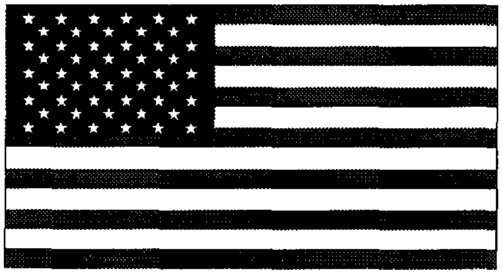
PB92-189562

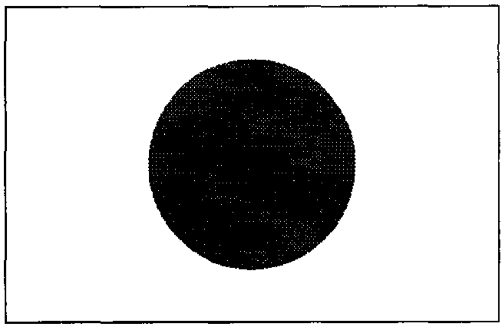
NIST Special Publication 832, Volume 1

Earthquake Resistant Construction Using Base Isolation

[*Shin kenchiku kozo gijutsu kenkyu iin-kai hokokusho*]

Earthquake Protection in Buildings Through Base Isolation





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Technology Administration
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- Electromagnetic Fields[1]
- Electromagnetic Technology[1]

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- Inorganic Analytical Research
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- Process Measurements
- Surface and Microanalysis Science
- Thermophysics[2]

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- Atomic Physics
- Molecular Physics
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- Quantum Metrology
- Ionizing Radiation
- Time and Frequency[1]
- Quantum Physics[1]

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- Automated Production Technology
- Robot Systems
- Factory Automation
- Fabrication Technology

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- Ceramics
- Materials Reliability[1]
- Polymers
- Metallurgy
- Reactor Radiation

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- Structures
- Building Materials
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- Systems and Software Technology
- Computer Security
- Systems and Network Architecture
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- Applied and Computational Mathematics[2]
- Statistical Engineering[2]
- Scientific Computing Environments[2]
- Computer Services[2]
- Computer Systems and Communications[2]
- Information Systems

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[1] At Boulder, CO 80303.

[2] Some elements at Boulder, CO 80303.

PB92-189562

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U.S. DEPARTMENT OF COMMERCE
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Building Center of Japan (MOC) (Noel J. Raufaste, Editor)

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This is Volume 1 of a two volume series on energy dissipating systems for buildings and other structures. This volume, *Earthquake Protection in Buildings through Base Isolation* describes energy dissipating systems and reviews their applications and effectiveness. The documents include guidelines for evaluating energy dissipating systems and a directory of the systems used in buildings and other structures. The two volume reports were produced by the Building Center of Japan under sponsorship of the Japanese Ministry of Construction (MOC) to describe the state-of-art of energy dissipating systems and to review their use in mitigating damages from earthquakes. The subjects addressed in these reports include: the history and types of passive energy dissipators; their applications, evaluations, and performance; and case histories of these systems exposed to seismic loading.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)

active damper; base isolation; damping; devices; evaluation; passive damper; performance; seismic; structures; wind loads

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Earthquake Resistant Construction Using Base Isolation

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Earthquake Protection in Buildings Through Base Isolation

Noel J. Raufaste, Editor

Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899

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Technology Administration
Robert M. White, Under Secretary for Technology

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ABSTRACT

This report is Volume One of a two volume series on passive energy dissipating systems for buildings and other structures. This volume, *Earthquake Protection in Buildings Through Base Isolation,* describes energy dissipation systems and reviews their applications and effectiveness. These documents provide guidelines for evaluating energy dissipating systems and a directory of the systems used in buildings and other structures. The original reports in Japanese were published by the Building Center of Japan under the sponsorship of the Japanese Ministry of Construction (MOC). The MOC provided these reports to the National Institute of Standards and Technology for their translation into English and for publication. The subjects addressed in these reports include: the history and types of passive energy dissipators; their applications, evaluations, and performance; and case histories of these devices exposed to seismic loading.

KEYWORDS: active damper, base isolation; damping; devices; evaluation, passive damper; performance, seismic; structures; wind loads.

Translated from Japanese by Amerind Publishing Co. Pvt. Ltd., New Delhi, under contract to The National Technical Information Service, Department of Commerce.

CONTENTS

FOREWORD

This is one volume of a two volume series on energy dissipating devices for buildings and other structures. Volume 1, *Earthquake Protection in Buildings through Base Isolation,* describes energy dissipating devices, reviews their use for application, and discusses their effectiveness. Volume 2, *Survey Report on Framing of the Guidelines for Technological Development of Base isolation Systems Buildings,* addresses the performance of these devices and provides examples of buildings installed with such devices and case studies. The two-volume reports were produced by the Building Center of Japan under sponsorship of the Japanese Ministry of Construction (MOC) to describe the state-of-the-art of energy dissipating devices and to review their use in mitigating damages from earthquakes.

These reports were made available to the National Institute of Standards and Technology (NIST) for translation into English and for publication through the Panel on Wind and Seismic Effects. The Panel is one of 16 comprising the U.S.-Japan Program in Natural Resources (UJNR). The Panel, composed of U.S. and Japanese agencies participating with representatives of private sector organizations, develops and exchanges technologies aimed at reducing damages from high winds, earthquakes, storm surge, and tsunamis. NIST provides the chairman and secretariat of the U.S.-side Panel on Wind and Seismic Effects; the Public Works Research Institute, MOC, provides the Japan-side chairman and secretariat.

These volumes were translated under contract by the National Technical Information Service (NTIS). The English translations convey the technical contents of the two reports; no further efforts were made to editorialize the translated manuscripts.

The U.S.-side Panel is indebted to the Japanese-side Panel for sharing useful design and construction information about an emerging technology for mitigating damages to buildings and other structures from earthquakes and high winds. The U.S.-side also is appreciative of the efforts of Mr. Tatsuo Murota, Director, Structural Engineering Department of the Building Research Institute (BRI), MOC, and his BRI staff for reviewing the English translated versions. Finally, we would like to thank Ann Lavedan of NTIS for her patient and careful attention to the preparation of the translated manuscript.

PREFACE

In this report, we have tried to examine topics related to response-control structures, base isolation structures and to analyze the trends of future technological developments.

Current studies of response-control structures and base isolation structures are being pursued from various viewpoints. A number of such buildings and structures have been built in various countries. In Japan, too, several new buildings have incorporated the base isolation concept. If we include the plans that have already been approved by the Minister of Construction, this number exceeds ten. In Japan, base isolation structures use laminated rubber bearings and most of them were developed by construction companies. In the future, in addition to base isolation systems using laminated rubber, we expect to see the use of active response-control systems, such as the active mass response-control system. These techniques may be used in various types of structures. It thus becomes necessary to conduct research on technological development; the government must ascertain safety of these structures and prepare guidelines for systematic technological development of these structures.

Traditionally, earthquake-resistant structures have meant those constructed using materials with adequate strength and ductility so as to withstand an earthquake. Based on lessons from the damage due to earthquakes, seismic design methods for earthquake-resistant structures rely on the mechanical dynamics, taking fundamental period of vibration of the structure, its restoring-force characteristics, energy absorption efficiency, etc. into account. Theoretically, the response-control or base isolation concepts which form the main theme of this report are not entirely different from conventional techniques. The only difference is that the fundamental period of vibration of structure, the restoring-force characteristics or energy absorption properties depend on structural elements in conventional systems but on mechanical equipments in response-control or base isolation systems. Studies on mechanical properties of such equipment, and surveys on the existence of special problems inherent to response-control or base isolation are the main focus today. Studies on earthquake ground motion are also important topics not only for conventional earthquake-resistant structure, but for these new structural systems

This report is a first step toward the study of response-control structures and the base isolation structures. The report itself examines the current status of response-control structures and the base isolation structures, and more detailed studies will be required in the next step.

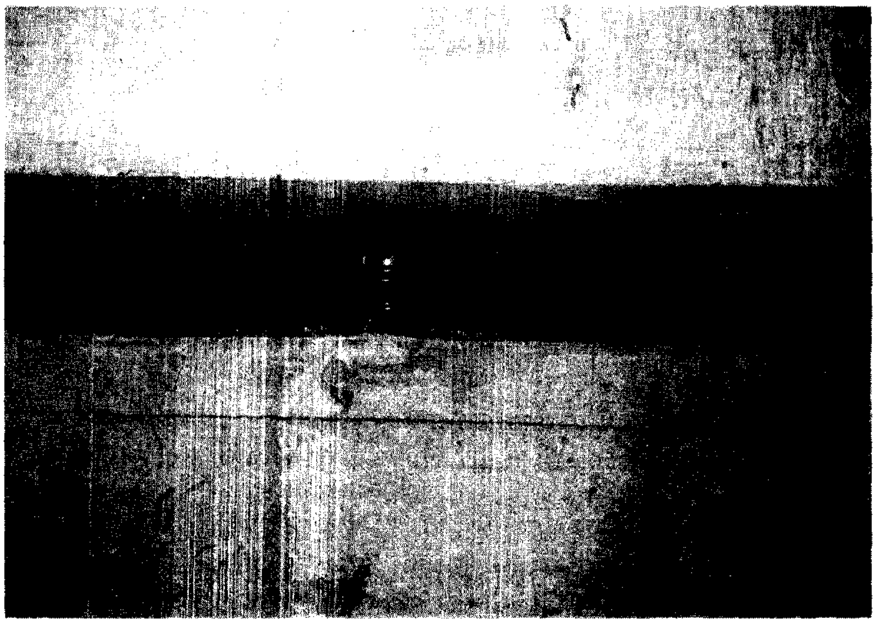
The Ministry of Construction asked us to prepare a survey report on framing guidelines for technological developments of base isolation buildings. To do so, an expert Committee on "Advanced Technology for Building Structures" and a Special

Task Group were set up at the Building Center of Japan to study new building structure techniques. This report presents their findings. We express our gratitude to Prof. Umemura who, as the adviser to the Expert Committee, guided the project, and to all other members of the Expert Committee as well as the Special Task Group who completed the study in so short a time that the report could be presented in this form. Thanks are also due to the Building Center of Japan for the administrative help they rendered.

Hiroyuki Aoyama
Chairman, Expert Committee on Advanced Technology
for Building Structures

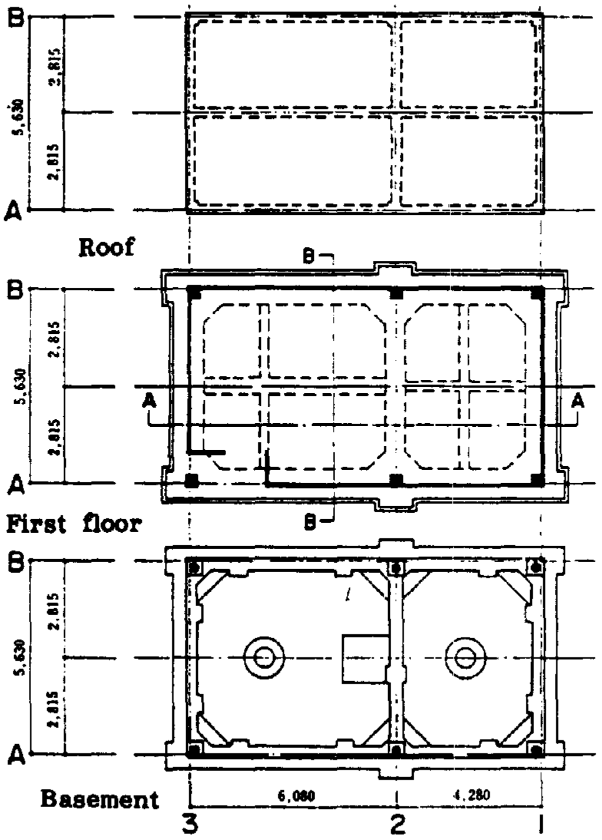
Name of the building:	Yachiyodai Unitika-type Base isolation Apartments Yachiyo City, Chiba Prefecture
Observations started:	April 1983

Base isolation device

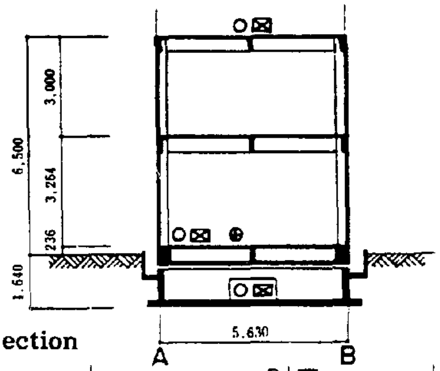


View of the Base isolation apartments

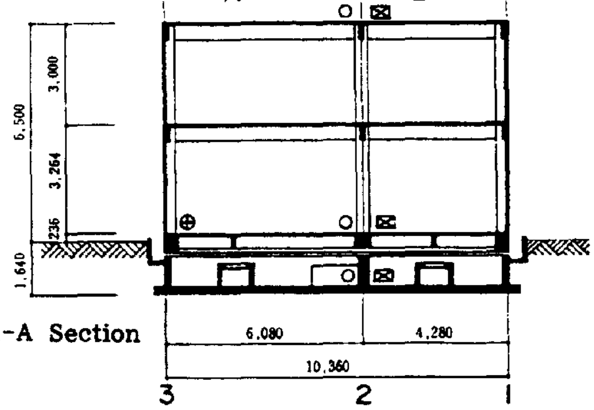
BUILDING OUTLINE



PLAN

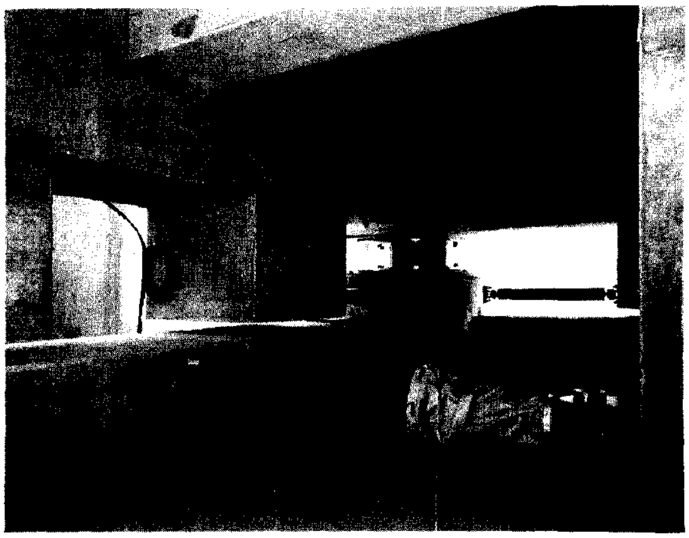


B-B Section

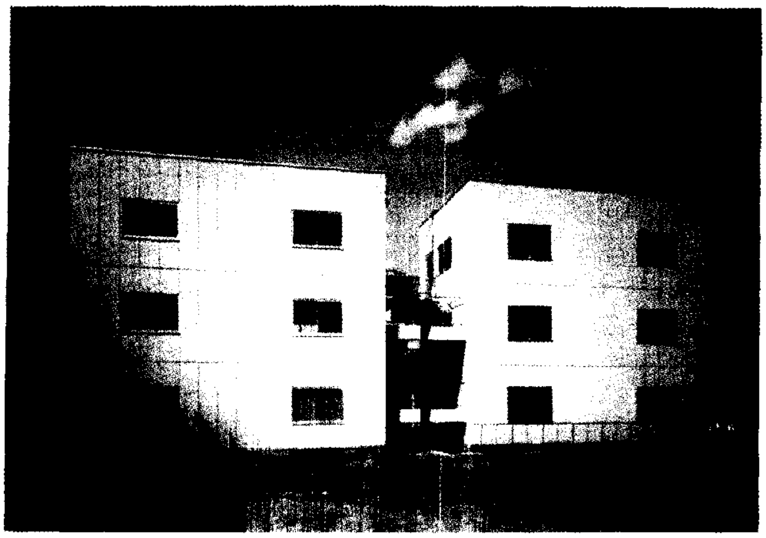


A-A Section

Name of the building	Tohoku University Experimental base isolation building Sendai City Miyagi Prefecture
Observations started:	June 1986

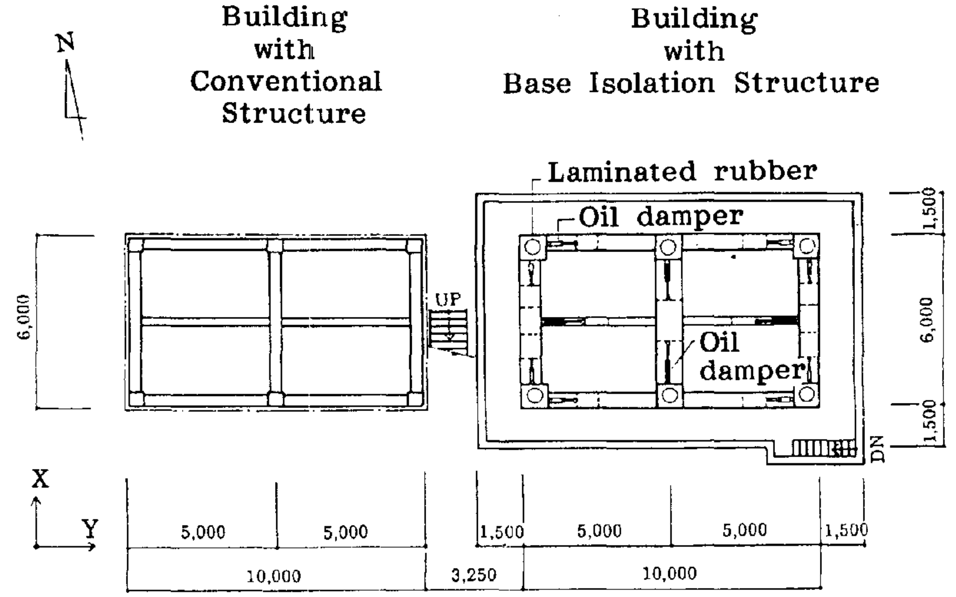


Base isolation device

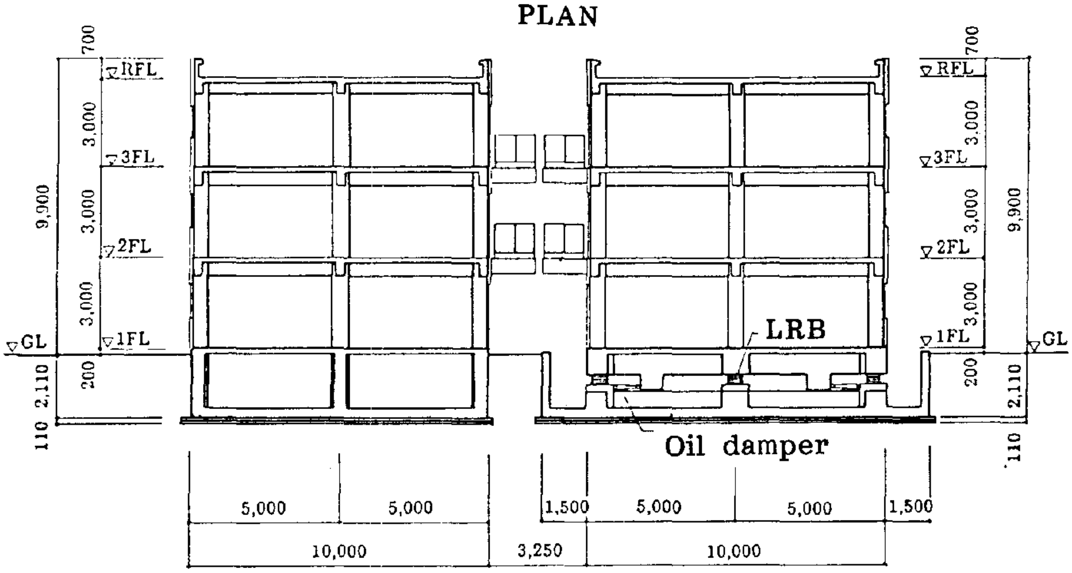


View of the experimental base isolation building.
Left-Building with conventional structure
Right-base isolation structure.

