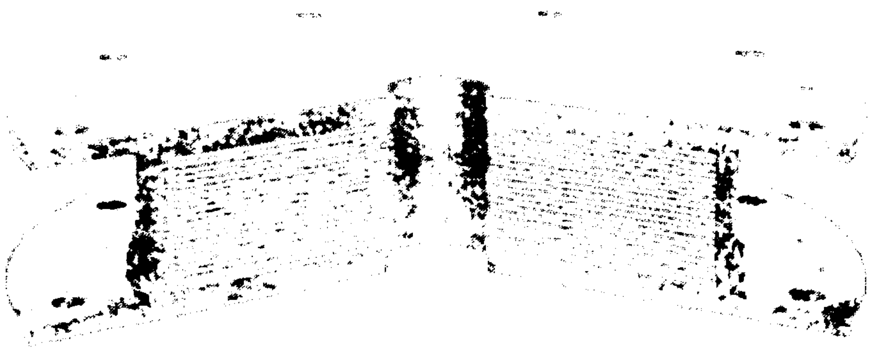


Fig. 7.2. 200-Ton Rubber Bearing Cut to Show Structure

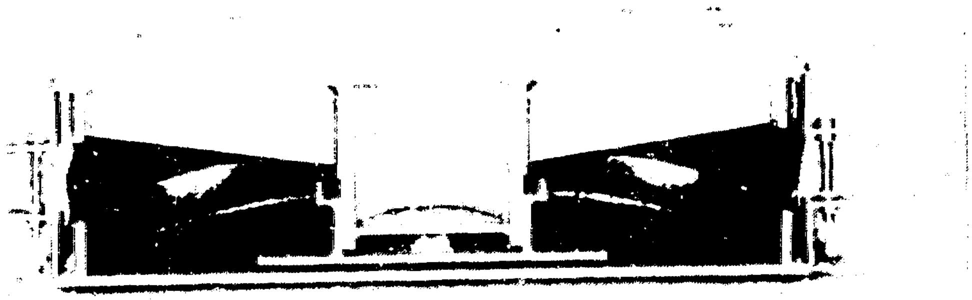


Fig. 7.3. Viscous Damper Cut to Show Structure

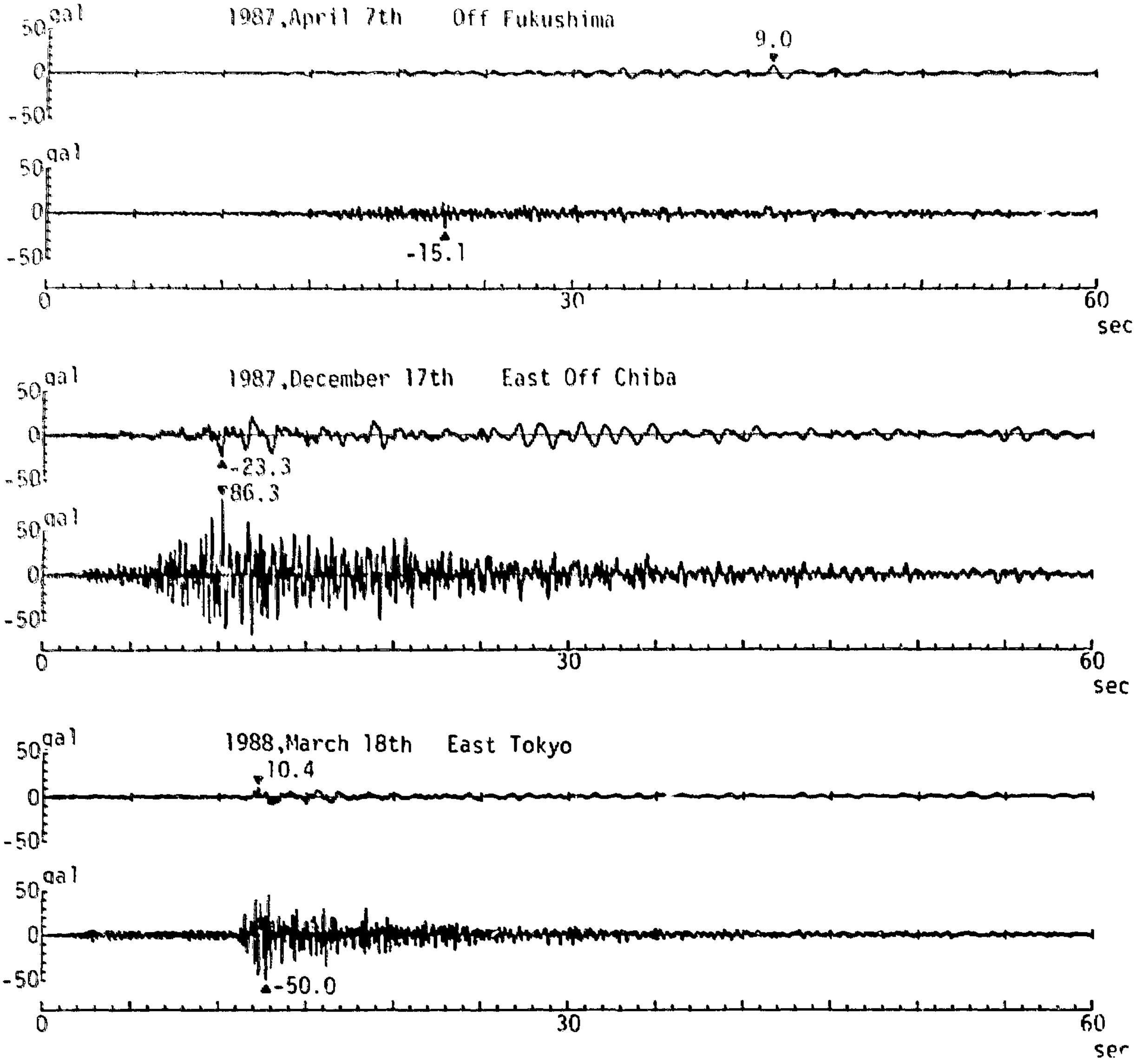
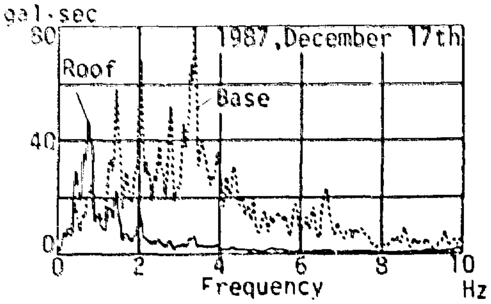


