REPORT NO.
UCB/EERC-88/20
DECEMBER 1988

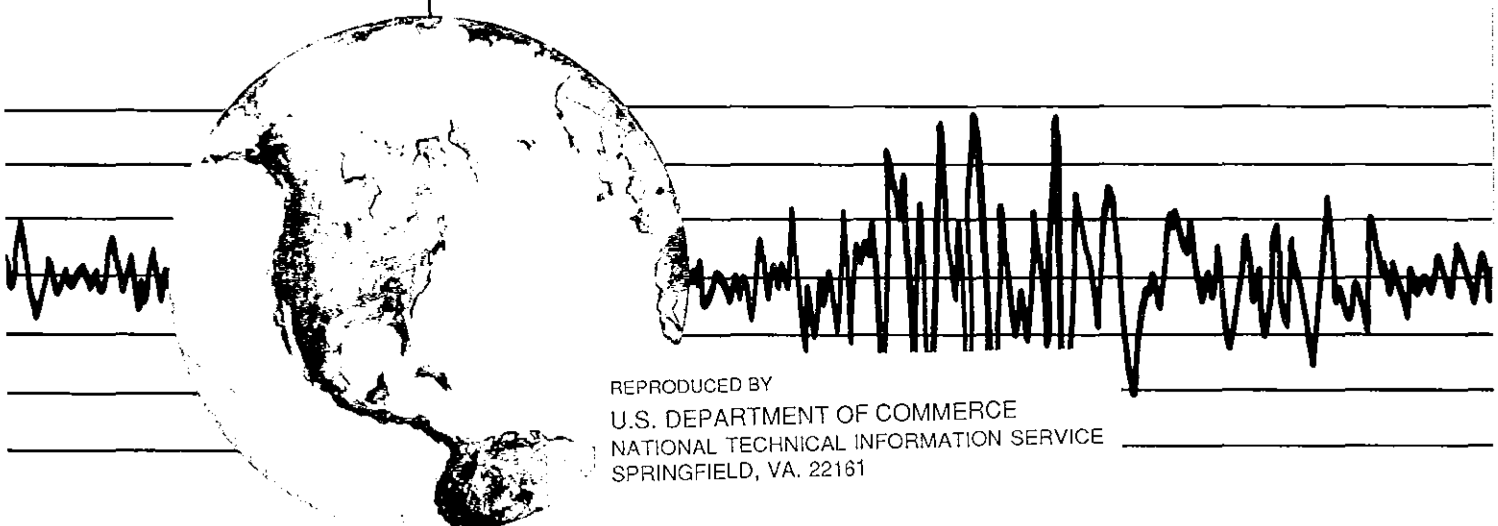
EARTHQUAKE ENGINEERING RESEARCH CENTER

BASE ISOLATION IN JAPAN, 1988

by

JAMES M. KELLY

Report to the National Science Foundation



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15. Supplementary Notes

16. Abstract (Limit: 200 words)

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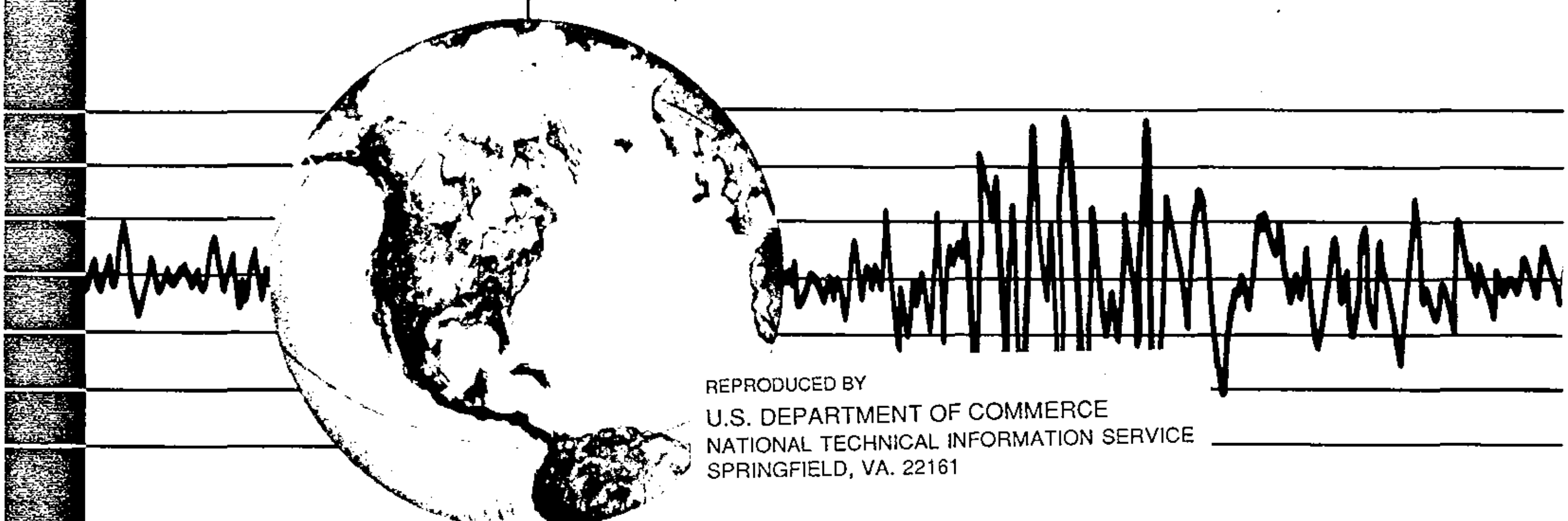

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James M. Kelly
Professor of Civil Engineering
University of California at Berkeley

Report to the National Science Foundation

Report No. UCB/EERC-88/20
Earthquake Engineering Research Center
College of Engineering
University of California, Berkeley

December 1988

ACKNOWLEDGMENTS

This report was prepared by Professor James M. Kelly with assistance from the members of the base isolation study group.

The visit to Japan by the group was supported by the National Science Foundation with grant no. CES-8800434.

PREFACE

Over the past ten years or so, the National Science Foundation has supported fundamental research on base isolation for mitigation of the effects of earthquakes on structures and equipment. The initial research came at a time when interest in the concept of base isolation was growing worldwide. The NSF-sponsored research has led to many developments. Worldwide applications of this technology range from buildings to bridges and include special structures such as nuclear power plants. NSF provided research support which acted as the catalyst that led to the first major implementation of base isolation in the United States at the Foothill Communities Law and Justice Center in San Bernardino County, California.

Since completion of the San Bernardino County building in 1985, many United States researchers have asked why base isolation has not been implemented in the United States at a faster pace. Even though there are currently several base isolation projects underway or in the planning stage in the United States, the response to the above query is that additional research is needed to allow the concept to be implemented in the course of general practice of structural engineering.

NSF has provided the University of California at Berkeley, through the principal investigator Professor James M. Kelly, a grant to develop a coordinated multidisciplinary United States research plan that addresses the issues that are blocks to accelerated implementation of the base isolation concept. The first phase of this plan was to collect the appropriate research data being generated by others and in particular the Japanese. Professor Kelly assembled a team of researchers to go to Japan and determine the state-of-the-research there and then use these data to assist in the preparation of a research plan. Other countries were not visited because most of the team members had first-hand knowledge of research being done in such countries as France, Germany, New Zealand, etc. The results of the research expedition are reported in this document in detail.

The expectation of this research project is the development of a detailed research plan for base isolation research in the United States. This plan will be written such that the research will be goal-oriented and each individual research project will be coordinated with other research projects in the group, allowing a systems approach to the research. As noted previously, completion of the research contained in the overall plan will accelerate the implementation of the base isolation concept in the United States by professionals.

Base isolation has applications not only in California but across the United States. At this time, it appears that the first widespread implementation of base isolation systems will be in California. The reason for this is that the current economics of the base isolation systems are such that in a competitive environment base isolation systems are more appropriate to higher seismic loadings. The past five years have shown that the greatest interest in the subject is in California but applications are also in Utah.

Research issues are broad based and range from properties of basic materials to design methodologies. It is therefore important to involve the appropriate disciplines and interests in any research that is conducted.

Even though the details of the research expedition to Japan are covered in the report that follows, there are several interesting observations that resulted from planning and conducting the research expedition. Initial investigation into who should be contacted in Japan resulted in the conclusion that in Japan, base isolation research is being conducted by the private sector with one general exception. The exception is that the government of Japan is supporting base isolation research in connection with its nuclear program. We concluded that most data would be available from the private sector and we scheduled workshops with them.. We met with research groups in manufacturing that supply base isolation systems, with research groups in the construction industry that carry out base isolation research, and with the research groups that contract research from the government's nuclear program. Most of our time was spent with the research groups in the private sector that support their own research with internal resources. This research is conducted in laboratories associated with the manufacturing and construction companies or research institutes directly connected to these groups.

It is important to contrast this with the method of research support for base isolation systems in the United States. Like Japan, the United States has an effort in base isolation associated with the nuclear program (DOE). The scope of the United States program, however, appears to be smaller than that of the Japanese program. In contrast with the overall Japanese program, the principal means of support for base isolation research in the United States is the National Science Foundation where the level of support is approximately one-half million dollars per year.

It is difficult to determine the size of base isolation research support in Japan. In speaking with the executive of the Japanese "big six" construction companies, however, we determined that the total sales for the six are about 750 to 1,000 billion yen per year per company. Of that amount, approximately one percent is spent on research. Currently, about four percent of the research effort of the six is in the area of base isolation research. This translates to about $14 million to $19 million per year, in contrast with the NSF expenditure of $500,000 per year. In the United States, engineering and construction companies historically allocate between 0.2 and 0.4 percent of sales to research and development with essentially no resources directed toward base isolation research. We therefore noted that the private sector in Japan is giving significant support to base isolation research while the United States private sector is apparently providing little. In addition, the Japanese nuclear industry has a significant and coordinated base isolation research program.

We learned that the Japanese companies view base isolation as an important new element in seismic engineering and earthquake hazard mitigation. This is because Japan is a seismically active area and base isolation is a new and advanced technology that will aid the individual Japanese companies in obtaining or maintaining a competitive edge in their businesses.

It was obvious to the participants that the United States needs to continue research efforts in base isolation in a fashion that will also enable United States engineering and construction companies to maintain or obtain a competitive edge in their businesses. It is unfortunate that the United States has to depend so heavily on NSF and other government agencies for research support in the civil engineering fields. This research effort could be supplemented by additional resources from the United States private sector, providing technological, social, and business benefits to the United States.

The research team would like to acknowledge the able assistance provided by Mr. Alexander DeAngelis and his staff at the NSF Tokyo Office in helping to make this research endeavor possible.

A. J. Eggenberger,
National Science Foundation

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INTRODUCTION

A base isolation study group led by Professor James M. Kelly of the Earthquake Engineering Research Center of the University of California at Berkeley visited Japan between May 24, 1988 and June 5, 1988. The group consisted of the following members:

Dr. A. J. Eggenberger, National Science Foundation

Dr. I. Buckle, Dynamic Isolation Systems

Dr. F. F. Tajirian, Bechtel National Corporation

Professor N. Mostaghel, University of Utah

Professor M. Constantinou, State University of New York at Buffalo

Dr. N. Vaidya, Paul C. Rizzo Associate

Dr. A. T. Onesto, Energy Technology Engineering Center (ETEC)

The purpose of the visit was: (1) to learn of recent developments in base isolation in Japan; (2) to examine the base isolation systems that have been implemented in Japan; (3) to learn of the performance of these buildings in recent earthquakes; (4) to discuss the possibilities for future cooperation between base isolation researchers in Japan and the United States; (5) to understand the reasons for the enthusiastic acceptance and implementation of this technology in Japan; and (6) to ascertain the amount of funding for base isolation research in Japan.

The following sites were visited:

(1) Kajima Corporation Technical Research Institute, Tokyo

(2) Bridgestone Corporation, Tokyo

(3) Oiles Industries and Sumitomo Construction Co., Fujisawa City

(4) Ohsaki Research Institute of Shimizu Construction Co., Tokyo

(5) Ohbayashi-Gumi Corporation, Tokyo

(6) Takenaka Komuten Ltd, Tokyo

(7) Tadotsu Nuclear Power Engineering Test Center (NUPEC), Tadotsu

(8) Mitsubishi Heavy Industries, Takasago

(9) Central Research Institute of the Electric Power Industry (CRIEPI), Tokyo

(10) Taisei Corporation, Tokyo

(11) Okumura Corporation, Tsukuba Science City

(12) Building Research Institute, Ministry of Construction, Tsukuba Science City

(13) Public Works Research Institute, Ministry of Construction, Tsukuba Science City

(14) Tohoku University Experimental Building, Sendai

A copy of the trip itinerary follows, and a summary of the observations of the group at each site is given in the next section. The body of the report presents more detailed analyses of individual base-isolated demonstration buildings and concludes with a summary of what the group was able to determine as the current state of implementation of base isolation for commercial applications.

ITINERARY FOR BASE ISOLATION STUDY GROUP 0523

May 23(Mon)	9:30am	Please assemble in front of United Airlines counter. George Shiobara will meet you here.
	11:15am	Leave San Francisco via UA 819 for Tokyo. Lunch and snack will be served on board. Your flight time is 10 hours and 40 minutes. (Overnight on board)
May 24(Tue)	1:55pm	Arrive at Narita New Tokyo Int'l airport. After Immigration and Custom clearance, you will meet your throughtout guide. He will accompany with you until you leave Tokyo on 6/05. Transfer to hotel by private coach. (Holiday Inn Tokyo)
May 25(Wed)		You have appointment with Kajima Corporation between 9:00am and 2:00pm. Kajima Corporation is located near from Tobitakyu station of Keio Line. You can take Keio Line from Shinjuku station and take 30 minutes from Shinjuku station to Tobitakyu station. From your hotel to Shinjuku station, I would like to suggest that you better to take subway or JR(Japan Rail Line). Because in the morning, surface traffic is very crowdy. If you take a taxi from your hotel to Shinjuku station, you need one hour or more and much expense. This is wasting time and money. Please ask your throughout guide about a measure to Shinjuku.
	9:00am	Visit Kajima Corporation including luncheon until 2:00pm.
	2:00pm	Leave Kajima Corporation for Bridgestone Corporation. From Kajima to Bridgestone, you have to take a rail way but you have to change 2 or 3 times. Please have your guide check how you can go to Bridgestone from Kajima.
	3:00pm	Visit Bridgestone including dinner until 7:00pm.
	7:00pm	Leave Bridgestone for your hotel. * You will take Rail way and Subway few times. I guess you need approximately YEN 1,200 ($ 10) for your transportation per person. While you stay in Japan, please always provide small money for example 1,000 YEN bill or coin. Casher in your hotel will help your exchange anytime. When you purchase ticket for train and subway, drink, cigarete and phone, all items are sold by vending machine and you need coin or 1,000 YEN bill. Purchase by 5,000 YEN and 10,000 YEN bill by vending machine is not available. (Holiday Inn Tokyo)

May 26(Thu)	9:00am	You have appointment with Oilers Technical Center whic is located at Fujisawa. Please leave your hotel for Tokyo station before 7:30am. You can go to Tokyo station on your foot by 15 minutes. Please take a Tokaido Line of JR to Fujisawa. All train bound for Tokyo is very crowdy between 6:30am and 8:30 am, but bound for Yokohama and Fujisawa is no probem. I guarantee you can teke a seat.
	2:00pm	Leave Oilers Technical Center for your hotel by Tokaido Line.
	4:30pm	Leave your hotel for Shimizu Construction by subway. Approximately 10 minutes to Hibiya station by subway.
	5:00pm	Visit Shimizu Construction (Dr.Ohashi's office) until 8:00pm including dinner.
	8:00pm	Leave Shimizu Construction for your hotel. (Holiday Inn Tokyo) I guess you need approximately YEN 2,000 per person for your transportation.
May 27(Fri)		You have appointment with Obayashi Gumi at 9:00am. You have to go to Ikebukuro station by JR or subway then you take Seibu Ikebukuro Line to Kiyose station. Please leave your hotel before 7:30am.
	9:00am	Visit Obayashi Gumi until 12:30pm including snack lunch.
	12:30pm	Leave Obayashi Gumi for Takenaka Komuten. On the way to Takenaka, you have to change 3 times. Please have your guide check how you can go.
	2:30pm	Visit Takenaka Komuten until 5:30pm.
	5:30pm	Leave Takenaka Komuten for your hotel. (Holiday Inn Tokyo) I guess you need approximately YEN 1,500 per person for your transportation.
May 28(Sat)	8:00am	Leave hotel for Tokyo station by private car. Please leave your large baggage at Holiday Inn.
	9:44am	Depart Tokyo station for Kyoto by bullet train "Hikari 345" 2nd class.
	12:32pm	Arrive at Kytoto station. On arrival, proceed to half day Kyoto sightseeing by private coach with your guide. Terminate at hotel. (Holiday Inn Kyoto) Foy your lunch, You have no time to take a lunch at Kyoto. I would like to suggest you purchase box lunch at Tokyo station before you depart and take it on board. Various box lunch are available on the platform of your train (Hikari 345) at Tokyo station.
May 29(Sun)		Full day Nara sightseeing tour by private coach with your guide. Please talk with your guide regarding your departure time and lunch. (Holiday Inn Kyoto)

May 30(Mon)	8:00am	Leave your hotel by private coach for Kyoto station.
	8:53am	Leave Kyoto for Okayama by bullet train "Hikari 211".
	10:22am	Arrive Okayama.
	10:39am	Leave Okayama for Sakaide by JR train.
	11:20am	Arrive Sakaide.
	11:30am	Leave Sakaide for Tadotsu by JR train.
	11:43am	Arrive Tadotsu.
	1:00pm	Visit Nuclear Power Engineering Test Center until 4:00pm.
	4:39pm	Leave Tadotsu for Takamatsu by JR train.
	5:11pm	Arrive Takamatsu. Then transfer to your hotel by private coach. (Takamatsu Washington Hotel)
May 31(Tue)	9:00am	Leave hotel for Takamatsu station by private coach.
	9:56am	Leave Takamatsu for Okayama via Sakaide by JR train.
	10:12am	Arrive Sakaide.
	10:54am	Arrive Okayama.
	11:02am	Leave Okayama for Himeji by bullet train "Hikari 266"
	11:27am	Arrive Himeji and change to Sanyo Dentetsu line for Takasago.
	12:00pm	Arrive Takasago.
	12:00pm	Visit Mitsubishi Heavy Industries until pm including luncheon.
	3:27pm	Leave Himeji for Tokyo by bullet train "Hikari 268" * You have to leave Takasago for Himeji in time to connect with Hikari 268.
	7:08pm	Arrive Tokyo. Transfer to your hotel by private coach. (Holiday Inn Tokyo)
Jun 01(Wed)	9:00am	Leave hotel for Central Research Inst by subway.
	9:30am	Visit Central Research Inst of Electric Power Ind.
	1:00pm	Leave Tokyo station for Higashitotsuka station by Yokosuka JR Yokosuka Line.
	2:30pm	Visit Taisei Corporation until 4:30pm After visit, return to your hotel. (Holiday Inn Tokyo) I guess you need approximately YEN 1,500 per person for your transportation.
Jun 02(Thu)	8:30am	Leave your hotel by private coach for Tsukuba Science City.
	10:00am	Visit Okumura Gumi until 2:00pm
	2:30pm	Visit Building Research Institute, Ministry of Construction until 4:00pm.
	4:00pm	Leave Tsukuba for Tokyo by private coach. (Holiday Inn Tokyo)
Jun 03(Fri)	8:30am	Leave hotel for Ueno station by private coach.
	9:44am	Leave Ueno station for Sendai by bullet train "Yamabiko 13"
	11:34am	Arrive Sendai. Then Shimizu Construction in Tohoku University Campus by private coach.
	1:00pm	Visit Shimizu Construction Co until 3:00pm.
	3:00pm	Leave Campus and transfer to your hotel. (Sendai Plaza Hotel) Sendai is small but nice city. I hope you enjoy your stay in Sendai. After your visit in Sendai, still you have enough time. Lets go out from hotel until become dark.

Nippon Express Travel U.S.A., Inc.

Jun 04(Sat)		Free until departure.
	1:00pm	Leave Hotel for Sendai station by private coach.
	2:00pm	Leave Sendai for Tokyo(Ueno) by bullet train "Yamabiko 116"
	4:00pm	Arrive Ueno station. Then transfer to your hotel by private coach. (Holiday Inn Tokyo)
Jun 05(Sun)		Free until departure
	1:00pm	Leave hotel for Narita Int'l airport by private coach.
	3:40pm	Leave Tokyo for San Francisco by UA 820. Dinner and snack will served on board.
	8:55am	Arrive San Francisco.

* On Jun 5th, pleas provide YEN 2,000 per person at Narita Int'l airport. (Narita New Tokyo Int'l airport facilities user fee)
  Your throughout guide will say good by for you at Passport Control of Narita.

In case of emergency :	Ambulance and Fire	Call 109
	Police	Call 110
	If you lost your way	Find police box around you.
	NSF TOKYO	224-5505
	Nippon Express Tokyo	542-2801 Mr.Nakamura is person in charge of your group.

OBSERVATIONS AT SITES VISITED

1. Kajima Corporation Technical Research Institute, Tokyo

The visit to Kajima included a tour of the base-isolated acoustic laboratory building and the large earthquake testing facilities which include bearing test machines, a large shaking table and a large reaction wall. The Kajima isolation system consists of (unfilled) steel laminated elastomeric bearings with steel bars to provide damping. The bearings are designed to be more flexible in the vertical direction than other systems used in Japan. The vertical isolation frequency for the Kajima system is 5 Hz. This low frequency is intended to provide isolation from earthquakes as well as microtremors and ambient ground vibrations. The effectiveness of the system during both earthquakes and other ground vibrations has been demonstrated in the acoustic laboratory building, built in 1986 and consisting of a 2-story reinforced concrete building supported on 18 bearings. Damping is provided by 14 round steel bars. In addition, oil dampers are used to reduce vertical and rocking motions during earthquakes. To date, Kajima has designed three buildings on seismic isolation, the largest of which is ten stories high. Kajima is also marketing computer floor isolation systems which consist of rollers combined with rubber stoppers to limit excessive displacements. The rollers roll in dishes with prescribed curvatures. In the event of an earthquake the floor would slide within the confines of the dish periphery and return to its original position by the action of its own weight.

Kajima's large bearing testing machine, completed in 1988, is unique. It is a tri-axial machine capable of applying dynamic horizontal load along two perpendicular axes in real time while simultaneously maintaining a vertical load on the bearing. The same laboratory also houses a 4 m x 4 m shaking table with 5 controlled degrees of freedom and a maximum payload capacity of 20 tonnes. The maximum horizontal acceleration that can be applied at full payload is 1.2g and the frequency range is 0—30 Hz. A 12 m reaction wall equipped with 24 hydraulic actuators for pseudodynamic testing of large panel elements is housed in the same facility.

Kajima is also involved in the MITI/CRIEPI program (see Site 9 below) for liquid metal fast breeder reactors (LMFBR). They are currently testing high-damping rubber bearings in conjunction with Bridgestone. The results have been very encouraging. Kajima feels that when high-damping rubber bearings are used the need for additional damping devices such as the steel bars that are currently used will be eliminated.

2. Bridgestone Corporation, Tokyo

Bridgestone is a major tire manufacturer as well as the leading elastomeric bearing manufacturer in Japan. Bridgestone's annual budget for base isolation research is $800,000. Bearings of various sizes and load capacities are manufactured, ranging to a maximum load of 600 tonnes. Most sizes are standardized and are available as shelf items. They are made of low-damping (about 3%) natural rubber with a durometer hardness of 40. Because of the low inherent damping in the bearings additional damping devices are required in actual applications. The useful life of these bearings has been estimated by the Japan Building Center to be about 30 years. In Japanese specifications bearings are required to be replaced if their mechanical properties change by more than 20%.

The bearings are usually rigidly bolted to the foundation and the superstructure rather than dowelled — the currently preferred connection detail in the United States. Tests have shown that bolting increases the stability of the bearings at large horizontal displacements without causing excessive tensile stresses in the rubber. Special details, such as rounding of the steel shim edges, are specified to reduce stress concentrations. The bearings are designed to carry an average pressure of less than 1000 psi and to have a vertical-to-horizontal stiffness ratio of about 1600. Bridgestone also manufactures floor isolation systems that consist of stacks of miniature bearings with load capacities between 1 and 4 tonnes bolted to interleaving metal plates.

Recent developments in bearing design and newly developed high-damping elastomers were described. In 1988, Bridgestone began to market a steel-laminated elastomeric bearing with high damping. These bearings have damping values which exceed the damping of the bearings which were manufactured by LTV Oilstates of Texas for the Foothill Communities Law and Justice Center in California (the first base-isolated building in the United States). In general the bearings are manufactured to much higher standards than those in the United States. This results in the cost of the Bridgestone bearings being about ten times higher than for comparable U.S. bearings. The study group toured the Bridgestone testing facilities and witnessed a dynamic test of a small bearing (their large bearing test machine is at another site). Much research and development

(R&D) effort is devoted to demonstrating the long life expectancy of their new bearings (60 years) using analytical and accelerated experimental testing techniques.

3. Oiles Industries Co., Ltd, Technical Research Laboratory and Sumitomo Construction Co., Fujisawa City

The Oiles technical building, the fourth isolated structure built in Japan, was constructed by Sumitomo and completed in February 1987. The 5-story office building is supported on 30 piles 15 m long. The isolation system consists of 35 lead-rubber bearings. Oiles has a license from New Zealand to manufacture this type of bearing in Japan. Oiles prefers to use dowel type connections. Oiles also markets computer floor isolation systems which consist of sliding bearings with steel springs to provide a restoring force. Sumitomo is currently constructing two buildings on seismic isolation, including a 10-story reinforced concrete office structure. Its system is currently being marketed in the United States. Sumitomo is also involved in the development of passive control systems to enhance the damping in buildings using friction devices.