BUILDING OUTLINE

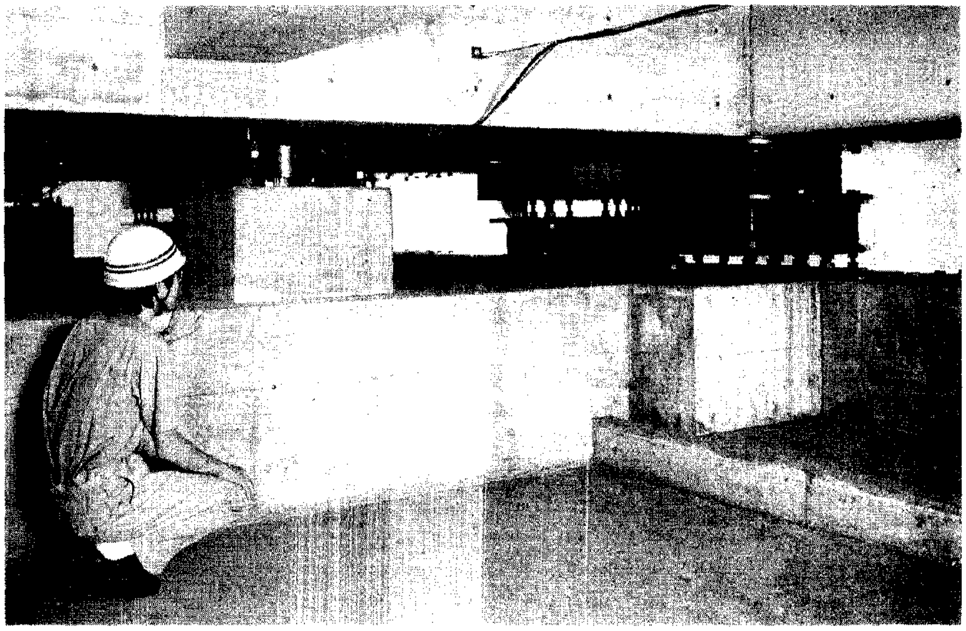


PLAN

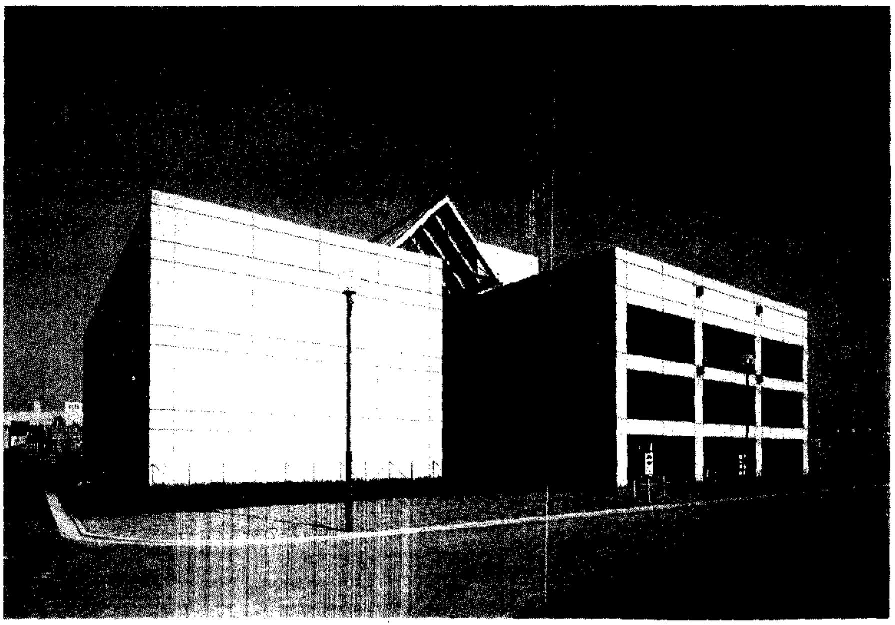


SECTIONAL VIEW

Name of the building:	Kajima Institute of Construction Technology, Acoustic and Environmental Vibration Test Laboratory Chofu City ,Tokyo
Observations started:	June 1986

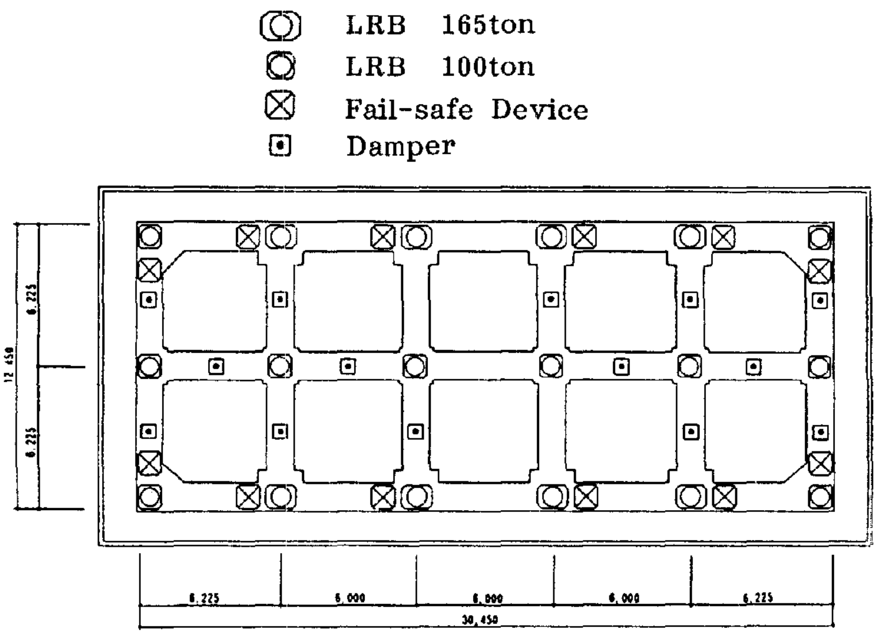


Various devices fitted at the foundation.

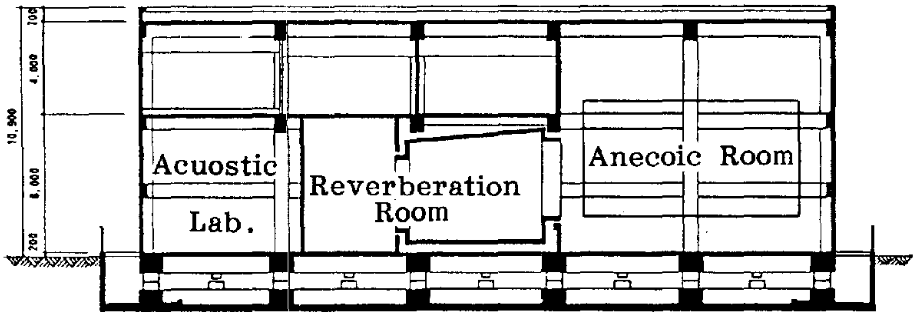


View of the acoustic and environmental vibration test building.
(Left - base isolation building; Right - building with conventional technique).

BUILDING OUTLINE

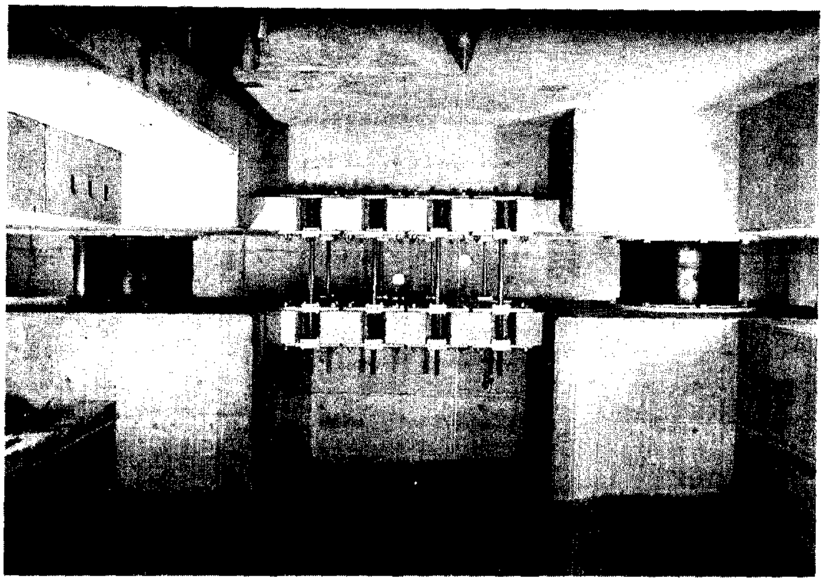


FOUNDATION PLAN

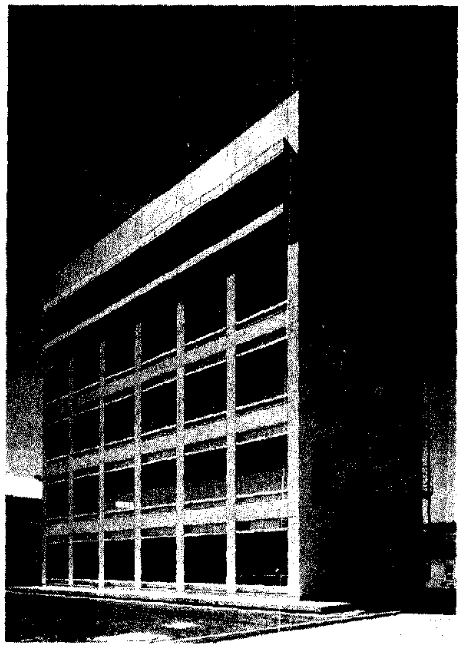


SECTIONAL VIEW

Name of the building:	Obayashi Technical Research Institute 61st Experimental Wing (Hi-tech R&D Center) Kiyose City,Tokyo
Observations started:	August 1986

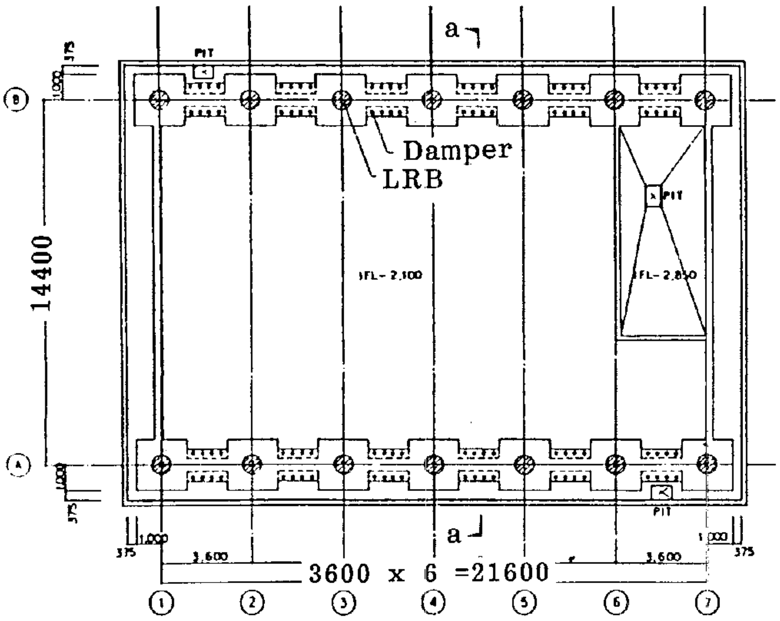


Base isolation device.

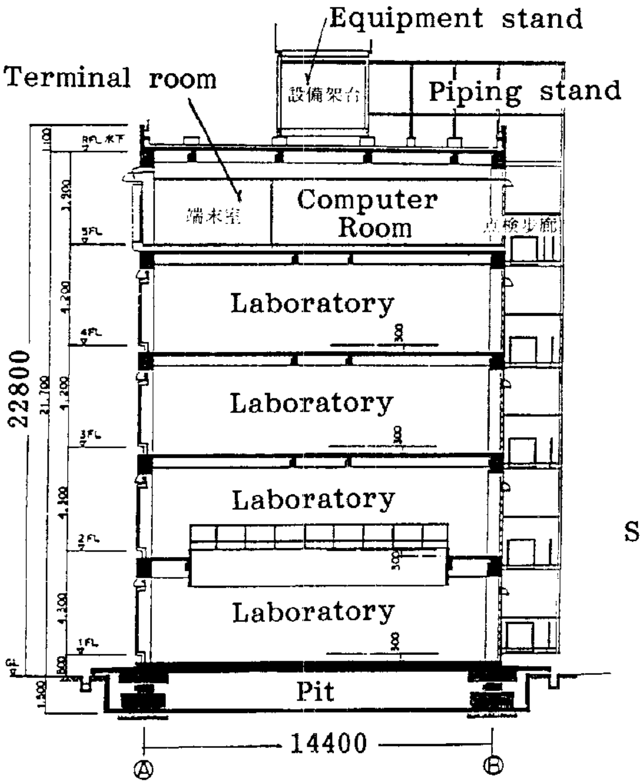


View of the 61st Experimental Wing.

BUILDING OUTLINE



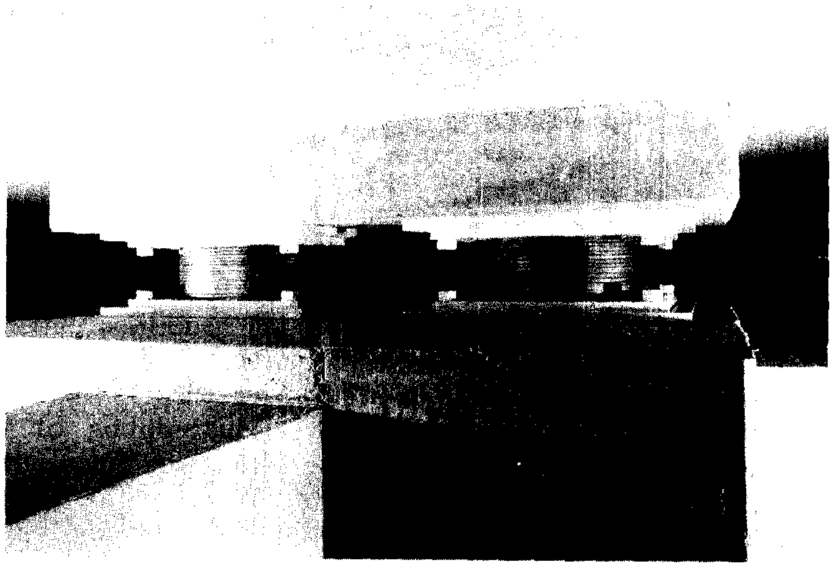
FOUNDATION PLAN & POSITION OF BASE ISOLATION DEVICES



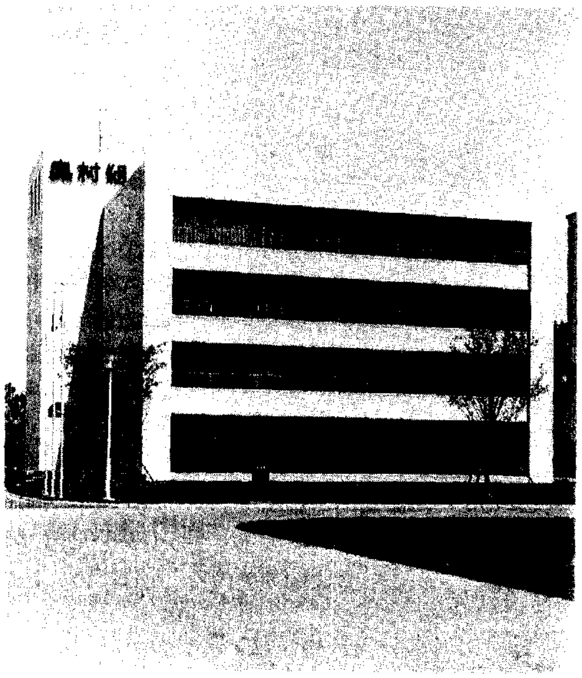
SECTIONAL VIEW (a-a)

Name of the building: Okumura Gumi Tsukuba
Research Laboratory Administrative Wing
Tsukuba City, Ibaraki Prefecture