Fig. 8. Observed Earthquake Records in EW Direction



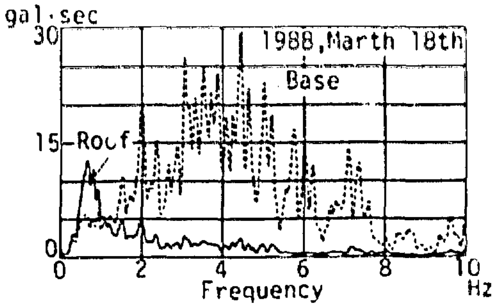
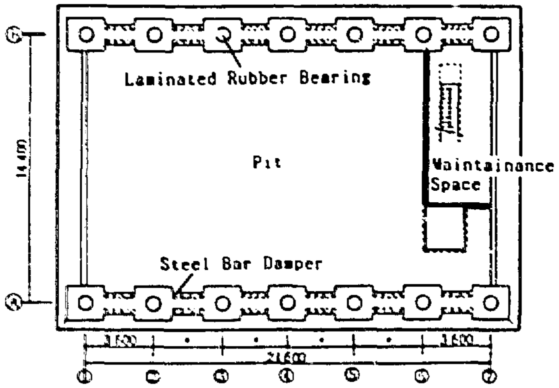
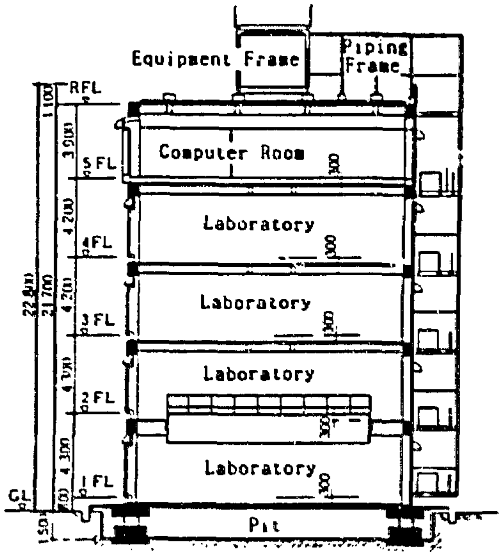