4. Ohsaki Research Institute, Tokyo

This institute is one of the Shimizu Construction Company's two research facilities. The study group visited its Ginza office in Tokyo where extensive research in earthquake engineering is performed. A video of the work conducted at the institute was shown. Several advanced soil-structure-interaction analysis programs have been developed at the institute and are being verified using experimental data. The institute is also involved in base isolation research. Its annual budget in this area is about $1.6 million. Shimizu constructed the testing facility at Tohoku University in Sendai at a cost of $1 million (see Site 14 below).

5. Ohbayashi-Gumi Corporation, Tokyo

The first isolated structure built by Ohbayashi-Gumi was a "high-tech" research and development center at the company's technical research site. The building is a 5-story reinforced concrete building with a total floor area of 1620 m^2 and a height of 22 m supported on 14 elastomeric bearings. Damping is provided by 96 steel bars. Ohbayashi invests about $1.3 million annually on base isolation research. To date Ohbayashi has designed and started construction on three other buildings, including an 8-story office building. Ohbayashi is currently testing high-damping rubber bearings and lead-filled rubber bearings. The study group toured their extensive testing facilities, and at the same site two large scale-model base-isolated test buildings were examined. The first is a concrete box-like structure, 6 m x 9 m in plan supported on four high-damping rubber bearings which are soft vertically (5 Hz vertical frequency). Tests are underway to demonstrate the vibration isolation capabilities of this system. These bearings were purchased from the United States through Base Isolation Consultants (BIC) of San Francisco. The other model consists of two identical structures, one conventionally founded on a fixed foundation and the other isolated. The superstructure consists of 4 steel columns supporting a 2-tonne concrete block. The isolation system consists of 4 rubber bearings and 4 steel dampers. Both structures are instrumented so that observations and comparisons of the performance of the two can be made during real earthquake motions.

6. Takenaka Komuten Ltd, Tokyo

The Funabashi Chikuyuryo Company dormitory in Chiba, built by Takenaka Komuten in 1986, is a 3-story reinforced concrete structure and is supported on 14 elastomeric bearings ($11,000 each) and 8 viscous dampers ($6000 each) The bearings are unique in that they were designed for 300% maximum shear strain and are bolted to the foundation and superstructure. The viscous dampers are very effective during microtremors. Takenaka is also developing an isolation system capable of supporting a 150-tonne load with a horizontal frequency of 0.2 Hz. Company engineers presented Takenaka's program on commercial developments in base isolation.

7. Nuclear Power Engineering Test Center, Tadotsu

The shaking table of the Nuclear Power Engineering Test Center (NUPEC) at Tadotsu is the largest such facility in the world. It was completed in 1982 at a cost of 30 billion yen (approximately $230 million), with a yearly operating budget of about 1 billion yen (approximately $8 million).

The table is 15 m x 15 m x 3.5 m in size and has a payload capacity of 1000 tonnes. Maximum horizontal accelerations of 1.84g and maximum vertical accelerations of 0.92g can be applied. The performance characteristics of the table are as follows:

Weight of Table	420 tonnes
Maximum Payload	1000 tonnes
Maximum Stroke	±20 cm horiz., ±10 cm vert.
Maximum Velocity	±75 cm/sec horiz., ±37.5 cm/sec vert.
Maximum Acceleration (at 500 tonnes load)	2.72g horiz., 1.36g vert.
Degrees of Freedom	1 horizontal, 1 vertical
Actuators	7 horiz. each ±450 tonnes, 12 vert. each ±300 tonnes
Frequency Range	0-30 Hz
Duration of Excitation	20 sec at maximum velocity
Hydraulic Power Supply	11—1080 lpm at 2100 N/cm^2 (2980 psi)
Data Acquisition	300 channels
Foundation	45 m x 90 m x 21 m, 150,000 tonnes

The table has been used to test several large-scale nuclear components for light water reactors. Scale factors ranged from 1 to 3.7 with model weights from 290 to 750 tonnes. The Tadotsu table will be used in the early 1990s to perform large-scale tests on a seismically isolated Liquid Metal Fast Breeder Reactor (LMFBR) as part of the MITI/CRIEPI research program (see Site 9 below).

At the Tadotsu site, NUPEC is constructing a large scale soil-structure- interaction (SSI) test facility at a cost of $25 million to $50 million. Large-scale nuclear building models will be excited by large dynamic actuators. The purpose of these tests is to verify the seismic stability of nuclear power plants located on softer quaternary rocks and to verify methodologies for SSI analysis. The objective of this program is to increase the number of sites available in Japan where nuclear plants could be located. It is currently required that Japanese nuclear plants be founded directly on stiff bedrock.

8. Mitsubishi Heavy Industries, Takasago

The earthquake testing facility of Mitsubishi Heavy Industries (MHI) includes a large shaking table and a large bearing test machine. MHI's main interest in base isolation is in its applicability to nuclear plants, specifically LMFBRs. MHI recently completed tests sponsored jointly by CRIEPI and EPRI (Electric Power Research Institute, California, U.S.A.) to examine the behavior of 1/4-scale elastomeric bearings with lead plugs. Significant shaking table tests performed at the facility included a 1/3-scale turbine model supported on a three-dimensional isolation system consisting of GERB type helical steel springs and viscous dampers. MHI is currently doing tests for the MITI/CRIEPI program.

9. Central Research Institute of the Electric Power Industry, Tokyo

The main purpose of visiting the Central Research Institute of the Electric Power Industry (CRIEPI) was to learn about its seven-year, $50 million MITI-sponsored program for qualifying a seismic isolation system for the LMFBR. This program is now in its second year and will run through 1992. The decision of whether to use seismic isolation in the demonstration FBR (DFBR1) will be made in 1989. Hitachi and Kajima have been selected by CRIEPI to lead the seismic isolation program. Other reactor manufacturers and construction companies are also participating in the program. The main objectives of the program include the selection of the most suitable seismic isolation devices, performing large-scale tests on the selected isolators, identifying the effects of long-period motions on isolated power plants, and performing large-scale shaking table tests at Tadotsu (these are planned for the early 1990s). The program also includes the construction of a large-scale isolated nuclear building model and observation of its response during actual earthquakes. Construction of the building model is set for 1990. The program will result in design guidelines for the seismic isolation of nuclear buildings. It will also evaluate cost savings when base isolation is used, the licensing of seismic isolation, maintenance requirements and other technical uncertainties. The two main candidates for horizontal isolation devices are high-damping elastomeric bearings and elastomeric bearings with lead plugs. Methods for vertical isolation are also being investigated. As part of this program CRIEPI is collaborating with the Okumura Corporation in monitoring the response of a demonstration isolation building in Tsukuba Science City (see Site 11 below).

10. Taisei Corporation, Tokyo

Taisei Corporation is marketing a sliding type isolation system which consists of elastic sliding bearings (the sliding surface is bonded to an elastomeric bearing) and neoprene bearings to provide the restoring force. This is known as the TASS system. It is the only sliding system currently marketed for the seismic isolation of buildings in Japan. Sliding type isolation systems have been used more extensively for the isolation of computer floors and equipment. A building currently under construction was examined. The building weighs 2200 tonnes and is supported on 8 sliding bearings with 8 neoprene bearings to provide the restoring force. The friction coefficient of the sliding interface is 0.1.

Taisei has implemented an isolation system for equipment in a radar tower at Narita airport. The isolated structure is 5 m x 5 m in plan and weighs 10 tonnes. The isolation system consists of 8 roller bearings and 8 steel plates acting as horizontal restoring springs. The system is designed for a maximum horizontal displacement of 20 cm and maximum acceleration of 0.35g.

Taisei verified the characteristics of the TASS system using the company shaking table, a three-degree-of-freedom 4 m x 4 m table with a maximum load capacity of 20 tonnes.

11. Okumura Corporation, Tsukuba Science City

The Okumura isolated building visited is located in Tsukuba Science City. It is a 4-story reinforced concrete building supported on 25 unfilled rubber bearings. Damping is provided by 12 looped steel bar dampers. The bearings were manufactured by Showa-Densen-Denran. The steel bars were designed to remain elastic up to 30 mm horizontal displacement. To enhance damping at low strains (before yielding of the steel), unconfined lead plugs were added to the steel bar mechanism. CRIEPI has sponsored a program to test the building using roof-mounted dynamic shakers and snap-back free vibration tests. This building has experienced several earthquakes. The largest acceleration measured at the base was 0.2g resulting from an earthquake with a magnitude of 5.1 and an epicenter 5 km from the building. The accelerations in the building were reduced to less than 0.02g. In addition Okumura has built two other structures, a 3-story and a 4-story apartment house. Okumura is currently testing high-damping rubber bearings in their large bearing dynamic test machine. Okumura is also interested in using high-damping rubber bearings in lieu of the steel dampers.

12. Building Research Institute, Ministry of Construction, Tsukuba Science City

The Building Research Institute (BRI) is conducting research in seismic isolation and is involved in the approval process for base-isolated buildings. An overview of the status of the implementation of base isolation in Japan and the review process followed by the Ministry of Construction for issuing building permits for base-isolated structures was presented by institute personnel.

In addition to base isolation BRI is interested in the development of passive and active control systems for the seismic protection of building structures. Passive control systems include friction and viscous dampers which, when incorporated in a building, will significantly enhance damping during earthquakes. One system currently being tested jointly with Sumitomo-Kensetsu and which is co-sponsored by BRI and the Japan Association of Building Research Promotion is a viscous damped wall. Such a system has been incorporated in a test structure 8 m x 4 m in plan and 11 m in height. The walls are hollow steel tubes filled with a viscous fluid and a steel plate which is embedded in the fluid. The motion of the plate during earthquakes is resisted by the viscous fluid and provides damping of about 10 percent. The walls extend the full height of the structure and are 20 cm x 240 cm in the long direction of the test structure and 20 cm x 140 cm in the short direction. The structure and surrounding area is instrumented to measure the response during earthquakes. Five earthquake motions have been recorded since completion of the structure in 1987. The strongest occurred in December 1987 with a peak horizontal acceleration of 0.086g at the foundation level and 0.22g on the roof. The effective damping of the structure was estimated to be 11.3 percent. Numerical analysis showed that without the viscous dampers the roof accelerations would have been about 0.85g.

The BRI testing laboratory includes a massive 25 m high reaction wall. Pseudo-dynamic tests on a full-scale 5-story reinforced masonry building were recently performed to failure. The tests were part of the U.S.-Japan research program on masonry structures.

13. Public Works Research Institute, Ministry of Construction, Tsukuba Science City

The Public Works Research Institute (PWRI) carries out research in all areas related to public works undertaken by the Ministry of Construction. PWRI's interest in base isolation is in the applicability of the concept to bridge structures. Currently there are no base isolated bridges in Japan, but there are plans to construct as many as ten isolated bridges by the end of 1989.

PWRI has performed shaking table tests on bridges at its facilities. Lead-rubber bearings and high-damping rubber bearings have been tested. Bearing tests showed that the equivalent damping in the lead-rubber bearings ranged from 0.15 to 0.20 and the corresponding range for the high-damping rubber bearings was 0.10 to 0.16.

14. Tohoku University Experimental Building, Sendai

Tohoku University and Shimizu have constructed two identical full-sized 3-story reinforced concrete buildings on adjacent sites. One is a conventional building and the other is base-isolated; the dimensions of and construction techniques used for the two superstructures are identical. The original isolation system consisted of 6 laminated rubber bearings and 12 oil dampers. Static and dynamic loading tests were performed on the isolated building to verify its dynamic characteristics. A total of 18 earthquakes has been recorded in the buildings. The largest measured acceleration was 0.04g. In all cases the conventional building amplified the base motions so that the roof accelerations were several times greater than those at the base, while for the isolated building the accelerations were reduced and the building responded as a rigid structure with minimum acceleration amplification between the base and the roof. The original isolation system has since been replaced with high damping elastomeric bearings and the structure is monitored to observe its response to actual earthquake motions.

IMPLEMENTATION OF BASE ISOLATION IN JAPAN

Active development of base isolation began in the United States in the mid 1970s. Experimental research was carried out at the Earthquake Simulator Laboratory of the Earthquake Engineering Research Center (EERC) of the University of California at Berkeley. Several types of isolation systems were studied using very large structural models representing low- and medium-rise steel frames or reinforced concrete buildings. This research at EERC led to further experimental work at other American institutes. Acceptance of this new seismic design approach has, however, been slow. The first base-isolated building in the United States, the Foothill Communities Law and Justice Center in San Bernardino County, was completed in December 1985, and another in Salt Lake City, Utah was completed in late 1988.

In contrast, base isolation research and development was slow to start in Japan, but since the first large base-isolated building was completed in 1986 the use of base isolation has increased very rapidly. There are now (late 1988) seventeen base-isolated buildings either completed or under construction and many others in the design phase or undergoing analysis.

In Japan the large construction companies have taken the leading role in developing base isolation technology. These companies have decided that base isolation is superior to conventional seismic design and can provide a competitive edge in the construction industry. They are therefore aggressively marketing the technology to potential clients. The first buildings on base isolation were, accordingly, demonstration projects with the construction companies building them for their own use. More recent projects have been for a variety of clients and have included office buildings, manufacturing facilities, and apartment blocks.

The most common form of base isolation used in Japan is steel-laminated natural rubber bearings with additional devices to enhance the damping in the system. The rubber compounds used have very low intrinsic damping and the additional elements, such as steel rods, viscous dampers, hydraulic shock absorbers, and lead plugs, among others, have been used to produce the necessary damping in the system. In a way these designs mirror the research history in the United States where in extensive shaking table testing many energy-absorbing mechanisms were tried in parallel with the rubber bearings. As the experimental research progressed over a period of ten years, the various additional dampers were shown to be unnecessary, inconvenient and sometimes deleterious and the damping was incorporated in the elastomer itself through appropriate compounding. The high-damping natural rubber isolation system used in the San Bernardino building evolved from this research program. Recently Bridgestone Corporation developed a natural rubber with high damping and several of the construction companies in Japan are evaluating this approach. These isolators have been installed in one demonstration building as described below.

DEMONSTRATION BUILDINGS ON BASE ISOLATION SYSTEMS

There is a long history of innovative earthquake-resistant design in Japan. Many ingenious devices and structural systems have been proposed and some implemented. A review of these unconventional approaches has been given by Izumi [1]. None of these has achieved enough acceptance by the structural engineering profession in Japan to achieve widespread use.

The acceptance of base isolation as an earthquake-resistant design strategy has also been very slow in Japan although proposals for its use were made in the late seventies. A construction company called Unitika advertised a natural rubber isolation system called the Yurine bearing in 1978 but no use was made of the technique.

The first isolated building in Japan was built in 1982. It is a small two-story house built on six natural rubber bearings produced by Bridgestone Corporation. The building was constructed by Tokyo Kenchiku Structural Engineers and research on its seismic response has been carried out by faculty at Fukuoka University. Details of the structure, the isolation system, and a bearing under test are shown in Figures 1 through 4. It is approximately 10 m by 5 m in plan and was constructed in a conventional way so as to allow its use as housing. It is located in Yachiyo City in Chiba Prefecture, an area that experiences relatively frequent earthquakes. In fact within three years seventeen earthquakes were recorded on the system of strong motion accelerographs installed in the building.

The rubber bearings used in this building are 30 cm in diameter and 8.2 cm high. The elastomer is a relatively unfilled natural rubber providing a natural period of approximately 1.8 seconds and damping of approximately 3%. A variety of different types of additional damping components was investigated in the building including an elasto-plastic type using a cantilevered steel rod, a sand type using friction between a steel rod and sand, a frictional type and a damper using precast concrete plates that rub against the side of the building. The damper with the most satisfactory performance in forced-vibration and free-vibration tests was the elasto-plastic damper; this provided an equivalent damping of around 20% for the system.

Observations of the earthquake response of the building over a three-year period after completion and installation of the seismometers reported by Tada *et al.* [2] have

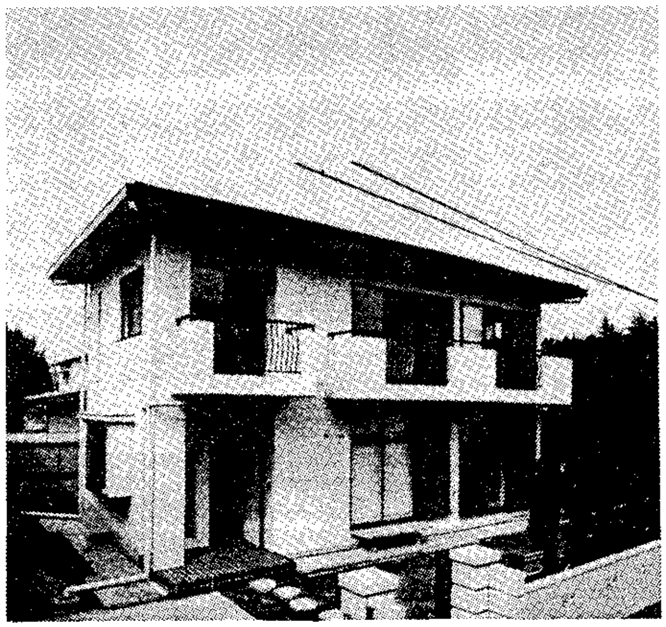


Figure 1 Base-Isolated Dwelling in Yachiyo City

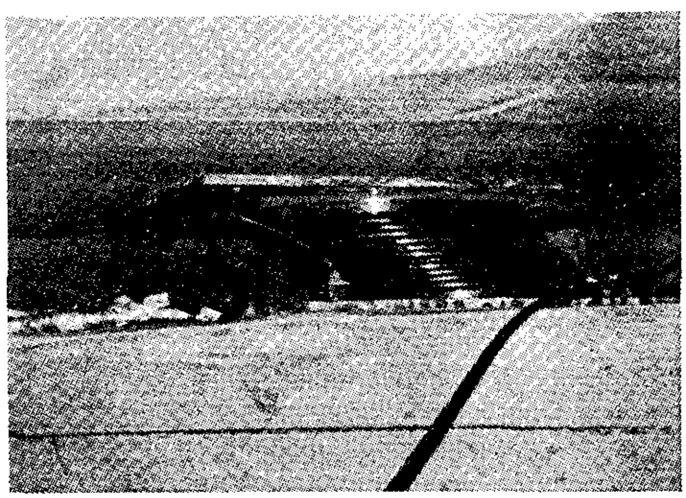


Figure 2 Deformation of Isolation Bearing in Pull-Back Test of Building

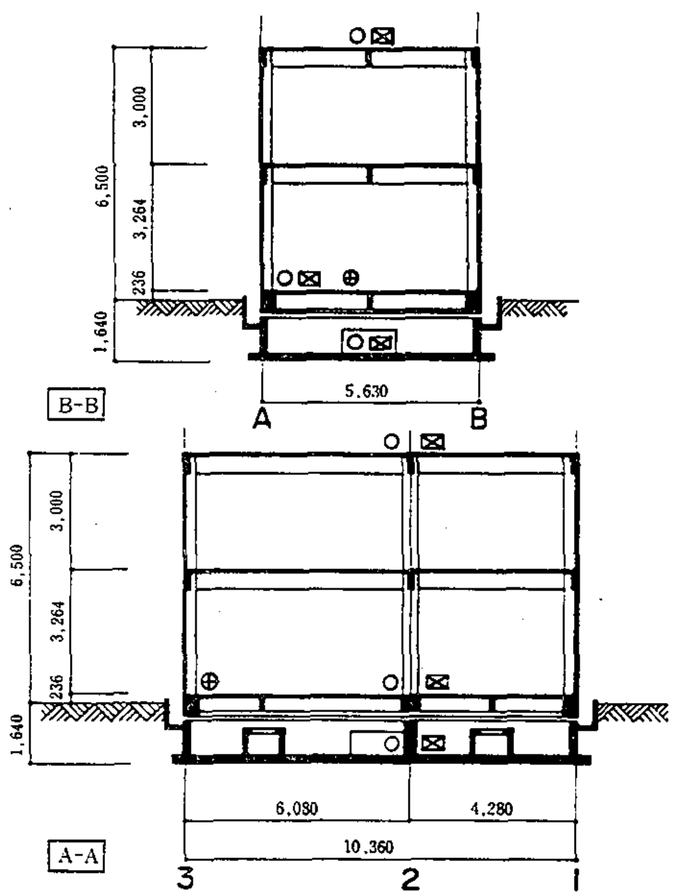


Figure 3 Cross Sections of Building

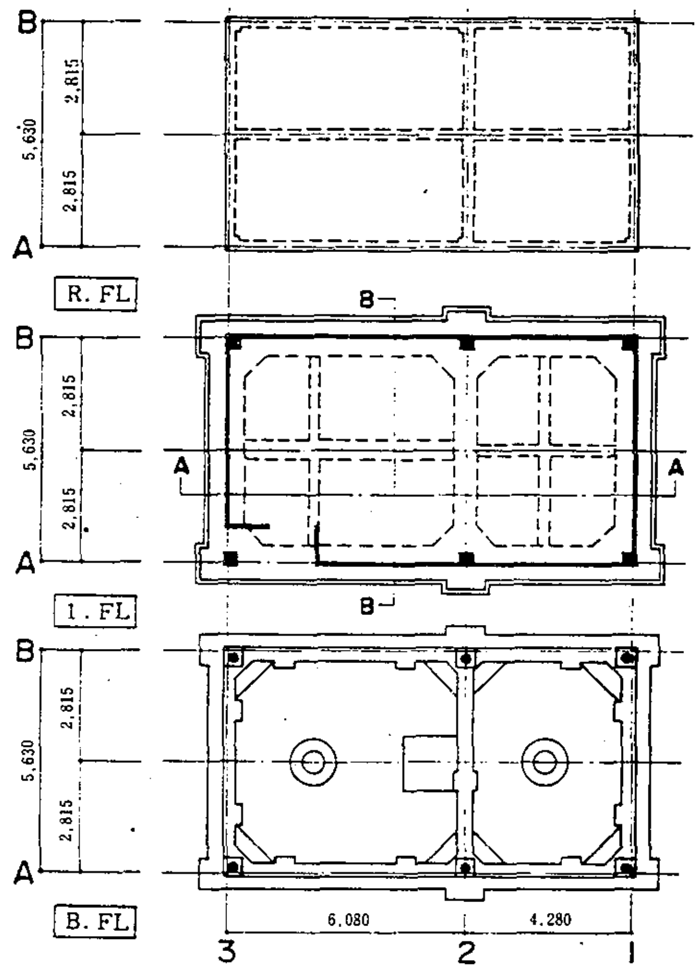


Figure 4 Building Plan and Bearing Layout

been highly favorable although the ground motions experienced have in most cases been quite small. The roof accelerations have always been less than the ground accelerations, sometimes dramatically so, and as expected the acceleration reduction ratio increases with increasing ground motion. The highest recorded input during the initial monitoring period occurred in late 1985 when a peak ground motion of 10.2%g produced a peak roof acceleration of 2.4%g. A summary of the recorded data is shown in Figure 5. The observation program is continuing and in December 1987 an earthquake with a ground motion of 13.1%g was recorded. The maximum roof acceleration in this case was only 3.5%g, demonstrating the remarkable attenuation of the isolation system.

Almost certainly as a result of the entirely favorable response of the building in Yachiyo City a number of much larger buildings using base isolation were constructed in Japan with many being completed in late 1986 and 1987. In almost every case these buildings were designed and built by construction companies as demonstration buildings and are used by the companies as offices and laboratories. These buildings were built to test the feasibility of the isolation systems, to observe their responses to earthquakes and to demonstrate the technology to potential clients.

The first of these larger buildings to be completed was the Okumura Construction Co. Technical Center in Tsukuba City, Ibaraki Prefecture. The building is a four-story reinforced concrete building 20 m in length and 15 m wide by 14 m high. The isolation system is comprised of natural rubber bearings, provided by Showa-Densen-Denran, and a number of steel elasto-plastic coil type dampers similar to those used in the Yachiyo City house. Photographs of the building bearings and the dampers are shown in Figures 6 through 10. The bearings are 500 mm in diameter by 140 mm high and 25 are used in the building. Twelve of the steel dampers are included in the system.

The building is used as an office building for the Okumura Corporation Research Institute. It has a total floor area of 1330 m^2 and a total weight of 2250 tonnes. A test program on the building has been carried out jointly by the Okumura Corporation and the Central Research Institute of the Electric Power Industry (CRIEPI). Static tests on the elements and the building and forced- and free-vibration tests on the building were carried out. The building was extensively instrumented with seismometers and its response to earthquakes has been observed as part of this experimental program. The results of the various studies have been reported by Abe et al. [3] and Aoyagi et al. [4].