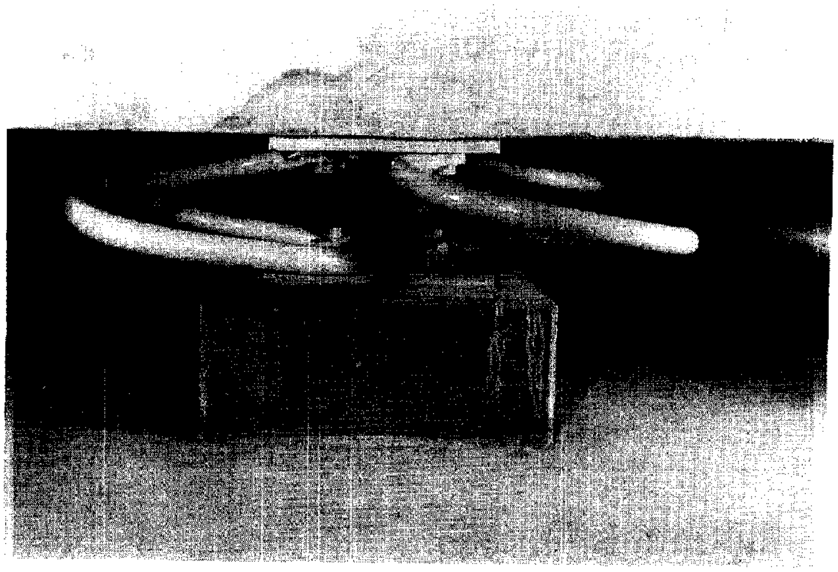
Observations started: September 1986



Base isolation device

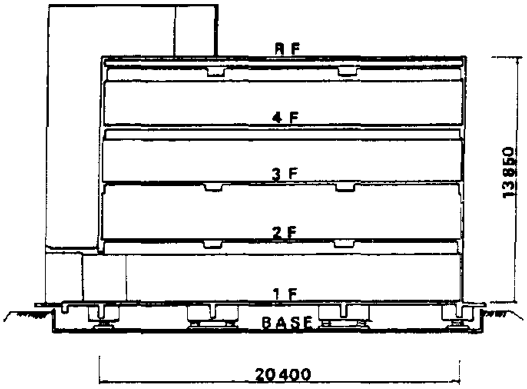


View of the administrative wing

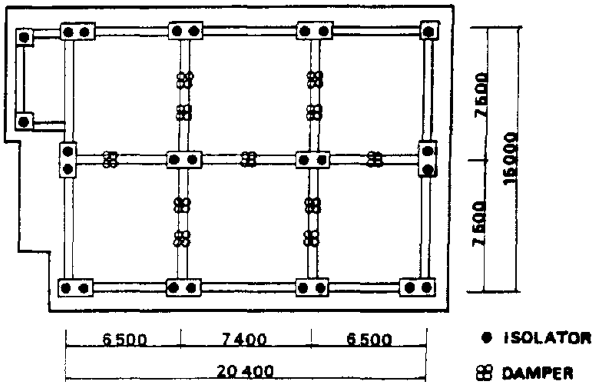


Steel - loop type damper

BUILDING OUTLINE

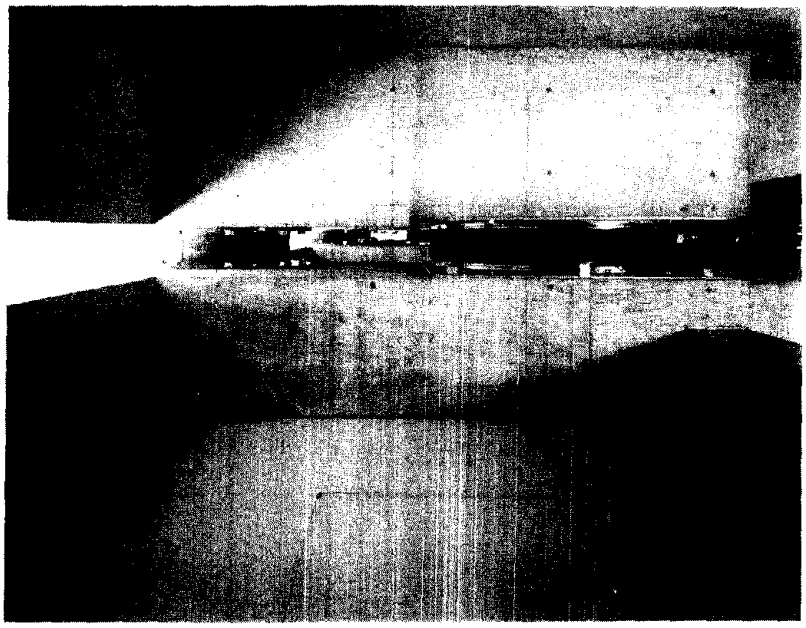


SECTIONAL VIEW

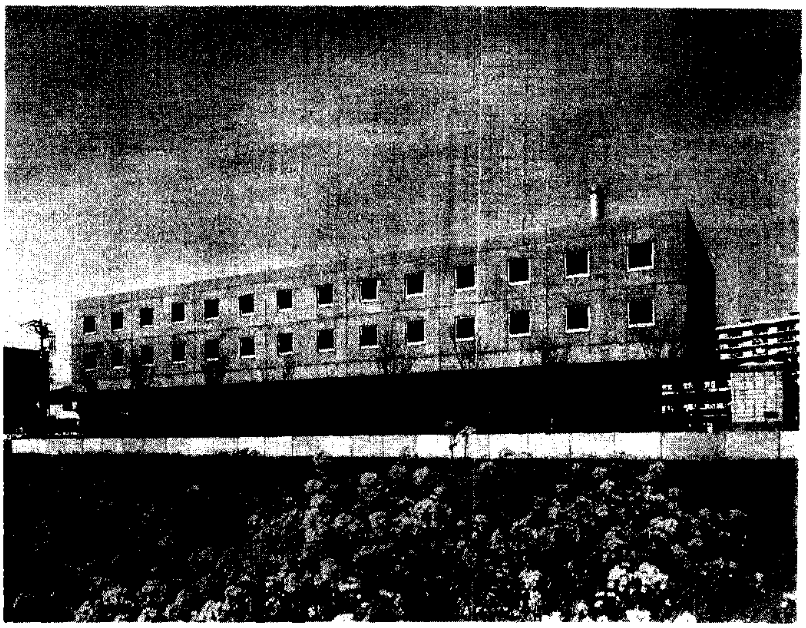


POSITIONS OF BASE ISOLATION DEVICES

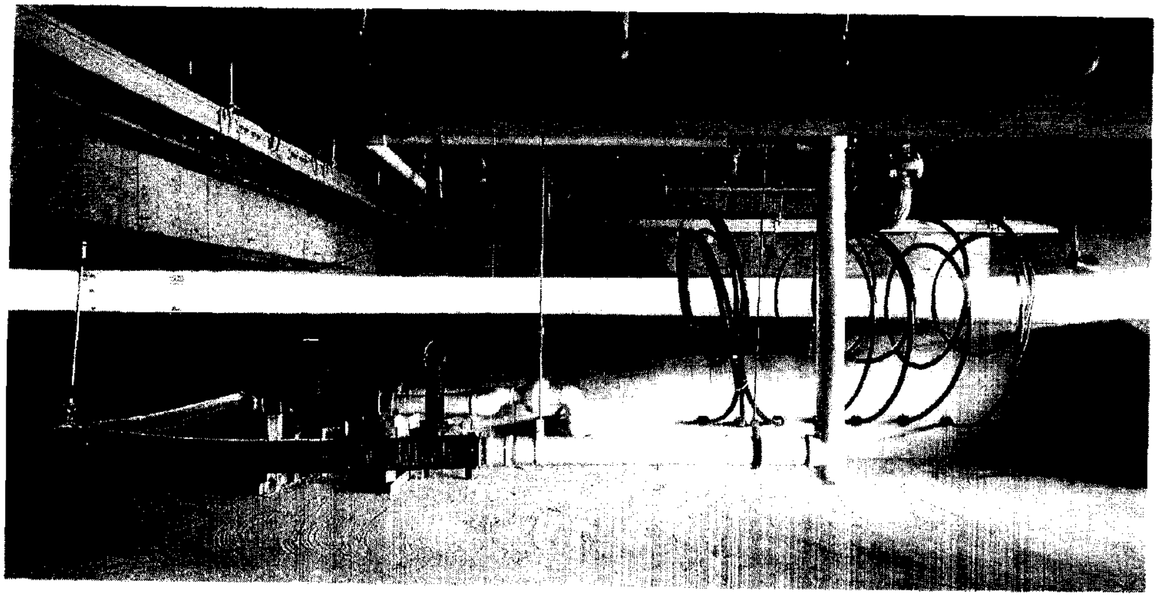
Name of the building:	Takenaka Komuten Funabashi Taketomo Dormitory Funabashi City, Chiba Prefecture
Observations started:	April 1987



Base isolation device

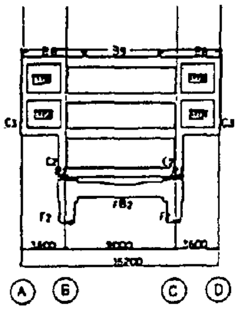


View of the Taketomo Dormitory

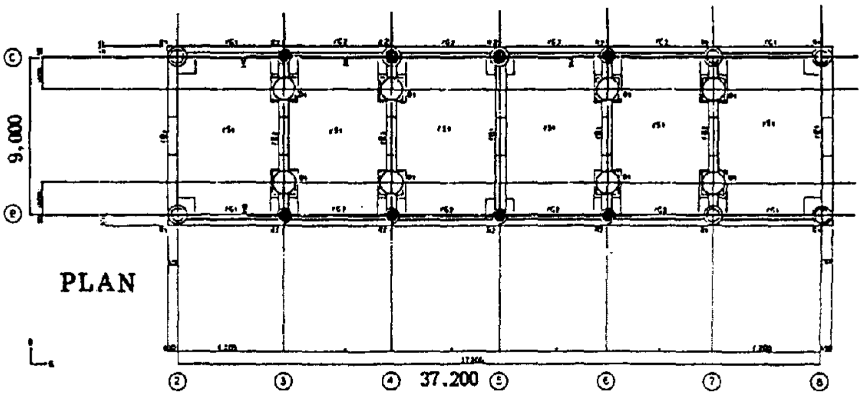


Piping and wiring

BUILDING OUTLINE



SECTIONAL VIEW

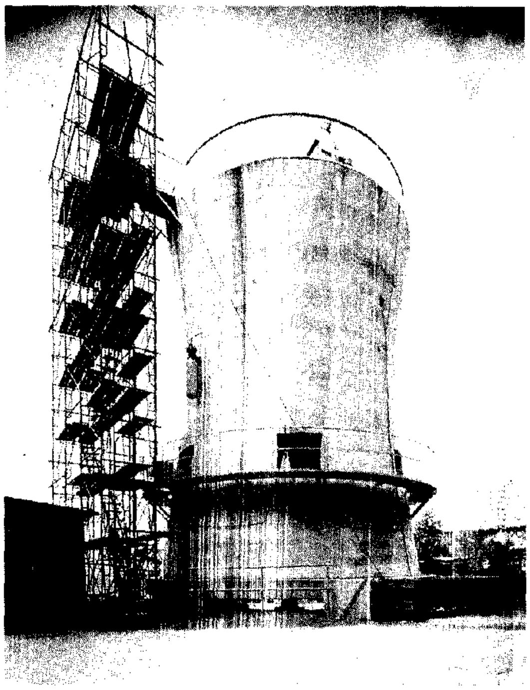


□: Viscous damper
680dia
○: LRB 200ton
●: LRB 150ton

ARRANGEMENT OF DEVICES

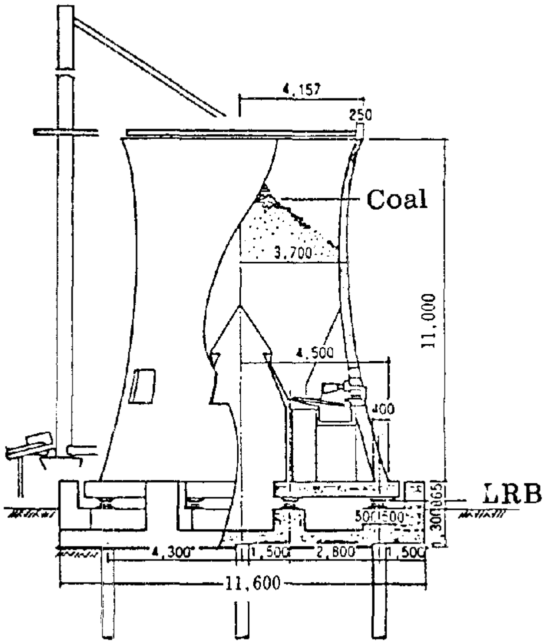
Name of the building:	Takenaka Technical Research Center Model Test Structure Koutou-ku Tokyo
Observations started:	1984

Base isolation device

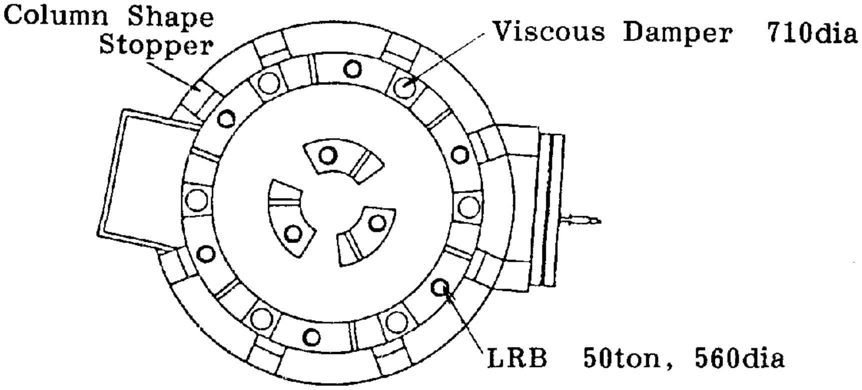


Large-scale experimental structure

BUILDING OUTLINE

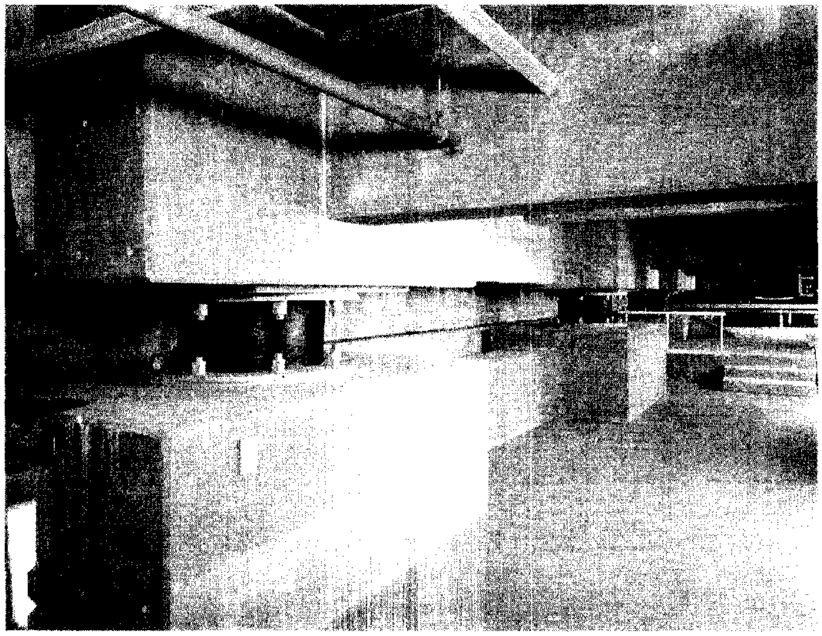


CROSS SECTION

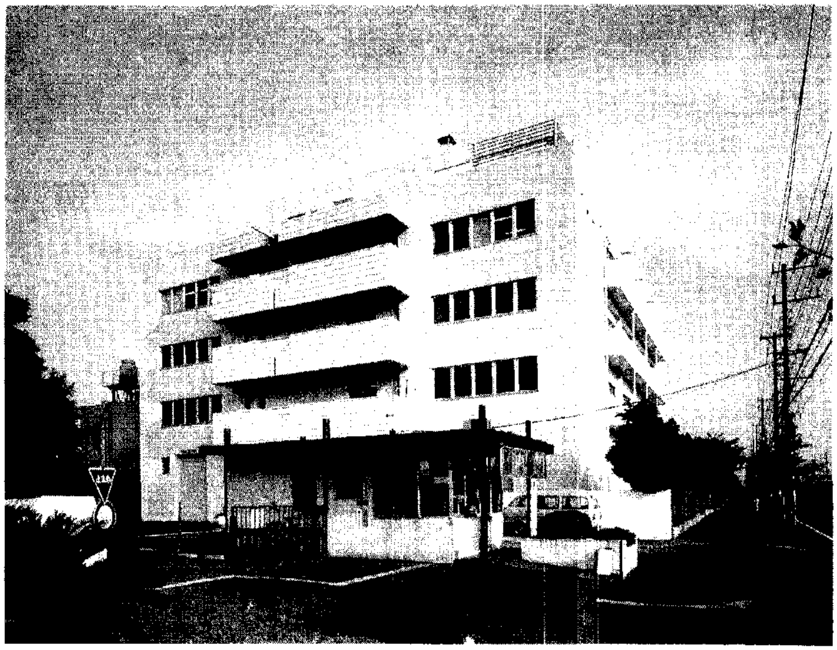


FOUNDATION PLAN

Name of the building:	Oiles Industries Technical Center (TC wing) Fujisawa City, Kanagawa Prefecture
Observations started:	April 1987

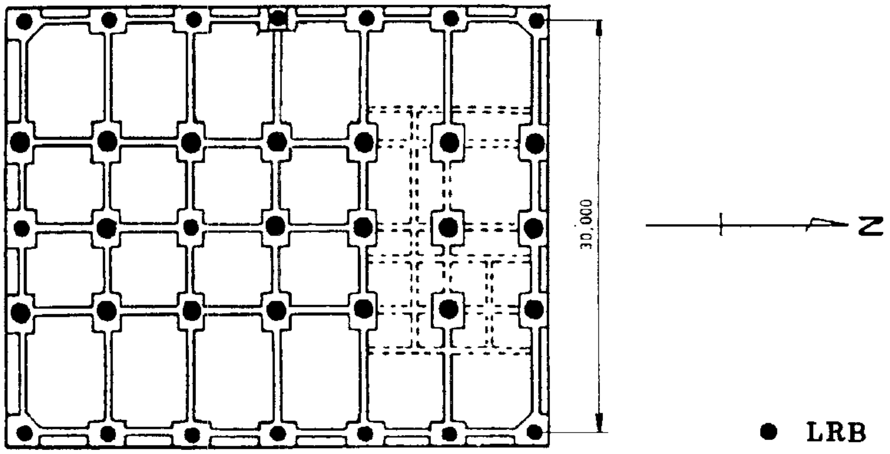


Base isolation device

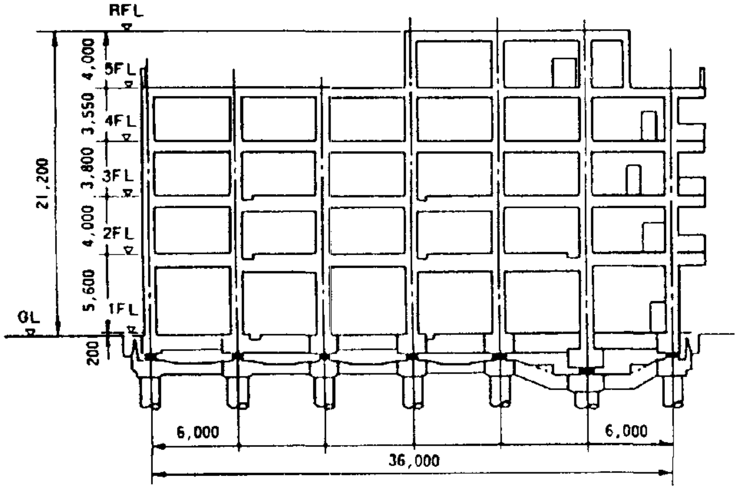


View of the TC wing

BUILDING OUTLINE



PLAN



SECTIONAL VIEW

LIST OF JOURNALS REFERRED TO IN THE REPORT

TRANSLITERATION	TRANSLATION
Dai 7 kai Nippon jishin kogaku symposium	7th Japan Symposium of Earthquake Engineering
Obayashi-gumi gijutsu ken-kyusho-ho	Report of Obayashi Technical Laboratories
Denryoku doboku	Electric Power Construction
Doboku gijutsu	Journal of Civil Construction Technology
ICU genshiryoku seminar	ICU Atomic Power Seminar
JEES	Japan Earthquake Engineering Symposium
Kikai no kenkyu	Studies in Mechanics
Nikkei mechanical	Nikkei Mechanical
Nippon genshiryoku joho center	Japan Atomic Power Information Center
Nippon gomu kyokai-shi	Journal of the Japan Rubber Association
Nippon kenchiku gakkai, Chugoku Kyushu-shibu	Journal of the Chugoku Kyushu Chapter of Architectural Institute of Japan
Nippon kikai gakkai koen ronbun-shu	Papers Presented at the Japan Mechanical Engineers' Association
Nippon kenchiku gakkai ronbun hokoku-shu	Transactions of Architectural Institute of Japan
Nippon kenchiku gakkai taikai	Proceedings of Annual Conference of Architectural Institute of Japan

Nippon kenchiku gakkai, Tohoku-shibu	Journal of the Tohoku Chapter of Architectural Institute of Japan
Nippon kenchiku gakkai, Tohoku-shibu kenkyu happyo-kai	Seminar of the Tohoku Chapter of Architectural Institute of Japan
Nippon zosen gakkai-shi	Journal of Japan Ship-building Association
Rinji jigyo iin kai kenkyu hokoku	Research Bulletin of Temporary Working Group
Seisan kenkyu	Monthly Journal of Institute of Industrial Science, Tokyo University
Taisei kensetsu gijutsu kenkyusho hokoku	Bulletin of Taisei Constructions Research and Development Laboratory
Tohoku daigaku kenchiku gakuho	Bulletin of Architectural Department, Tohoku University

OUTLINE OF THIS REPORT

This report is a summary of the studies (Stage 1) by the Expert Committee set up at the Building Center of Japan (BCJ) to examine response-control structures and base isolation structures during the fiscal year 1986 (FY). It consists of six chapters. The main topics covered in each chapter and brief contents are:

Chapter 1. Aims and Objectives of the Survey - deals with the organizational details and course of study and is in the nature of an introduction.

Chapter 2. Outline of response-control (or damper) structures. Section 2.1 explains the technical terminology used in this report (including the terminology for common reference). Here, we have defined response-control and base isolation structures as follows:

> Response-control (or damper) structure is a structure which controls or restricts the response of buildings to external turbulence using a fixed device or mechanism that acts on the entire structure or its parts. The base isolation structure mentioned below is one such example.
>
> Base isolation structure (also called "Menshin" structure) is a structure which controls or restricts the response of buildings to seismic waves by increasing mainly the fundamental period of the structural system employing such mechanisms as laminated rubber bearings sliding supports, a flexible first story or devices or mechanisms similar to these.