Fig. 9. Fourier Spectra of Observed Earthquake Records in EW Direction



(a) Plan of Basement Floor



(b) Section of Transverse Direction

Fig. 10. High-Tech. R&D Center

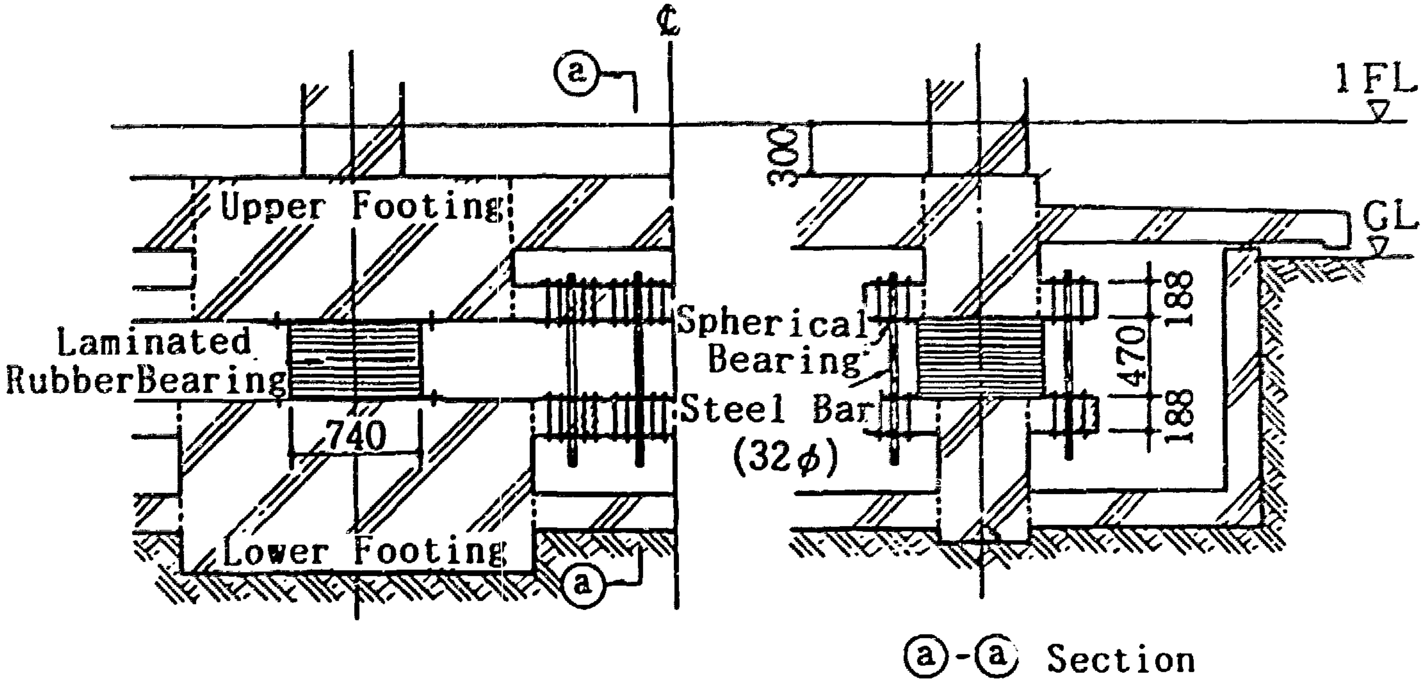


Fig. 11. Detail of Base-Isolation System

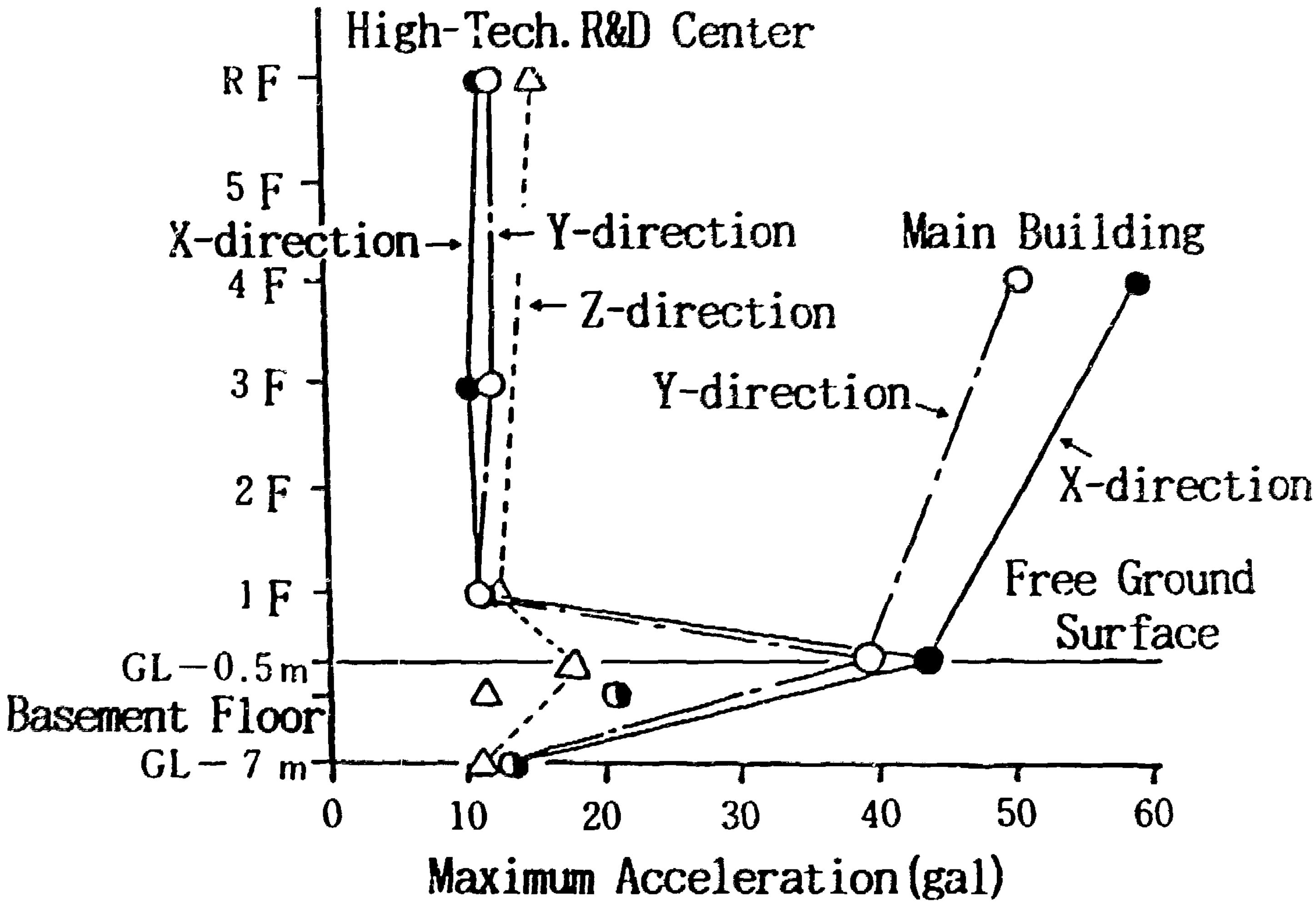


Fig. 12. Amplification of Peak Acceleration (Dec. 1987 Chiba Toho-Oki Earthquake)

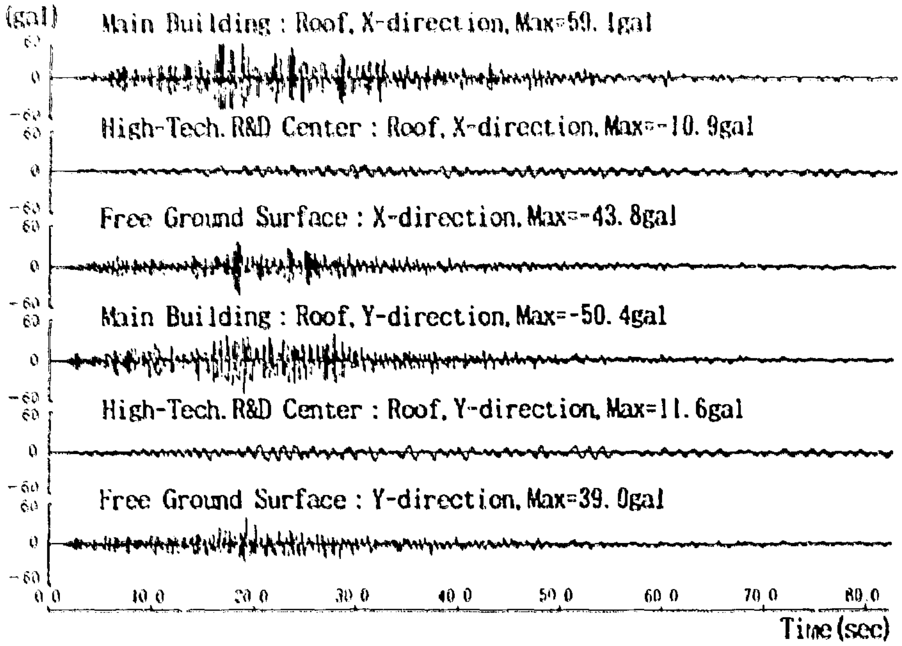


Fig. 13. Time History of Acceleration (Dec. 1987 Chiba Toho-Oki Earthquake)