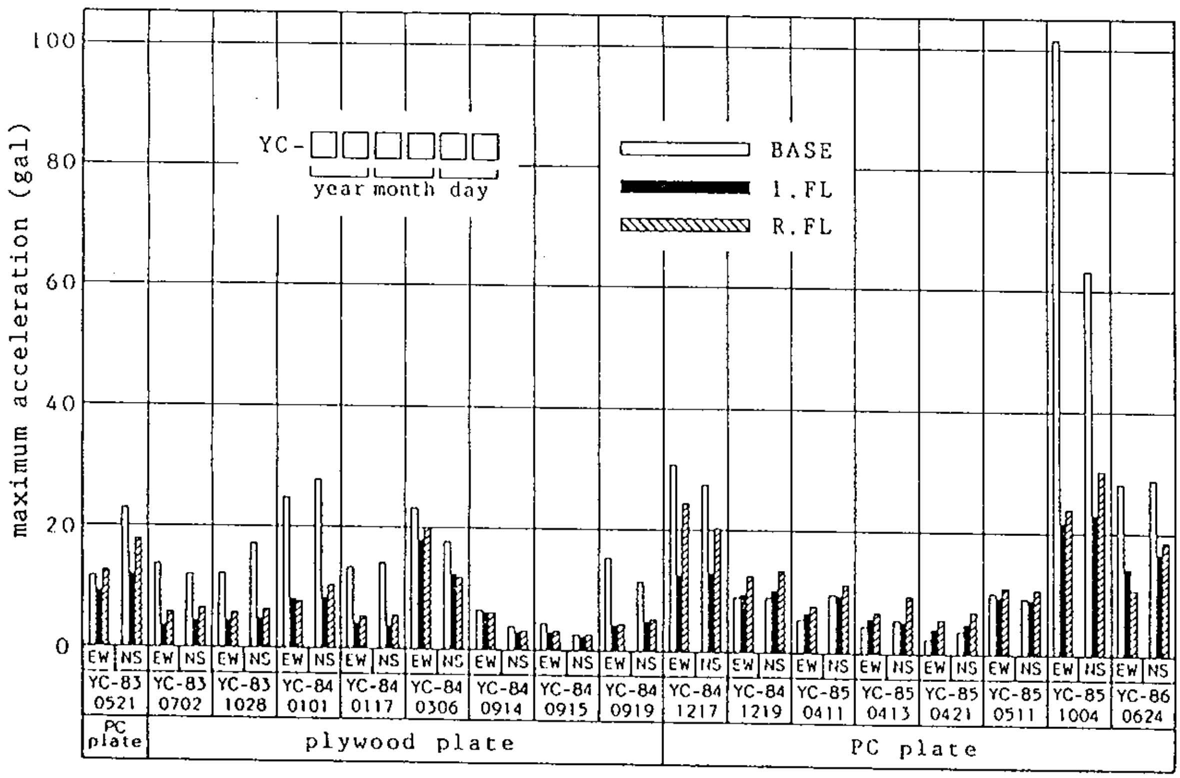


Figure 5 Peak Acceleration Distribution at the Yachiyo City Building

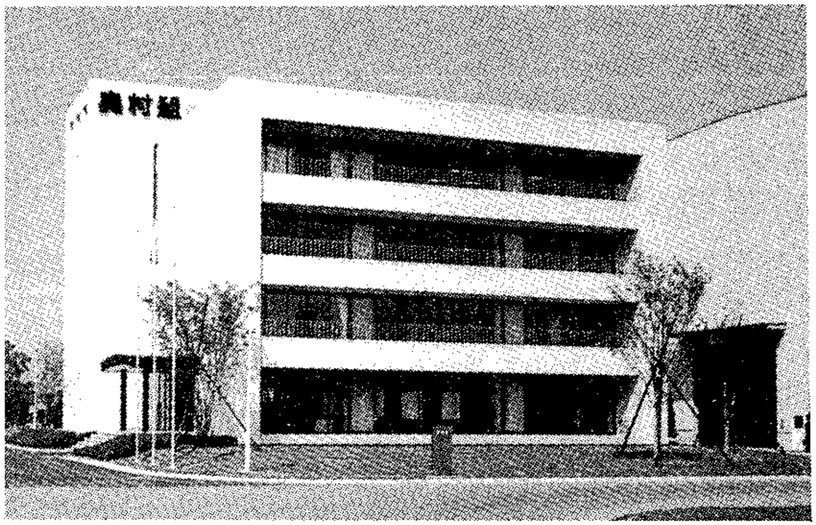


Figure 6 Okumura Company Demonstration Building
in Tsukuba Science City

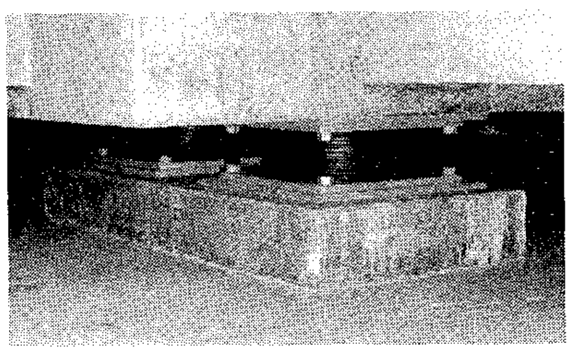


Figure 7 Isolators in Okumura Building

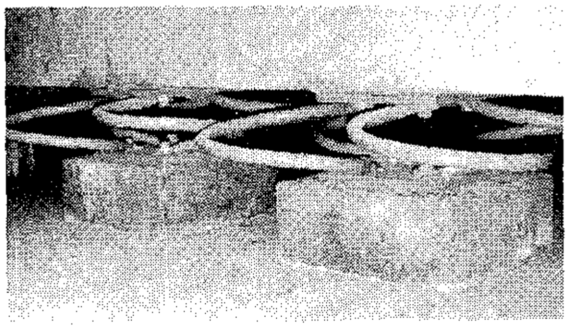


Figure 8 Coil Type Elasto-Plastic Steel Dampers

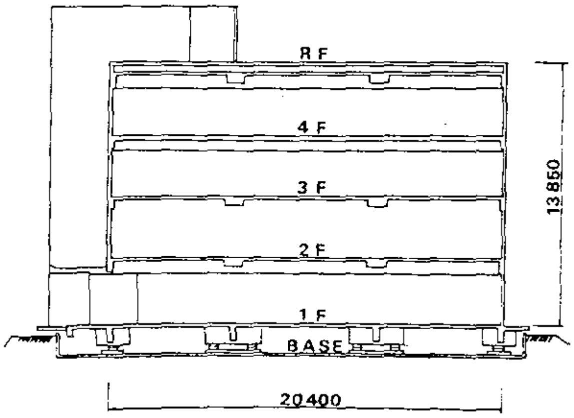


Figure 9 Section through Building

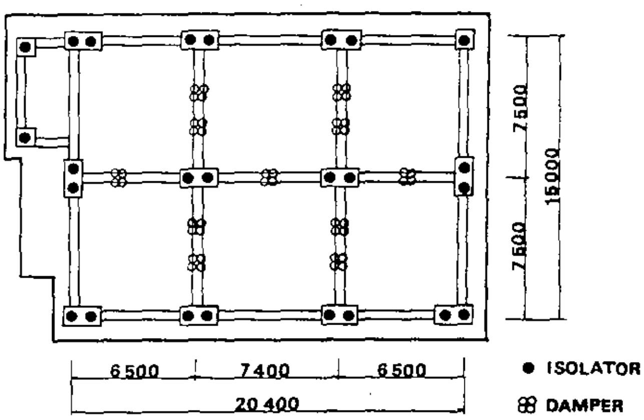


Figure 10 Plan of Base-Isolated Building Showing
Layout of Isolators and Dampers

At small strains the bearings and dampers provide a period of about 1.1 seconds with a damping ratio of 2.5%. The dampers are elastic up to a displacement of about 3 cm and provide no damping for displacements below this level. The predicted maximum damping which can be provided by the dampers under large excursions is about 18% at which stage the period lengthens to about 1.8 seconds. The building has responded well in earthquakes. Twenty-six events were recorded in 1987, the maximum peak ground acceleration measured was 20%g while the measured peak amplification of the roof was 2.0%g, a remarkable attenuation of response.

The fact that the dampers do not yield until 3 cm displacement results in the building being very responsive to small low-frequency input producing an amplification of the input at these frequencies. This is to be expected since for small input the system is almost undamped. To compensate for this effect an additional damper in the form of a shear lead plug has been added to increase the damping for low-level inputs. As of this writing no information on the response with these additional elements in place has been reported.

The next major base-isolated structure to be completed was constructed by the Ohbayashi Corporation as a research laboratory at the company's research institute. It is again both a demonstration building and a test structure for the Ohbayashi Corporation's base isolation system.

The building is a five-story reinforced concrete structure 1624 m^2 in total area. It is 22 m long, 15 m wide and 22 m high. The isolation system uses 14 natural rubber isolators 756 mm diameter and 406 mm thick. The isolators are in two rows along the long sides of the building and are designed to provide a horizontal period of about 3 seconds and a vertical frequency of 15 Hz. Damping is provided by 96 vertical steel rods between the foundation and the superstructure, each rod being 32 mm in diameter. They are arranged in groups of eight between the isolators. The building and the isolation elements are shown in Figures 11 through 14.

The building is extensively instrumented with strong motion accelerographs and has experienced some earthquakes (Takeda *et al.* [5]). In one event a peak ground acceleration of 4.4%g was recorded with 0.71%g being recorded at the roof of the building. This is to be compared with the accelerations recorded in an adjacent administration building, an entirely conventional four-story reinforced concrete structure. In this building, the

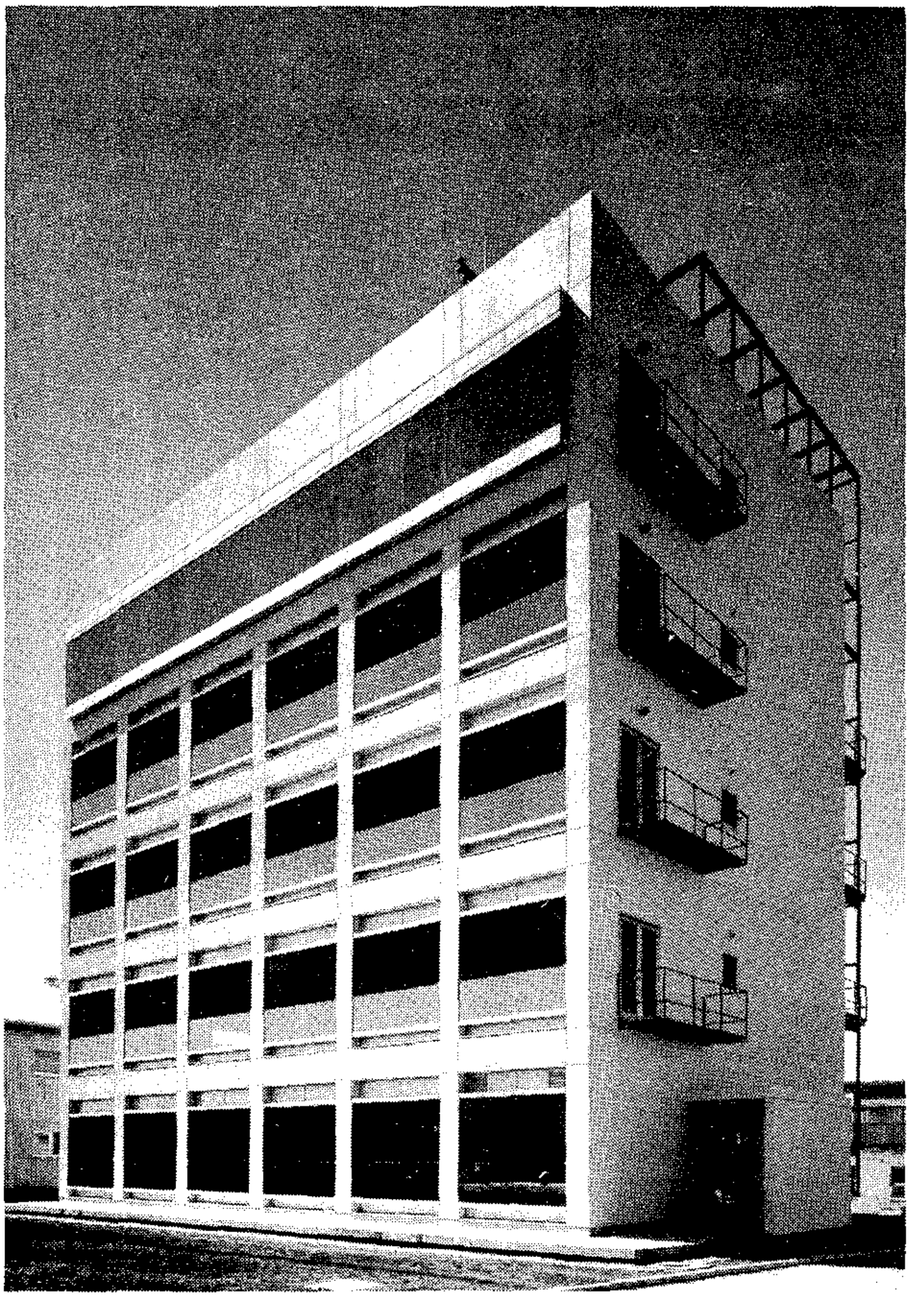


Figure 11 Ohbayashi-Gumi Ltd. Demonstration Base-Isolated Building
(High Tech Research and Development Center)

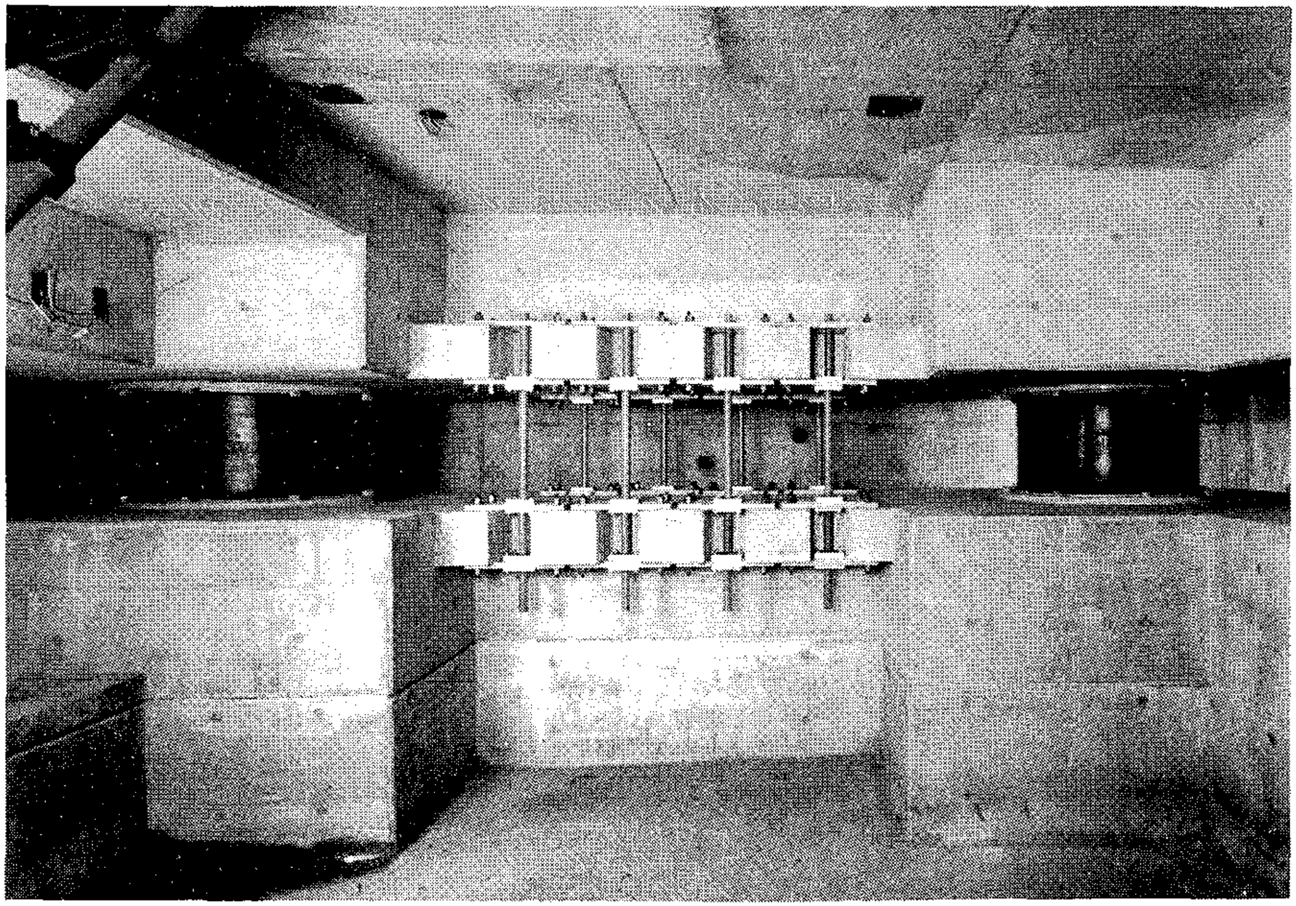


Figure 12 Isolators and Cantilever Type Elasto-Plastic Steel Dampers

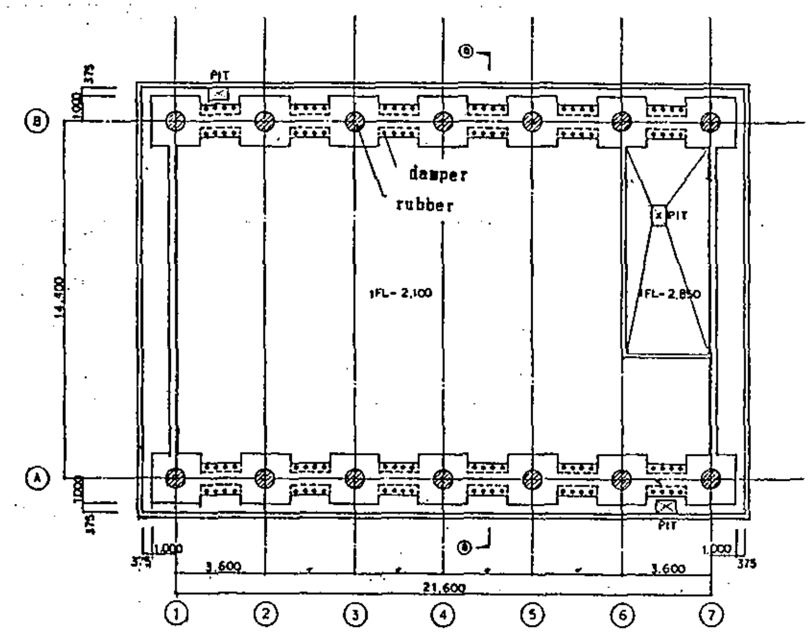


Figure 13 Plan of Building—Layout of Isolators and Dampers

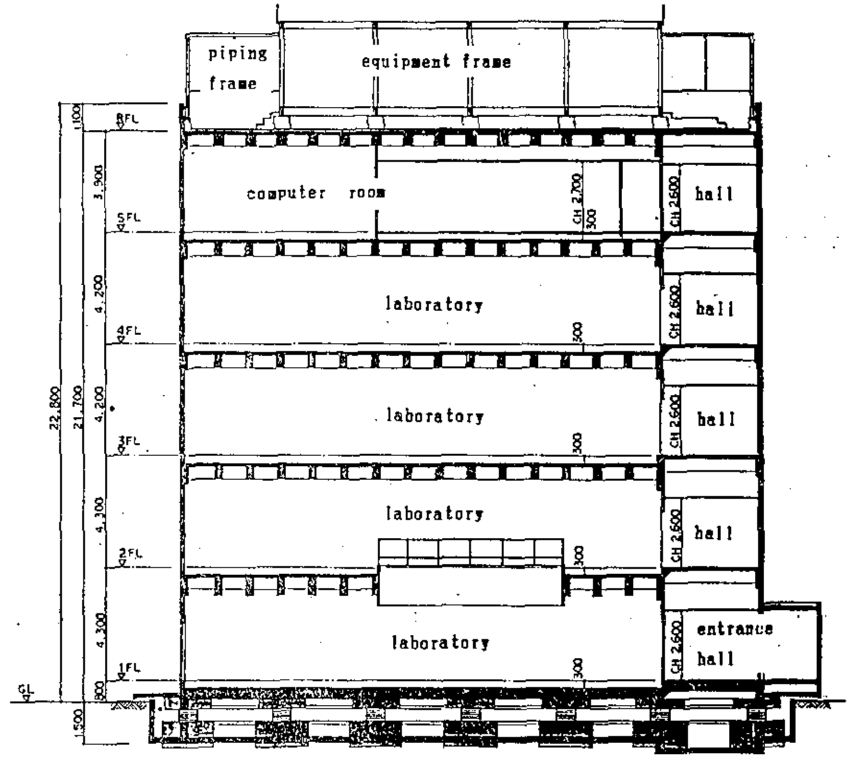


Figure 14 Section through Building

roof acceleration was recorded at 5.9%g.

The next building to be completed was the Oiles Company Technical Center in Fujisawa City, Kanagawa Prefecture. This is currently the largest base-isolated building in Japan and is used as a laboratory facility at the research institute of the Oiles Industry Company. Oiles Industry is a manufacturer of self-lubricating bearings, roller and sliding bearings for bridges. Oiles has an agreement with the Development Finance Corporation of New Zealand to manufacture lead-filled base isolation bearings in Japan. The company commissioned the design and construction of the demonstration building at their plant in Fujisawa City. The building was designed and built by the Sumitomo Construction Company.

The Oiles Technical Center (Figure 15) is a five-story reinforced concrete frame building 36 m by 30 m in plan (Figure 16), with column grids at 6.0 m and 9.0 m centers. A vertical section of the building is shown in Figure 17. As a technical center, the building houses the Departments of Research, Technical Development, Quality Assurance, Technical Information, and Mechanical Development. The Oiles Patent Office and Computer Center are also located in the building.

Construction began in April 1986 and was completed in February 1987. It has a floor area of 4800 m^2 and a total weight of 7500 tonnes above the isolators. Thirty-five lead-filled elastomeric isolators support the structure with diameters ranging from 650 mm to 800 mm. The lead plugs vary from 130 mm to 160 mm in diameter. All bearings are 363 mm high.

The building was designed with a base shear coefficient of 0.2, the same as that required for a conventional building. No economy was therefore possible in the design and the rationale for construction was improved seismic safety, damage-free performance in major earthquakes and its use as a demonstration building. For this last purpose the building serves three useful functions. First, it is used to show building owners, architects, and structural and building service engineers, typical details and configurations necessary to construct and maintain a base-isolated building. Second, it is used as a full-scale isolation test laboratory. Both forced- and free-vibration tests have been conducted on the building and these are repeated from time to time to check the durability and reliability of the isolation system. Useful data on the recovery of hysteretic damping after free-vibration testing have also been obtained. Third, the building is instrumented

Figure 15 Oiles Industries Ltd. Demonstration Building in Fujisawa City

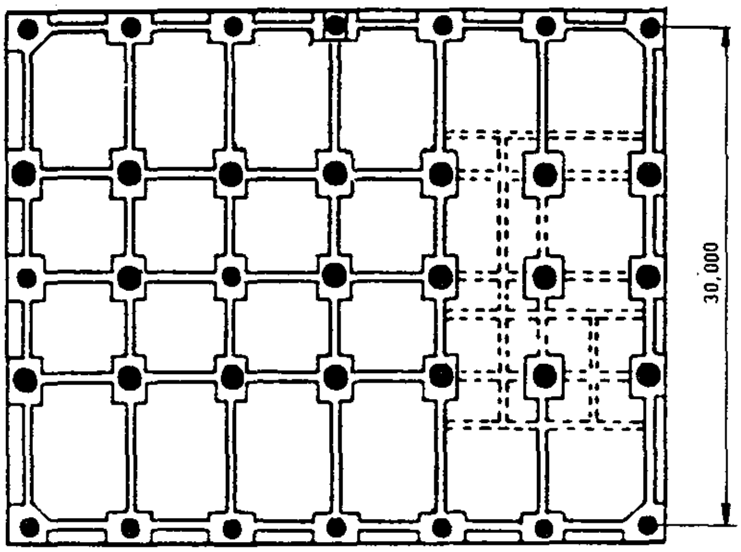


Figure 16 Plan of Building Showing Location of Isolators

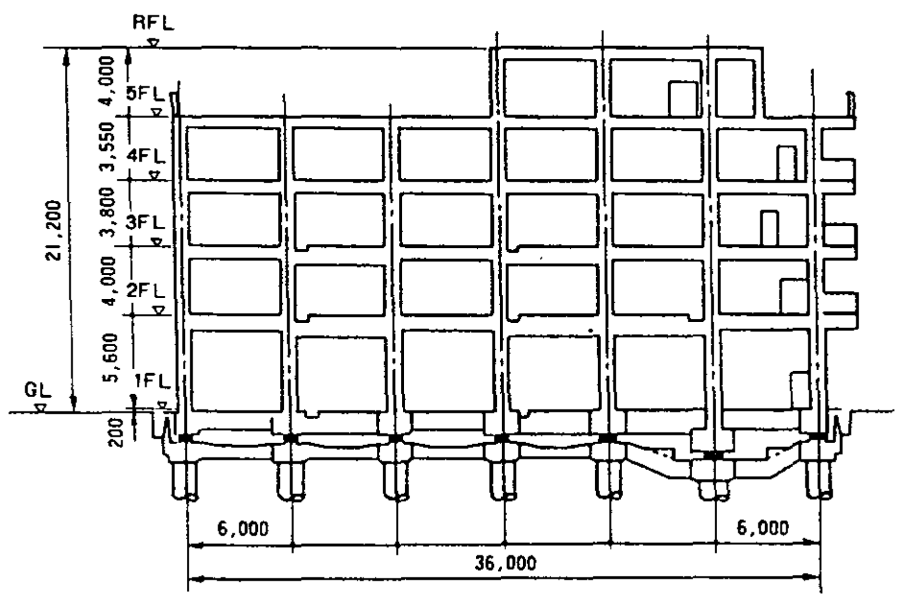


Figure 17 Section through Building

with twenty-seven strong motion accelerographs, eight displacement transducers, and nine stress sensors in the piles. Records of structural response have been obtained for several earthquakes [6]. While most of these have been low-level events for which the hysteretic dampers have barely yielded, measurable attenuation in floor accelerations has been demonstrated and the design assumptions have been confirmed. Figure 18 illustrates acceleration records from the building during the east Tokyo earthquake of March 18, 1988. The measured peak ground acceleration was 6.2%g and at the roof 4.3%g. The relative displacement at the isolation system for this input was just under 1 cm.

A laboratory building at the research institute of the Kajima Corporation was completed at about the same time as the Oiles Technical Center. This structure, the Environmental Engineering Laboratory located near Tokyo, is a functional building that doubles as a full-scale experimental model for advanced construction technology. The facility consists of two adjacent buildings, an acoustic/environmental vibration laboratory and a thermal control/air flow/equipment laboratory. The two buildings are connected by a corridor and an atrium roof (Figure 19). The thermal control laboratory was constructed using conventional precast concrete technology and is supported on a standard concrete foundation. The acoustic laboratory is of similar construction but is supported on a base isolation system consisting of eighteen laminated rubber bearings, fourteen hysteretic dampers, and an unknown number of oil buffers (energy-absorbing devices) as shown in Figure 20. The foundations and the base floors of the two buildings therefore differ fundamentally. Figure 21 shows the locations of the various supports and isolation devices used for the acoustic laboratory and Figure 22 shows a section through the building.