To examine all aspects of the response-control structure, we have proposed, in Section 2.2, various methods of classification of structures from three different viewpoints: 1) basic principles of dynamics; 2) methods of implementation; and 3) position of devices. Representative models of each method of response-control structure are given. Important considerations for these classifications and the types of response-control structures in each class are also discussed.

Classifications according to the above three viewpoints are as follows:

1. Classification according to the basic principles of dynamics:

   Response-control structure:

   methods based on control and adjustment of restoring-force characteristics;

   methods based on control and adjustment of damping;

   methods based on control and adjustment of mass;

   methods based on control and adjustment of input force;

   (or a combination of the above).

2. Classification according to the method of implementation:

   Response-control structure:

   passive control type;

   active control type.

3. Classification according to position of devices:

   Response-control structure:

   external type (insulation type);

   internal type (noninsulation type).

Section 2.3 reviews the history of seismic response-control building technology and the cases of base isolation structure approved by Minister of Construction.

Trends in other fields, such as civil construction other than buildings, using response-control techniques in Japan as well as overseas, and the proposal for wind response-control structures are discussed.

Chapter 3. Possible applications of response-control structures - discusses the greater flexibility in design that can be expected by using response-control techniques and refers to several occupancies of buildings where the response-control technique can be used in the future. These applications will contribute to the solution of the following technological problems:

1. Ensuring safety of structures under emergency conditions;

2. Reducing cross section of structural members;

3. Prevention of vibration, sliding or tumbling of furnitures;
4. Prevention of damage to or peeling off of nonstructural elements;
5. Prevention of uncomfortable vibrations; and
6. Ensuring performance of machines or equipments installed in buildings, etc.

Chapter 4. Various aspects of response-control structures - discusses topics to be dealt with so that the response-control structure can be developed properly in the future. In Section 4.1, some comments are offered from a technical point of view about: 1) external turbulence; 2) methods of dynamic analysis; 3) design methods; 4) response-control devices; 5) construction; and 6) maintenance management.

In Section 4.2 we have discussed social and governmental issues such as: 1) guidelines for technological development; 2) simplification of the permission process; 3) options for designers and developers; 4) encouragement of high technology; 5) exchange, accumulation and active use of technical information; and 6) method of evaluation of the effect of response control.

Chapter 5. Evaluation of the effectiveness of the response-control structure. Section 5.1 discusses some aspects of evaluation, particularly for base isolation structures of Menshin type.

Five points are raised for evaluation: 1) safety; 2) living comforts; 3) performance; 4) economy; and 5) flexibility of structural design.

Section 5.2 discusses in greater detail evaluation of the safety of Menshin structures using base isolation. Here we have offered some comments on: 1) the design criteria; 2) design seismic ground motions; 3) method of dynamic analysis; 4) method of bearing design; 5) performance of base isolation equipment; 6) construction; and 7) maintenance management.

Chapter 6. Summary – reviews the salient points noted during this study and considered useful for the effective development of response-control structures in the future (1987 onwards):

1) preparation of guidelines for the evaluation and approval of base isolation structure;
2) preparation of guidelines for the performance of base isolation equipment;
3) exchange, collection and dissemination of technical information about response-control structures; and
4) study of methods of evaluation of performance of response-control structures.

The following three appendices are provided:

- Appendix 1. Variability of the performance of response-control structures;
- Appendix 2. Examples of response control against wind;
- Appendix 3. Bibliography.

CHAPTER 1

AIMS AND OBJECTIVES OF SURVEY

Traditionally, while designing structures to withstand vibrations due to earthquakes or wind, the aim was to make the structure vibration resistant by improving its strength, ductility and stiffness.

Devices to prevent the propagation of vibrations to the structures or the installation of devices that will absorb the energy of vibration have long been proposed. Only recently, however, has such research progressed so that the findings can be used in actual construction. Structures using this technique are variously referred to as "Seishin structure," "Menshin structure," "Boushin structure" or "Genshin structure" in Japan. The aim of these techniques is to improve safety and damping of sway; the technological details involved touch several disciplines.

Such a response-control or base isolation structure generally tries to regulate the response of a building to vibrations by using some kind of device. Naturally, to ensure safety and proper design, knowledge of structural dynamics alone is not enough. It is equally necessary to pay attention to the safety and endurance of the devices used, including their upkeep and maintenance. This method uses some qualitatively different approaches than those used in the conventional structural design such as "earthquake-resistant design."

The enforcement of the current (conventional) regulations for buildings is unreasonable in those modern buildings incorporating response-control structures and base isolation structures. We do need, however, to evolve new design and safety standards based on the properties of response-control structures or base isolation structures. For this purpose, further study is required of various aspects including factors related to structural design such as design earthquake ground motions and design wind effects and the evaluation of required performance of such structures for different occupancies.

Of course, it is also necessary to develop devices (gadgets) to ascertain the performance and reliability of response-control structure or base isolation structure.

Today, there is no consensus in the building construction industry on the policy of using response-control structures or base isolation structures. Various research laboratories are probing all the aspects mentioned above and are independently conducting research or experiments. There is seemingly some confusion about use of the terms "response-control structure" and "base isolation structure."

It is therefore essential to evolve some method of evaluation of the feasibility and safety of these structures. The response-control structure or base isolation structure is a technology with bright future. Since its development is likely to be continuous, for the systematic progress of this work, it is necessary to compile information on various approaches to and topics of technological development in the field.

Aware of these various needs, the Ministry of Construction decided to conduct a survey of these issues in cooperation with the Building Center of Japan, as a sequel to their on-going study; the study proposal was sent to the Building Center of Japan.

At the Building Center of Japan, an Expert Committee on Advanced Technology for Building Structures (Adviser: Hajime Umemura, Professor Emeritus, Tokyo University; and Chairman, Hiroyuki Aoyama) was formed. At the first stage of the study, it was decided to collect information on the technological and legal aspects of the response-control structure and analyze the trends of future technological development.

Under the Expert Committee for Advanced Technology for Building Structures a Special Task Group (STG) was formed to conduct this study; this STG actually conducted the work under the guidance of the Expert Committee. The findings were submitted to the Ministry of Construction in the form of a report. The present report is an edited version of the same report for the general public. The names of the members of the Expert Committee and Special Task Group are listed elsewhere in this chapter.

1) Approach

1) The study will be carried out in two stages. Stage 1 will be conducted in FY 1986 and Stage 2 in FY 1987 and after.

2) In Stage 1, in FY 1986, the essential topics related to response-control structures and base isolation structures will be compiled and the future technological developments will be assessed. These will be pursued in the following order:

   a. compilation of the technical terminology to be used;
   b. classification and compilation of the present proposals;
   c. an overview of the current status, problems faced and merits of each method;
   d. expected architectural applications;
   e. identification of problems and topics related to response-control structure and base isolation structure;
   f. identification of topics for future studies; and
   g. summary of findings and introduction to Stage 2.

3) During Stage 2 in FY 1987 and after, the parameters for evaluation of safety in the base isolation system are to be compiled; based on the findings in Stage 1,

some further study of topics which the Expert Committee considers important will be carried out.

2) Organization

1) The organization of Stage 1 will be as follows:

   1. A special task group (STG) to be formed within the Expert Committee;
   2. The Expert Committee should assign the task to STG and give it directions under which to operate and conduct the study;
   3. Based on the guidelines of Expert Committee, the STG should prepare a classification and compilation of various proposals and list the problems in each method to be reported to the Expert Committee;
   4. Structure of the Expert Committee and STG will be as described below.

2) Organization for Stage 2 will be decided after considering the findings in Stage 1; the strength of members may be increased if necessary.

Expert Committee on Advanced Technology for Building Structures

Consultant/Adviser

Hajime Umemura	Chairman of the Board of Directors, Shibaura Institute of Technology, Professor Emeritus, Tokyo University

Chairman

Hirouki Aoyama	Professor, Department of Architecture, Faculty of Engineering, Tokyo University

Members

Masanori Izumi	Professor, Department of Architecture, Faculty of Engineering, Tohoku University
Yutaka Inoue	Professor, Department of Architecture, Faculty of Engineering, Osaka University
Kiyoshi Kaneta	Professor, Department of Architecture, Faculty of Engineering, Kyoto University
Masahiro Kawano	Assistant Professor, Department of Architecture, Faculty of Engineering, Kyoto University
Koichi Takanashi	Professor, Department of Building and Civil Engineering, Institute of Industrial Science, Tokyo University
Hideyuki Tada	Professor, Department of Architecture, Faculty of Engineering, Fukuoka University
Kiyoshi Nakano	Professor, Department of Architecture, Faculty of Engineering, Tokyo Denki University

Hideo Moriya	Professor, Department of Architecture, Faculty of Engineering, Chiba University
Makoto Watabe	Professor, Department of Architecture, Faculty of Engineering, Tokyo Metropolitan University
Makoto Tateishi	Chief, Building Guidance Division, Housing Bureau, Ministry of Construction
Tatsuo Murota	Director, Structural Engineering Department, Building Research Institute, Ministry of Construction
Takeshi Goto	Director, Building Center of Japan
Toshihiko Kimura	President, Kimura Structural Engineers
Shoichi Yamaguchi	President, Tokyo Kenchiku Structural Engineers
Toshikazu Takeda	Deputy Director, Technical Research Institute, Obayashi Corporation
Kozo Touyama	Head, Second Research Division, Kajima Institute of Construction Technology, Kajima Corporation
Isamu Harada	Assistant Director, Design Division, Shimizu Corporation
Shiro Yajima	Manager, Technology Development Department, Taisei Corporation
Shigetaka Abe	Deputy Manager, Structural Engineering Section, Building Design Department, Tokyo Main Office, Takenaka Corporation

Special Task Group

Adviser

Masanori Izumi	Professor, Department of Architecture, Faculty of Engineering, Tohoku University

Chairman

Tatsuo Murota	Director, Structural Engineering Department, Building Research Institute, Ministry of Construction

Members

Yoshitsugu Aoki	Assistant Professor, Department of Architecture, Faculty of Engineering, Tokyo Institute of Technology
Jun Kanda	Assistant Professor, Department of Architecture, Faculty of Engineering, Tokyo University
Tetsuo Kubo	Assistant Professor, Department of Architecture, Faculty of Engineering, Nagoya Institute of Technology
Akira Wada	Assistant Professor, Department of Architecture, Faculty of Engineering, Tokyo Institute of Technology
Yoshikazu Kitagawa	Head, Civil Engineering Division, IISEE, Building Research Institute, Ministry of Construction
Yuji Ohashi	Scientist, Dynamics Division, Structural Engineering Department, Building Research Institute, Ministry of Construction
Takayuki Teramoto	Chief Structural Engineer, Nikken Sekkei Ltd.
Hidetoshi Nakagami	President, Jyukankyo Research Institute, Inc.
Hiroshi Okada	Manager, Structural Engineering Department, Technical Research Institute, Obayashi Corporation

Satoshi Bessho	Chief Research Engineer, Second Research Division, Kajima Institute of Construction Technology, Kajima Corporation
Masaru Sukagawa	Manager, Technical Development Department, Technology Division, Shimizu Corporation
Soichi Kawamura	Manager, Earthquake Engineering Section, Technology Research Center, Taisei Corporation
Yutaka Hayamizu	Chief Research Engineer, Structural Engineering Group, Technical Research Laboratory, Takenaka Corporation

Associate Members

Yasuyuki Fujiwara	Assistant Manager, Building Guidance Division, Housing Bureau, Ministry of Construction
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Hitoshi Shiobara	Scientist, Structural Engineering Department, Building Research Institute, Ministry of Construction

CHAPTER 2

RESPONSE-CONTROL STRUCTURES

2.1. Terminology

Various proposals and studies about response-control structures and base isolation structures have long been made in Japan, as mentioned in Section 2.3. The definitions of terms vary according to the proposer or researcher and there is no uniformity in this respect. Our definition of terms and classification of structures have been compiled based on this earlier literature.

2.1.1 Earlier terminology

In this section several definitions of terms used by earlier researchers are compiled. Examples of such previously defined terms are as follows:

1. Damper type earthquake-resistant structure (Seishinsei Taishin Kozo): A structure in which vibrations are damped, thereby imparting earthquake-resistant properties (Takabeya, Ref. 1).

2. Vibration control (Seishin): The amplitude of the vibrations developed in the structure (subjected to vibration) due to the earthquake is controlled using some mechanism (mainly damper or attenuating mechanism).

3. Seismic vibration prevention (Boshin), vibration isolation (Menshin): Seismic waves are not allowed to pass to the structure due to some blocking mechanism which cuts off seismic waves from the structure.

4. Earthquake-resistant (Taishin): To make the structure withstand seismic vibrations.

5. Earthquake-resistant (Taishin): To fix the structure with respect to space coordinates of seismic motion.

6. Vibration protection (Boshin), Menshin: To fix the structure with respect to absolute fixed space coordinates.

7. Seismic response control (Seishin): To impart such properties to the structure that seismic vibrations are controlled.

(Definitions 2 to 7 are by Kobori and Minai. Ref. 2)

8. Menshin or base isolation method, Genshin method: Structural approach in which the seismic vibration incident upon the structure are damped (Izumi, Ref. 3).

9. Base isolation (Menshin) structure: A structure in which the response of the main parts of the building to the seismic vibrations is damped by placing some artificial auxiliary mechanism in the support (bearing) region. (Bulletin of Denryoku Central Research Laboratory, Ref. 4)

References

1. Takabeya, Fukuhei. 1938. Damper-type vibration-resistant structures. Kenchiku Zasshi, No. 636.

2. Kobori, Takuji and Ryoichiro Minai. 1960. Analysis of damper systems (Studies on damper structures, Part 1).Kenchiku Gakkai Rombun Hokoku-shu, No 66.

3. Izumi, Masanori and Yoichi Kishimoto. 1975. Studies on damping methods in buildings. Tohoku Daigaku Kenchiku Gakuho, No.16.

4. Matsuda, Yasuji; Sakae Aoyagi and Tetsu Shiomi. 1985. Survey of Menshin structure. Bulletin of Denryoku Central Research Laboratory, October, 385010.

The following technical terms are used for the response-control structure or base isolation structure. Although the terms are not clearly defined, we have provided some explanatory comments for each of them for reference.

Base isolation: This is very close to the term "Menshin" used in Japan. Generally, it indicates a structure using laminated-rubber support or sliding support.

Soft or flexible first story: The horizontal stiffness of the lowest floor or the first floor above the ground is considerably lower than that of the upper floors thereby increasing the period of oscillation of the entire system.

Response control: This term was used at the Ninth World Conference on Earthquake Engineering and covers many terms such as "Seishin" or "Menshin" generally used in Japan.

2.1.2. Terminology used in this report

Considering the definition of terms used in earlier studies and considering the use of these terms in modern building industry, some terms are redefined below for the purpose of the present study.

Response-control structure: This is a structure which controls or restricts the response of buildings to external forces through a specific device or mechanism that acts on the entire structure or its parts.. The base isolation structure mentioned below is part of this.

Base isolation (or Menshin) structure: This is a structure which controls or restricts the response of buildings to seismic waves by increasing mainly the period of oscillation with the help of such mechanisms as laminated-rubber bearings, sliding supports, a flexible first story, or devices and mechanisms similar to these.

Base-isolation: Among various types of base isolation structures, rubber-laminated bearings or sliding supports are provided at the foundation of a building.

Flexible first story: The horizontal stiffness of the lowest or the first story above the ground is made considerably lower than that of the upper stories, thereby increasing the fundamental period of oscillation of the entire system.

By the way, in mechanical engineering, we have terms such as vibration elimination, vibration prevention, which are similar to the terms response-control and base isolation. Although they are not directly used in this report, the meaning of these terms is given here for the reference.

Vibration elimination: To isolate instruments or equipment from vibrations of a supporting structure or vibrations of a building.

Vibration prevention: To cut off the vibration of machinery not to pass to the supporting structure or building.

2.2. Classification and Characteristics of Response -Control Structures

2.2.1. Classification

1) Previous classification

There have been many proposals and studies about response-control and base isolation structures but little uniformity in the definition of terms used by various authors or researchers.

This nonuniformity is also found in the classification of response-control structures. Hence, the criteria of classification have varied. The main classifications of the response-control structures in the past can be listed as follows:

1 Residential buildings
  - Vibration-insulation structure
  - Fixed structure
    - Flexible structure
    - Rigid structure

(Sano & Muto, Ref. 1)

2. Base isolation structure, Genshin structure
  - Insulation type
  - Adjustable restoring-force type
  - Energy-absorption type (damping type)
  - Self-regulatory type
  - Pendulum type

(Izumi, Ref. 2)

3. Base isolation structure
  - Period lengthening type
  - Energy-absorption type
  - Decoupling type
  - Screening type
  - Special-structure type

(Kumar & Maini, Ref. 3)

4. Base isolation method
   - Adjustable-period (of oscillation) type
   - Energy-absorption type
   - Insulating type
   - Special-structure type
   - Self-regulatory type
   - Screening type

(Denryoku Central Research Laboratory, Ref. 4)

5. Damper method
   - Passive damping
     - Adjustable mass-and-stiffness distribution type
     - Adding external vibrating system for damping
     - Increase damping by adding damper
     - Using hysteretic damping of individual structural elements to reduce vibration
   - Active damping
     - To add an automatic system which senses vibrations of the building and then controls them within the permissible limits

(Sakurai and Aizawa, Ref.5)

6. Seismic response-control
    - To cut off the path of seismic wave transmission
    - To isolate the frequency band of the response-control system from the frequency band of seismic motion
    - To make the system aperiodic and asynchronous by imparting non-linear characteristics
    - To use energy-absorption mechanism

(Kobori and Minai, Ref. 6)

References

1. Sano, Toshiki and Kiyoshi Muto. 1935. Earthquake-resistant and wind-resistant buildings. Tokiwashobo Publishers.

2. Izumi, Masanori. 1986. Base isolation structures of today. Kenchiku Gijutsu, April.

3. Kumar, R.R. and T. Maini. 1979. A review of Seismic isolation for nuclear structures. EPRI NP-1220--SR-1979.

4. Matsuda, Yasuji; Sakae Aoyagi and Tetsu Shiomi. 1985. Survey of base isolation structure. Bulletin of Denryoku Central Research Laboratory, October, 385010.

5. Sakurai, Joji and Satoru Aizawa. 1971. Studies on vibration damping in buildings. (Part 1) Experiments on elastomer damper. Nippon Kenchiku Gakkai Taikai, November.

6. Kobori, Takuji and Ryuichiro Minai. 1960. Analysis of response-control system. (Studies on response-control structures, Part 1). Kenchiku Gakkai Ronbun Hokoku-shu, No. 66.

2) Classification used in the present study

In this study, we decided to classify the structures in order to explore the current status of response-control structures. To do so, we have tried to classify the structures, as shown below, from three perspectives: 1) basic principles of dynamics; 2) method of implementation (passive or active); and 3) according to position or placement. The details are mentioned in Section 2.2.2. Here, the main classifications of response control structures from these three perspectives are given.

1. Classification according to the basic principles of dynamics:

Response control structure
- Based on control and adjustment of restoring-force characteristics.
- Based on control and adjustment of damping.
- Based on control and adjustment of mass.
- Based on control and adjustment of input vibration.

(or a combination of the above).

2. Classification according to the method of implementation:

Response control structure ─┬─ Passive control type
└─ Active control type

3. Classification according to position or placement of response-control devices:

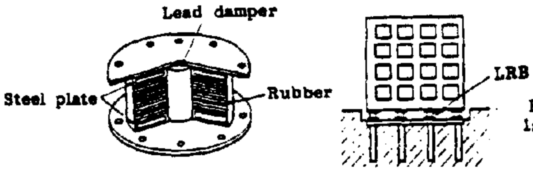
Response-control structure ─┬─ External type (insulation type).
└─ Internal type (noninsulation type).

3) Examples of Classifications

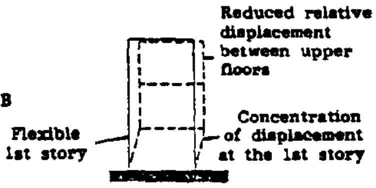
The following are schematic examples of response-control structures classified according to the three criteria.