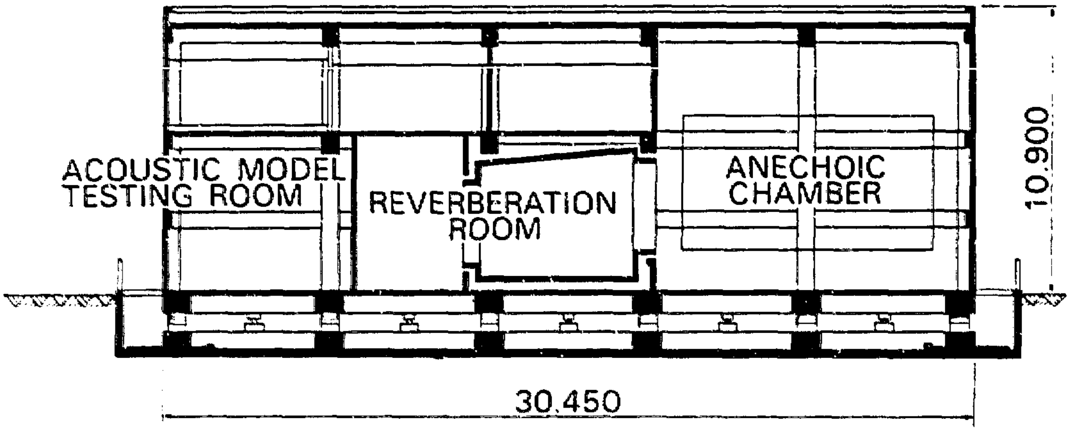


Fig. 14. Cross Section of Acoustic Environmental Vibration Laboratory Building

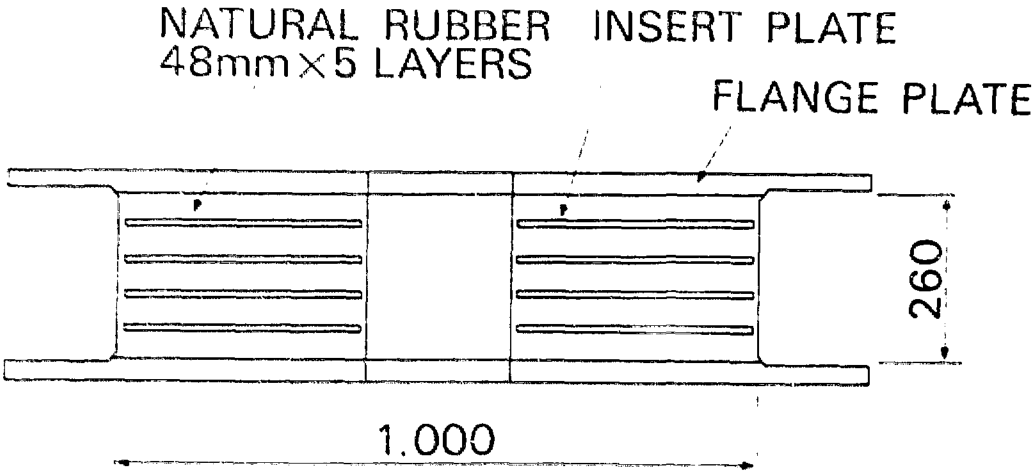


Fig. 15. Laminated Rubber Bearing