The structure represents a full-scale model of an operational laboratory designed for earthquake motion isolation. The building is supported on a foundation that provides a complete mechanism for isolation against earthquake motions and other ambient vibrations. Inside the isolated structure, acoustic and vibration experiments can be performed with a high degree of accuracy.

Soft vertical rubber springs are utilized to isolate the building and filter out microtremors caused by external ground-transmitted vibrations. Fail-safe blocks which limit ultimate system displacements are used to provide secondary protection against primary system failure. The horizontal frequency of the building is 0.5 Hz and the vertical

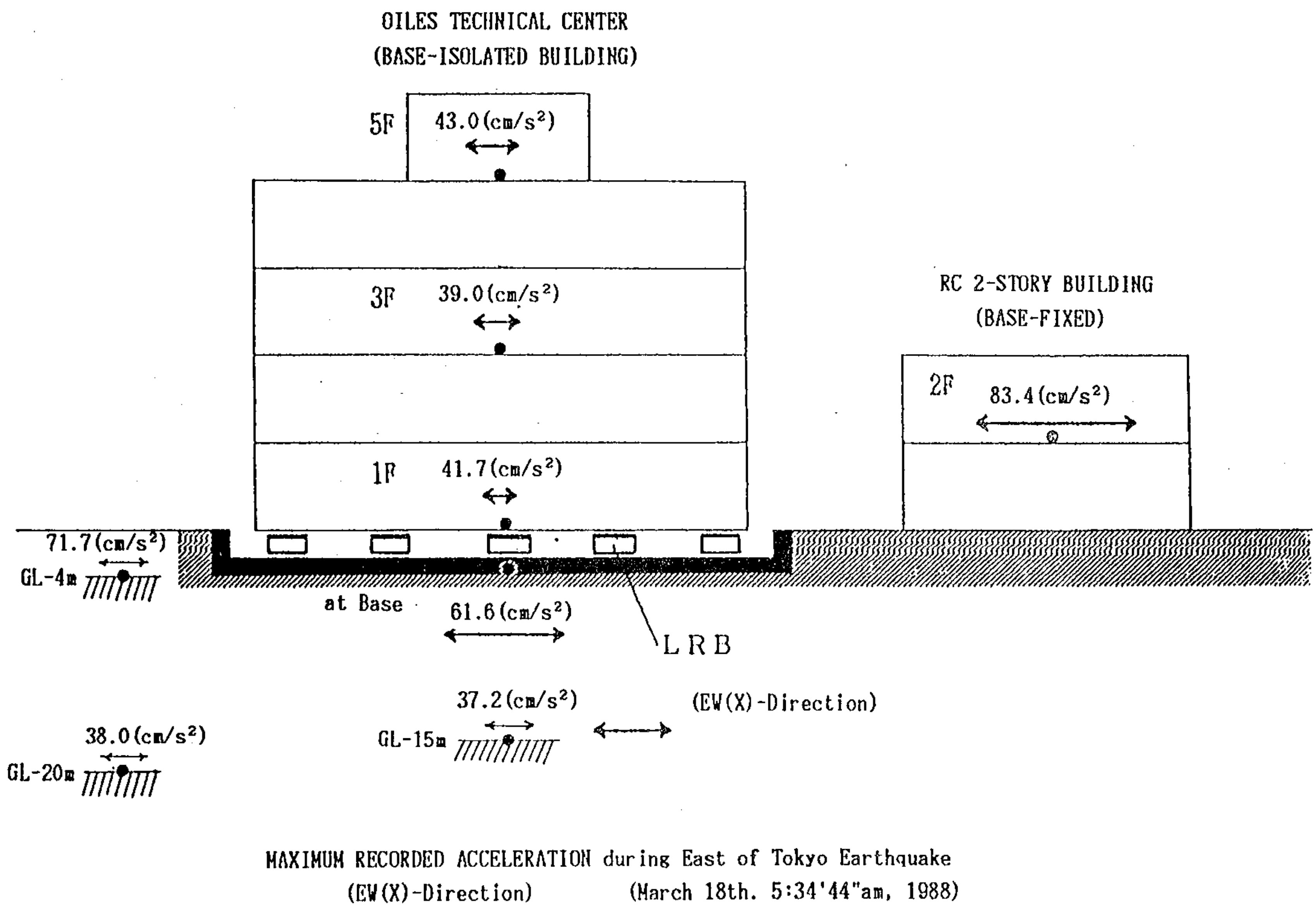
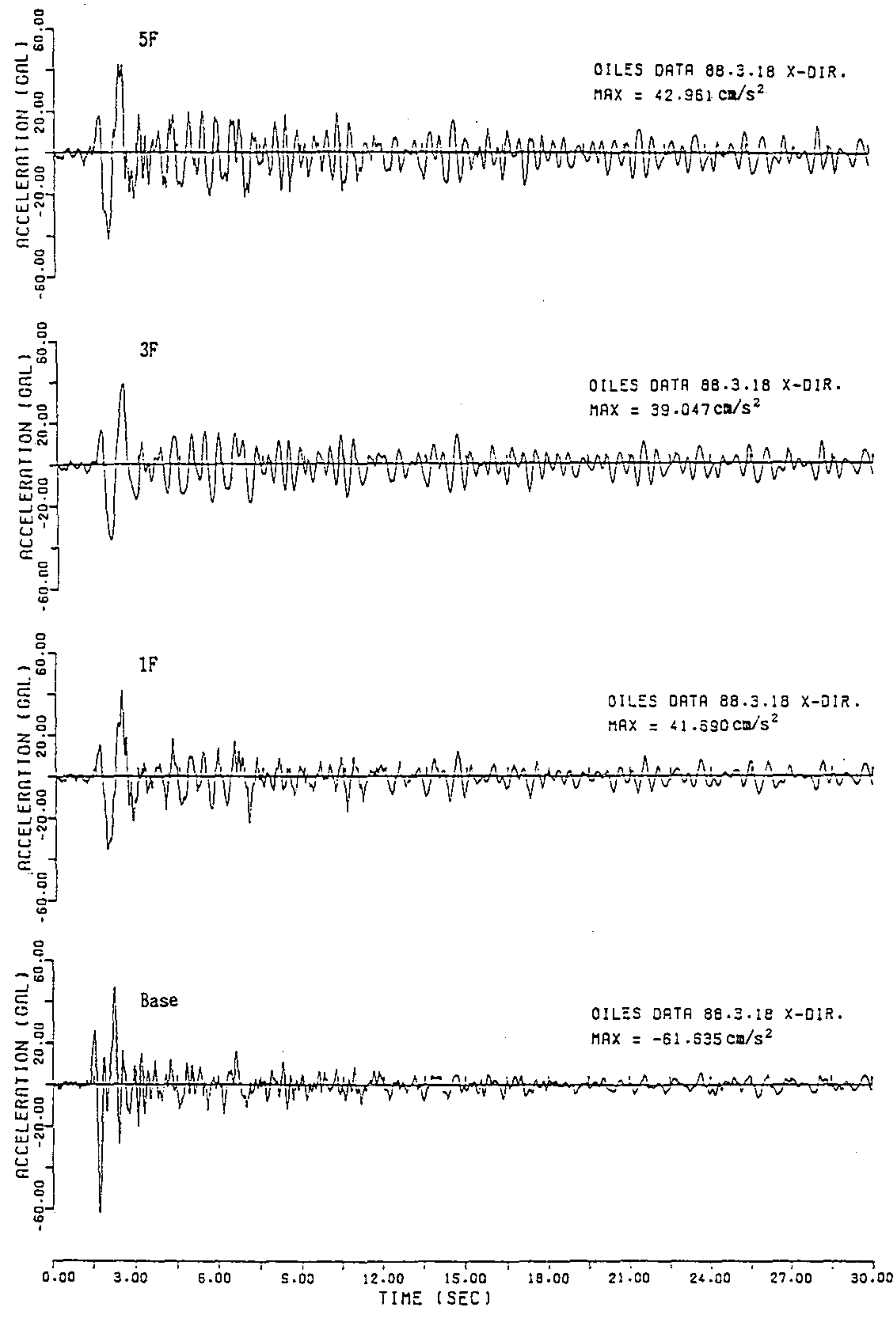


Figure 18(a) Location of Strong-Motion Accelerographs and Maximum Recorded Accelerations during East Tokyo Earthquake, March 18, 1988



Observed Acceleration of OILES TC Building(X-Direction)1988.3.18

Figure 18(b) Observed Time Histories during East Tokyo Earthquake, March 18, 1988

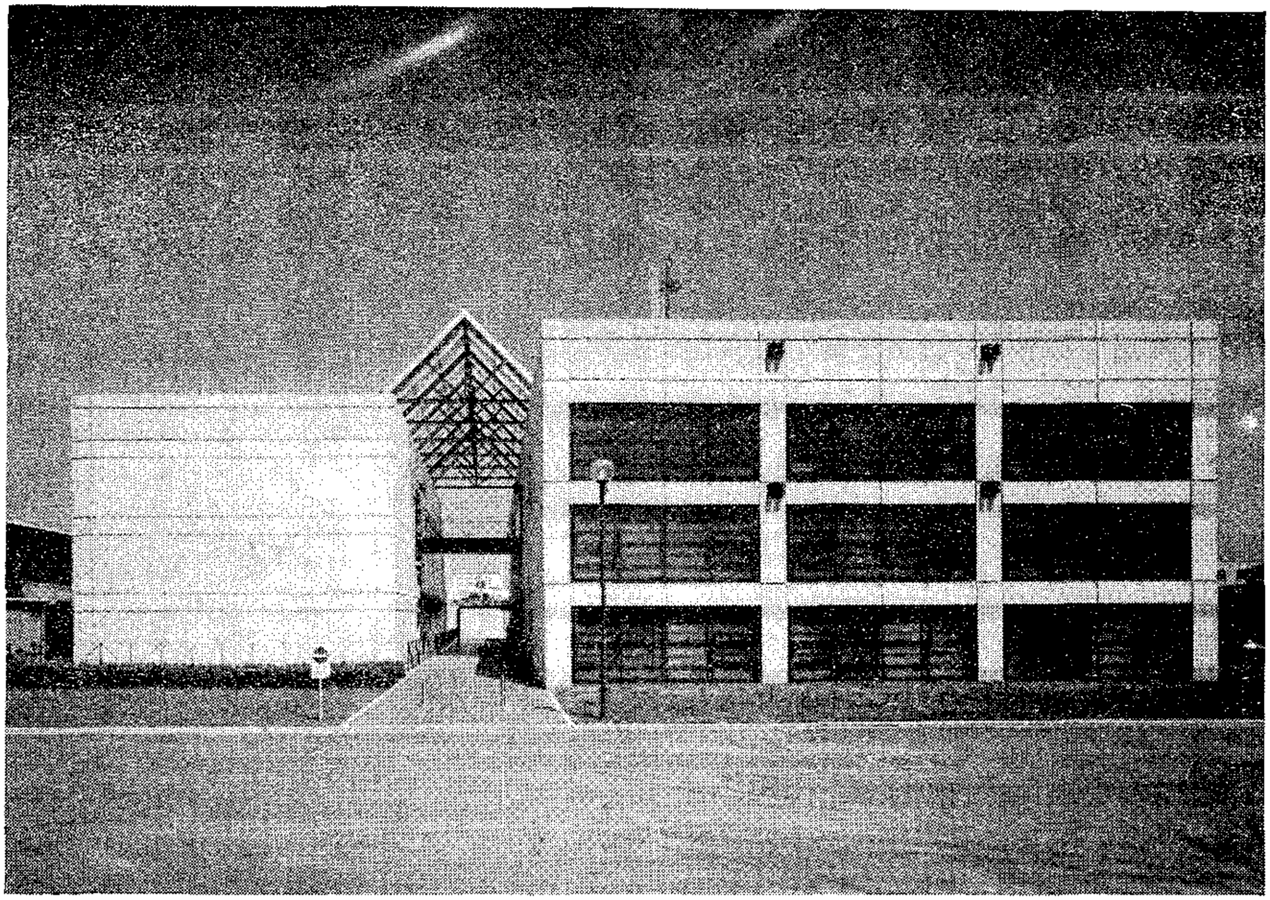


Figure 19 Kajima Corporation Demonstration Building
(Environmental Engineering Laboratory)

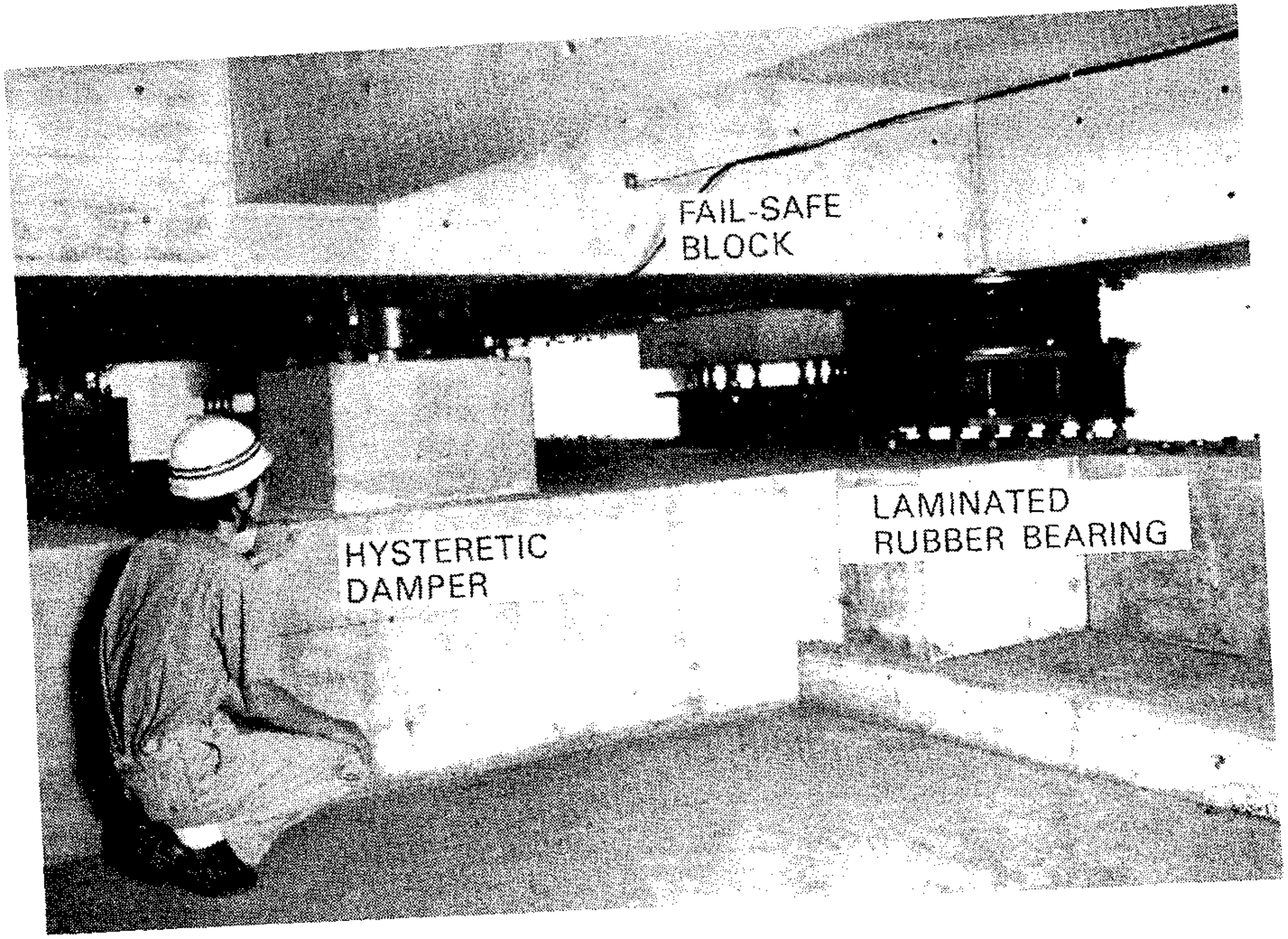


Figure 20 Isolators, Dampers, and Oil Buffers as Installed in the Kajima Building

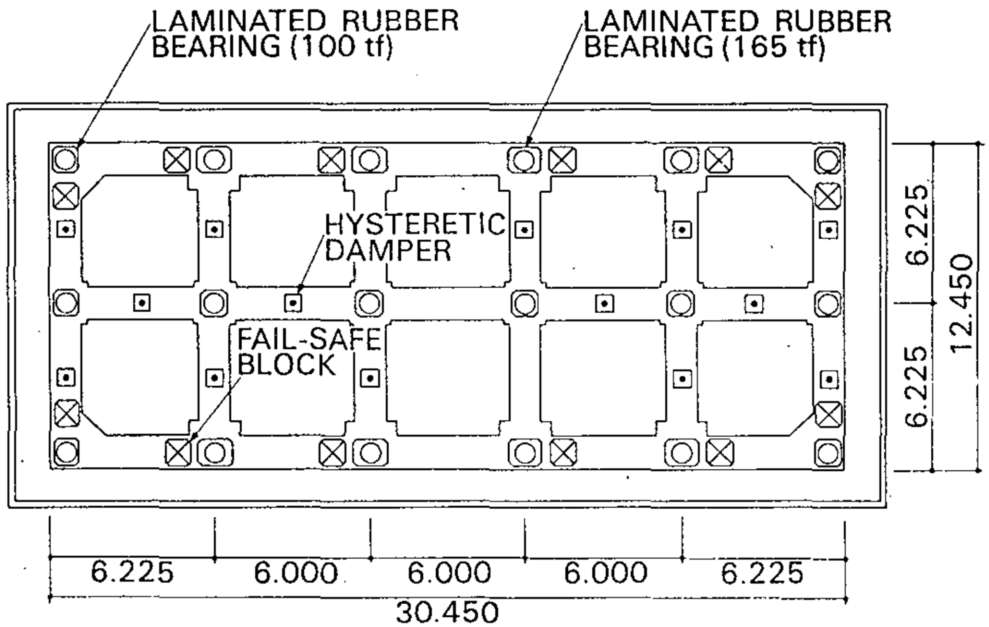


Figure 21 Plan of Kajima Building Showing Layout of Isolation System Components

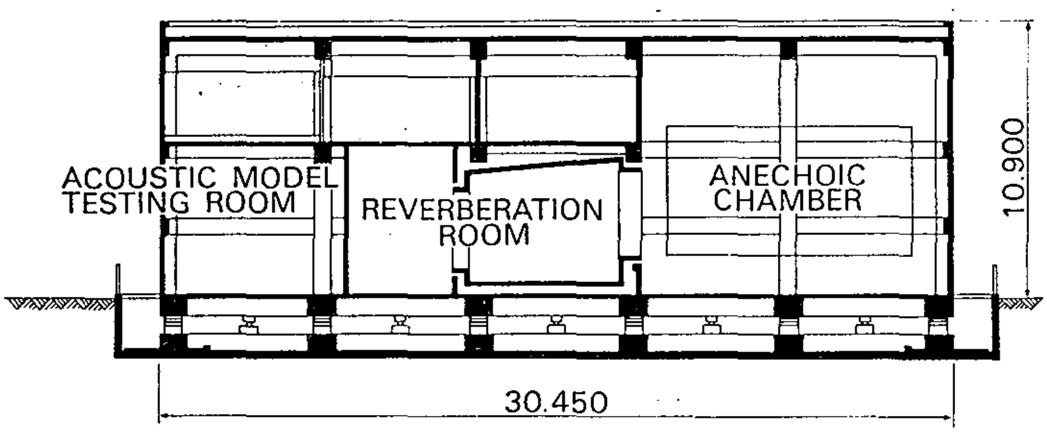


Figure 22 Cross-Section of Kajima Laboratory

frequency at the design weight is 5 Hz. This low vertical frequency is achieved by thick layers of soft natural rubber. The bearing shown in Figure 23 has a shape factor of 5.2 and consists of five rubber layers each 48 mm thick and four steel insert plates each 5 mm thick. The bearing has a design load of 3.1 MPa and a design shear displacement of 20 cm.

The thick-layered laminated bearings do not provide sufficient energy absorption and dampers are incorporated to increase overall system damping. The hysteretic damper and concrete deformation retainer are shown in Figure 24. The steel rod at the center dissipates horizontal vibration energy through inelastic flexural deformation. The deformation retainer protects the steel rod from damage at the fixed end and improves the fatigue strength by a factor of 4. According to a Kajima spokesperson the shape of the deformation restrainer was determined through trial and error.

Oil buffers are incorporated to reduce vertical vibrations and rocking motions during an earthquake. Figure 25 illustrates an oil buffer damping device. Analytical methods have been used to demonstrate that vertical response can be reduced by over 50% with these buffers. The reaction force of the oil buffer is proportional to its velocity.

Two ancillary components are included in addition to the primary isolation components. Fail-safe blocks are used adjacent to the rubber bearings to provide secondary protection against failure of the primary system. The block shown in Figure 26 is provided with a mechanism to adjust clearance between the device and the foundation. Slide bearings (Figure 27) are used to support the passageway and atrium roof joining the two laboratories.

Analysis, testing, and recorded earthquake data [7] have demonstrated that the isolation system can reduce peak building accelerations by a factor of 4 to 5. Measurements of micro-tremors have demonstrated 20 db reductions for frequencies greater than 10 Hz. The elastic stiffness of the hysteretic damper acts as a wind brace for the building. The system is designed to limit wind response to less than 1 gal for winds with a one-year return period. The validity of the analytical model predicting wind response has been demonstrated by measurements. Motions of 27 mm and accelerations of 0.41 gal have been recorded with 16 m/sec winds.

The Takenaka Construction Company began a study of base isolation systems in 1982 and in 1984 constructed a full-scale test model using a 550 ton coal silo (Figures 28

165tf RUBBER BEARING

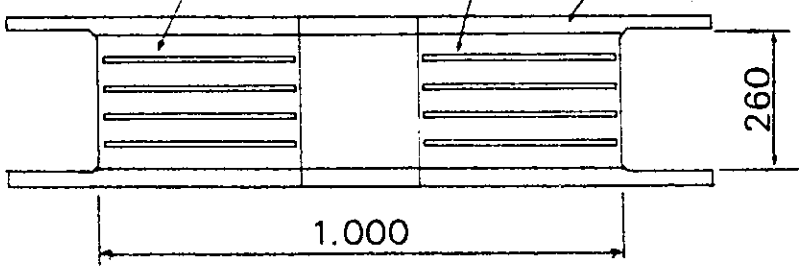
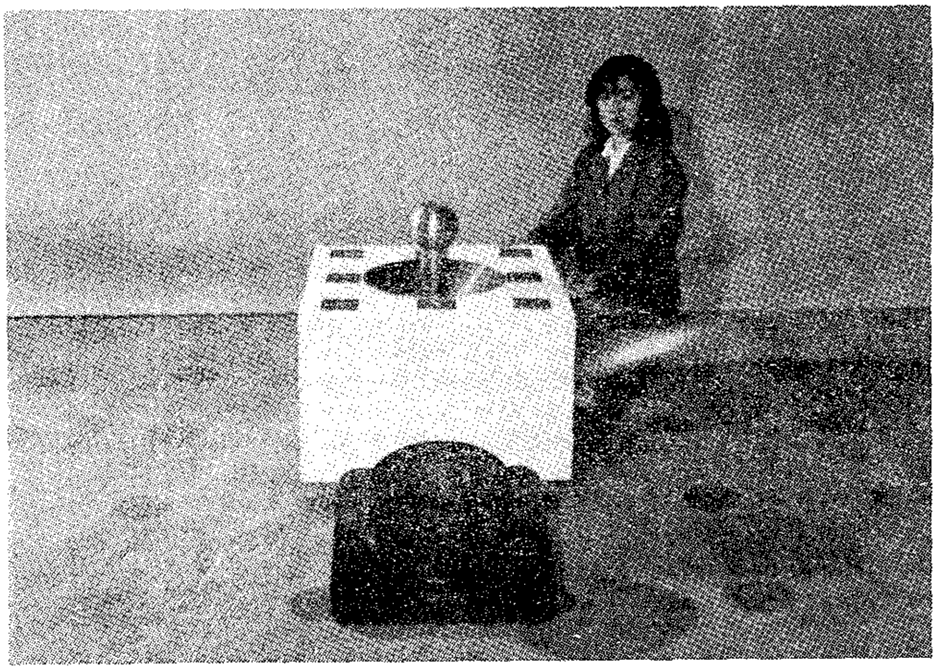