1) Classification according to the basic principles of dynamics:

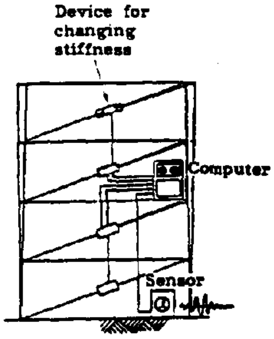
Methods based on control and adjustment of restoring-force characteristics.



Laminated Rubber

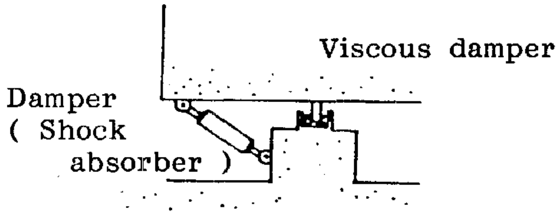


Flexible First Story

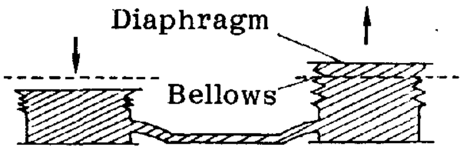


Variable Stiffness Mechanism

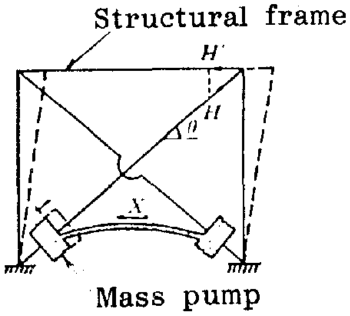
Methods based on control and adjustment of damping



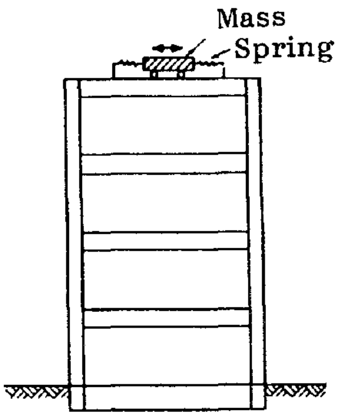
Methods based on control and adjustment of mass



Mass Pump

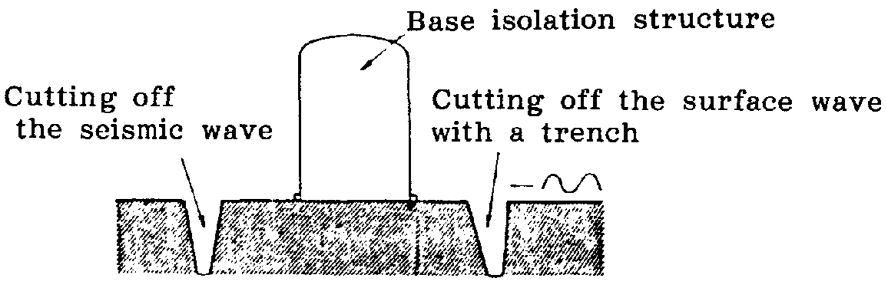


Mass pump fitted
into the frame

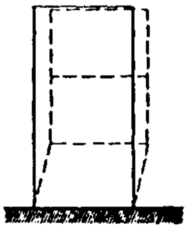


Dynamic Damper

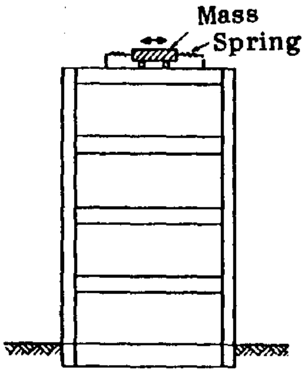
Methods based on control and adjustment of input force



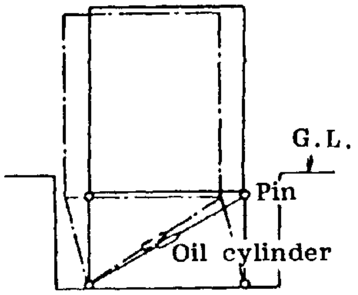
2) Classification according to the method of implementation



Flexible First Story

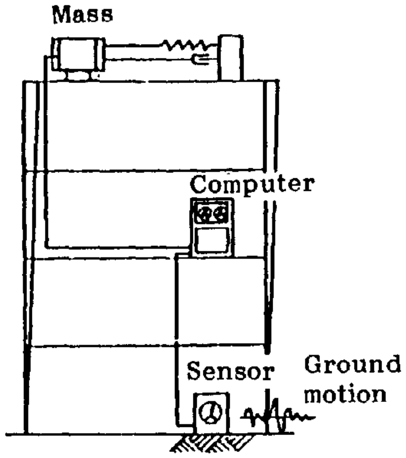


Dynamic Damper



Variable Stiffness Mechanism

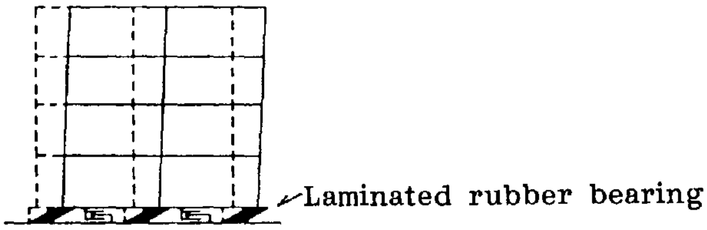
Active type



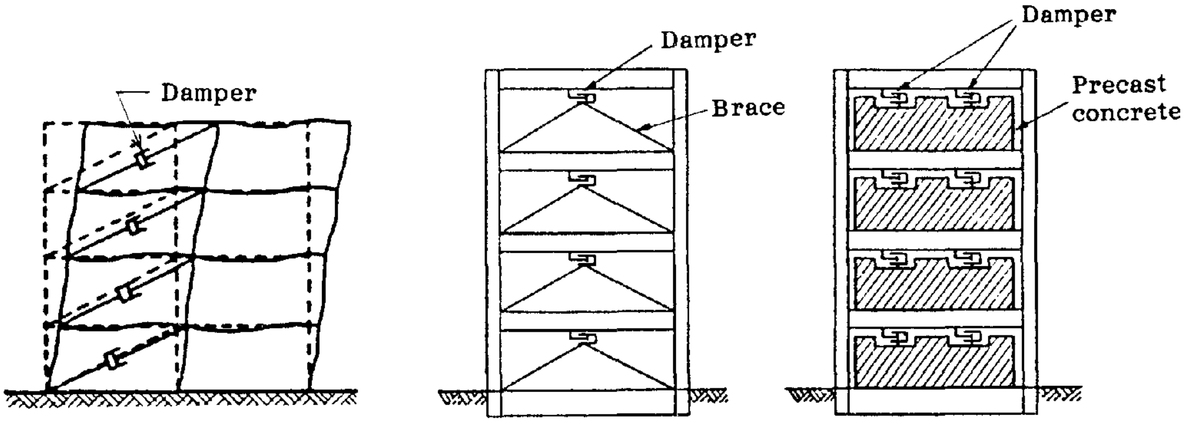
Active Mass Damper

3) Classification according to position of device

External (Insulation) type



Internal (Non-insulation) type



Any given response-control structure can be variously classified from these three perspectives. A so-called base-isolation type structure can be said to be of adjustable stiffness and damping type or of passive control type or of external type structure.

2.2.2. Classification according to the basic principles of dynamics

1) Equation of motion

The resultant motion of a building when it is subjected to external forces such as earthquakes, winds or dynamic force due to the vibration of machinery employed within the building, can be represented by the following equation:

$$m(\ddot{x} + \ddot{y}_0) + f(\dot{x},\ x) = p. \qquad (1)$$

Here, m, f(x,x) and p are, respectively, the mass of the building as a dynamical system, reaction force developed in the system and external force acting on it. x, $\ddot{x}$ and $\dot{x}$ are respectively the quantitative response of displacement of the system with respect to its origin, acceleration and speed. $\ddot{y}_0$ is the seismic acceleration incident on the system. Even in multistoried structures, where the degree of freedom of motion of the building is more than 2, a similar expression can be used after replacing each term in this equation by a matrix or vector.

To simplify the process, we shall assume below that only an external force due to an earthquake acts on the building. [If only the seismic force is present, the term of external force "p" becomes zero, if wind load is present or if the excitation source is present within the system, a similar treatment is possible even if the external force is not zero.] By rearranging eq. (1) we get:

$$m\ddot{x} + f(\dot{x}, x) = -m\ddot{y}_0. \qquad (2)$$

In eq. (2), if we expand the term of reaction force $f(\dot{x}, x)$ in terms of the term dependent on the velocity of the system (damping term) and term dependent only on the shape of the system (reactive force term), we can write,

$$m\ddot{x} + c\dot{x} + f(x) = - m\ddot{y}_0. \tag{3}$$

The term of reactive force in eq. (3) is a function only of the displacement response of the system and represents statically acting reactive force (static spring reactive force). If we assume that the following linear (elastic) relationship exists between the static spring reactive force (spring stiffness of the system is denoted as k) and the response displacement of the system, then

$$f(x) = k \cdot x. \tag{4}$$

Eq. (3) can be rewritten as

$$m\,\ddot{x} + c\dot{x} + k \cdot x = - m\ddot{y}_0. \tag{5}$$

If the time dependence of the system is nonlinear, assuming partial linearity, eq. (3) may be written in terms of incremental terms, as follows:

$$m_i\ddot{x} + c_i\dot{x} + k_i \cdot \Delta x + f_i(x) = - m_i\,\ddot{y}_0. \tag{6}$$

Suffix *i* in eq. (6) represents the condition of motion at the time t_i.

The motion of a building under the action of a dynamic external force can be determined using eqs. (1) to (6). Accordingly, to control the quantitative response of the system to external force (displacement, velocity, acceleration and spring reactive force developed in the system), it is necessary to control the shape parameters of the system, namely, *k*, *c* and *m* in the above equation of motion and the magnitude of external force incident on the system ($\ddot{y}$) in the above expression). We shall discuss below the control methods based on the equation of motion.

2) Target response to be reduced

The object of the response-control structure is to reduce the response of the building. This reduction is desired in any of the following four responses (or their combination):

1. System displacement (relative displacement, or incremental deformation), (x)

2. Reactive force developed in the system (static spring reactive force), (f)

3. System acceleration (absolute acceleration), ($\ddot{x} + \ddot{y}_0$)

4. System velocity (absolute velocity), ($\dot{x}+\dot{y}_0$)

The relationship among these four response parameters can be summarized after considering eqs. (1) to (6) as follows:

1. If we minimize the deformation (x) developed in the system, the reactive force developed in the system (f) will also be small [eq. (4)]. In the case of an elastoplastic system, this relationship may not be exact but may hold good for the system where hysteretic damping force can be ignored. On the other hand, it is necessary to reduce the reactive force ($f = k \cdot x$, if displacement (x) is to be reduced.

2. Reduction in absolute acceleration ($\ddot{x}+\ddot{y}_0$) and reduction in the reactive force ($f = k \cdot x$ are interdependent. The amplitude of force developed as a reaction is proportional to absolute acceleration [eq. (2)].

3. By reducing the displacement response of system (x), it is possible to reduce the velocity response (x). As a result, the amplitude of absolute velocity ($\dot{x} + \dot{y}_0$) also decreases.

3) The basic principles of response-control structure

A. A structure in which the restoring-force characteristics are controlled:

i) Control of linear elastic stiffness

This approach tries to reduce the stiffness of the system so that the fundamental period of oscillation of the system is longer than the predominant period of vibration of the external seismic force, thereby reducing response acceleration. Figure 1 is a typical example of a response spectrum of an elastic system with one degree of freedom. Here, we can see that the response acceleration decreases in the range of fundamental period of the system larger than that of resonance [here, the absolute acceleration of ($\ddot{x} + \ddot{y}_0$) is assumed. Hereafter, unless specifically mentioned, absolute acceleration is assumed.]

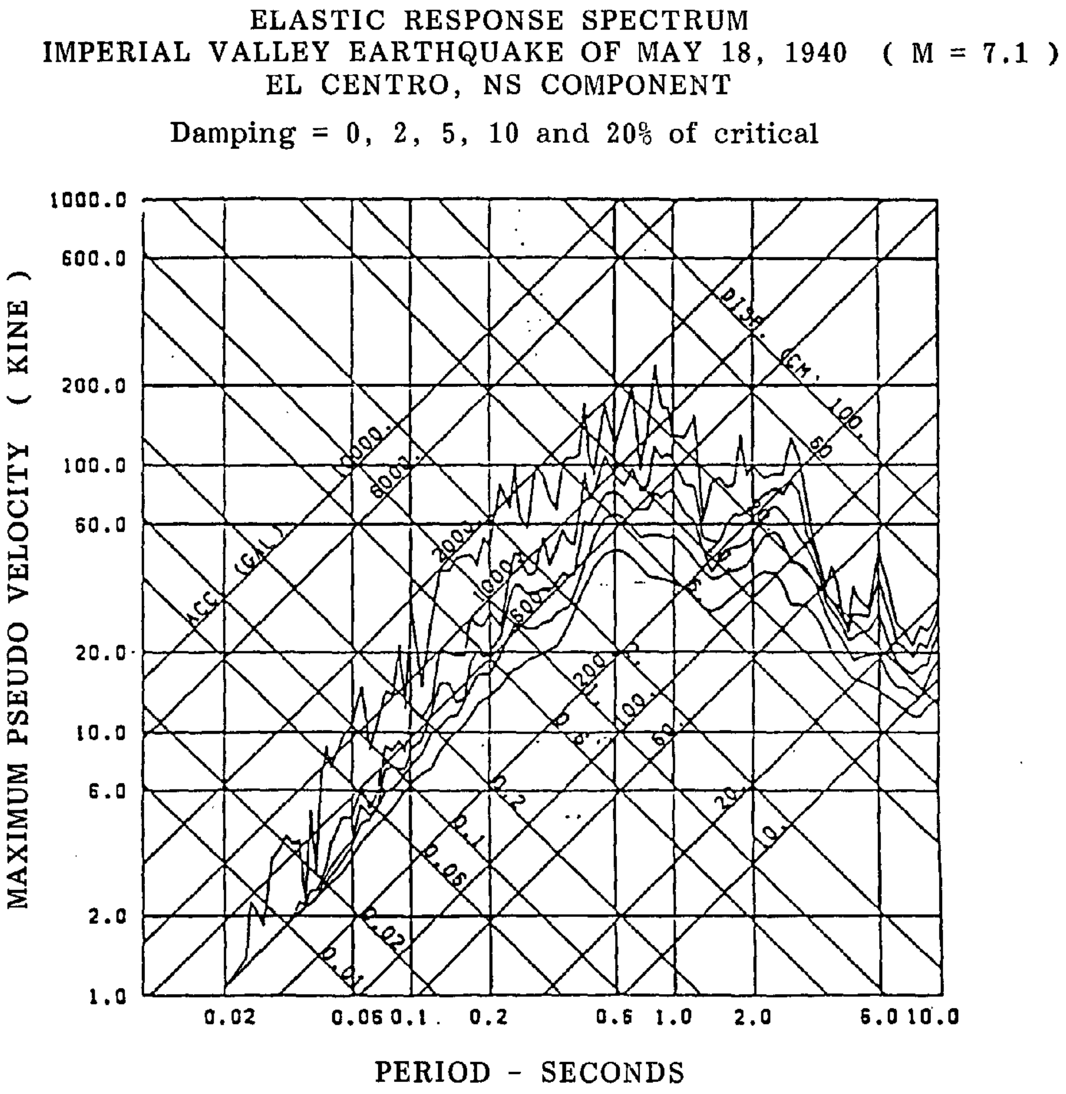


Fig 1. Example of the elastic response spectrum of a system with one degree of freedom.

Let us consider an extreme case in which the stiffness k is assumed to be zero. If we ignore the term due to viscous damping, then from the relationship of eqs. (3) and (4), the response ($\ddot{x}$) and input ($\ddot{y}$) are in phase opposition and the absolute acceleration response, which is the sum of these two, becomes zero. Behavior of such a system is similar to that of the seismograph. If the stiffness of the system is assumed finite, some reactive force $f = k \cdot x$ is generated in the system under such conditions. We must note that as we reduce stiffness k, the response deformation occurring in the system(x) increases according to the relationship of expression (4). [In an extreme case, as mentioned above, it becomes a ground displacement.]

ii) Control of nonlinear elastic stiffness:

Here, an attempt is made to reduce the response of the system by imparting some nonlinear properties to stiffness. In one case, some nonlinear properties are imparted to the restoring-force characteristics of the system using steel wire ropes as bracings, thereby avoiding resonance. In such a case, stiffness varies with the increase in displacement, thereby reducing the quantum of response.

In another case, the response can be reduced by modifying the oscillation properties of the system so artificially that an oscillating condition does not develop. This is achieved by actively controlling the stiffness. However, modification in the oscillation properties of the system does not necessarily reduce vibrations due to an external force; the response may actually increase as a result of modification in oscillation properties. Thus, it is important to control the modification in stiffness properties so that response does not increase.

iii) Control of elastoplastic restoring-force characteristics:

In this approach, the relationship between the displacement (x) and static spring reaction force $f= k \cdot x$ in eq. (4) , namely, the hysteresis of the system, is controlled.

When a load or external force is applied to the building, the yield condition may be developed in the structural members and their behavior may become plastic. As a result of the plastic behavior they absorb part of the vibration energies, which is proportional to the area enclosed by the hysteresis loop. It thereby attenuates the amplitude of vibration. The following conclusion can be drawn for the load-bearing capacity of the system to be controlled: The smaller the load-bearing capacity of the system, the larger is its elastoplastic response. To reduce the response, it is necessary to maintain large load bearing capacity in the area in which significant plastic deformations occur and to design structural frames so as to have significantly large area of the hysteresis loops.

B. A structure in which the damping of the system is controlled:

Here, the response is reduced by increasing the damping effect. The effect of response reduction by increasing damping can be seen in the response spectrum of Fig. 1. It is clear that the response value decreases as damping increases. The effect of increasing the damping can be estimated from eq. (3). Thus, increasing the value of damping force term ($c\dot{x}$) in this equation means reducing the static spring reactive force ($f = k \cdot x$). Damping dissipates some amount of energy by transforming it into heat using the damping mechanism. This results in reduction of the vibration energy accumulated in the system in the form of structural deformation or response vibrations.

When a building is considered as an elastic system, the vibration energy developed in the system due to the external force must be dissipated using the damping mechanism, otherwise vibrations continue for a long time without any damping in their amplitude.

Methods to control damping include base-isolation systems using a combination of various types of dampers and laminated rubber bearings or other systems using a combination of bearing wall or braced wall and dampers.

C) A structure in which the mass of the system is controlled:

In this approach, vibration properties of the system are modified and the vibration response is reduced by controlling the total mass (m) or its partial distribution in the system.

The earlier technique called "inertia mass pump" corresponds to this. Here, the value of mass (m) in motion is varied according to the response of the system and in the vibrating system is not allowed to reach steady state. If a system is designed properly, it will not reach steady state of vibrations, hence resonance which might cause a large response does not occur.

In this method, it is essential to control the system conditions with high-fidelity to the change of external conditions. If not, effectiveness of the system must be examined on reduction of the transient response.

D) A structure in which the input force is controlled:

This approach reduces the vibration response by controlling the input such as acceleration ($\ddot{y}_0$). Controlling the source of vibrations is one method to control input acceleration ($\ddot{y}_0$). When the source of vibrations is a natural one such as an earthquake, it is impossible to control its occurrence. We can attempt to isolate the earth's surface very close to the building from the rest by such methods as making a trench or moat. When the vibration source has lower energy, such as that due to automobile traffic, it may be possible to control the source itself.