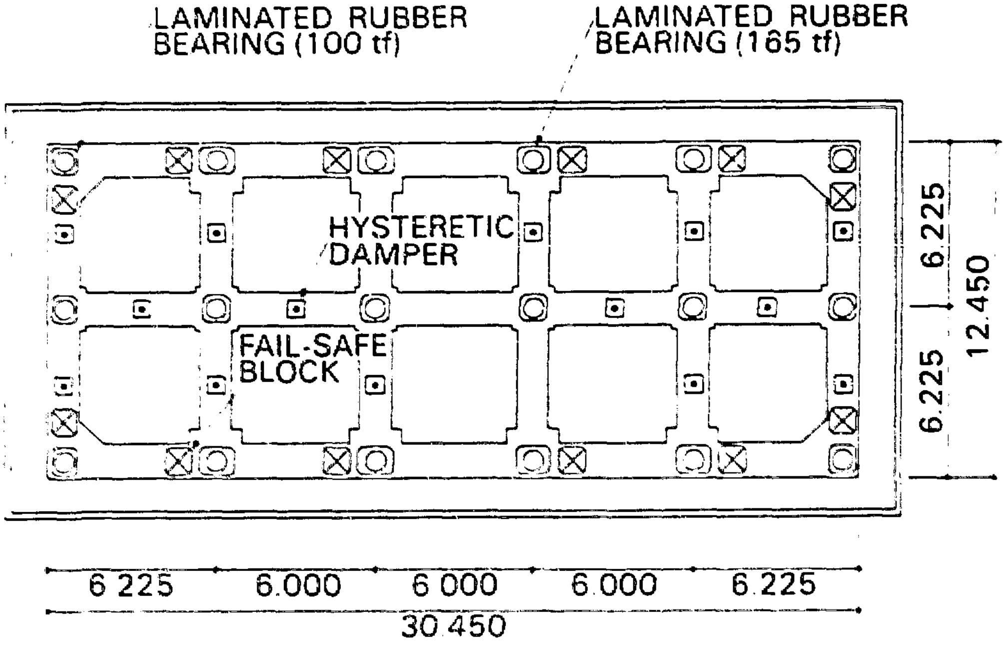


Fig. 16. Arrangement of Devices on Isolation Floor

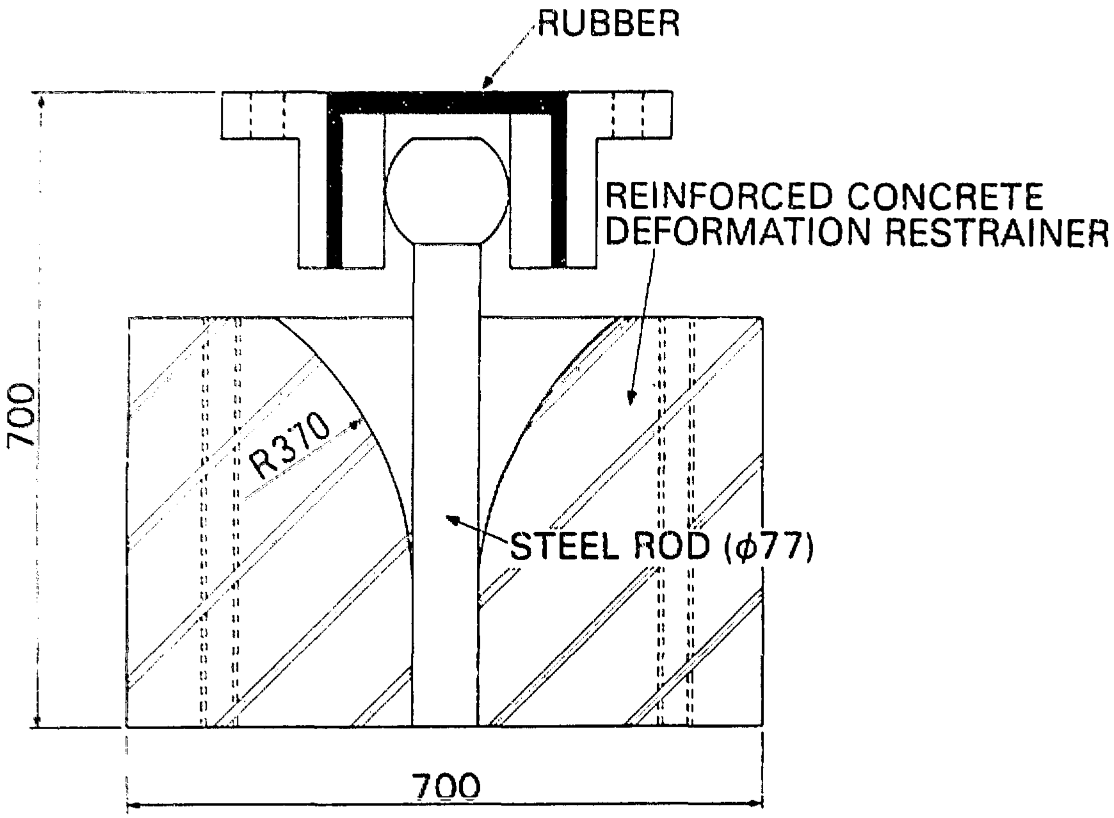


Fig. 17. Steel Rod Damper