Figure 23 Rubber Bearing in Kajima Building



HYSTERETIC DAMPER

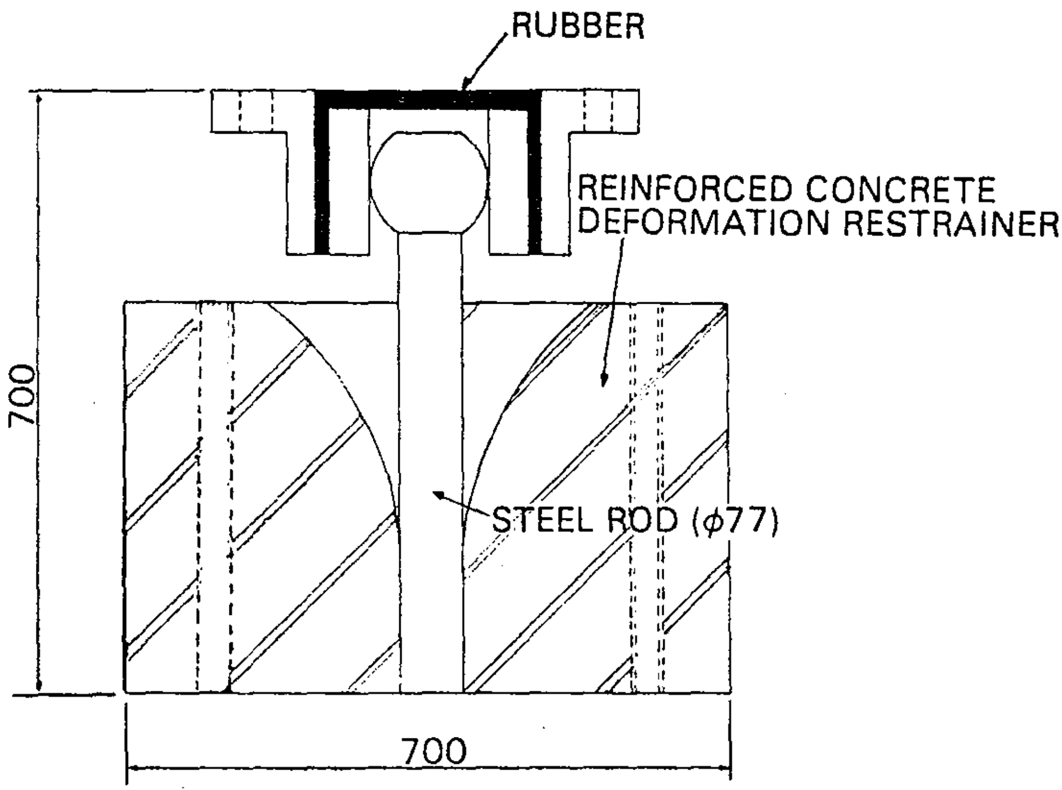
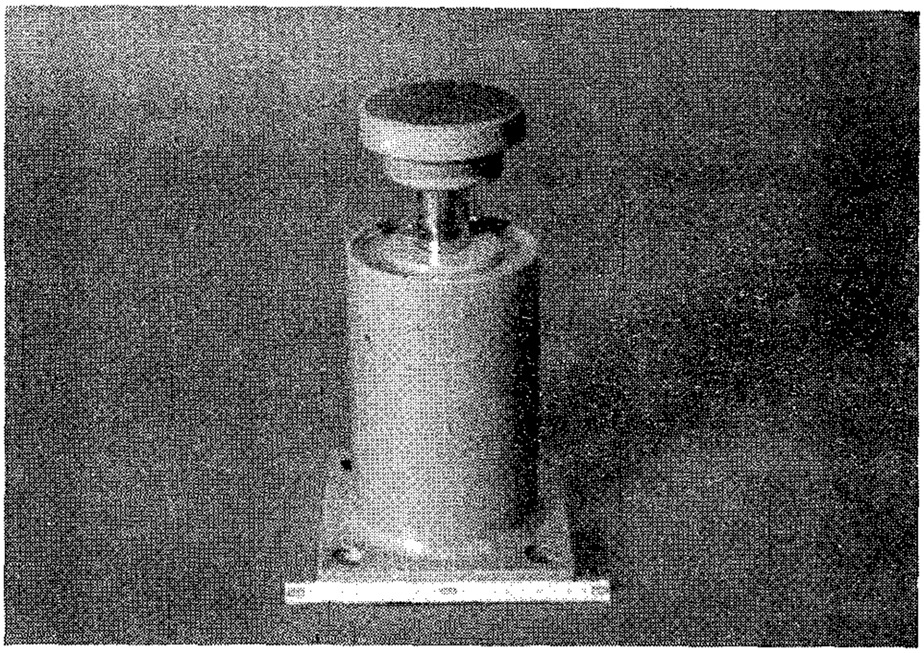


Figure 24 Hysteretic Steel Damper in Kajima Building



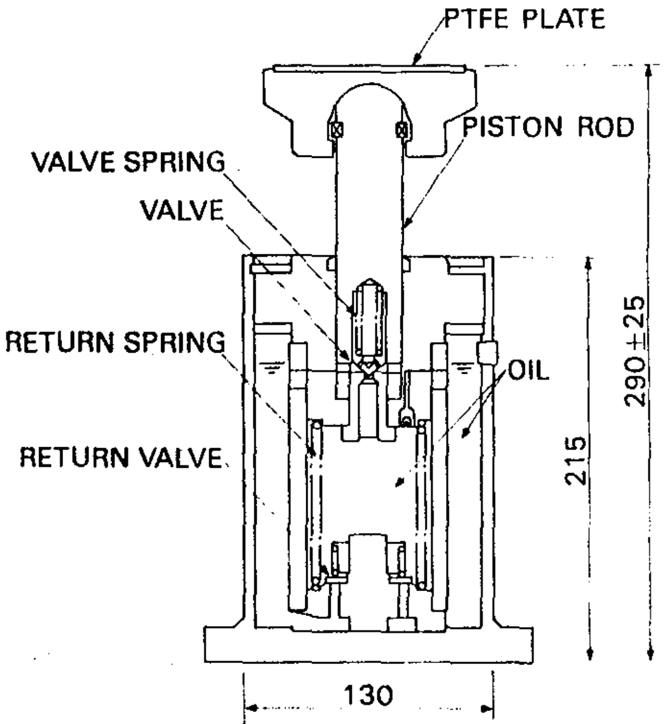


Figure 25 Oil Buffer for Kajima Building

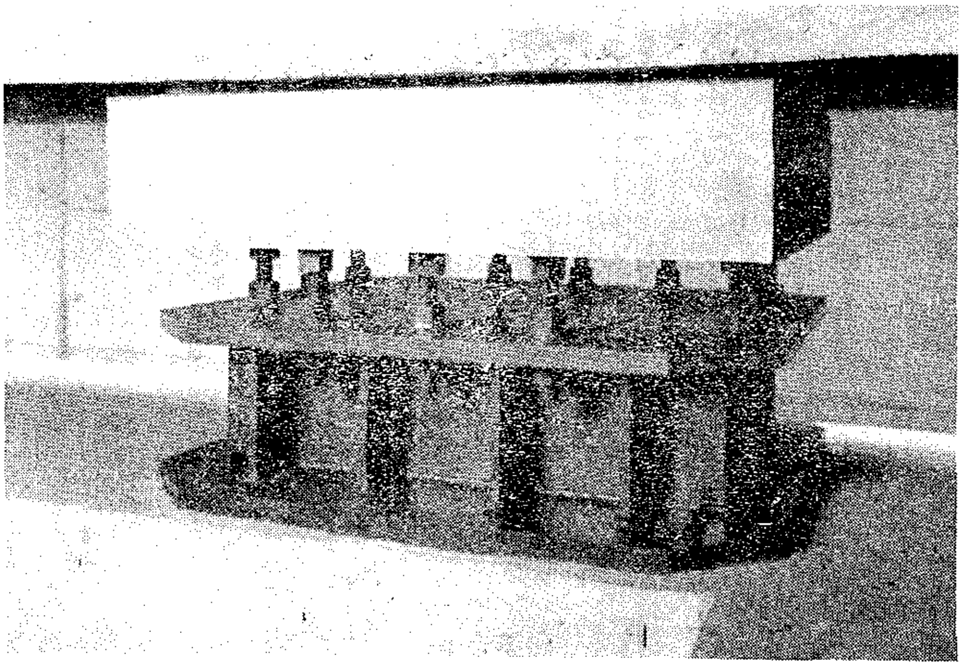


Figure 26 Fail-Safe Concrete Blocks in Kajima Isolation System

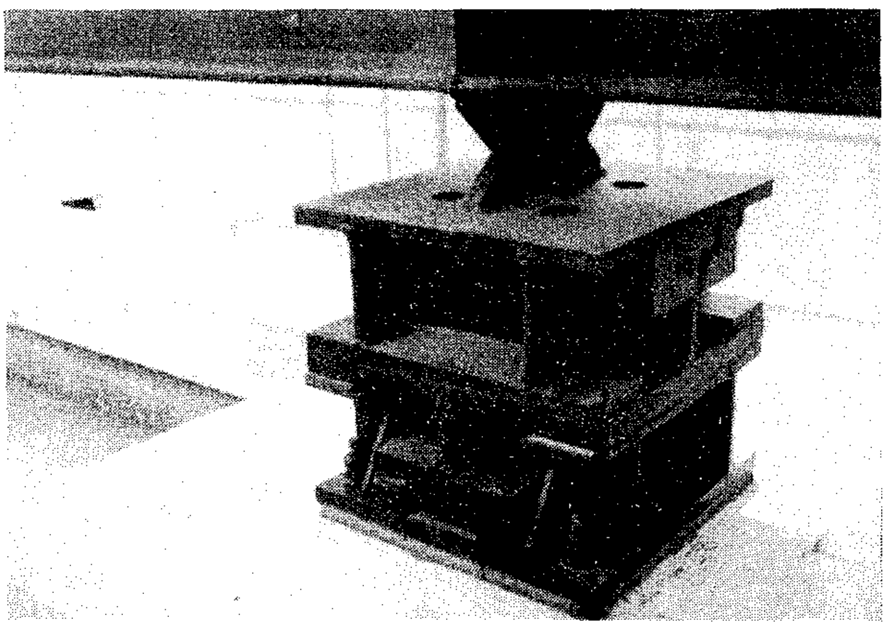


Figure 27 Sliding Bearings for Passageway between Isolated and Fixed Laboratories

through 30) mounted on natural rubber bearings provided by the Bridgestone Corporation. The damping in the isolators was very low, equivalent to about 2.4%, for an isolated period of 2.0 sec, and to provide adequate damping viscous fluid dampers (Figure 31) provided by Oiles Industries were included in the system. Free-vibration tests were carried out and the observed damping was about 12% [8]. The performance of the system in the tests was so satisfactory that the company designed and built its own demonstration building using this system. Known as the Funabashi Dormitory (located near the Nishi-Funabashi station about an hour's train ride from Tokyo), the building was designed and built as a research facility. The Takenaka technical research laboratory has instrumented the building and is presently collecting performance data.

The building (Figure 32) is a three-story structure housing quarters for single male employees of the Takenaka Corporation. The structural framework and the lateral load-resisting system consist of shear walls and reinforced concrete frames. The architectural design (Figure 33) for the facility includes an open atrium area on the second floor between two wings of residential rooms. This required that the second and third floors overhang the first.

If conventionally founded, the resulting structural system could lead to poor seismic performance. Base isolation removed this design obstacle. In addition, base isolation allowed a relatively large open area on the first floor to be unencumbered by shear walls that would typically have been required to transmit seismic forces to the foundation.

The foundation and the first floor dimensions are 9 m by 37.2 m, while the second and third floor dimensions including the overhangs are 16.2 m by 44.2 m. The total height of the building above the basement is about 11 m. The basement within which the base isolation system is situated has a clear height of about 1.5 m, not enough clearance to stand comfortably but enough to enable inspection of the base isolation system.

Poor soil conditions at the site required that the building be supported on piles placed to a depth of about 23 m bearing on a subsoil layer of fine sand. A total of 14 piles, one located at each building column, support the entire weight of the structure. The pile caps are tied together by a grid of grade beams. The base isolation bearings and the energy-absorbing devices are located on top of the grade beams.

The base isolation system for the building consists of 14 steel reinforced natural rubber bearings (Figures 34 and 35) provided by the Bridgestone Corporation, one at

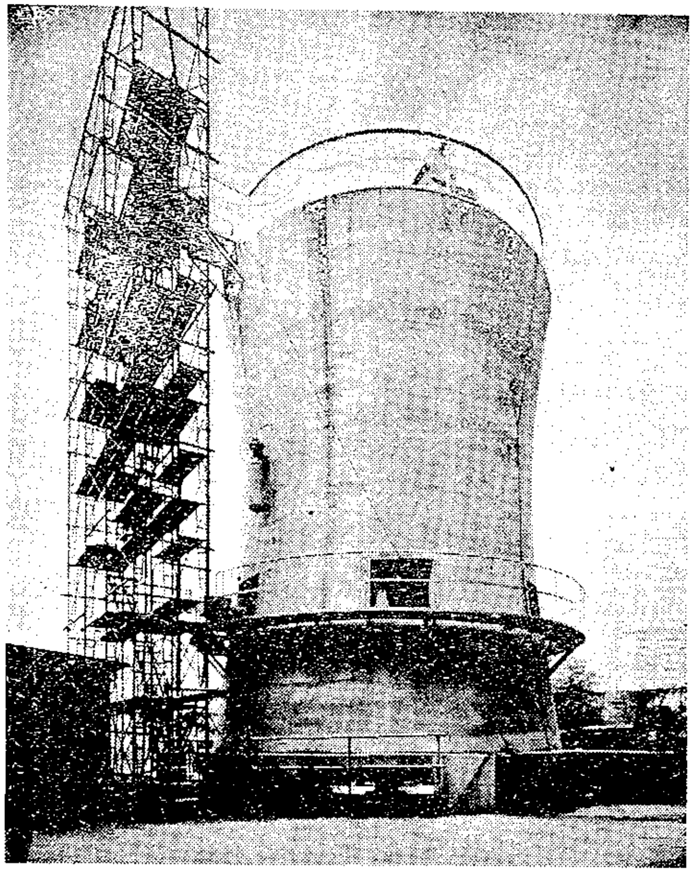


Figure 28 Takenaka Company Isolated Test Model (Coal Silo)

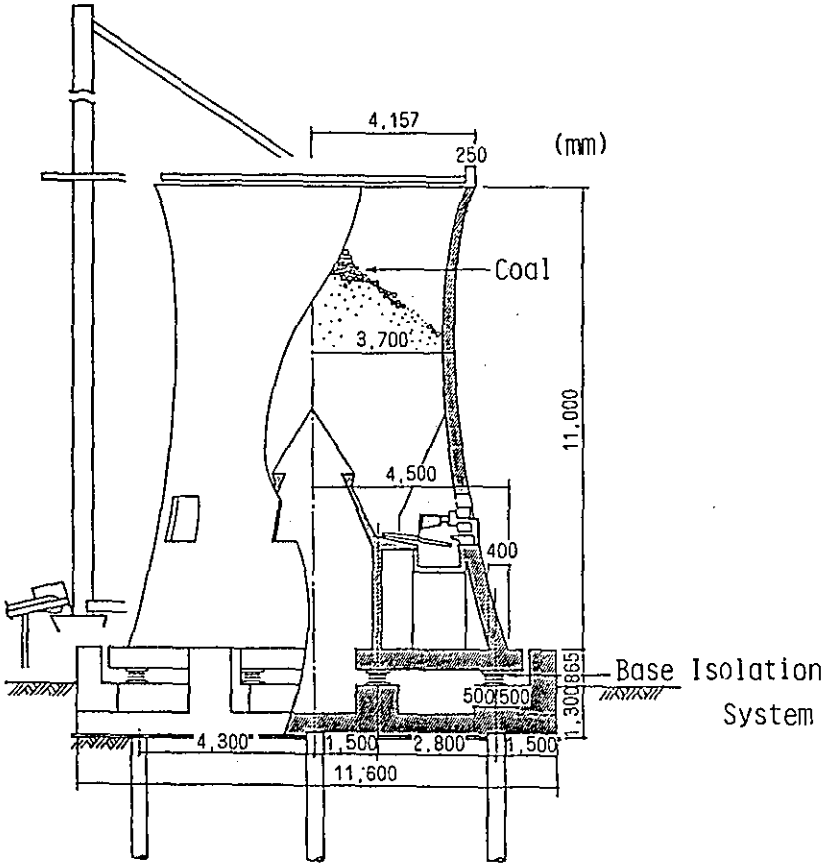


Figure 29 Section through Takenaka Test Model

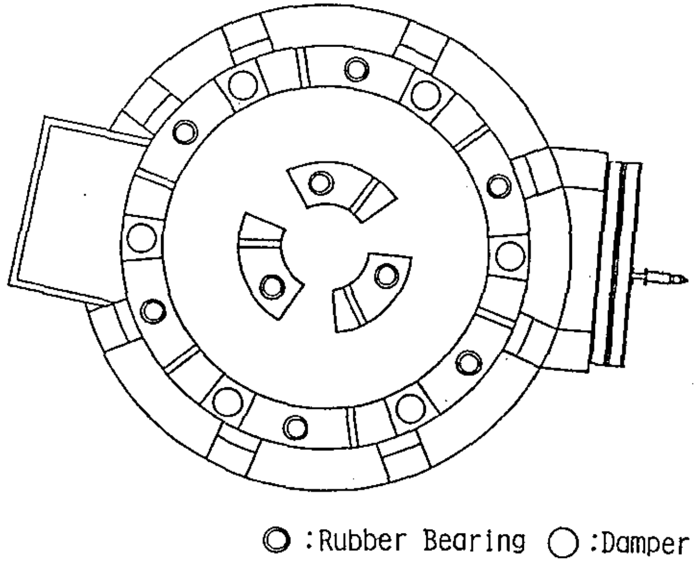


Figure 30 Plan of Test Model Showing Location of Isolators and Dampers

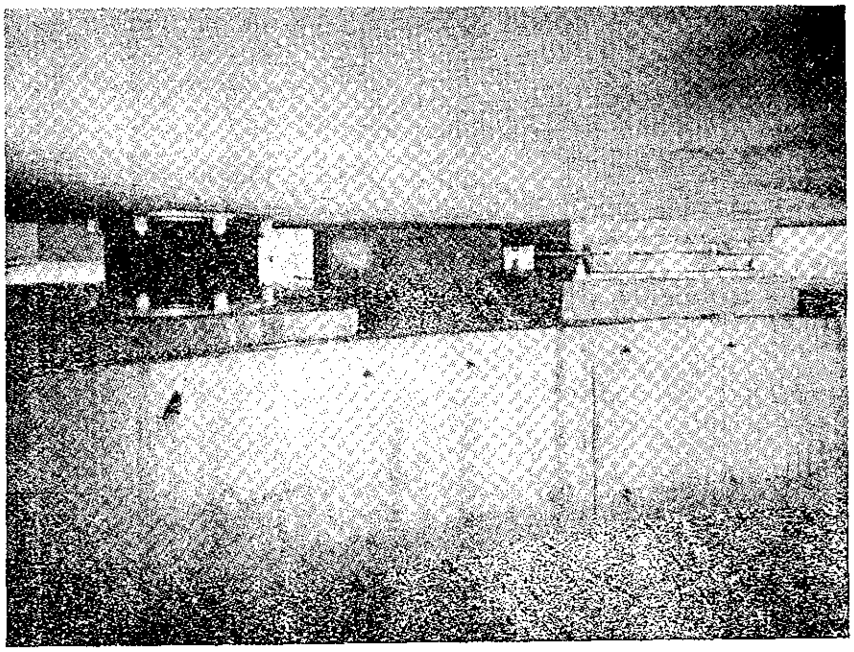


Figure 31 Rubber Bearings and Oil Dampers in Takenaka Test Model

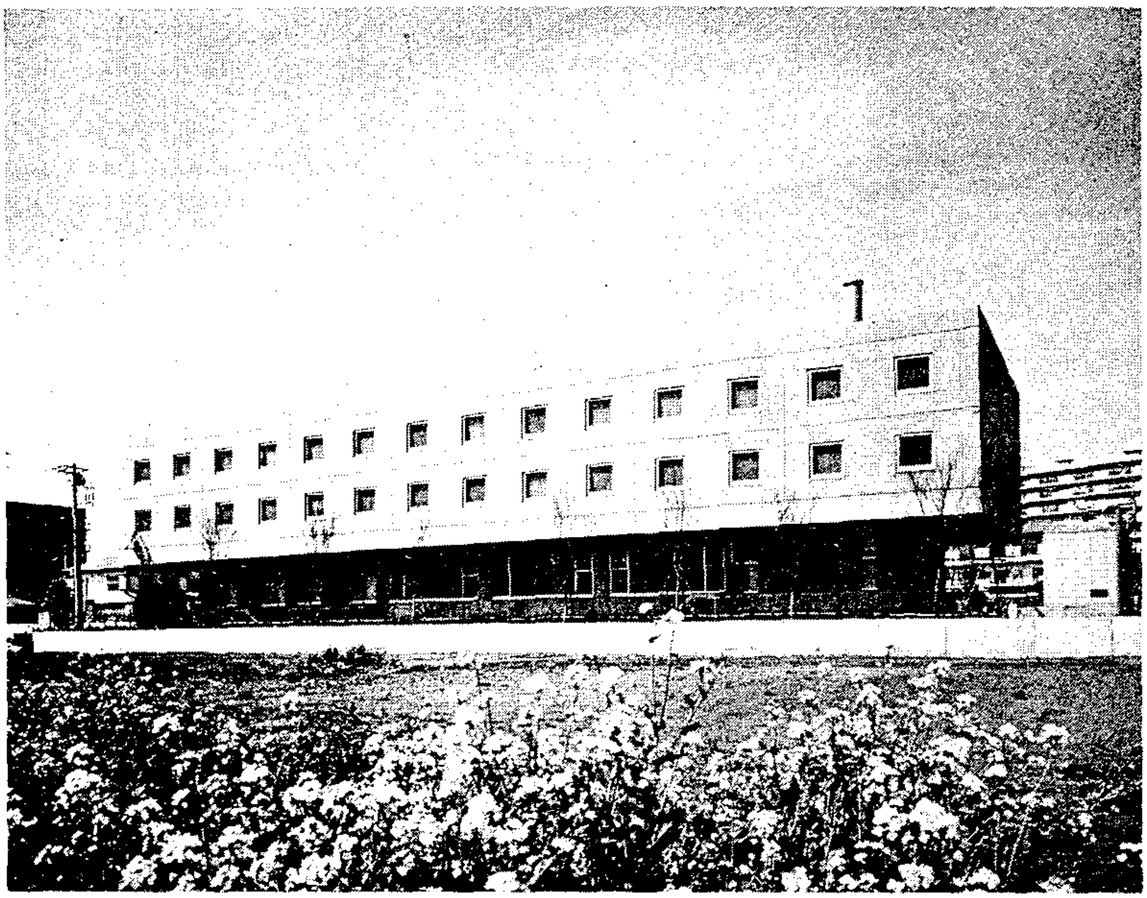


Figure 32 Funabashi Dormitory: Takenaka Company Demonstration Building

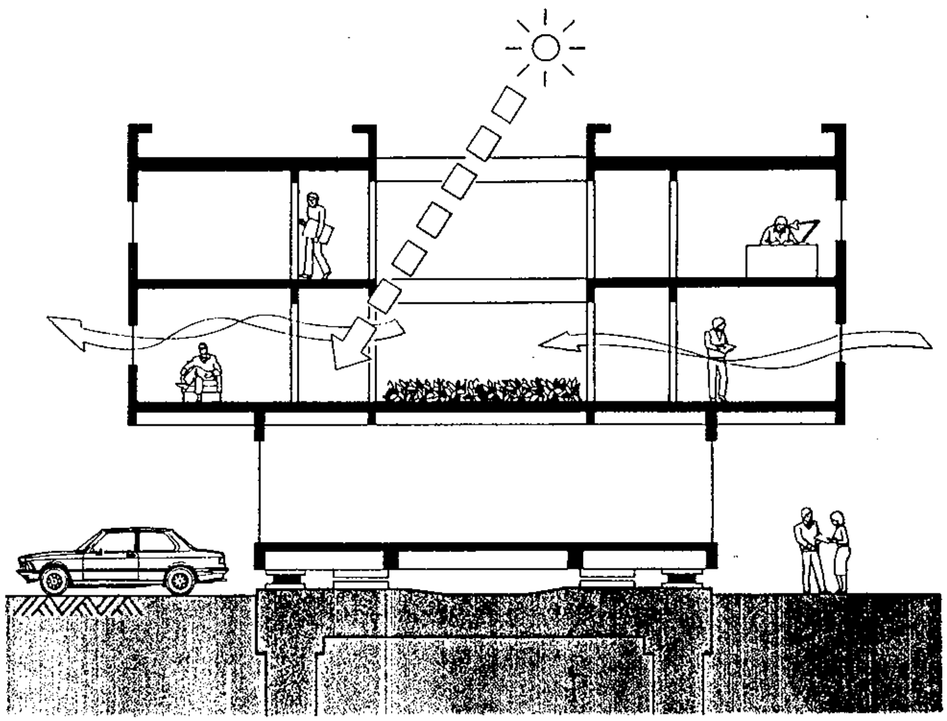


Figure 33 Cross-Section of Funabashi Dormitory
Showing Architectural Design

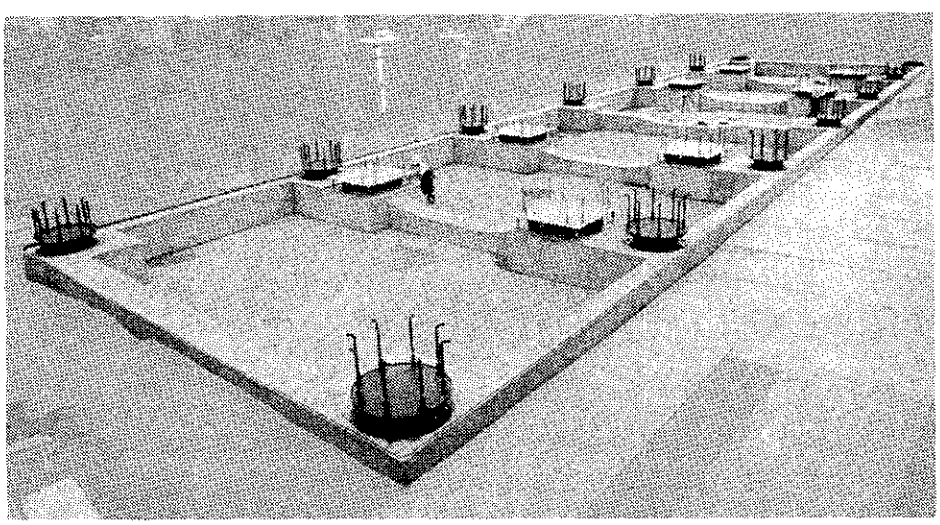


Figure 34 Isolators and Dampers in Funabashi Dormitory

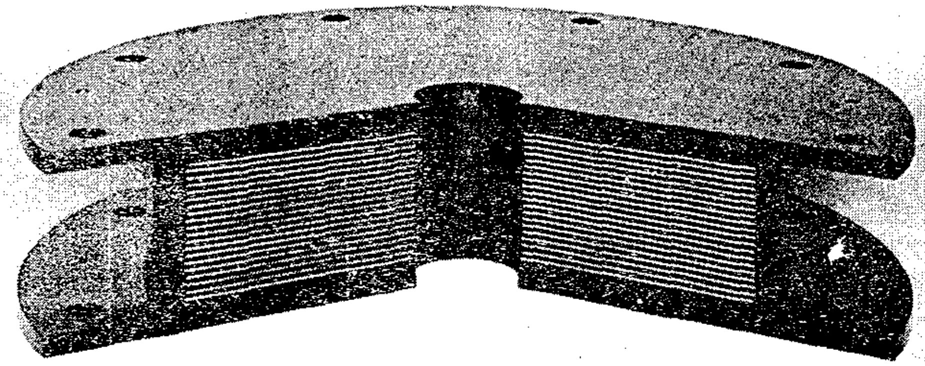


Figure 35 Rubber Bearings in Funabashi Dormitory

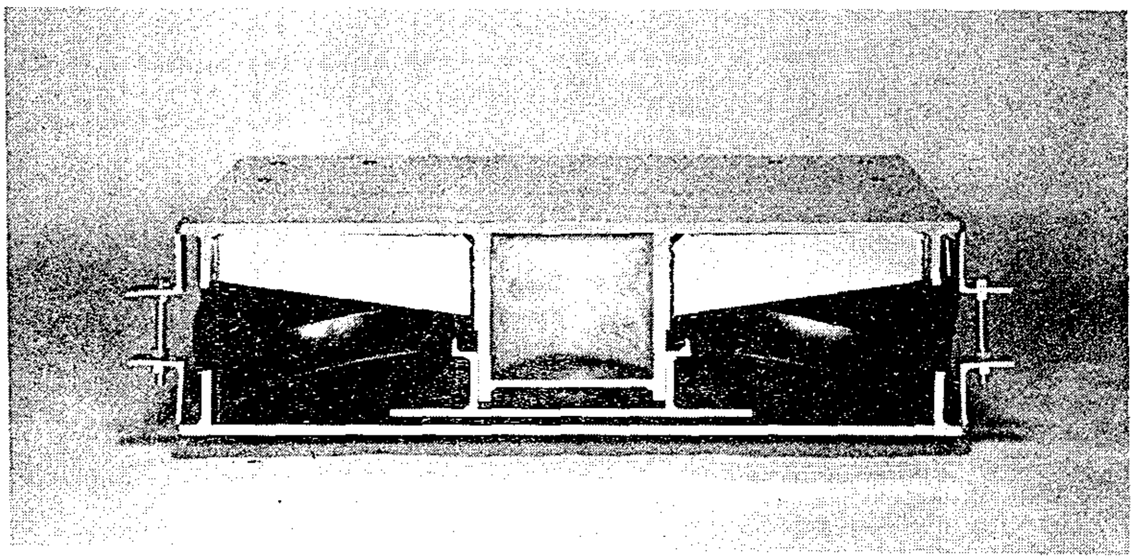


Figure 36 Viscous Dampers Used in Funabashi Dormitory

each pile location, supplemented by eight dampers. Of the 14 bearings, eight carry a vertical load of 150 tonnes, and six carry a vertical load of 200 tonnes. The 150-tonne bearings are 686 mm in diameter and 186 mm thick, while the 200-tonne bearings are 766 mm in diameter and 166 mm thick. Thus, the vertical pressure on the bearings is 4.06 MPa and 4.34 MPa, respectively.