When the external force is that of wind, it is generally impossible to control its occurrence and the magnitude of wind pressure incident on the building. Its effects can be modified by giving the appropriate shape to buildings. The technique of affixing spoilers to cylindrical chimneys, and thereby avoiding resonance, is one example of this type of control.

While considering the control of systems existing within a building, the input to the system will be ($\ddot{x}+ \ddot{y}_0$) as is clear from expression (2).

2.2.3. Classification according to the method of implementation

A response-control structure, or a structure which can restrict and control the response of a building to external turbulence, may be classified in two ways: 1) that in which it is necessary to apply some form of external energy for this control; and 2) that in which such energy is not required. We term this classification as classification according to the method of implementation. The former is called the active method while the latter is called the passive method.

In terms of this classification, the following methods to reduce the effect of external force can be classified as active methods. The seismic vibrations or the vibrations in a building are sensed by an accelerometer and then the stiffness of the braces is controlled accordingly by a computer such that vibrations of the building are reduced (variable stiffness mechanism) or some mass is placed on the top floor of the building and the vibrations are reduced through an actuator (active mass damper). Methods such as base-isolation using laminated rubber bearings or a flexible first story are classified as passive methods.

According to the law of increase of entropy, if there is no energy incident from the external source in nature, the system is transformed into a chaotic one with the passage of time and it does not return to its original state (irreversible entropy). On the other hand, if external energy is applied on to the system, it turns into a still more ordered state or the state of still less entropy.

Consider the high-rise, multistory steel-structure buildings. Large amount of energy is applied to iron ore, the most stable iron form, by melting it in a furnace or rotary converter and ultimately iron sections of high strength are manufactured by reduction. These materials are used as specified by computer-aided structural design. The steel structure is built up to a height of 200 meters using large cranes. The energy used for the construction of one building consists not only of heat and electricity, if we consider human knowledge, past experience and accumulation of information, the total energy consumed will be substantial. A building made with such energy inputs is subjected to extremely low entropy conditions or, in other words, to high potential energy conditions, that is, in an unstable condition. Unless proper rust-proofing treatment is carried out, the steel bars may return to their original iron oxide form. Thus, under the action of loads present in the structure, columns and beams, under the above circumstances, may weaken and finally the building may collapse. This is the meaning of unstable condition.

It may appear that construction of a building amounts to defying the universal law of increase in entropy. A life of 60 years means maintaining the original strength even after it is subjected to various kinds of external forces during that time.

Generally, maintaining things in the state of lowest entropy is a refined way and also often suitable for their use or exploitation. Thus a computer-controlled traffic signal system in a metropolis is not as simple as the elevators in a tall multistoried building. Roads are provided for vehicular traffic and elevators for human traffic. In addition, there is a software control to regulate large volumes of traffic. It is possible to create a state of low entropy by controlling this kind of information. However, if the computer fails, we know the chaos that will ensue in such a high-volume traffic.

Previously, the hardware approach, both static and dynamic, was practiced to help buildings withstand static forces, earthquakes and other shocks and to prevent undesired vibrations due to wind. Even this approach may be realized using computer control or electronic techniques similar to the example of the traffic signal. Thus, the vibrations similar to an incident earthquake may be induced in the building much before the actual seismic wave reaches the building. The actuator is operated under computer control and the building structure is maintained under low entropy condition.

Previously, buildings were protected from external turbulence by a combination of hardware approaches and were made safe enough to last 60 years. The future approach may be to keep the building structure under a state of low entropy by software control. This technique has been proposed in quite a few cases and may be implemented in some buildings in the near future.

In areas other than building constructions, particularly where cost is no consideration, such as in defense or space applications, this approach is possible. The Control Configuration Vehicle (CCV) is one such example. This is a kind of aircraft which is purposely designed to be unstable and then stability is imparted by computer control. There are many hitherto impossible features in this machine. The aircraft can change its course while flying straight in the air without changing the direction of its nose.

Another example is that of the large parabolic antenna fitted to a space satellite. While the inclination of antenna changes, no vibrations are caused to its skeleton and the desired rotation is achieved in one step where it stops automatically. The structure of the parabolic antenna skeleton is specially made such that the stiffness can be varied according to the current flowing through it. The stiffness is controlled by a computer.

These techniques are very expensive today. There is another problem in addition to cost while applying such techniques to buildings. In the earthquake-resistant structure or base isolation (Menshin) structure incorporated in the building, the hardware may be expected to behave as per their designed performance perhaps once in 100 years in response to an earthquake. This poses no problem. However, when the control is achieved by software or other active methods such as actuators requiring some energy input for operation, the system may not operate faultlessly during such a rare phenomenon as an earthquake. As mentioned in other applications above, if the system is designed such that its computer operates normally all the time and it vibrates the building continuously with a given amplitude without any ill effect on human beings, the computer can be expected to impart vibrations of a specified amplitude to the building when the external force (seismic waves or winds) is incident, whether small or large. It is difficult to ensure the reliable operation of any device if it is supposed to operate only once in 100 years, suddenly with the occurrence of earthquake.

Devices such as laminated rubber, steel-rod damper, lead damper, oil damper, sliding friction and others used to make response-control structures of base isolation structures, act dynamically as hardware components. Methods based on devices such as the computer, electronic techniques, actuators and others can be called software dependent mechanisms. As mentioned earlier, some electrical energy is usually necessary for operation of the latter and they are called "active" since they actively respond to the structure. The former devices do not require any external energy and act only at the time of an earthquake. For this reason they are called "passive." By the way, some persons say that designing an earthquake-resistant structure to withstand an earthquake is an active human activity and so the structure can be called an active system.

2..2.4. Classification according to the Position of Dampers

There are two types of controlling response: the response-control or base isolation (Menshin) structure using certain types of devices outside the building, or the "base isolation method," and the other method based on installing certain mechanisms inside the building. Here the former is called the "external" type and the latter the "internal" type. It may be difficult to determine whether the place in which the device is installed is within or without the building. The boundary will vary according to the structure. Here, we have used the term "inside" for that area which is used for residential purposes. If most of the energy at the time of an earthquake can be absorbed by the device installed outside, then the response of the upper structure can be controlled in the elastic region and the deflection of the upper structure occurring at the time of an earthquake can be minimized. As a result, the design of secondary structural members is easier than that of the main building. Conversely, devices installed "inside" the building, design of the upper structure or the secondary structural members, becomes only slightly easier compared to the conventional building design but there is no material difference since, in this method, some deformation of the building itself is allowed.

2.3 . Examples of Proposals for Response-control Structures and Actual Constructions

2.3.1. Examples of historical importance in the Japanese construction industry

The effect of response-control can be confirmed using the theory of vibrations or the response analysis. Such scientific analysis, in particular numerical analysis, has become possible only in the last 20 years. However, even without such sophisticated analysis, people have considered separating the building from the earth's crust to reduce the shock of an earthquake. Proposals aiming at reducing the intensity of earthquake effect or controlling the vibrations of a building in response to an earthquake were made long before such sophisticated techniques as response analysis were developed. Most of these proposals were only as suggestions or ideas and rarely were they tested in practice. These ideas have often emanated from people with varying expertise in the subject, people who were novices in construction or specialists who offered suggestions based on theoretical knowledge and practical experience. We discuss below the ideas about those structures or cases of buildings and the theory of antiseismic structure published in papers mainly in Kenchiku Zasshi (Journal of the Architectural Institute of Japan).

1) Base isolation structures in the Meiji period

The oldest published report about the base isolation structure is probably a paper by Mr. Kozo Kawai based on a lecture in May 1891 and titled, "Structures free from the maximum vibrations during earthquake - synopsis of the lecture." This article appeared in the December 1891 issue of Kenchiku Zasshi of the Architectural Institute of Japan (previously the Japan Building Society) (Fig. a).

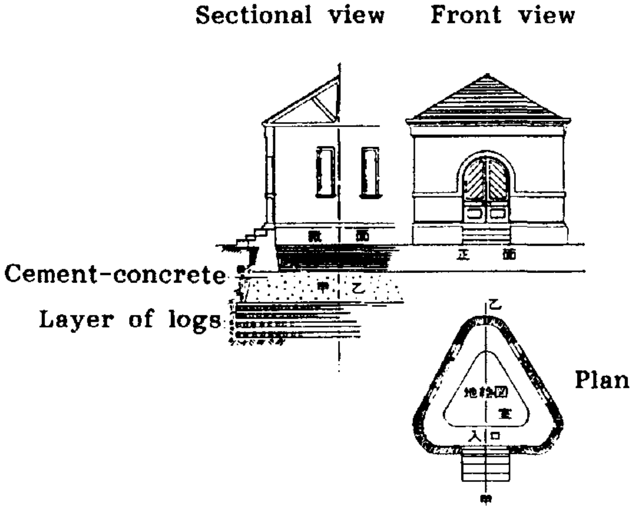


Fig. a. Kozo Kawai: Structures free from maximum seismic vibrations.

This report discusses a building equipped with precision instruments such as chemical balances and various meters which are sensitive to vibrations. Among the ideas mentioned in this paper are these: 1) Several layers of logs are arranged on the excavated surface of the earth's crust and held by fasteners. Cement concrete is cast on these logs and then the building is constructed over them; 2) Since it is known that high-rise buildings or flexible buildings sway easily, the building is made low and the structure is triangular in shape; 3) To cut off the seismic wave, a deep trench is dug around the building; 4) To protect instruments such as balances from seismic vibrations they are mounted on wheels so they can slide. Experts today may question Mr. Kawai's knowledge or the effectiveness of these measures. The first serious research on earthquake engineering in Japan began with the Nobi earthquake of October 1891. As a step toward modernization and to make the structure fire-resistive, the concept of the brick structure was borrowed from western Europe. Since such explanations as Mr. Kawai's predated the beginning of the scientific studies mentioned above, there were probably no alternative measures available. In this paper, the objective is not to make the structure itself earthquake-proof but to protect precision instruments from any damage. This confirms the value of the response-control structure. The first base isolation structure proposed for a patent was the one designed by J.A. Calantarients, an English doctor, who applied for a U.S. patent in 1909 (Meiji 42) (Fig. b). In this structure, the building is isolated from the foundation using layers of talc so that the building slides during an earthquake. In this type of structure, considerable relative displacement is expected between the building and its foundation during an earthquake. For this purpose, separate connecting fixtures (joints) were proposed for gas pipes and drainage, allowing similar relative displacement.

Incidentally, in a letter written to an American friend, Calantarients mentions that the base isolation structure proposed by him is not a copy of base isolation (Menshin) structure proposed in Japan 25 years earlier, but is superior to that. The paper by Mr. Kawai, mentioned above, was published 18 years before Calantarients' design, which means that even before the publication of Mr. Kawai's paper some Japanese proposals for a base isolation structure were known abroad. The details of that base isolation structure are, however, not known today.

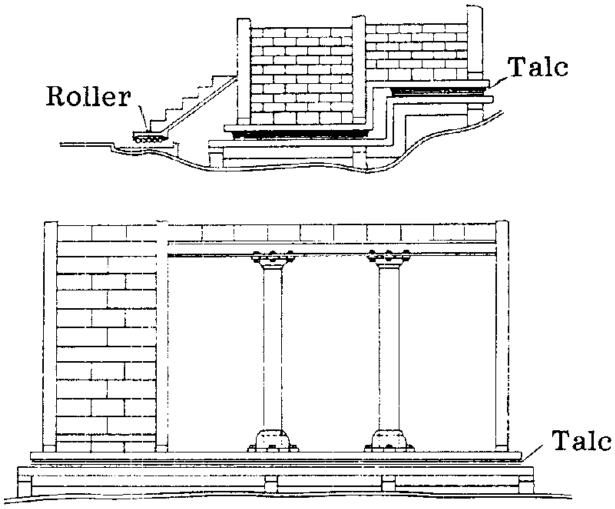


Fig. b. Calantarients' base isolation structure (1909)

2) Theories about earthquake-resistant buildings and seismic coefficient

Three years before Calantarients' proposal, that is in 1906, a severe earthquake occurred in San Francisco. Calantarients' design was probably inspired by this earthquake. The great San Francisco earthquake was the first in which the modern American city on the Pacific Coast was aslo affected. All bricks and wooden structures not protected by antiseismic treatment were greatly damaged and more than half of San Francisco was engulfed in fire (about 28,000 houses in an area of 12 square kilometers). Contrarily, reinforced concrete houses that were under construction showed greater fire resistance or earthquake resistance. Prof. Toshiki Sano of Tokyo Imperial University was a member of the team investigating the earthquake damage. He noticed the advantage of reinforced concrete structures and thought this would be a useful innovation in Japan where earthquakes are quite common; he started studies in that direction. Later, Prof. Sano prepared a thesis entitled "Antiseismic building structures" (1914, Taisho 3) based on his experience of the earthquake resistance of buildings. This study is the foundation of the science of antiseismic building structure throughout the world. In his book, Prof. Sano mentioned the concept of "seismic coefficient," a term indicating the seismic force operating on buildings. The seismic coefficient is the ratio of acceleration due to earthquake acting on the building to the gravitational acceleration. The seismic force acting on the building can be calculated by multiplying the weight of the building by the seismic coefficient. He also suggested providing greater strength, and stiffness of the building to help it withstand an earthquake.

From 1906 (Meiji 39), studies were undertaken at the Architectural Institute of Japan, at the request of the then mayor of Tokyo, Mr. Yukio Ozaki, to draft building regulations for Tokyo to be known as the Tokyo Metropolitan Building Regulations. This study was completed in 1913 (Taisho 2) and the findings were submitted to the Tokyo Municipal Government. This was the beginning of the Building Regulations Act which is the first form of modern building regulations enforced in Japan. Although the Tokyo Metropolitan Building Regulations were framed after considering many building examples in cities of Europe and the USA, the section on the strength of these buildings was prepared by Prof. Sano. Based on these proposed regulations, the Metropolitan Building Regulation Act was passed in 1919 (Taisho 8) and, consequently, the Metropolitan Building Construction Rules were passed in 1920 (Taisho 9). Here, for the first time, specifications for the structural design of buildings were enumerated. The load and external forces taken into consideration while laying these specifications were the dead load and the live load of the floors only. The allowable stress of the material was so defined that safety factor is three.

The great Kwanto earthquake of 1923 (Taisho 12) caused heavy damage to building structures around Tokyo. This calamity provided a great impetus to the studies of antiseismic structures and the Building Regulations Act was greatly modified as a result. The specifications for structural design in the Metropolitan Building Construction Rules were modified as a result. The specifications for structural design in the Metropolitan Building Construction Rules were modified in 1924 (Taisho 13), the year after the Kwanto earthquake, the seismic force in which was determined according to Prof. Sano's concepts of seismic coefficient. The guidelines indicated that the safety factor should be 3 while the horizontal seismic coefficient should be assumed to be more than 0.1. Similarly, obligatory positions of bracings and bearing walls for buildings of steel construction, and the length of lap joints of steel reinforcements or the reinforcement ratio in columns for reinforced concrete construction were defined for the first time.

Around the same time, maybe as a result of the heavy damage caused by the Kwano earthquake, proposals for base isolation structures were offered in Japan and patents were even applied for. In 1924 (Taisho 13), the same year as the Metropolitan Building Construction Rules were modified to include the consideration of the seismic coefficient, Kenzabro Kito and Okiie Yamashita proposed base isolation structures and patents were awarded to their proposals. Kito's patent, "Earthquake-resistant gadgets for buildings," proposed using concave dish-like parts between the foundation and the columns and ball-bearings were inserted between the dishes thereby supporting the building (Fig. c). Yamashita's patent, "Earthquake-resistant devices for building structures," proposed a structure wherein some sliding motion is allowed between the foundation and the columns thereby reducing the impact of an earthquake on the actual structure (Fig. d).

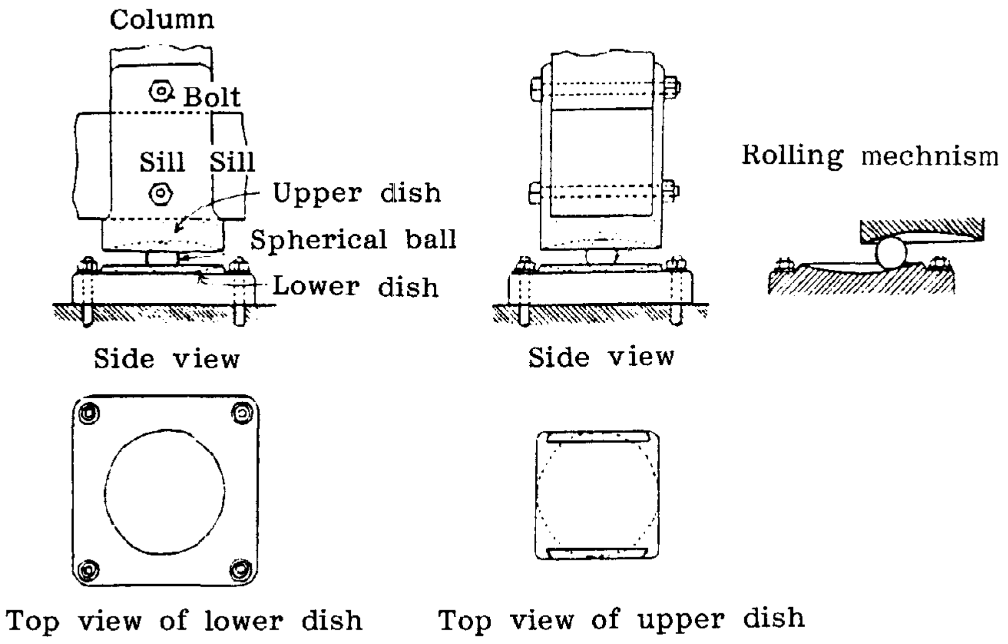


Fig. c. Kenzabro Kito. Antiseismic devices for buildings (1924).

It also provided for a spring between the foundation and the column so that the column returns to its original position (after the earthquake is over).

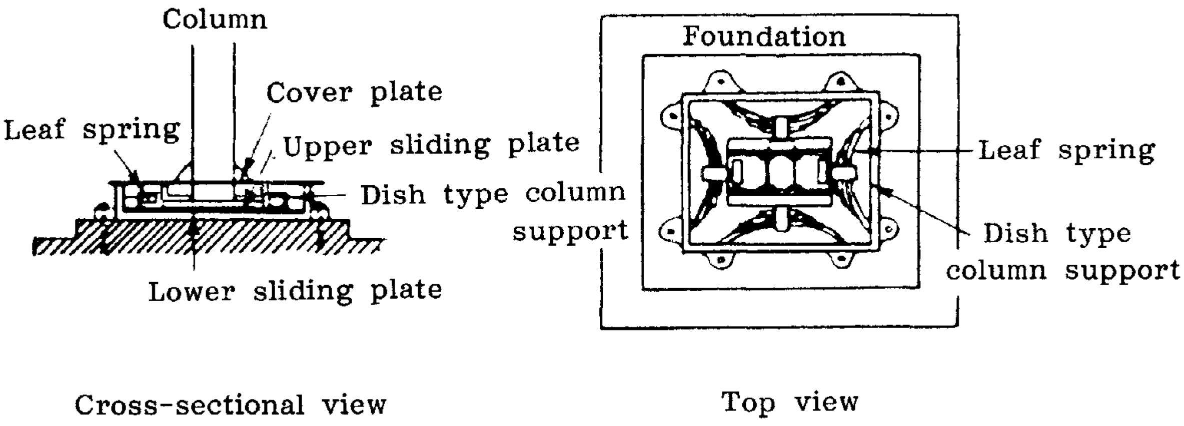


Fig. d. Okiie Yamashita. Antiseismic devices for structures (1924).