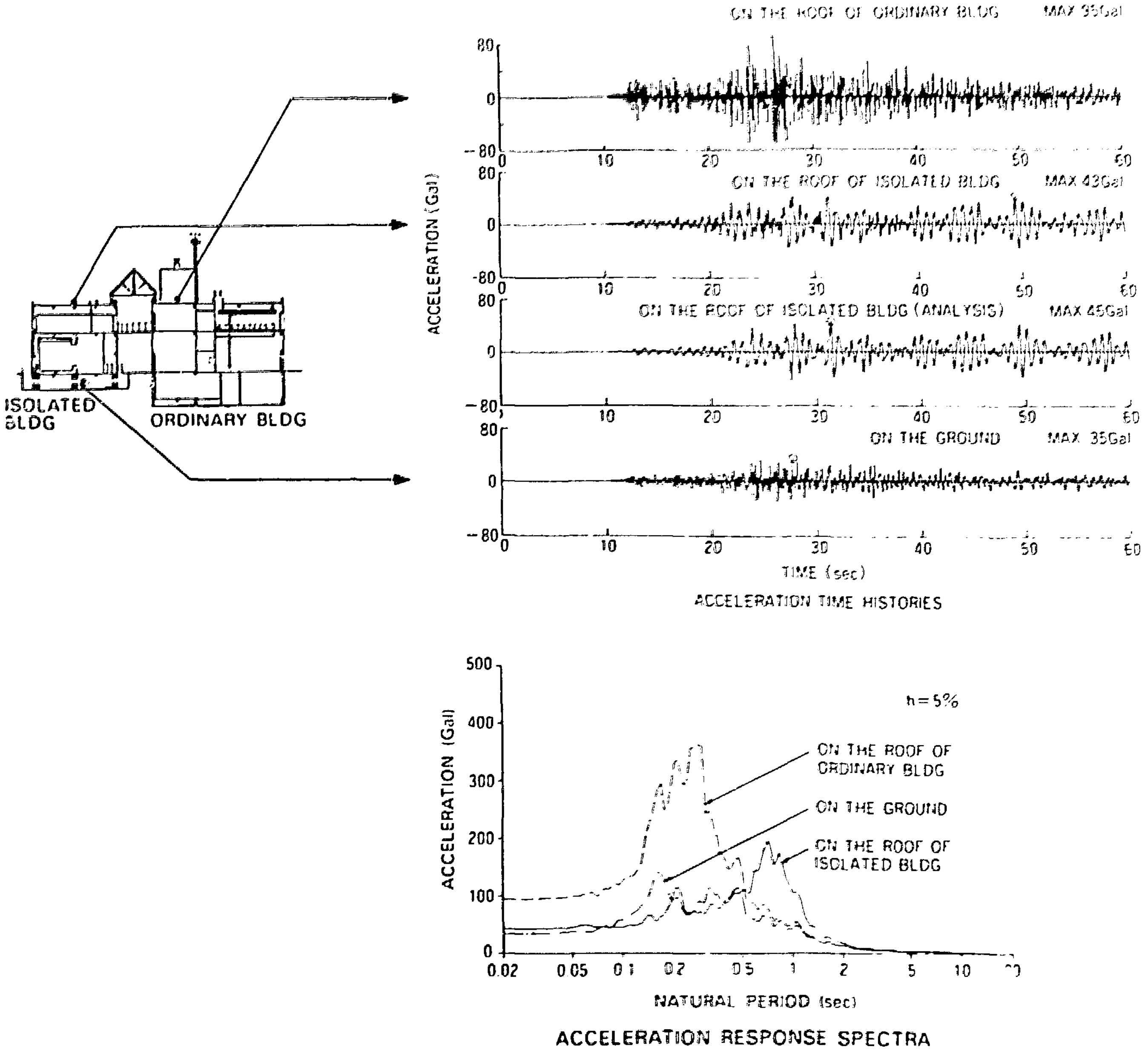


Fig. 18. Earthquake Observation Records from Dec. 17, 1987

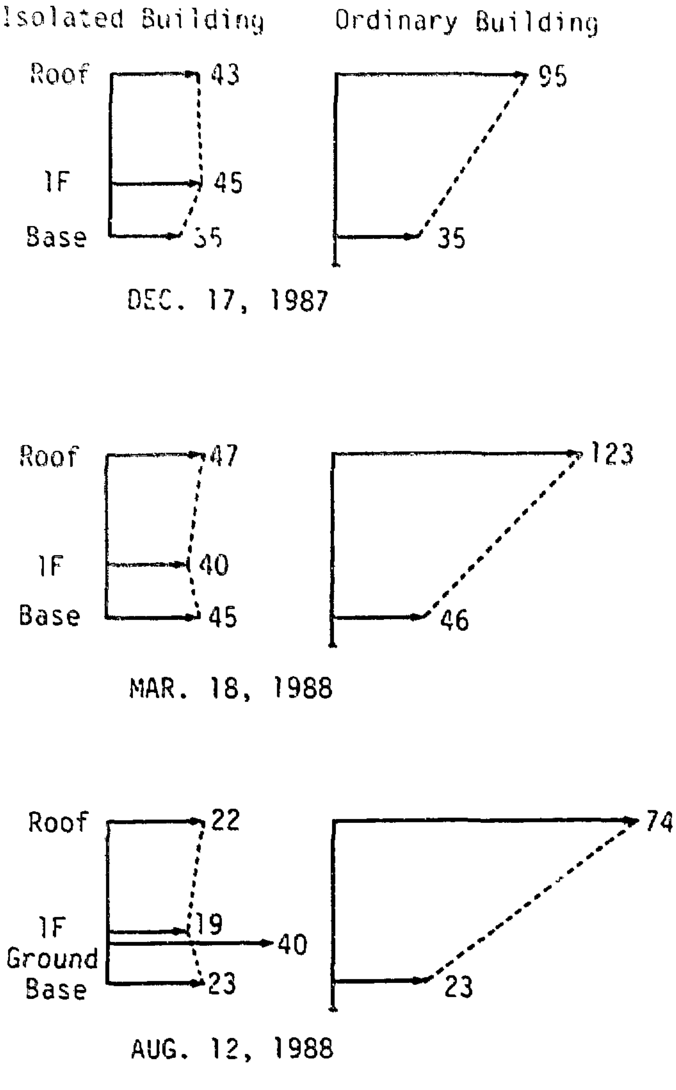
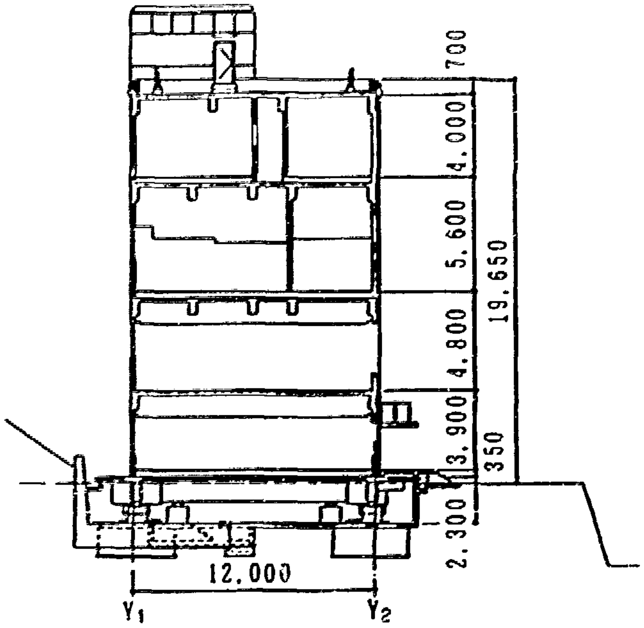