The viscous polymer based dampers are unique to this system. Each damper is about 150 cm^2 in plan with a total height of about 30 cm. A viscous polymer is contained within the lower part of the damper. The upper bearing plate of the damping mechanism (see Figure 36) is fixed to the superstructure and positioned on top of the viscous fluid. The drag of the viscous fluid on the bearing plate as it displaces horizontally during an earthquake produces a damping force proportional to the relative velocity. The building, the base isolation system, and its performance are described in reference [9].

The rubber bearings in this system serve predominantly to support the building's weight, reduce the fundamental frequency of the base-isolated structure and provide a lateral restoring force. The dampers serve to absorb seismic energy and control displacements. While the damping devices do not support vertical load, the viscous damper adds to the horizontal stiffness of the base isolation system. The design shear strain in the bearings is 300%.

A potentially very large market for base isolation systems is the seismic protection of museums. Priceless artifacts have been damaged during severe earthquakes in museums in Greece, Yugoslavia, and Italy and there are many museums located in highly seismic areas. The first museum to be built on a base isolation system is the Japanese Christian History Museum in Osio, Kanagawa Prefecture. The region is subject to frequent earthquakes and is designated by the government as requiring positive countermeasures against seismic attack. A base isolation system was adopted for this museum to protect the many exhibits concerning the history and development of Christianity in Japan.

The building, shown in Figure 37, is a reinforced concrete structure with two stories above ground and one at basement level. The building has a total floor area of 550 m^2, weighs 830 tonnes and is carried on 12 natural rubber isolators provided by the Bridgestone Corporation. They are 435 mm in diameter and 220 mm in height and provide a

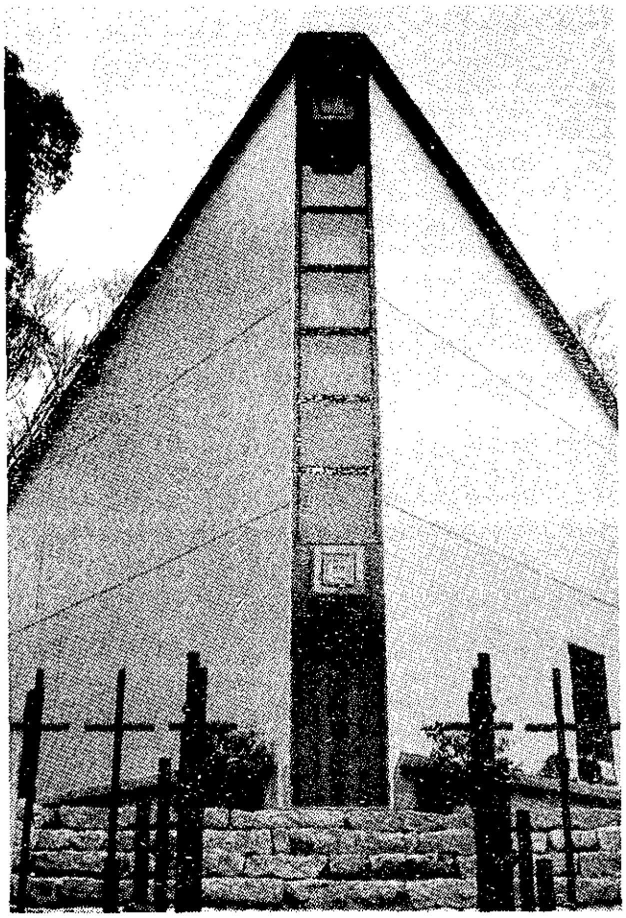


Figure 37 Base-Isolated Christian History Museum in Osio

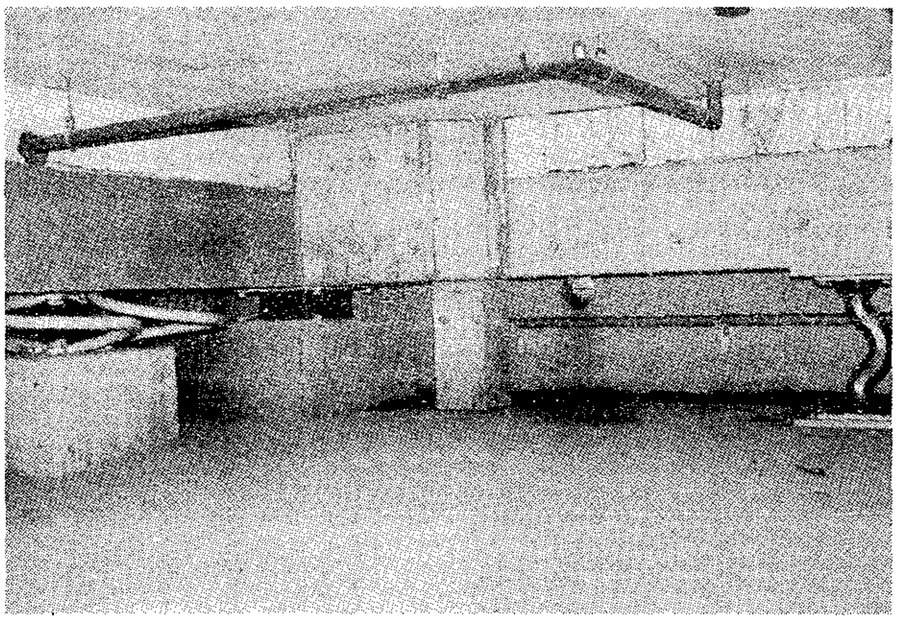


Figure 38 Isolation System for the Christian History Museum
(Bearings, Coil Dampers, Lead Dampers)

natural period of 1.9 seconds. The system includes 12 steel dampers of the type used in the Yachiyodai House and the Okumura Corporation building. With these features, the period of the isolated structure is 1.3 seconds. Another type of damper is incorporated to provide damping at small displacements when the steel dampers are less effective. This damper consists of lead bars in the form of a J attached between the foundation and the superstructure. A view of the complete isolation system is shown in Figure 38 and details are given in reference [10].

The building was constructed by TCRI and Yunichika Corporation and was opened to the public in April 1988. The response of the building to earthquakes is being studied by researchers at Fukuoka University. As of this writing, no earthquake response has been reported.

In a joint research program, Tohoku University and Shimizu Construction Company constructed two full-sized test buildings side by side on the Sendai campus in northern Japan. Construction was completed in May 1986. The buildings are three-story reinforced concrete structures, one conventionally founded and the other base isolated. The dimensions and construction methods for the superstructure were otherwise identical. Each building has a rigid frame structure, and the outer walls consist of lightweight concrete panels. The plan dimensions of each building are 6 m by 10 m, the total combined area being 180 m^2. The site consists of an 18 m layer of loam with gravel with an average shear wave velocity of 310 m/sec overlying sandy tuff. The site frequency from micro-tremor observations is about 4 Hz.

A general view of the buildings is shown in Figure 39; the structure on the right is base isolated. Plan and elevation views are shown in Figure 40. The isolation system consists of 6 laminated unfilled elastomeric bearings and 12 oil dampers. Figure 41 shows the bearing dimensions and oil dampers. The oil dampers have an equivalent damping ratio of 15% for a wide range of shear strain including small strains. The viscous oil used is expected to have a life of at least ten years.

Several static tests have been performed on the isolated building to confirm the bearing stiffness and damping properties. A static horizontal load was applied at the base of the isolated building using jacks to displace the building by ±170 mm. Forced-vibration tests were performed to confirm the dynamic properties of the buildings. Vibration exciters were placed on the center of the roof slab and the natural frequencies

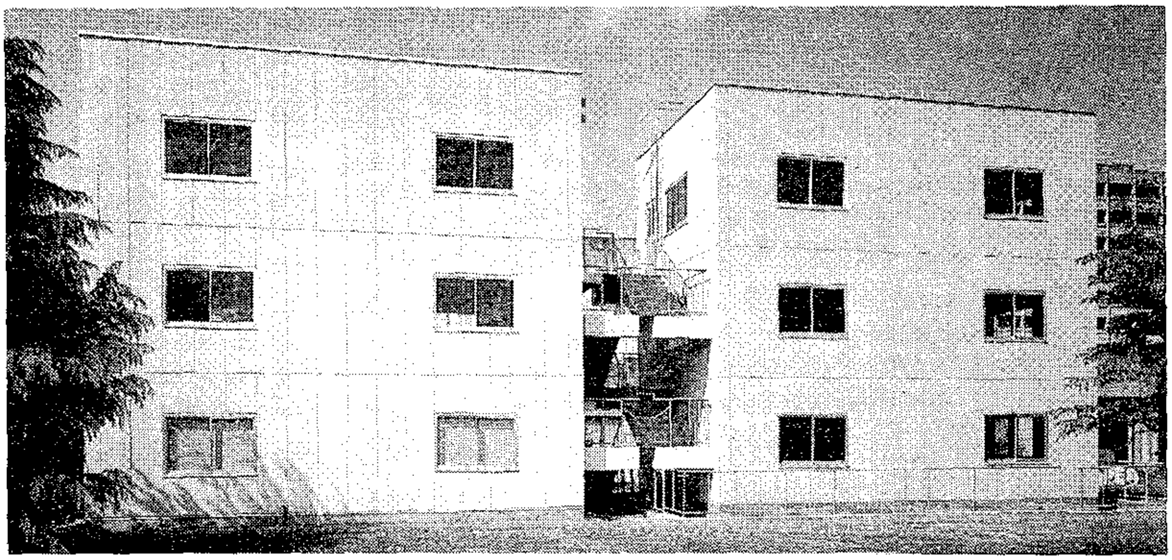


Figure 39 Shimuzu Company Test Buildings at Tohuku University

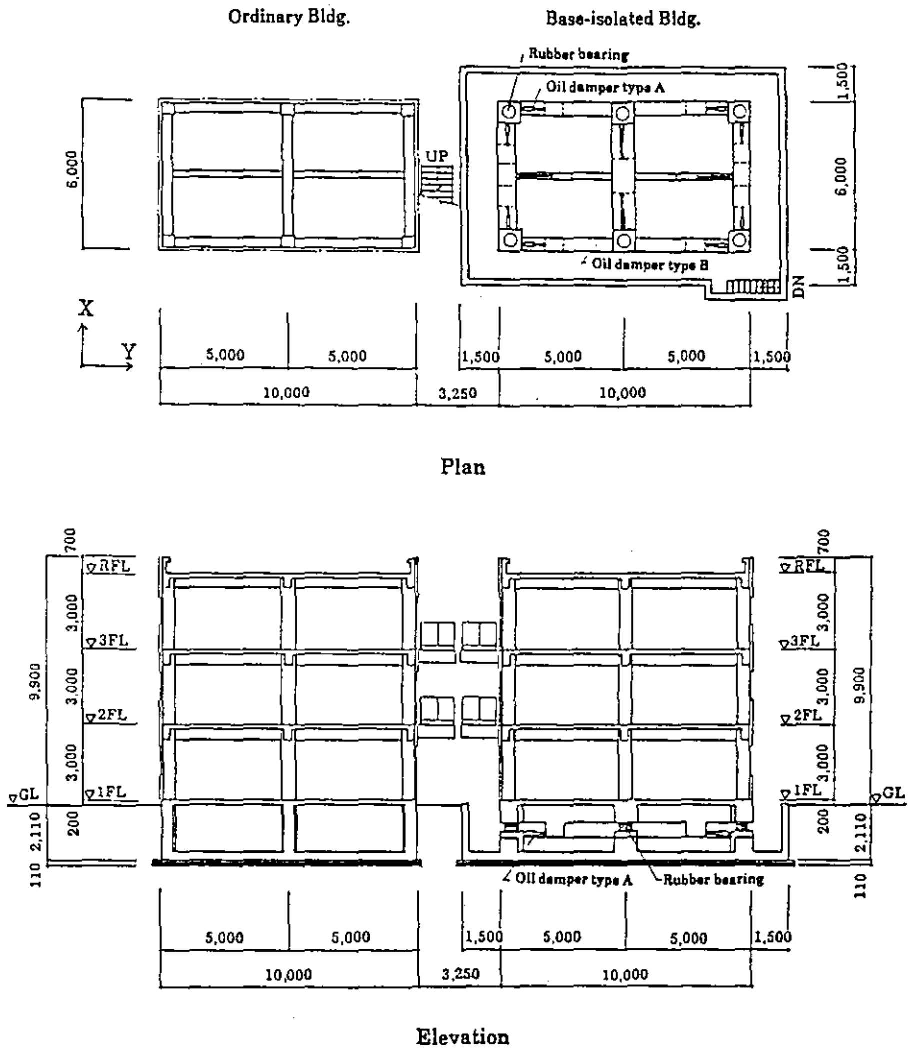


Figure 40 Layout of Test Buildings Showing Isolators and Dampers

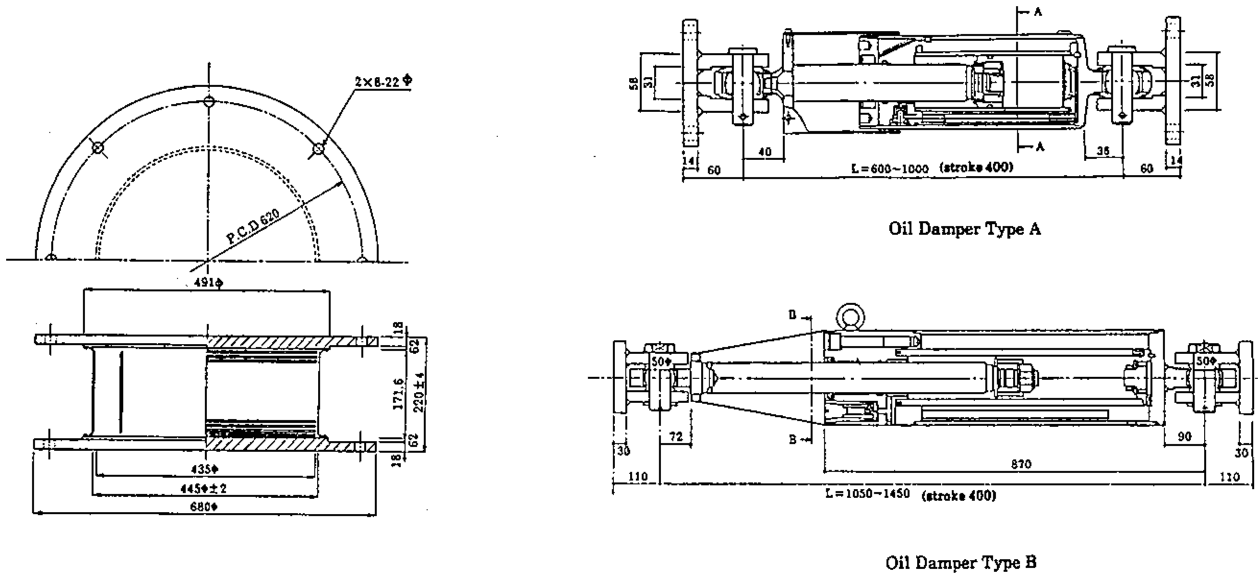


Figure 41 Dimensions of Elastomeric Bearings and Oil Dampers

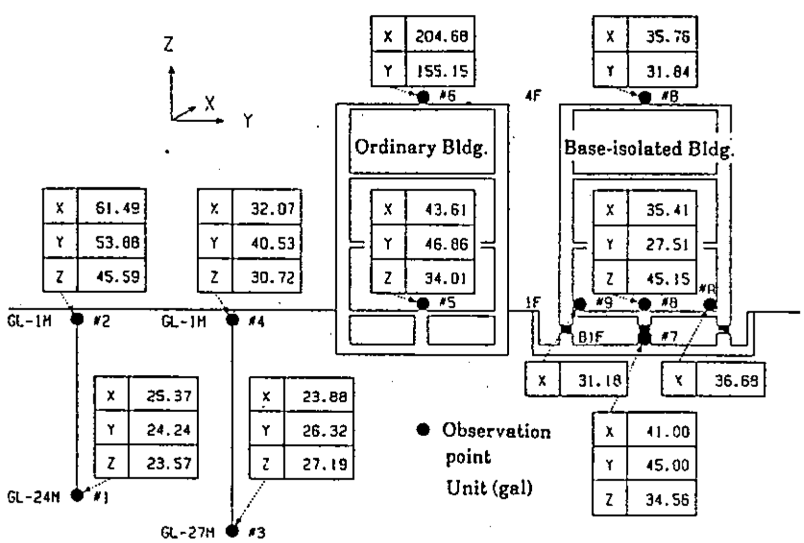


Figure 42 Recorded Maximum Accelerations during Earthquake of February 6, 1987

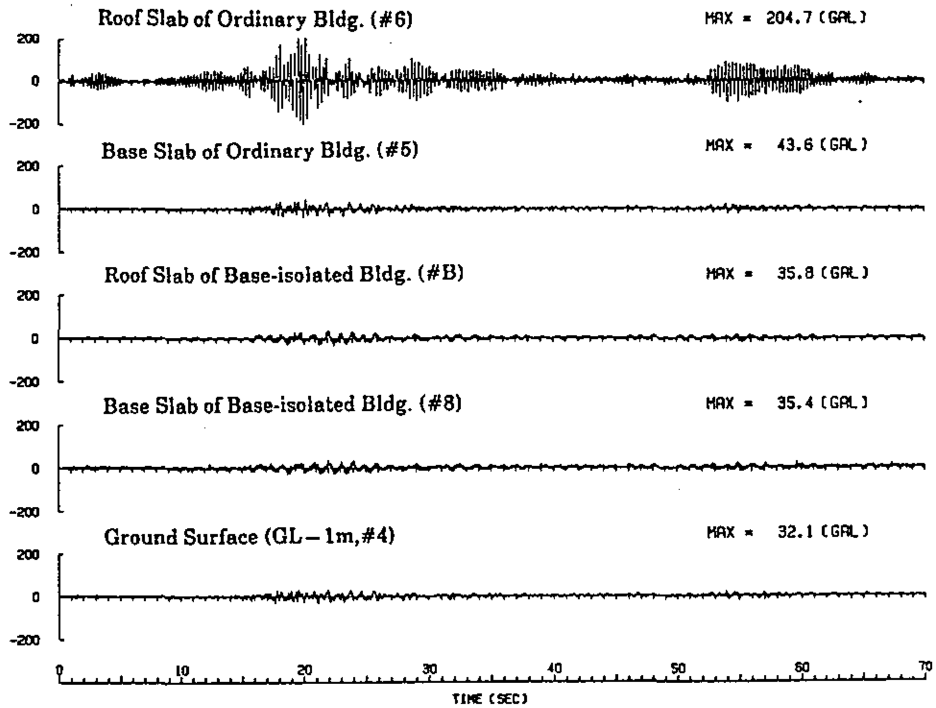
and damping ratios were obtained experimentally. The natural frequencies of the conventional building were 3.6 Hz in the x-direction and 4.4 Hz in the y-direction. The frequencies of the isolated building with the oil dampers were 0.72 and 0.73 Hz, respectively. The damping ratios of the isolated building were 16% in the x-direction and 15% in the y-direction. The damping of the bearings alone is less than 2%.

The buildings have been instrumented with 11 strong motion accelerographs installed in the base rock at elevation -27 m, near the surface in the free field, on the base slab, and on the roofs of the two buildings. Thirty earthquakes were recorded [11] between June 1, 1986 and July 20, 1987, most of which were low-level events. The largest acceleration recorded on the ground surface was 981 gals (.091g) and the corresponding peak accelerations at the roofs were 272 gals for the conventional building and 42 gals for the isolated structure. One of the strongest earthquakes recorded at the site was the earthquake of February 6, 1987 (magnitude 6.7, epicentral distance of 168 km). The values of maximum acceleration for this earthquake are shown in Figure 42 and the time histories of acceleration are shown in Figure 43.

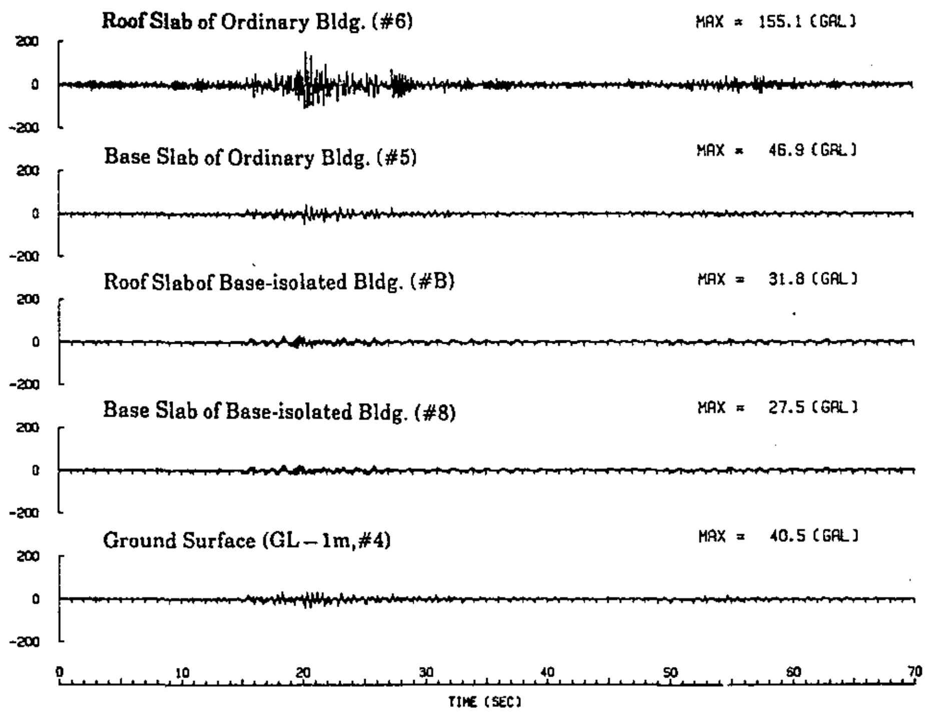
The amplification functions in the x-direction for the thirty earthquakes are plotted in Figure 44(a). The mean value of amplification is 5.95 in the conventional building and 0.99 in the isolated structure. The amplification factors in the y-direction are shown in Figure 44(b). The mean amplification values are 3.08 and 0.89 in the conventional and isolated buildings, respectively. The results for these earthquakes demonstrate the effectiveness of the isolation system in reducing accelerations induced in the superstructure.