3) Controversy between flexible and stiff structures

Although the great Kwanto earthquake provided a good impetus for studies on earthquake-resistant buildings, it initiated controversies which continued for several years about categorization of structures that can withstand earthquakes. One such controversy was that of flexible and stiff structures, articles on which were published in the issues of Kenchiku Zasshi, in the early years of Showa period (around 1930), shortly after the Kwanto earthquake. This controversy continued for several years. This debate was between Prof. Sano and Prof. Muto of Tokyo Imperial University on the one hand, who held that to make a building withstand an earthquake, it is necessary to reduce its period of oscillation and make it stiff and on the other hand, Mr. Kenzabro Majima, Chief of the Naval Architecture Department, who felt that the period of oscillations should be increased and the structure made flexible so as to make it earthquake-resistant. Since all these persons were directors of earthquake-resistant structural design in Japan, and were advocating the opposite view, considerable interest was generated in this subject.

It was almost 20 years before the effect of the base isolation structure in response to earthquake could be examined analytically. It became possible to do so with the development of strong-motion seismographs that can record the acceleration generated by a severe earthquake and the development of computing techniques for response analysis. The flexible-stiff controversy mentioned above began 30 years before such analysis could be carried out.

Even at that time, the basic equation for the condition of vibrations in a building during an earthquake was known. Theoretical solution of this equation considering some external force such as the harmonically oscillating force was also obtained. However, at that time, the real nature of seismic motion was probably not known. Most of the flexible-stiff controversy was due to differences in the assumptions of the two sides regarding earthquake motion. Both the flexible and stiff approaches try to avoid resonance of the building structure with earthquake motion from the dynamic point of view, but there is considerable difference of opinion about the period of earthquake motion the resonance at which period or frequency is to be avoided.

We cannot determine whether flexible structure or stiff structure is better unless the properties of earthquake motion are clearly understood. Therefore, the flexible-stiff controversy ended inconclusively.

Based on the present knowledge about earthquake motion, it appears that the flexible structure advocated by Mr. Majima was a progressive approach. Flexible structure is one of the principles of the base isolation structure and highrise multistoried buildings in Japan can be built only with this flexible structure. However, as a result of this controversy, most buildings in the world thereafter incorporated the stiff structure. The Metropolitan Building Regulations were so modified that the height of buildings was restricted to 100 shaku (31 meters), mainly to restrict urban population density. Later buildings were also based on stiff structure to increase the resistance of a building. At this time seismographs were not recorded nor were they analyzed; as such, the concept of stiff structure, in which the structure is made stiff enough to be earthquake-resistant, was well received.

During the flexible-stiff controversy, proposals for the base isolation structure started appearing in Kenchiku Zasshi. In 1927 (Showa 2) Taro Nakamura discussed earthquake resistance of buildings in terms of energetics and suggested that if some energy absorbing device is installed in the building, its earthquake resistance will increase. He proposed a damper mechanism consisting of braces with a pump damper In the same year, he discussed the case of a seven-story reinforced concrete building where the joints at both ends of the basement columns were of hinge structure and free horizontal slide was allowed between the ground and the building. In addition, he proposed the installation of the pump type damper (hydraulic damper) for energy absorption (Fig. e). Ryuichi Oka made many proposals for the base isolation foundation for a few years since 1928 (Showa 3). In such a foundation, base isolation columns with a hemispherical surface at the bottom were erected on the foundation plate as shown in the figure (Fig. f). During an earthquake, some horizontal displacement is allowed between the foundation and the upper structure as a result of swaying of the base isolation column. Also, as a result of friction in the spherical pin joints, the force of damping acting against the vibration also increases so that the same structure can resist vibrations due to wind load. Mr. Oka's idea, "Base isolation devices for buildings" was patented in 1932 (Showa 7). This type of foundation is used in many buildings, some of which are mentioned below:

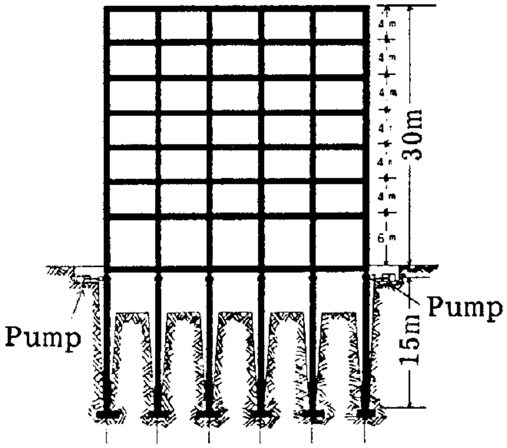


Fig. e. Taro Nakamura. Device for seismic energy absorption (1927).

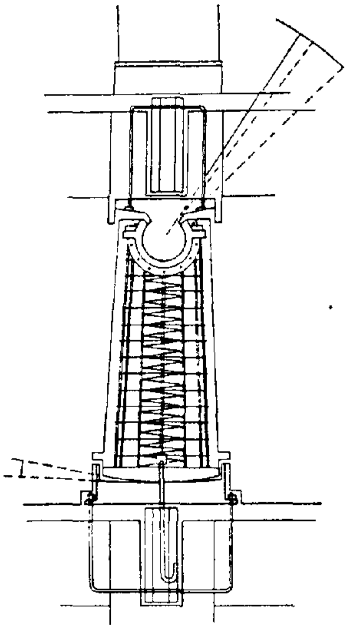


Fig. f. Ryuichi Oka. Base isolation foundation (1928)

*Insecticide sprayers stocking room, sewage section, Civil Engineering Department of the Tokyo Metropolitan Council (located on Shibaura reclaimed land, Shiba-ku, Tokyo, 1932, reinforced concrete structure, total floor area about 30 m^2).

*Fudo Chokin Bank, Himeji Branch (1934, reinforced concrete structure, three floors above ground, one basement floor, total floor area about 790 m^2).

*Fudo Chokin Bank, Shimonoseki Branch (1934, reinforced concrete structure, three floors above ground, one basement floor, total floor area about 640 m^2).

The insecticide sprayers stocking room of the Tokyo Metropolitan Council was a structure of 8.2 x 3.5 m in plan size to test the effect of the base isolation foundation. Next to it was constructed an identical building, without base isolation. It was constructed for comparison with the structure with base isolation foundation. Two buildings of the Fudo Chokin Bank are three-storied reinforced concrete structures. The Himeji Branch building has base isolation columns in the basement. Shimonoseki branch uses base isolation columns between the ground floor and foundation slabs.

While the flexible-stiff controversy raged in Japan, it was proposed in the USA that if the first floor of a building is made flexible, the force of an earthquake is not transmitted so strongly onto the remaining floors. Such a structure was called the "Flexible first story" (or "Soft first story"). In Japan, too, a similar proposal by Kenzabro Majima, as mentioned above, was patented ("Earthquake resistant building structure") in 1934 (Showa 9). According to Majima's idea, in a two-story structure, the ground and the first floors are structurally separate and the first floor is supported by columns of low stiffness (Fig. g). Accordingly, two-story buildings were basically "Flexible first-story type." Even if the columns of low stiffness collapse, a part of the first floor would still be supported by part of the ground floor which is structurally independent.

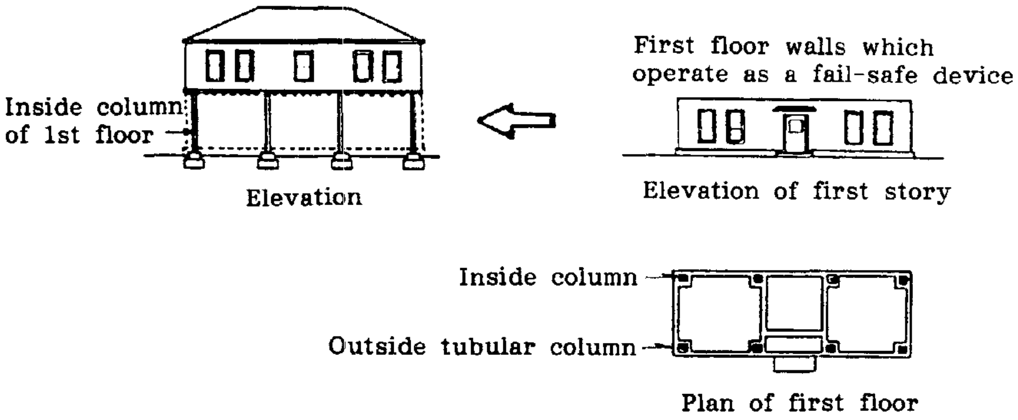


Fig. g. Kemzabro Majima. Earthquake-resistant residential buildings (1932).

In 1938 (Showa 13), Oka constructed the basement of a building as a watertight float and the structure was supported by the buoyancy equivalent to the mass of excavated earth. He was granted a patent for this idea ("Foundation methods for buildings"). In the same year, Fukuhei Takabeya of Hokkaido University, based on his model shaking-table tests, proposed a structure in which a heavy mass mounted on rollers is placed on the top floor of a building and vibrations in structure are damped using the inertia of that mass (Fig. h).

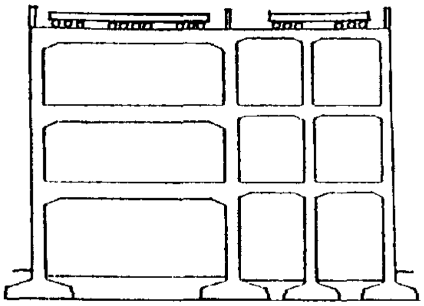


Fig. h. Fukuhei Takabeya. Response-control type earthquake-resistant structure (1938).

This idea was patented in 1940 (Showa 15) as "Damper-type earthquake-resistant structure." According to Takabeya, before this patent, Sezawa published a report of experiments and analysis of a structure in which a kind of pendulum-like device, which may be called a dynamic damper, is fitted to the structure. Ryuichi Ika also published a report of model experiments using the roller structure of Oakabeya and the other original proposals for base isolation structures.

4) Strong-motion earthquake records and the computer

Knowledge of earthquake ground motion is necessary while designing earthquake-resistant structures. To gather such knowledge, it was necessary to develop a strong-motion seismograph and observation methods so that strong seismic ground motion could be recorded. At that time, Suehiro, head of the Earthquake Research Center of Tokyo University, explained the need to develop a strong-motion seismograph and observation methods but his suggestions were not well received in Japan. On the other hand, his views were understood in the USA where a strong-motion seismograph was developed and observations began in the early 1930's with California as its center. Acceleration records of strong seismic motion were first available from the USA. [An example is the record at the El Centro Transformer Substation of the famous Imperial Valley earthquake in 1940 (Showa 15).] Based on such records of observations, M.A. Biot of the California Institute of Technology discussed, for the first time, in 1932 (Showa 7) the concept of response spectrum of seismic motion. In the USA, it was proposed that the design seismic force (coefficient) be changed in response to the fundamental period of oscillation of the building; this idea developed into a structural design method with dynamic considerations. In Japan, acceleration records of strong earthquakes were not available until the end of World War II.

With the end of the War, Japan started its restoration. In 1950 (Showa 25), the Metropolitan Building Regulations were suspended; it was planned to bring new building regulations into force. At that time, structural design was based on such specifications as the Extraordinary Japan Standard Specification 532 "Load on Buildings," the Extraordinary Japan Standard Specification 533 "Guidelines for Design of Buildings" (1944, Showa 19) or Japan Building Specification 3001 "Structural Calculations for Buildings" (1947-Showa 22). In addition, concepts of "short-term" and "long-term" load, external force and allowable stresses were introduced. As a result, the level of allowable stresses (short-term) was greatly increased compared to the Metropolitan Building Regulations and, at the same time, it was decided to assume the horizontal seismic coefficient of more than 0.2.

At the end of the War, the Japanese economy started growing at an astonishing pace. Urban land became scarce and land prices soared. Available land had to be used most efficiently. Therefore, highrise buildings were in demand. Around 1950 (Showa 25), foresighted researchers initiated studies of nonlinear vibrations in building structures. However, it was only in 1959 (Showa 34) that Prof. Kiyoshi Muto of Tokyo University and his colleagues prepared a project to study the feasibility of high-rise buildings. The project was to construct a 24-story building at the Tokyo Railroad Station of the Japan National Railways (JNR). Analysis of the response of such high-rise buildings during an earthquake was analyzed on the latest analog computer, based on the records of strong earthquake motion in the USA. The results of this three-year study concluded that even high-rise buildings can be made earthquake-resistant if the fundamental period of oscillation is made longer.

The high-rise building of the Tokyo Railroad Station could not be constructed for various reasons but it was clear that high-rise building construction in Japan, a highly earthquake-prone country, was possible. With this, the 31-meter maximum limit on the height of buildings, set by the Metropolitan Building Regulations mainly to control population density, was removed, and a floor space index (FSI) was established (1963, Showa 38). Thereafter the high-rise building boom started in Japan with the construction of Kasumigaseki building . Although restriction on the height of buildings had been removed, approval from the Ministry of Construction had to be obtained for individual high-rise buildings, since the safety of the design was certified on the basis of computer-aided earthquake response analysis. Therein the designers have a tendency to assume smaller seismic force than that specified by regulations and as a result the design differs from normal antiseismic building design.

Once the record of strong earthquake motion and the use of computers were available, it was possible to analyze the effect of base isolation structures. The first such analysis in the world was done by Kiyoo Matsushita of Tokyo University and Masanori Izumi of Building Research Institute in the Ministry of Construction. Together they presented a paper on the analysis of base isolation structures wherein the foundation and the upper building are isolated using ball-bearings.

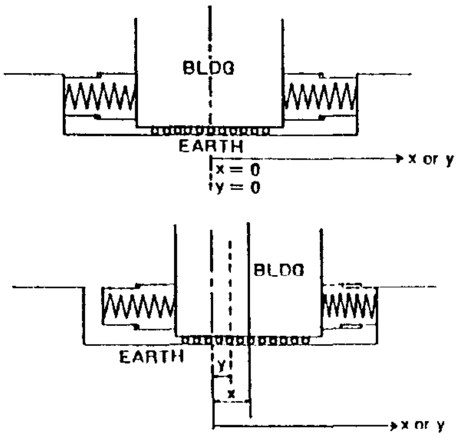


Fig. i. Vibration damper for seismic waves (1951).

Incidentally, prior to this, Sizuo Otsuki of Shimizu Constructions proposed using rollers which operate in the directions normal to each other at the foundation and the four sides are supported by springs (a device restricting the propagation of seismic wave), and called it the vibration damper (Fig. i). Otsuki determined the response of buildings fitted with this device assuming the seismic wave as a simple oscillating motion. Although the actual seismic motion is quite complicated, by superimposing the waves (Fourier transform), he showed that the method is effective if the fundamental frequency of oscillation of the system is small. Subsequently, in 1954 (Showa 29), Takuji Kobori of Kyoto University, during his study of nonlinear oscillating motion, noticed that using wires with pre-tension and twisted wires as braces, the initial stiffness of a building is increased. If the response amplitude increases beyond a certain limit, the pre-tension wires yield and shear off while the remaining twisted wires impart nonlinear recovery characteristics to the building. The increase in wire deformation of the building increases its stiffness as well. With this approach, resonance at the time of an earthquake is avoided. In 1957 (Showa 32), Takuji Kobori suggested a prototype of the response-control structure using the example of an atomic furnace where the reaction furnace is supported on both sides on hinges and a spring is horizontally placed. In 1960 (Showa 35), Kobori defined damping as experiencing seismic vibrations so that the seismic motion is restricted. He has published papers related to his study of the analysis of damper system. In 1957 (Showa 32), Yasuhisa Sonobe of Tokyo University published a report on analysis of the response-control structure using the friction damper and the results of a shaking-table test for a building where a mass is suspended from the top of the building. In 1964 (Showa 39), Chitoshi Katsuta of Tokyo Institute of Technology published a report about the Menshin device (vibration-reducing device) based on an electro-hydraulic type automatic control system. This was a sequel to his work on the development of a unique vibrating pad (Fig. j). In this device, a seismograph is fitted in a structure supported by ball-bearings. The relative displacement between the structure and the ground is detected and corresponding signal is sent to the servo-system which in turn controls and operates the actuator that in turn controls the behavior of the structure. Katsuta made further improvements in this device and obtained patent in 1965 (Showa 40) for the "Menshin device." In this patent, a diagonal member is installed in the foundation. An oil (hydraulic) cylinder with a servo valve, which operates with a signal from an earthquake motion detector mechanism, is fitted to this diagonal member. As a result, the upper structure is kept in a steady state even during an earthquake, irrespective of the ground motion.

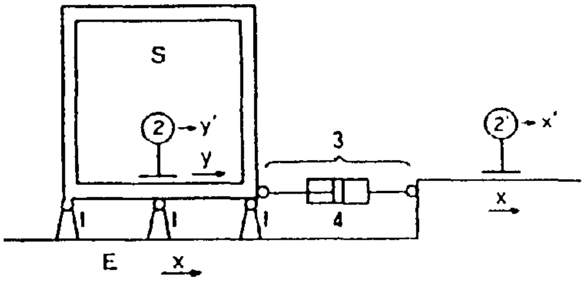


Fig. j. Chitoshi Katsuta. Base isolation method using auto-control (1964).

S - Structure; E - Earth's crust or underground structure in contact with earth's crust; 1 - Support column; 2 - Seismograph; 3 - Horizontal support including actuator; 4 - Servo-valve and actuator; X, Y, Y' - Displacement of earth's crust, structure and center of gravity of pendulum, respectively.

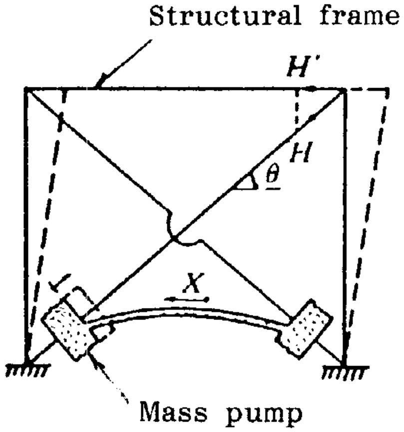


Fig. k. Shigeya Kawamata. Mass pump (1973).

[Key: 1 - Mass pump 2 - Frame]

Other patents were also awarded during this period. For the damper structure, we mention the proposal for "Earthquake-resistant foundation for structures" by Shin'ichi Ishida, wherein the earthquake energy is absorbed by the foundation pads installed between the upper level of the foundation and the columns by the nearby soil. In the other proposal for "Earthquake-resistant, wind-resistant and atom/hydrogen bomb-resistant buildings" by Shinya Mannen, a spherical structure is allowed to float in a spherical dish-type foundation filled with water. Both these methods are patented.

Developments continued and in 1973 (Showa 48), Shigeya Kawamata of Tokyo University published his findings about damping the earthquake response using a "mass pump" (Fig. k). In 1975 (Showa 50), Masanori Izumi of Tokhoku University described a method called "Genshin" in which the effect of the seismic force is reduced and the structure is made antiseismic. He published a review introducing the innovative proposals and studies on the "Genshin" approach, analyzed the "Genshin" structure and offered some design examples.

5) Development of laminated rubber bearings and base isolation structures

In 1969 (Showa 44), a primary school building was constructed in Skopjie, Yugoslavia, where they used rubber bearings designed by a Swiss national. These rubber bearings were flexible horizontally and vertically. The rubber bearings are effective in increasing the fundamental period of vibrations and thereby reducing the seismic force; but this support also has to bear the load of the building. The bearings in the Skopjie primary school posed some problems in supporting the vertical load and construction works.

The idea of improving the bearing capacity of rubber bearings in the vertical direction and maintaining its stiffness developed a few years later in France. This development used "laminated rubber": thin rubber sheets and steel sheets were arranged in many layers so that the composite material had flexibility horizontally and stiffness vertically and could support a large mass. Using such laminated rubber bearings, many base isolation buildings were constructed in the late 1970's including the Lambesc Primary School in Marseilles, the Coebereg Atomic Power Plant in South Africa and the Craus Atomic Power Plant in France. Using a similar idea, buildings were constructed in the 1980's such as the William Clayton Building in Wellington, New Zealand and the Foot Hill Law and Justice Center Building in California, USA.