Fig. 19. Maximum Acceleration Distribution



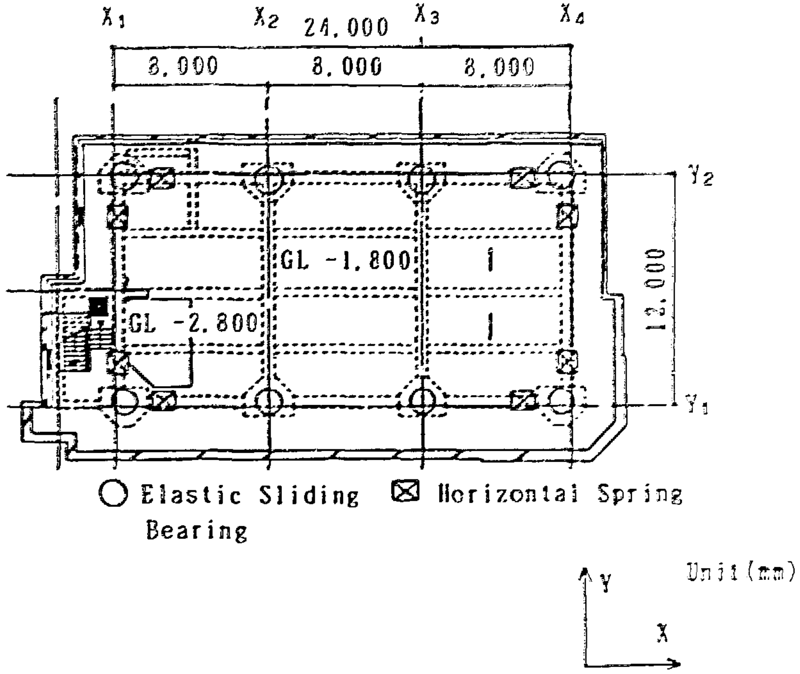
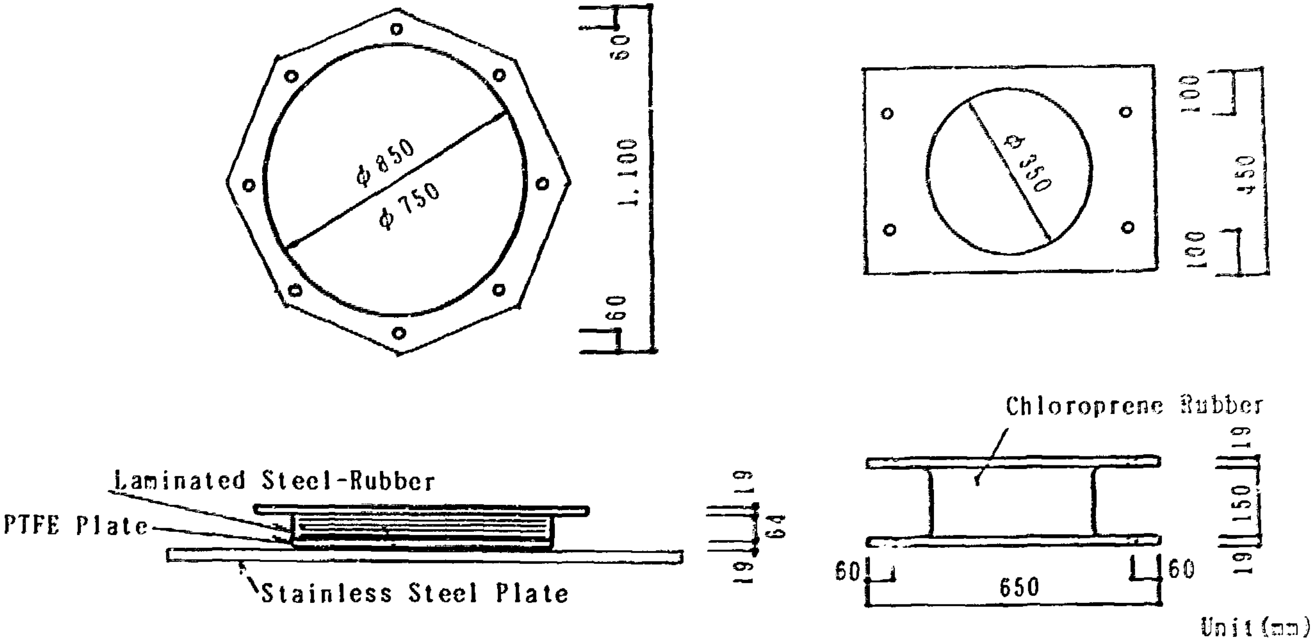


Fig. 20. Research Laboratory of Taisei Corp.