The isolation system described above has since been replaced by 6 high-damping rubber bearings manufactured by Bridgestone Corporation. The relationship between lateral stiffness and damping versus shear strain for these bearings is shown in Figures 45 and 46, respectively. The damping ratio at low strain levels is 19% and decreases to about 15% for higher strain. The buildings are being monitored for earthquakes to study the performance of these high-damping bearings.

A departure from the previous base-isolated demonstration buildings is that of the Taisei Corporation. This building was due to be completed in late 1988 on the grounds of the Taisei Technological Research Center in Yokohama. In contrast to other base isolation systems which use natural rubber bearings as primary isolation elements, the



X-DIRECTION



Y-DIRECTION

Figure 43 Acceleration Time Histories for Earthquake of February 6, 1987

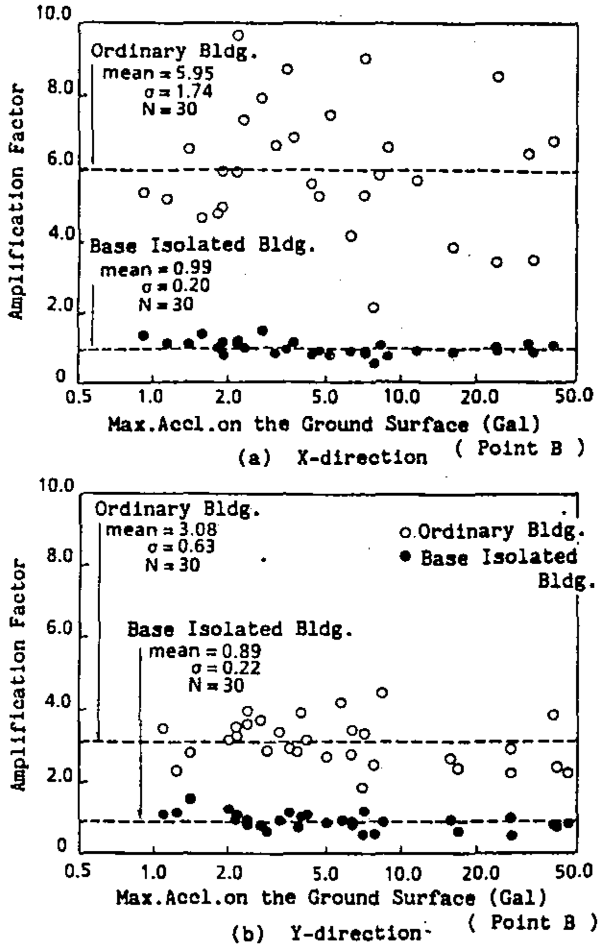


Figure 44 Amplication Factors for Test Buildings

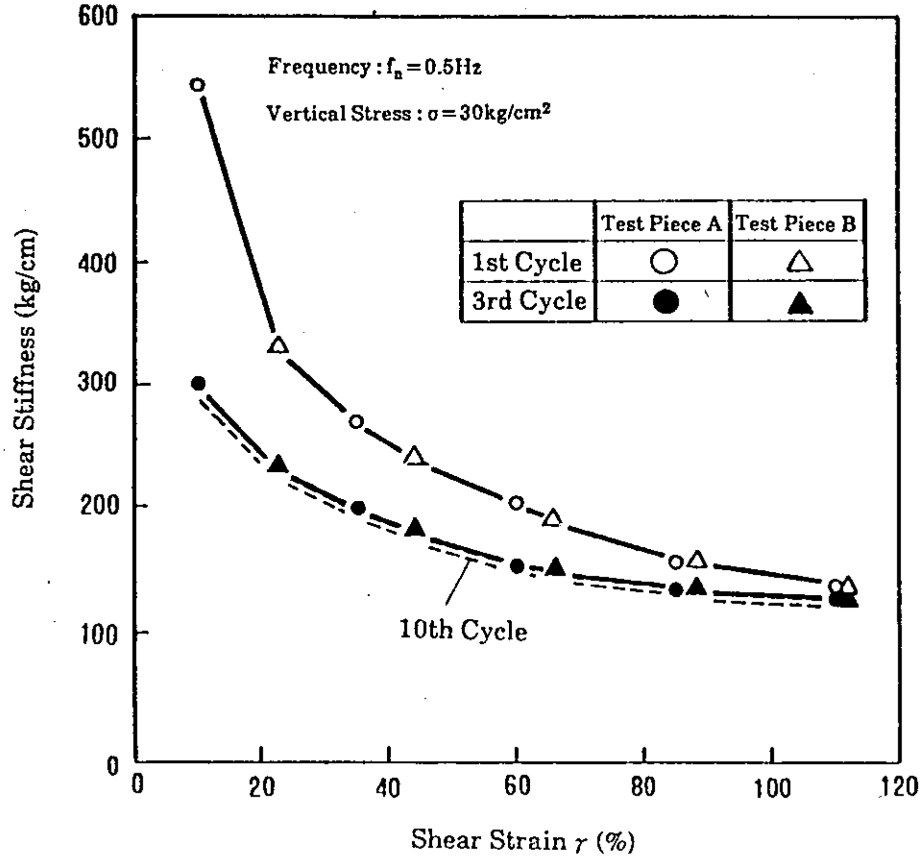


Figure 45 Relationship between Shear Stiffness and Shear Strain for High Damping Elastomer

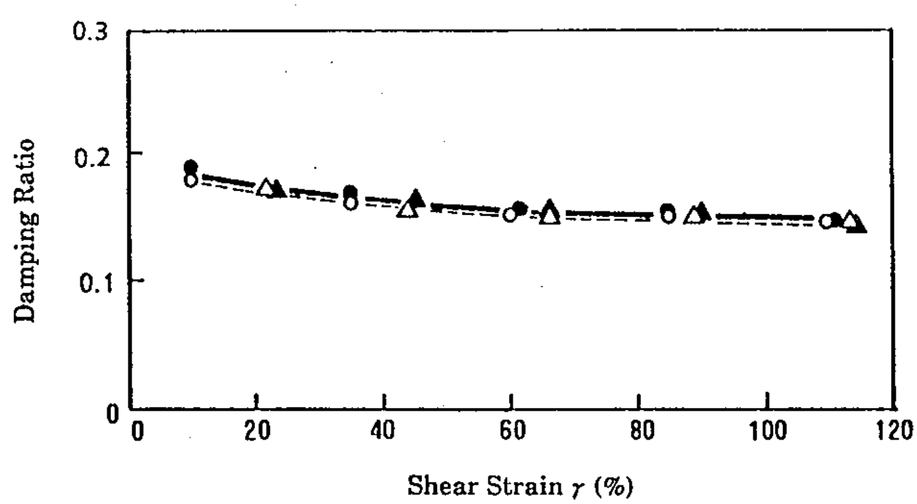


Figure 46 Relationship between Damping and Shear Strain

isolation system for this building uses a sliding system called TASS (Taisei Shake Suppression System).

The building shown in Figure 47 is a cast-in-place, four-story reinforced concrete structure with a plan area of 323 m^2. The building is supported on eight TASS bearings which use a teflon/stainless steel sliding surface and carry the entire vertical load of the building. A separate rubber bearing that carries no vertical load is positioned near each sliding bearing (Figures 48 through 50) to act as a restoring force and to control sliding displacement.

The sliding bearing has six layers of rubber under the teflon surface permitting a certain amount of movement before the interface begins to slide. Each bearing is 85 cm in diameter as loaded to 7 MPa. The friction coefficient varies from 0.1 to 0.16 and the isolation period before sliding occurs is about 1.2 seconds.

The building above the isolators was designed for a base shear coefficient of 0.15. Analyses of the response of the structure to El Centro 1940 and to Hachinohe 1968 were performed assuming a constant friction factor of 0.10 and it was concluded that the system would reduce the peak acceleration in the building considerably with a predicted maximum displacement of around 25 cm. Shaking table testing of a model for demonstration was carried out and the results are presented in reference [12].

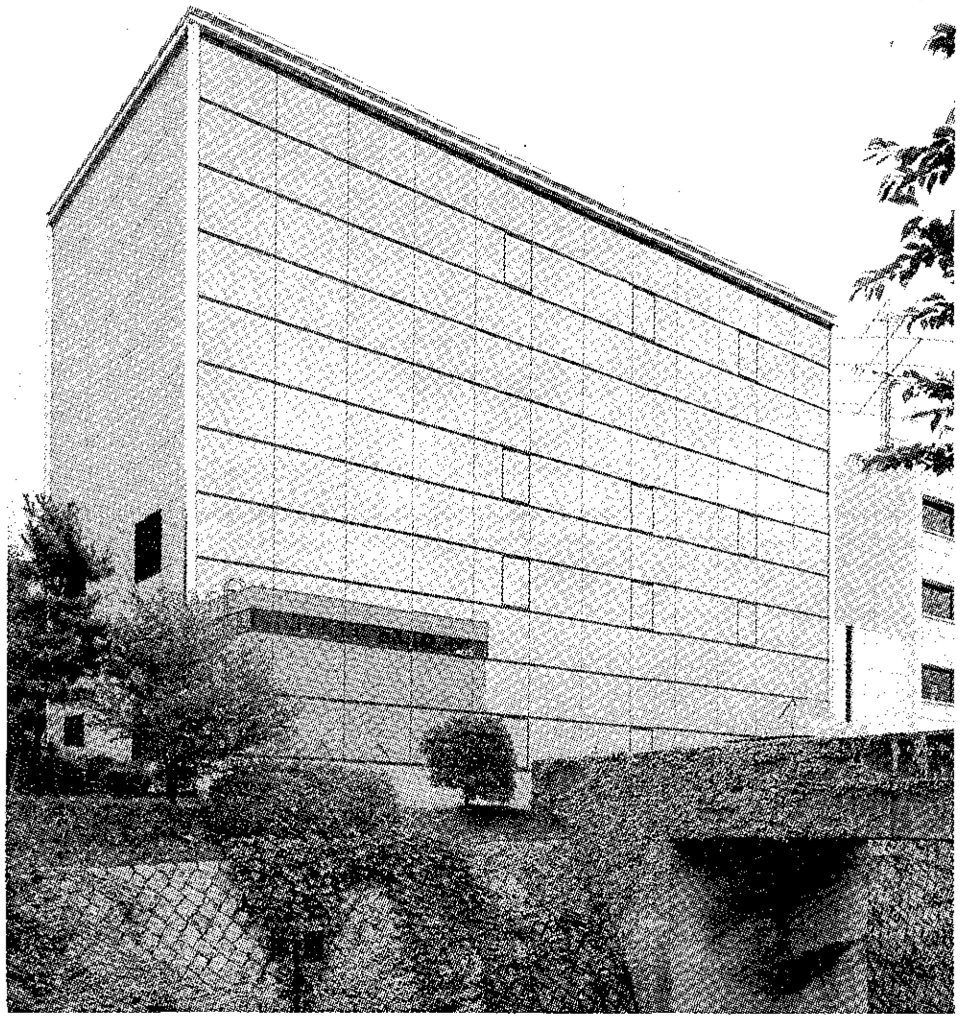


Figure 47 Taisei Corporation Demonstration Building on TASS System

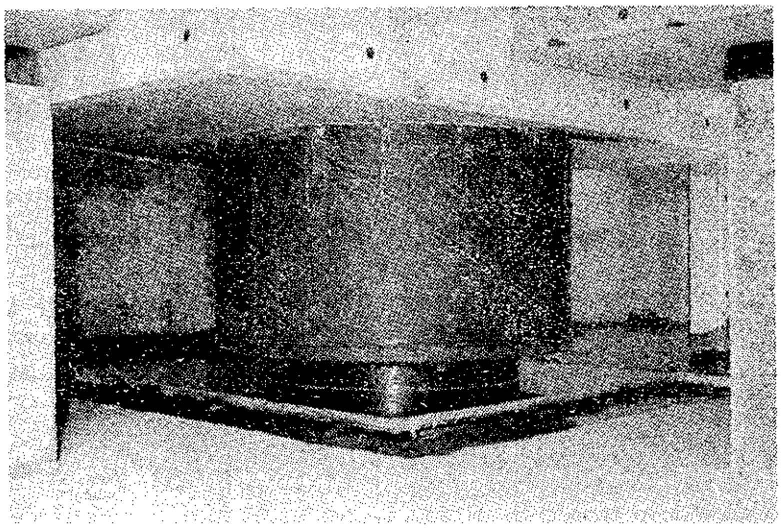


Figure 48 Vertical Load Support and Sliding Components

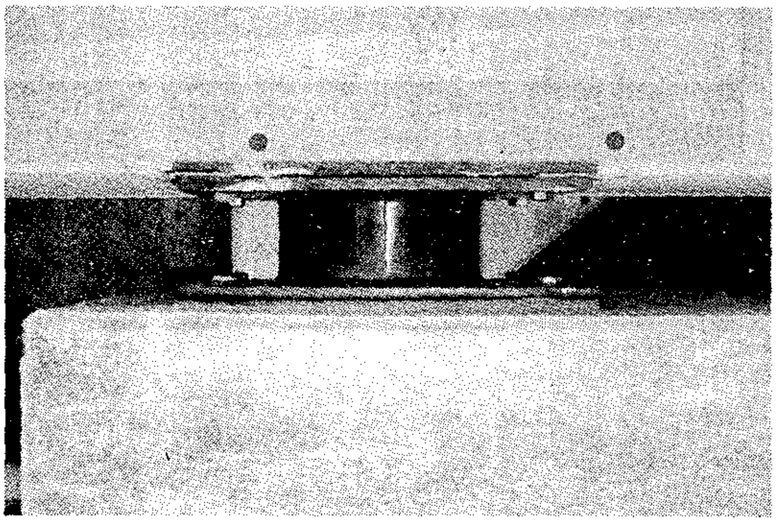


Figure 49 Horizontal Elastomeric Spring Used in TASS System

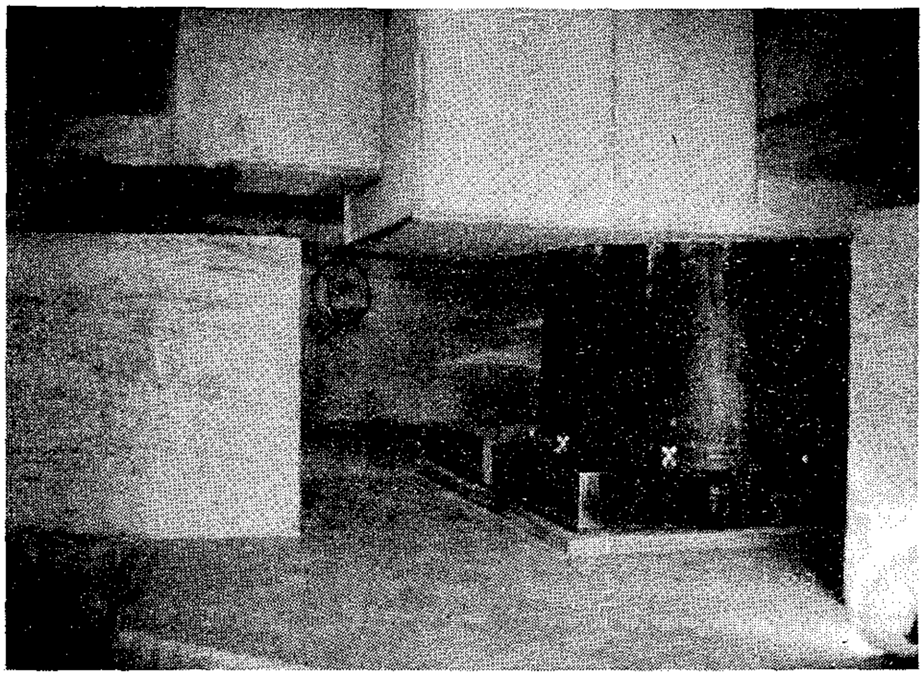


Figure 50 TASS System in Demonstration Building

COMMERCIAL BUILDINGS USING BASE ISOLATION

There is at present no design code for base-isolated buildings in Japan. Each design is reviewed by two committees in a review process that takes three months. A seven-member committee of the Japan Building Center acting as a consultant to the Ministry of Construction reviews the design and it is further reviewed by a committee of the Ministry of Construction before approval is granted. In the absence of a code the design criteria acceptable to the Ministry of Construction are as follows:

(a) soft ground sites are to be avoided (liquefaction potential);

(b) basin-shaped areas should be carefully studied for wave amplification and enhancement of long-period motions;

(c) height is restricted to a maximum of twenty stories;

(d) eccentricities should not be excessive;

(e) base shear coefficient should be greater than 0.15 and superstructure should be designed for ductility;

(f) the design philosophy is to allow for no damage for level 1 earthquakes ($PGV = 25$ cm/sec), minor damage for level 2 earthquakes ($PGV = 50$ cm/sec), and to activate fail-safe systems for level 3 earthquakes ($PGV = 75$ cm/sec);

(g) time history analyses must be performed using El Centro 1940 NS, Taft 1952 EW, and Hachinohe 1968 NS and EW (long-period motion);

(h) elastomeric bearings should be designed to carry an average pressure of less than 10 MPa; the allowable average shear strain (extreme lateral displacement divided by total rubber thickness) is a function of average pressure and is generally less than 200%;

(i) aging and fire-proofing of isolators should be checked; and

(j) provisions should be made for replacing the isolation mechanism if necessary.

Several construction companies have gained approval for commercial buildings that are now under construction and others are awaiting approval. A partial list of these buildings is given in Table 1. Such details as are available on the isolation systems and the design of the buildings follow.

TABLE 1

BASE-ISOLATED BUILDINGS IN JAPAN, JUNE 1988 (PARTIAL LIST)

(a) Building and Construction Company

BUILDING	CONSTRUCTION COMPANY	BUILDING USE
1. Yachiyodai Residence	TCRI*	Dwelling
2. Okumura Const. Tech. Ctr	TCRI & Okumura	Office
3. Ohbayashi Res. Inst.	Ohbayashi	Research Ctr
4. Oiles Const. Tech. Ctr	Sumitomo	Research Ctr
5. Kajima Const. Res. Inst.	Kajima	Laboratory
6. Nakano Apartment	TCRI & Okumura	Apartment
7. Shibuya Shimizu Building	Ohbayashi	Office
8. Tohoku Univ. Obs. Stn	Shimizu	Observ. Stn
9. Elizabeth Sanders Mus.	TCRI & Yunichika	Museum
10. Takenaka Dormitory	Takenaka	Dormitory
11. Tsukuba Mukizai Res. Inst.	Ohbayashi	Laboratory
12. Shimizu Const. Tsuchiura Off.	Shimizu	Office
13. Bridgestone Building	Shimizu	Office
14. Kumagaya Dormitory	Kumagaya	Dormitory
15. Minami-Koshigaya Apt.	Sumitomo	Apartment
16. Asano Building	Sumitomo	Office
17. Kogawa Apartment	Kumagaya	Apartment
18. Tokyu Const. Sugamihara Off.	Tokyu	Office
19. Jingu Apartment	Hazama	Apartment
20. Taisei Office Building	Taisei	Office

*TCRI: Tokyo Construction Research Institute.

(b) Construction Details

BUILDING	STORIES	DATE	ISOLATION SYSTEM
1. Yachiyodai Residence	2	1983	RB & Friction Dampers
2. Okumura Const.Tech.Ctr	4	1986	RB & Looped Steel Dampers
3. Ohbayashi Res.Inst.	5+(1)	1986	RB & Steel Bar Dampers
4. Oiles Const.Tech.Ctr	5	1986	Lead/Rubber
5. Kajima Const.Res.Inst.	2	1986	RB & Steel Cantilever Dampers
6. Nakano Apartment	4	1986	RB & Looped Steel Dampers
7. Shibuya Shimizu Building	5+(1)	1986	RB & Steel Bar Dampers
8. Tohoku Univ.Obs.Stn	3	1986	RB & Oil Dampers/HDRB
9. Elizabeth Sanders Mus.	2+(1)	1987	RB & Looped Steel Dampers
10. Takenaka Dormitory	3	1987	RB & Viscous Dampers
11. Tsukuba Mukizai Res.Inst.	1	1988	RB & Steel Bar Dampers
12. Shimizu Const. Tsuchiura Off.	4	UC	Lead/Rubber
13. Bridgestone Building	8	UC	RB & Steel Bar Dampers
14. Kumagaya Dormitory	3	UC	RB & Steel Bar Dampers
15. Minami-Koshigaya Apt.	10	UC	Lead/Rubber
16. Asano Building	7	UA	Lead/Rubber
17. Kogawa Apartment	3	UA	Not chosen
18. Tokyu Const. Sugamihara Off.	2	UA	Not chosen
19. Jingu Apartment	3	UA	Not chosen
20. Taisei Office Building	4	UC	TASS Sliding System

(1): Indicates underground floors
UC: Under construction
UA: Undergoing approval process
RB: Rubber bearing
HDRB: High Damping Rubber Bearing

Ohbayashi-Gumi Co. has completed an office building in Shibuya for Shimizu Co. This is a five-story (Figure 51) reinforced concrete building of 560 m^2 on twenty Bridgestone natural rubber isolators with 108 round steel bar dampers. It was granted Ministry of Construction approval in 1987 and was completed in 1988. Details of the building and the isolation system are shown in Figure 52.

Ohbayashi-Gumi has also recently completed an electron microscope laboratory at the Tsukuba Mukizai Research Institute. This building is only one story (Figure 53) and is 834 m^2 in area. It uses 32 Bridgestone bearings and 48 round steel bars as dampers. The need for isolation in this building is not dictated by seismic design requirements for the building but by the need to provide a high degree of seismic protection to the extremely sensitive instrumentation that it houses. The system provides a building which is both vibration isolated and seismically isolated. The design of the building was approved in 1987 and construction completed in 1988. In late 1987 Ohbayashi-Gumi was granted approval for an eight-story office building of 461 m^2 which is now under construction.

The Okumura Construction Co. in collaboration with Tokyo Kenchiku Structural Engineering completed a four-story apartment of 225 m^2 in 1987. It is carried on 12 rubber bearings and has 7 of the coil-type elasto-plastic dampers developed by Okumura. The same collaboration has built a 102 m^2 research laboratory for the Fujita Corporation in Kanagawa. It is a three-story reinforced concrete building on 4 rubber bearings with the coil-type dampers.

The Okumura Construction Company was granted permission in 1987 to build a three-story apartment house of 192 m^2 on 10 rubber bearings with 7 coil-type dampers.

The Shimizu Construction Co. has built two base-isolated buildings in addition to its demonstration building. One is a four-story office building of 170 m^2 on 14 lead-rubber bearings provided by Oiles Industries (see Figure 54). It is located in Ibaraki and is a branch office of the company. The second is an eight-story office building for the Bridgestone Corporation on 12 Bridgestone bearings. The dampers in this building are round steel cantilever bars.

In addition to the design and construction of the Oiles Technical Center, Sumitomo has recently completed the design of a ten-story apartment building and a seven-story office building both of which are to be isolated with lead-rubber bearings. The

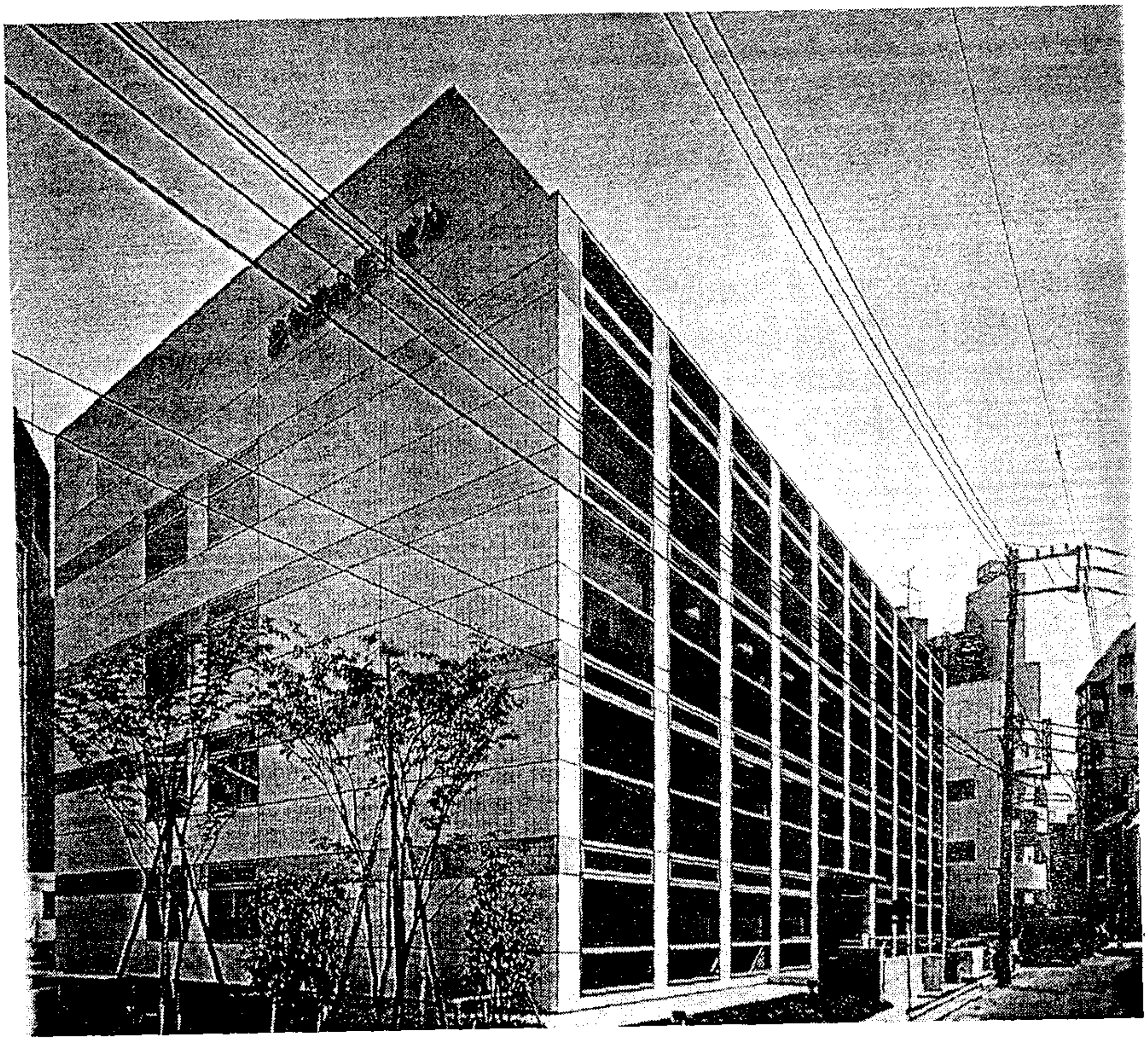


Figure 51 Shimizu Corporation Shibuya Office Building
Built by Ohbayashi-Gumi Ltd.

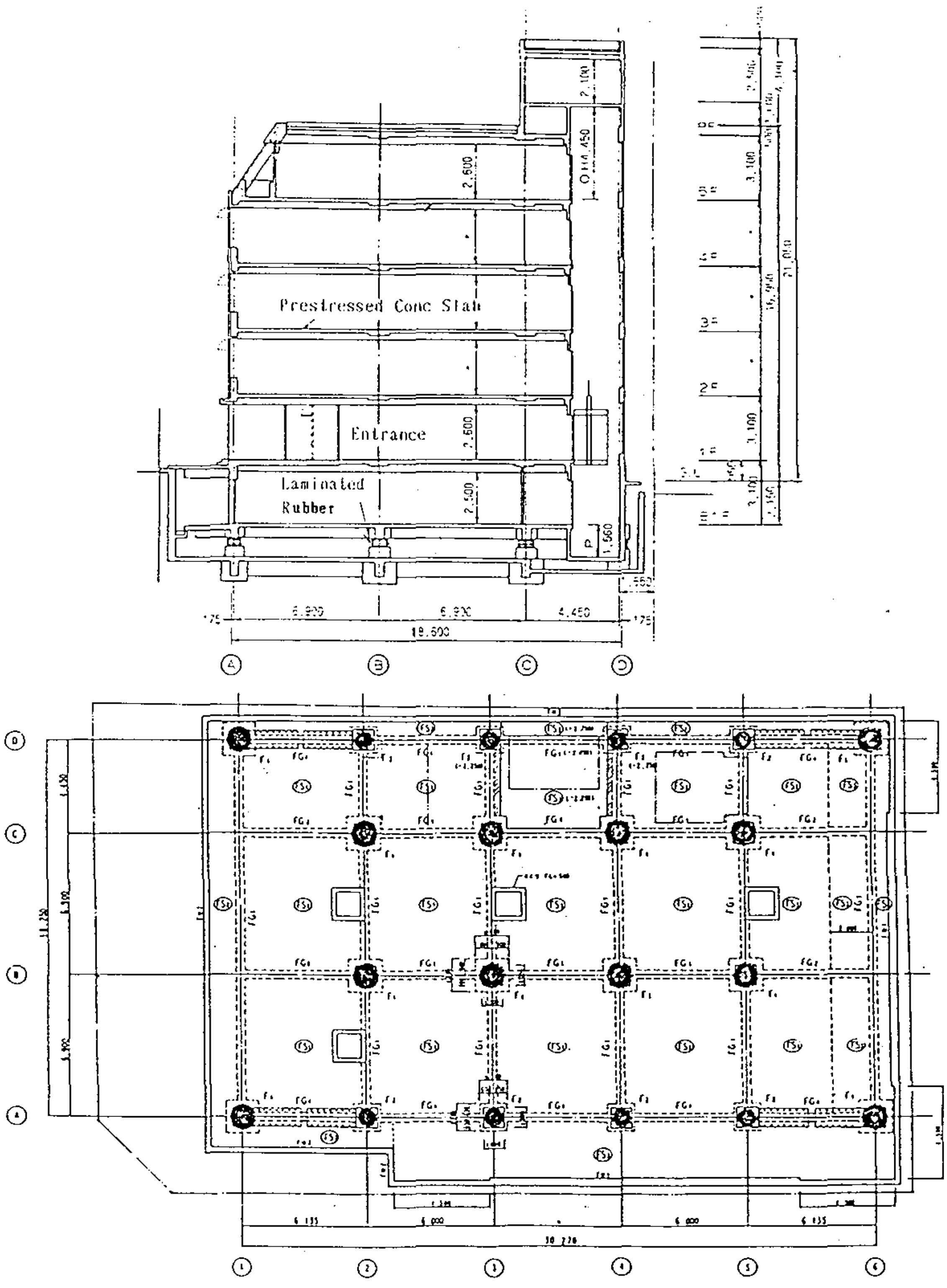


Figure 52 Plan and Section of Shimizu Corporation
Base-Isolated Building in Shibuya

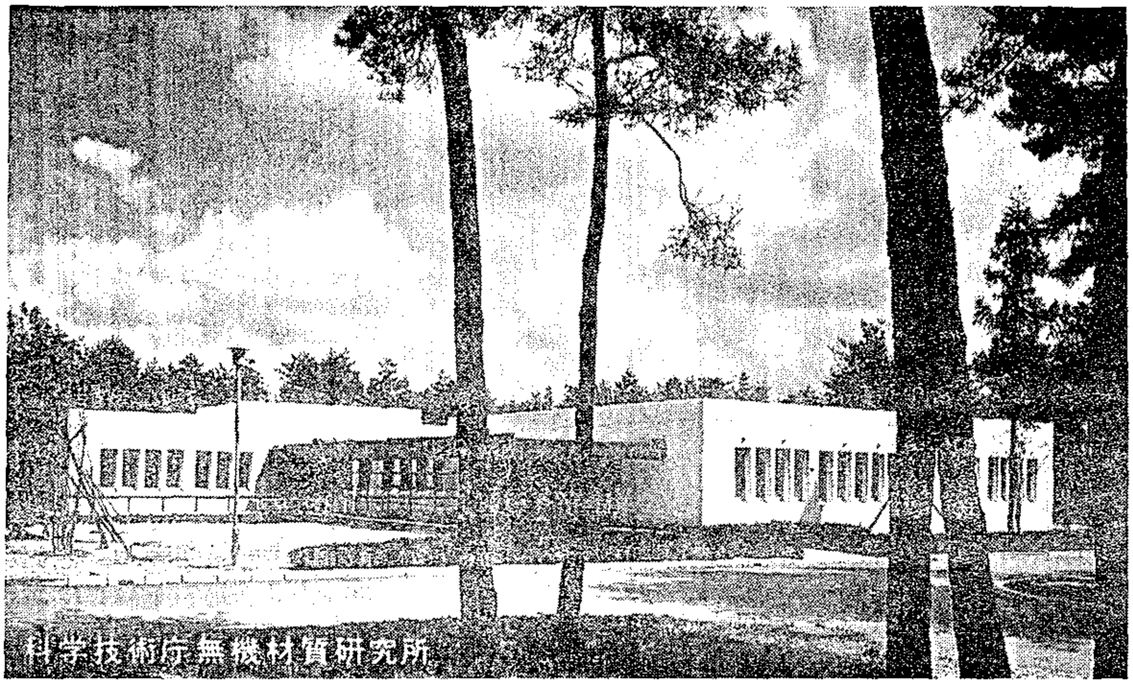


Figure 53 Electron Microscope Building by Ohbayashi-Gumi Ltd

Figure 54 Ibaraki Branch Office of Shimuzu Corporation

apartment building is known as the Itoh Mansion in Minami-Kosigaya near Tokyo (Figure 55). Its total weight of 660 tonnes will be supported on 14 lead-rubber bearings, each 900 mm in diameter with various lead plugs ranging from 160 to 222 mm in diameter. Eight uplift restrainers are used to resist overturning of the building in the transverse (narrow) direction (Figure 55). These devices are structural yokes which surround massive edge beams that run the length of the building. Each set of four uplift restrainers has a capacity of 500 tonnes. Two omnidirectional stoppers are used to control displacement (maximum limiting force is 400 tonnes). This building was approved in February 1988 and construction is underway.

Located in Nagoya City and to be known as the Asano Building, the seven-story office building is unusual in that it is to be isolated just below the second floor (Figure 56). The total weight to be supported above the isolators is 3800 tonnes. Ten lead-rubber bearings of diameter 800 mm and 900 mm and two horizontal stoppers are to be installed on a mezzanine floor within the first story of the building. The motivation for isolating at this level is to eliminate the trenches around the building which are necessary if the isolators are located in the basement. Such a detail permits the building to extend to the lot line and optimizes the use of expensive commercial real estate.

A consequence of this configuration has been the need to quantify the fire resistance of elastomeric bearings. Sumitomo has conducted tests on various bearings using different fire protection materials wrapped around each. Performance has been observed in three-hour tests at 1000 degrees centigrade in accordance with the Japanese equivalent of the ASTM standard. Excellent resistance has been demonstrated and this work appears to confirm previous work done by the Malaysian Rubber Producers' Research Association of England on unprotected bearings. The design for the Asano Building has been submitted for approval and should be under construction before the end of 1988.

The Fujita Corporation has built a small three-story reinforced concrete building on isolation bearings provided by Oiles Industries Ltd. The bearings are 450 mm in diameter and are 350 mm high, there are four in the isolation system and each carries a load of 85 tonnes. The building was initially constructed as fixed at the base and remained so for six months after which the isolators were installed. Forced vibration tests and observations of its earthquake response were carried out for both isolated and non-isolated states. Small earthquakes that occurred when the building was both fixed and isolated

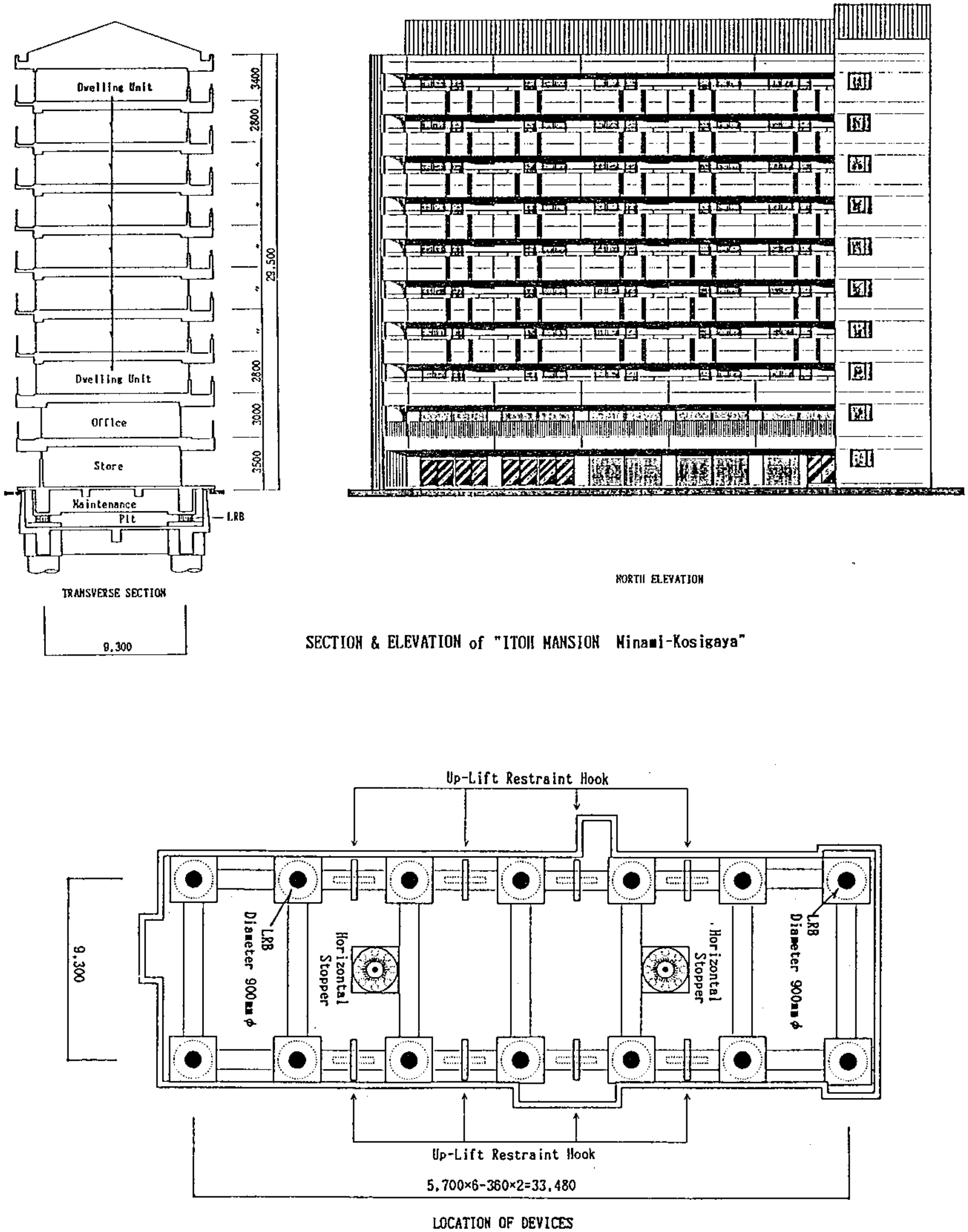
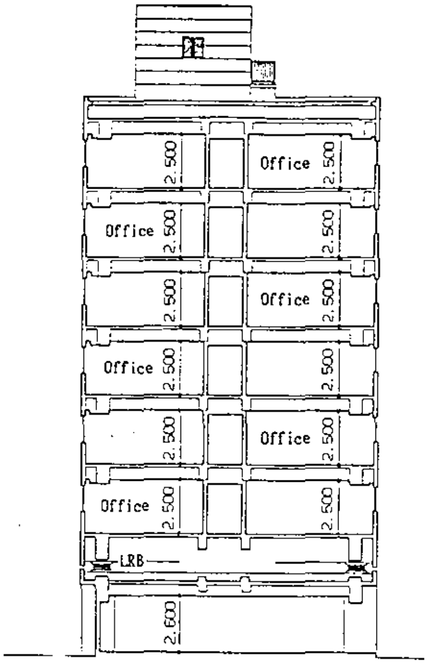


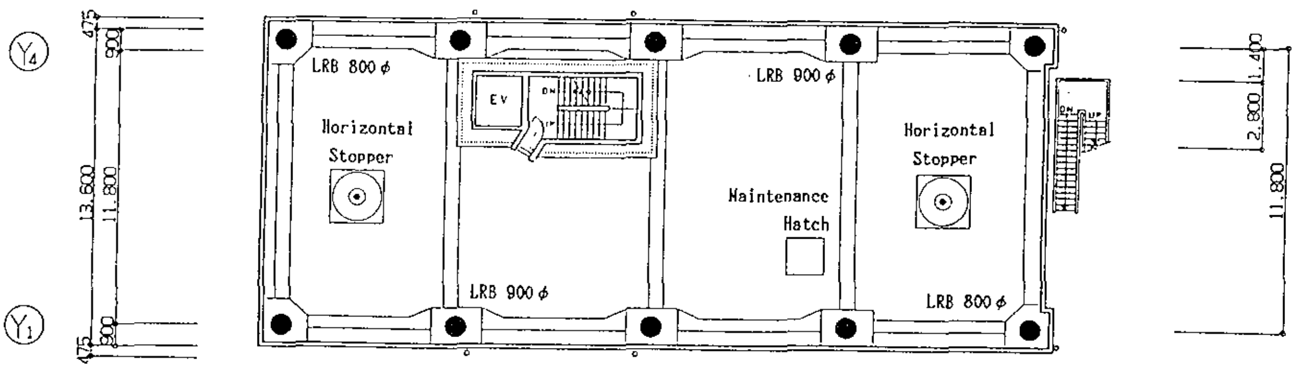
Figure 55 Itoh Mansion under Construction by Sumitomo Construction Company



SECTION

WEST ELEVATION

SECTION & ELEVATION OF "ASANO BUILDING"



MF LOCATION OF DEVICES

Figure 56 Asano Building under Construction by Sumitomo Construction Company and comparisons of the responses indicate that the amplification factor for ground acceleration was smaller for the isolated condition. The effectiveness of the system should of course increase as the earthquake intensity increases. The building on the four bearings is shown in Figure 57 and a close-up view of two of the bearings is shown in Figure 58.

Nikken Sekkei is designing a 6-story, 3.5 m by 22.5 m computer center using 28 low-damping natural rubber bearings 700 mm high and 600 mm in diameter. The period of the structure on rubber alone is about 3.0 seconds. The system will incorporate a set of friction dampers designed by Sumitomo Metal Industries, Ltd. The system will include 12 of the friction dampers. The total weight of the building is 7000 tonnes, and the floor area is 4500 m^2 and it is 24.8 m high. Approval is anticipated in May 1989 and construction will begin shortly after. An artist's rendering of the building is shown in Figure 59.

There are several other projects undergoing the approval process at this time, both offices and apartment buildings, the tallest of which is fourteen stories. No details of the isolators or superstructures are available. It is to be expected that the boom in the construction of base-isolated buildings in Japan will continue and will be very influential in stimulating acceptance of the strategy in other countries.

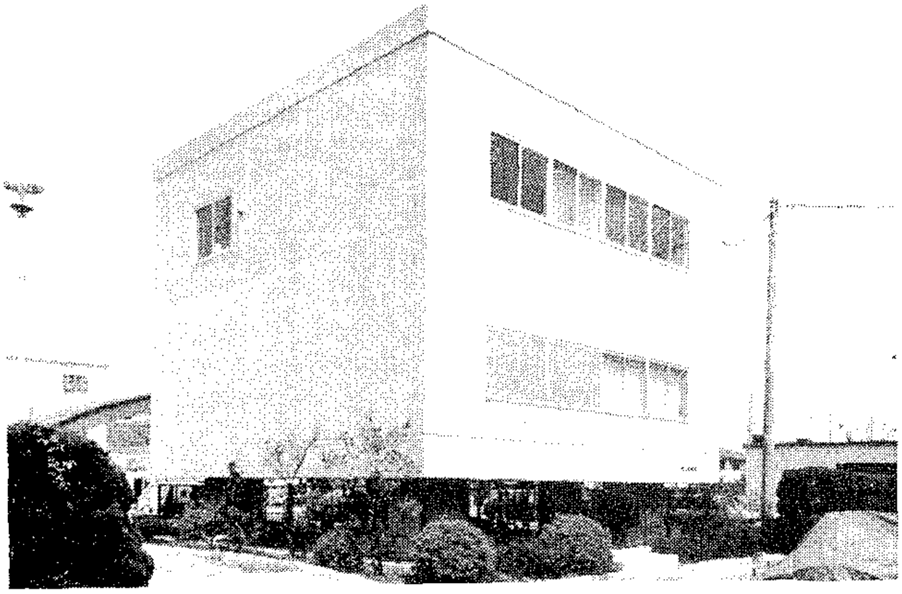


Figure 57 View of Fujita Corporation Base-Isolated Building

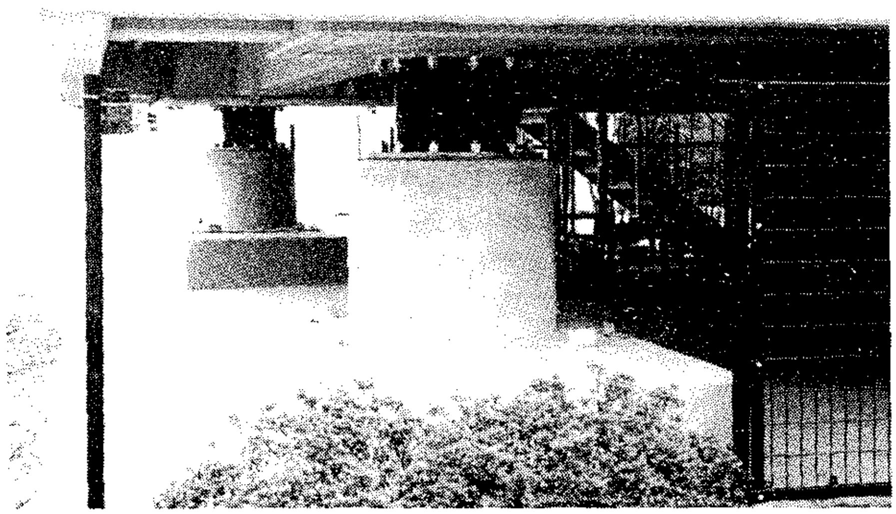


Figure 58 Isolators under Fujita Corporation Building

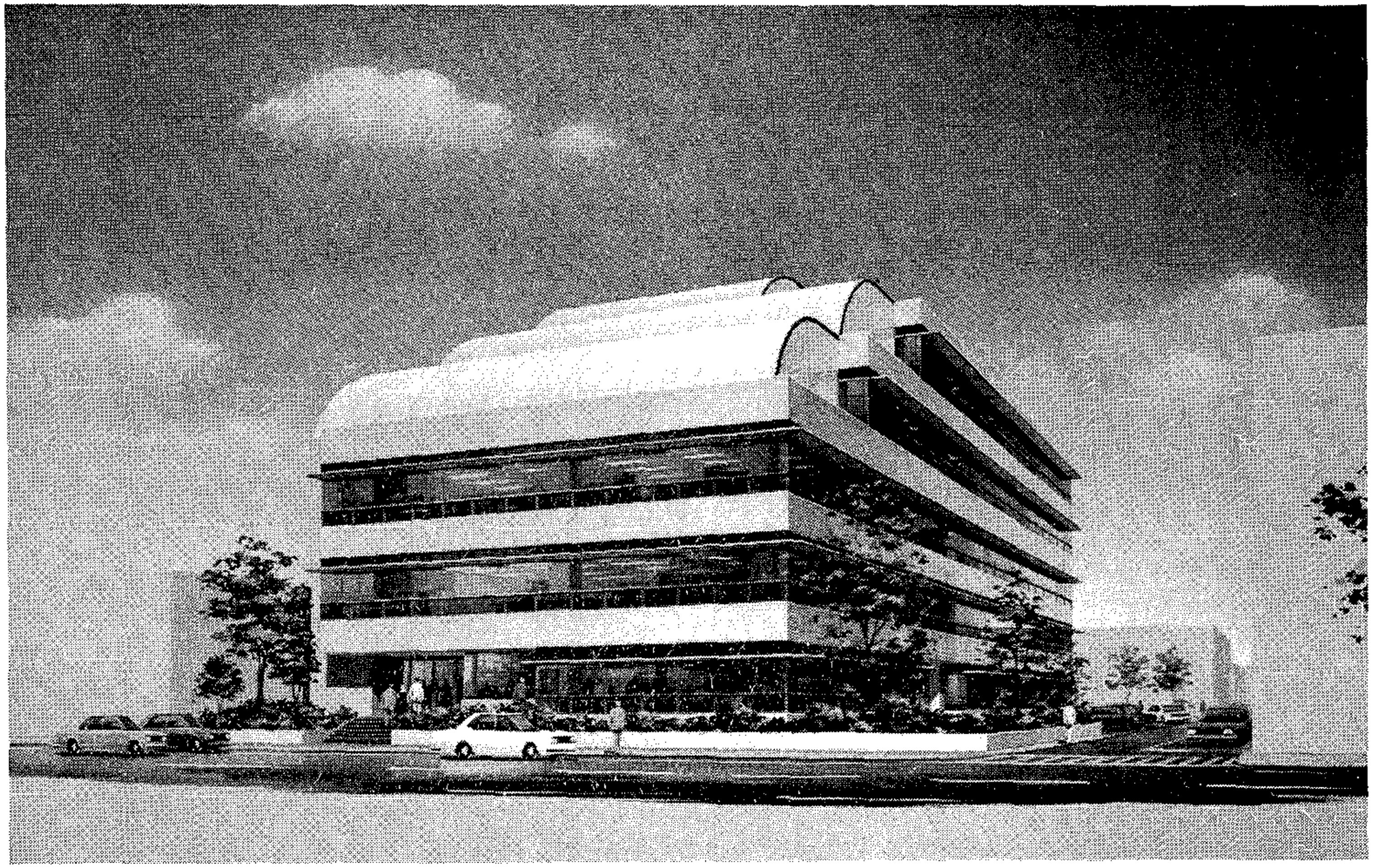


Figure 59 Rendering of Proposed Nikken Sekkei Base-Isolated Building

CONCLUDING REMARKS

Why has base isolation taken such a hold in Japan and why so rapidly? Research expenditures play a major role. Each of the large construction companies has invested about $3 million per year on base isolation research and development which combined with the investment by the bearing manufacturers such as Bridgestone and Oiles Industries puts total investment in base isolation research and development at approximately $25 million per year. This should be compared with a total of around $14 million made available for all earthquake engineering research by the National Science Foundation in the United States.

All the companies market base isolation very aggressively using videotapes, high-quality brochures, presentations on national television, technical papers in national and international conferences and numerous other formats. Most companies offer a multifaceted approach to isolation including approaches to seismic isolation, vibration isolation (against traffic-induced vibration), floor isolation systems for computer centers and energy-absorbing devices for interior walls.

The approval process is conducted at a higher level than in the United States where a building permit would be issued by the office of the city engineer, who may not be comfortable with a new technology. It is not reduced cost that has generated the boom. Base-isolated buildings in Japan are generally between 5% and 10% more expensive than conventional construction. The increased cost is justified in the increased safety of the buildings and the potential reduction in damage to the contents of the building due to moderate and severe earthquakes over the life of the building.

In the final analysis it is most probably the promise of increased safety and reduced damage that has led to the rapid acceptance of the new technology. Japan is a country where severe earthquakes are a certainty and the potential for catastrophic damage extremely high. Moderate earthquakes occur many times a year and are a constant public reminder of the danger. In contrast earthquakes in the United States, even in California, are less frequent and the public is not as alert to the danger. In addition there is a long-term bias toward low-cost, low-bid construction. The Japanese view appears to be that life-cycle costs rather than first costs are more important in deciding on an earthquake-resistant design strategy and it is this philosophy that has led to the rapid acceptance of base isolation in Japan.

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