(a)Elastic Sliding Bearing (b)Horizontal Spring

Fig. 21. Sliding-Type Base-Isolation System

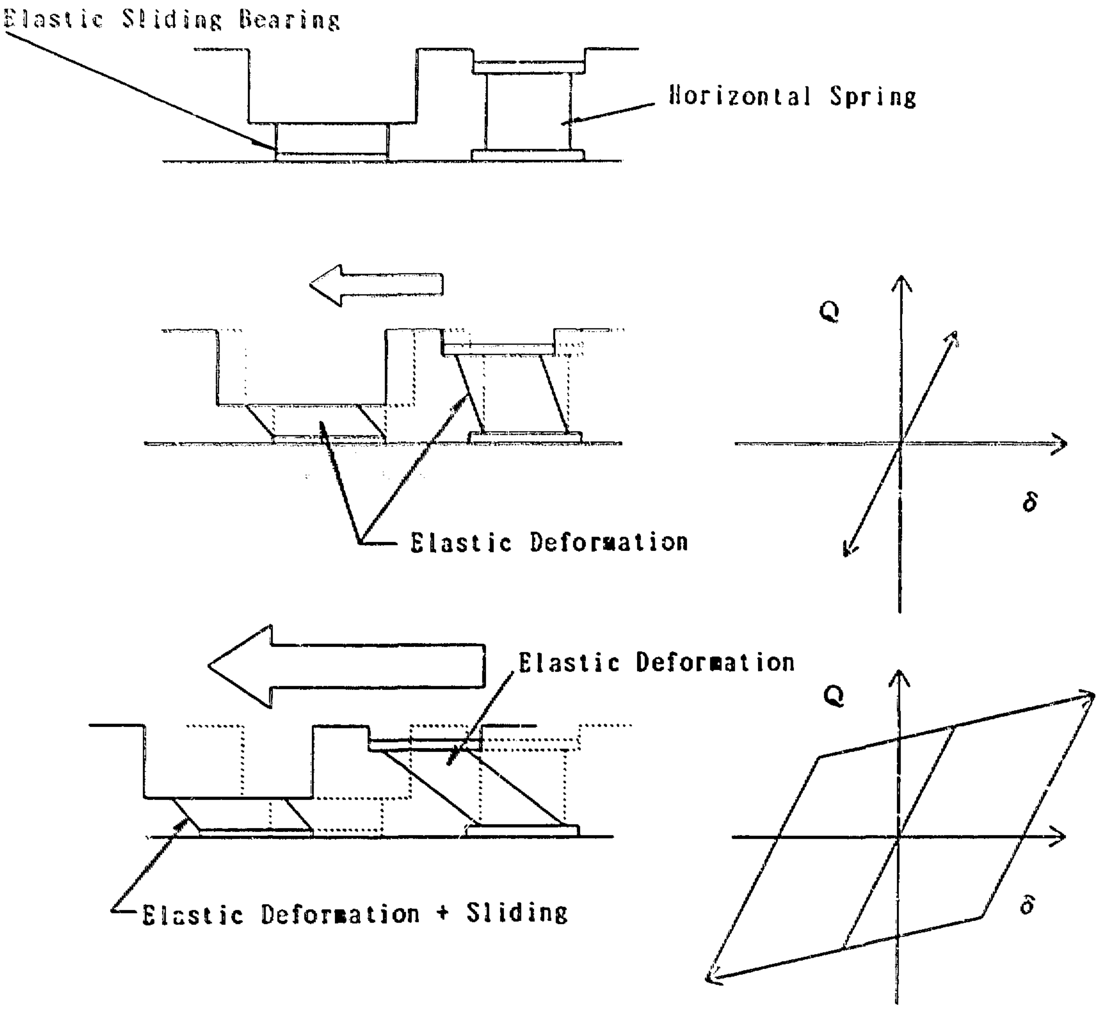


Fig. 22. Concept of System Functions

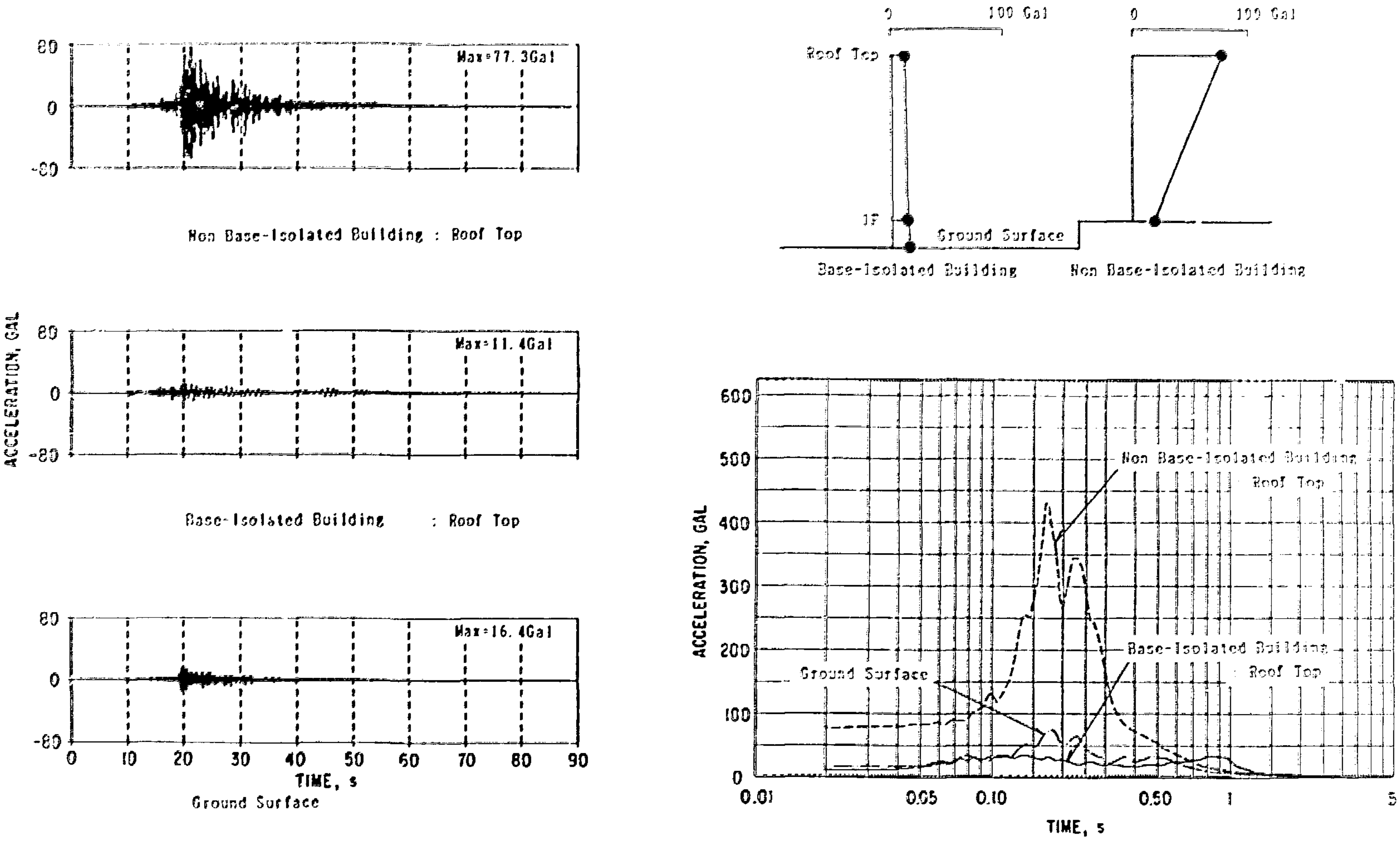


Fig. 23. Earthquake Observation Records (Aug. 12, 1988)