In Japan, with progress in the response analysis technique, it has become apparent that the seismic force greatly decreases as the fundamental period of oscillation of the building increases. In 1964 (Showa 39), the Architectural Institute of Japan published a book entitled <u>Design Guidelines for High-rise Buildings</u>. The Institute proposed the base shear coefficient for the design of high-rise buildings which will reduce hyperbolically as the fundamental period of building increases. The structural design specifications (as the Building Regulations), however, were not modified accordingly. The seismic force for the purpose of design was taken the same as before, and the horizontal seismic coefficient of at least 0.2 had to be assumed in the design.

With developments in the response analysis techniques and with the occurrence of Tokachi-oki Earthquake in 1968 (Showa 43), a survey under the Ministry of Construction involving wide ranging technological development was conducted for five years from 1972 (Showa 47). It was called "Development of new earthquake-resistant design methods" and aimed at modifying the structural design specification values (in the Building Construction Rules). In 1978 (Showa 53), an earthquake occurred near Miyagi prefecture and based on those observations, structural design specifications values (in Building Standard Law) were modified in 1981 (Showa 56). It was decided that the seismic force is to be determined from the fundamental period of the building. With this, the building designs could be approved even if the seismic force assumed is less than the previously set limits, provided, of course, that the fundamental period of the building is longer.

With modifications in the Building Standard Law and the construction of earthquake-resistant buildings in Europe and America using laminated rubber bearings, the studies on such buildings in Japan have been streamlined. The residential base isolation building using laminated rubber bearings was constructed by Hideyuki Tada of Fukuoka University in cooperation with Shoichi Yamaguchi and Unitika Ltd. and others (1983, Showa 58). It was noted by the Building Center of Japan as a special structure and was built with the approval of the Ministry of Construction. Housing is one of the uses of the base isolation structures. It was possible to apply this technique even to the atomic power plant buildings and by doing so studies of the Menshin or base isolation structure technology have rapidly expanded.

The response-control structure may involve other approaches in addition to the laminated rubber bearings and many buildings are constructed using these approaches. These include Building No. 1 of Tokyo Science University built by

Matsushita mentioned above. Here, the stiffness of the basement floor is reduced and the dampers are sandwiched between a double-column structure (1961, Showa 56). A similar double-column structure is used for the Union House, Auckland, New Zealand (1983, Showa 58). In another approach, a pendulum, as heavy as possible, is suspended from the top floor of the structure and by allowing it to swing, vibrations to the building are reduced. Such dynamic dampers are also used in the Sydney Tower, Australia (1975, Showa 50) and Chiba Port Tower (1986, Showa 61). In yet another approach, a mass is placed on the top of the building and is allowed to slide horizontally. This mass is controlled by an actuator which operates with a signal from a detector, thereby reducing vibrations to the structure. Examples of this approach (active mass damper) include City Corp Building, New York (1977 Showa 52) and the John Hancock Center Building, Boston. However, in these cases, the object is not to reduce the seismic force but to reduce the vibrations of the tower due to strong winds (for recent examples, readers are referred to the following section).

The history of response-control structures and building techniques used in the above examples as well as details of regulations involved, etc., are listed in Table 2.1.

[This draft is based on a similar paper published in the May 1987 issue of Kenchiku Gijutsu (Architectural Techniques) by Yuji Ohashi and Shoichi Yamaguchi.]

Table 2.1. Chronological survey of proposals for response-control structures

Earthquakes	Academic activities	Regulations	Social events	Proposals for response-control and Menshin structures
1	2	3	4	5
	Meiji 10 (1877) Civil Engineering Department started in Engineering College			
	Meiji 13 (1880) Japan Seismology Association established			
	Meiji 19 (1886) Building Society established			
Meiji 24 (1891) Nobi earthquake				Meiji 24 (1891) Kozo Kawai published a paper on structures that can be free from strong vibrations during earthquakes (Fig. a)
	Meiji 25 (1892) Association formed to estimate and minimize damage due to earthquake			
Meiji 39 (1906) San Francisco earthquake				
				Meiji 42 (1090) Calantarients proposed the Menshin structure (Fig. b)
		Taisho 2 (1913) Tokyo Metropolitan Building Regulations proposed		
	Taisho 3 (1914). Thesis on antiseismic building structures by Toshiki Sano			

		Taisho 8 (1919) Urban Building Regulations declared (building height below 31 m)		
		Taisho 9 (1920) Building Construction Rules declared (specifications for structural design)		
	Taisho 11 (1922). Paper on Earthquake-resistant structures for buildings by Tachu Maito			
Taisho 12 (1923) Great Kwanto earthquake			Taisho 12 (1923) Damages in and around Tokyo	
		Taisho 13 (1924) Construction Rules modified (seismic coefficient K = 0.1)		Taisho 13 (1924) Kenzabro Kito proposed Menshin devices for buildings (Fig. c) Yamashita proposed antiseismic devices for buildings (Fig. d)
	Flexible-stiff controversy			Showa 2 (1927) Taro Nakamura proposed arrangement for absorption of energy of seismic motion (Fig. e)
				Showa 3 (1928) Ryuichi Oka proposed Menshin foundation (Fig. f)
	Showa 7 (1932) M.A. Boit introduced the concept of response spectrum			
	Showa 8 (1933) Method for calculating coefficient for distribution of horizontal force in a reinforced concrete structure (Kiyoshi Muto)			

	Showa 9 (1934) 14th special group established in "Japan Society for Promotion of Science" to study seismic structures			Showa 9 (1934) Kenzabro Majima patent on seismic building structure (Fig. g)
				Showa 13 (1938) Fukuhei Takabeya proposed damper-type earthquake-resistant structure (Fig. h)
Showa 15 (1940) El Centro earthquake	Showa 15 (1940) 14th special group disbanded			
	Showa 16 (1941) Standardd for steel frame structure issued		World War II	
Showa 19 (1944) South East Sea earthquake	Showa 19 (1944) Temporary Japan Standard Specifications issued: "Outline of Earthquake-Resistant Building Structure"			
Showa 21 (1946) South Sea earthquake				
Showa 23 (1948) Fukui earthquake	Showa 23 (1948) Japan Building Specification 3001 issued structural calculations for buildings with K = 0.2		Show 23 (1948) Daiwa building collapsed	
		Showa 25 (1950) Building Construction Rules released with K = 0.2		
	Show 26 (1951) Building Codes in San Francisco released			Showa 26 (1951) Otsuki proposed a devices for restricting the propagation of earthquake vibrations (Fig. i)
	Kawasumi published a zoning map for seismic activity (Kawasumi Map)			
Showa 27 (1952) Off-Tokachi Earthquake	Development of SMAC	Showa 27 (1952) Zonal coefficients for earthquake prone area released		

	Showa 31 (1956) The First World Conference on Earthquake Engineering held; dynamic studies in full swing			
				Showa 32 (1957) Takuji Kobori published a paper -- "An experiment with response-control structures"
				Showa 35 (1960) Takuji Kobori published a paper -- "Analysis of response control structures"
Showa 39 (1964) Niigata earthquake	Showa 39 (1964) Design guidelines for high-rise buildings propsed	Showa 39 (1964) Restriction on the height of buildings (31 m) removed	Showa 39 (1964) Liquiefection of earth crust noticed	Showa 39 (1964) Senri Katsuta proposed Menshin method based on auto control (Fig. j)
Showa 43 (1968) Off-Tokachi Earthquake			Showa 43 (1968) Reinforced concrete buildings damaged	
				Showa 44 (1969) Elementary school at Scopjie Yugoslavia
Showa 46 (1971) San Fernando earthquake	Showa 46 (1971) Specifications for the design of reinforced-concrete building structures modified	Showa 46 (1971) Reinforce-concrete strucutre design standards modified	High-rise building boom started	
	Showa 47 (1972) Development of new aseismic design started			
				Showa 48 (1973) Shigeya Kawamata proposed a "mass pump" (Fig. k)
	Showa 52 (1977) New aseismic design project completed			

Showa 54 (1979) Off-Miyagi prefecture earthquake					
		Showa 56 (1981) Building Standard Law modified (the so-called new aseismic design method)			Development of laminated rubber

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2.3.2. Examples of response-control structures

The main examples of response-control structures in Japan and other countries are listed in Table 2.2. They are classified as follows:

1. Computer room-base isolation floor	2	(Japan - 2 cases)
2. Double-column structure	2	(Japan - 1 case)
3. Base isolation structure using laminated rubber	16	(Japan - 10 cases)
4. Dynamic damper	3	(Japan - 1 case)
5. Various damper units	5	(Japan - 2 cases)
6. Others	3	

Table 2.2. Examples of response-control structures in Japan and other countries

No	Name of Building	Location	No. of floors	Floor area m^2	Structure	Application or Occupancy	Year of Construction	Remarks (details of damper)
1	2	3	4	5	6	7	8	9
1	M.I.E. floor system					Computer room floor		Ball bearing support
2	Dynamic floor					-do-		Teflon sheets
3	Fudochokin Bank (now Kyowa Bank)	Himeji	+3,-1	791	RC	Bank branch	1934	Sway-type hinged column
		Shimonoseki	+3	641	RC	-do-	1934	
4	Tokyo Science University	Tokyo	+17,-1	14,436	Steel	School	1981	Double columns
5	Union House	Auckland, New Zealand	+12,-1		RC	Office	1984	-do-
6	Pestalochi Elementary School	Skopjie, Yugoslavia	+3		RC	School	1969	Rubber
7	Foothill Law and Justice Center	California, USA	+4,-1		Steel	Court	1986	Laminated rubber
8	W. Clayton Building	Wellington, New Zealand	+4		RC	Office	1983	Laminated rubber
9	Cruas Atomic Power Plant	France			RC	Atomic furnace	1984	-do-
10	Koeberg Atomic Power Plant	South Africa			RC	-do-	1983	-do-
11	Yachiyodai Apartments	Chiba, Japan	+2	114	RC	Housing	1983	-do-
12	Okumura Gumi, Tsukuba Research Center, office wing	Ibaraki, Japan	+3	1,330	RC	Research Center	1986	-do-
13	Tohoku University, Shimizu Construction Laboratory	Miyagi, Japan	+3	200	RC	Observatory	1986	Laminated rubber, oil damper

1	2	3	4	5	6	7	8	9
14	Obayashi Corporation, Technical Research Center, 61st Laboratory	Tokyo	+5,-1	1,624	RC	Laboratory	1986	Laminated rubber
15	Oiles Industries Technical Center, Fujisawa Plant, TC wing	Kanagawa, Japan	+5	4,765	RC	Laboratory, Office	1986	-do-
16	Funabashi Taketomo Dormitory	Chiba, Japan	+3	1,530	RC	Dormitory	1987	-do-
17	Kajima Institute of Construction Technology, Acoustic Laboratory	Tokyo	+2	655	RC	Research Laboratory	1986	-do-
18	Christian Museum	Kanagawa, Japan	+2	293	RC	Museum		Laminated rubber
19	Chiba Port Tower	Chiba, Japan	125 m	2,308	Steel	Tower	1986	Dynamic damper
20	Sydney Tower	Australia	325 m		Steel	Tower	1975	-do-
21	City Corp. Center	New York, USA	+59		Steel	Office	1977	Tuned mass damper
22	Hitachi Headquarters	Tokyo	+20,-3	57,487	Steel	Office	1983	Steel damper
23	World Trade Center	New York, USA	+110		Steel	Office	1976	VEM damper (visco-elastic material)
24	Columbia Center	Seattle, USA	+76		Steel	Office	1985	-do-
25	Radar Construction	Chiba, Japan			Steel	Instrument platform	1980	Roller bearing
26	Christchurch Chimney	Christchurch, New Zealand	35 m		RC	Chimney		Steel damper
27	Commerce and Industry Culture Center	Saitama, Japan	+30		Steel	Office	1987	Friction damper

1	2	3	4	5	6	7	8	9
28	Fujita Industries Technical Research Laboratory, (6th Laboratory)	Kanagawa, Japan	+3	3,952	RC	Research center		Laminated rubber
29	Shibuya Shimizu No. 1 Building	Tokyo	+5,-1	3,385	RC	Office		-do-
30	Fukumiya Apartments	Tokyo	+4	682	RC	Apartment		-do-
31	Lambesc C.E.S.	France	+3	4,950	Precast RC	School	1978	-do-

Note: + indicates floors above ground; and - indicates floors below ground.

Table 2.3a. Cases approved by the Ministry of Construction (1)

Item	(0) Yachiyodai Apartments	(1) Christian Museum	(2) Okumura Gumi, Tsukuba Research Center
1	2	3	4
Designed by	Tokyo Kenchiku Structural Engineers	Tokyo Kenchiku Structural Engineers, Unitika	Tokyo Kenchiku Structural Engineers, Okumura Inc.
Design requirements		Antiseismic. Prevent any damage to goods stored	Antiseismic. Protect computer and stored data. Measurement of response for technical studies
Appraisal No.	BCJ LC 99	BCJ Men1	BCJ Men2
Year of Appraisal	April 1982	July 1985	November 1985
Year of approval; No.	November 2, 1982; 455	November 19, 1985; Kana 61	December 24, 1985 Tochi 37
No. of stories	+2	+2, -1	+4
Total floor area, m^2	60.18	226.21	348.18
Occupancy	Housing (residential)	Museum	Research center

Structure	RC frame and shear wall	RC frame and shear wall	RC frame
Foundation	Raft foundation with cast in-situ piles	Deep foundation	RC cast in-situ raft
Isolator: Dimensions, mm	82 x 300 dia	Rubber 5 thick x 300 dia (12 layers)	Rubber 7 thick x 500 dia (14 layers)
Numbers	6	32	25
Bearing Capacity	$\sigma = 45$ kg/cm^2, 0.5 t/cm (32 t)	$\sigma = 60$ kg/cm^2, 0.5 t/cm (42.5 t)	$\sigma = 60$ kg/cm^2, 0.86 t/cm (120 t)
Damper	Friction force between PC plates	Uses plastic deformation of steel bars bent to make a loop (8 Nos.)	Uses plastic deformation of steel bars bent to make a loop (12 Nos.)
Base-shear coefficient used in design	0.2	0.15	0.15
Fundamental period at Small deformation	1.83 sec	1.4 sec	1.4 sec
at Large deformation		1.9 sec	2.1 sec
Input seismic wave	El Centro 1940 (NS) Hachinohe 1968 (NS) Hachinohe 1968 (EW) Taft 1952 (EW)	El Centro 1940 (NS) Hachinohe 1968 (NS) Taft 1952 (EW)	El Centro 1940 (NS) Taft 1952 (EW) Hachinohe 1968 (NS)
Input level	300 gal	300 gal, 450 gal	300 gal, 450 gal

Table 2.3b. Cases approved by the Ministry of Construction (2)

Item	(3) Obayashi Co. Technical Research Center	(4) Oiles Technical Center, Fujisawa Plant, TC wing	(5) Funabashi Taketomo Dormitory
1	2	3	4
Designed by	Obayashi Corporation	Oiles Industries, Sumitomo Constructions Yasui Building Designers	Takenaka Corporation
Design requirements	Antiseismic. Protection of computer and other laboratory equipment.	Antiseismic. Protection of computer and other laboratory equipment stored.	Safety and damage mitigation during earthquake
Appraisal No.	BCJ Men3	BCJ Men4	BCJ Men5
Year of Appraisal	February 1986	March 1986	April 1986
Year of approval; No.	February 27, 1986; Tok. 30	April 7, 1986; Kana 21	June 24, 1986; Chi 43
No. of stories	+5	+5	+3
Total floor area, m^2	351.92	1136.5	719.28
Occupancy	Laboratory	Research laboratory and office	Dormitory
Structure	RC	RC	RC
Foundation	PHC pile (cement grout method)	Concrete in-situ raft (earth-drilling method)	Concrete in-situ raft (earth-drilling method)
Isolator: Dimensions, mm	Rubber 4.4 thick x 740 dia (61 layers)	Rubber 10 thick x 24 layer (H = 363), OD = 650, 700, 750, 800	Rubber 7 thick x 670 dia (19 layers) (H = 187) Rubber 8 thick x 700 dia (18 layers) (H = 195)
Numbers	14	35	14
Bearing Capacity	200 t		200 t → 6 Nos. 150 t → 8 Nos.
Damper	Uses elasto-plastic hystersis of steel bars (96 Nos.)	Lead plug inserted in laminated rubber	Vicous damper (8 Nos.)

Base-shear coefficient used in design	0.15	0.2	0.15
Fundamental period			
at Small deformation	X = 1.33 sec Y = 1.24 sec	X = 0.895 sec: Y = 0.908 sec (at 50% deflection)	X = 2.09 sec
at Large deformation	X = 3.12 Y = 3.08 sec	X = 2.143 sec: Y = 2.148 sec (at 100% deflection)	Y = 2.10 sec
Input seismic wave	El Centro 1940 (NS) Hachinohe 1968 (NS) Hachinohe 1968 (EW) Taft 1952 (EW)	El Centro 1940 (NS) Hachinohe 1968 (NS) Hachinohe 1968 (EW) Taft 1952 (EW) KT 008 1980 (NS)	El Centro 1940 (NS) Taft 1952 (EW) Tokyo 101 1956 (NS) Hachinohe 1968 (NS)
	Man-made earthquake 2 waves	Man-made earthquake 2 waves	Man-made earthquake 4 waves
Input level	25 cm/sec, 50 cm/sec	25 cm/sec, 50 cm/sec	25 cm/sec, 50 cm/sec

Table 2.3c. Cases approved by the Ministry of Construction (3)

Item	(6) Acoustic & Environmental Vibration Test Laboratory, Kajima Corporation	(7) Christian Museum (reapplied)	(8) Fukumiya Apartments
	1	2	3
Designed by	Kajima Corporation	Tokyo Kenchiku Structural Engineers	Okumura Inc.
Design requirements	Reduce seismic input and insulate (isolate) from microtremor of ground	Antiseismic. Prevent any damage to stored goods	Safety of building. Added value in business
Appraisal No.	BCJ Men6	BCJ Men7	BCJ Men8
Year of Appraisal	May 1986	July 1986	December 1986
Year of approval; No.	December 5, 1986; Tok 473		March 3, 1987; Tok 44
No. of stories	+2	+2	+4

Total floor area, m^2	379.10	149.43	225.40
Occupancy	Research Laboratory	Museum	Apartment housing
Structure	RC	RC	RC
Foundation	Concrete in-situ raft (deep foundation)	Deep foundation	Concrete in-situ raft (miniature earthdrilling method)
Isolator: Dimensions, mm	320H x 1340 dia (48 thick x 5 layer); 308H x 1080 dia (38 thick x 6 layer)	4 thick x 435 dia (25 layers)	7 thick x 500 dia (14 & 16 layers)
Numbers	18	12	12
Bearing Capacity	165 t: 1340 dia 100 t: 1080 dia	$\sigma = 60\ kg/cm^2$; 0.55 t/cm (90 t)	
Damper	Elasto-plastic damper using mild steel bars (14 Nos.)	Uses plastic deformation of steel bars bent to make a loop (6 Nos.)	Uses plastic deformation of steel bars bent to make a loop (7 Nos.)
Base-shear coefficient used in design	0.2	0.15	0.2
Fundamental period at Small deformation	X: 0.828 sec Y: 0.809 sec	1.3 sec	1.4 sec
at Large deformation	1.80 sec	1.9 sec	2.2 sec
Input seismic wave	El Centro 1940 (NS) Taft 1952 (EW) Tokyo 101 1956 (NS) Sendai TH038-1 1978 (EW)	El Centro 1940 (NS) Taft 1952 (EW) Hachinohe 1968 (NS)	El Centro 1940 (NS) Taft 1952 (EW) Tokyo 101 1956 (NS) Hachinohe 1968 (NS)
Input level	25 cm/sec, 50 cm/sec	300 gal, 450 gal	25 cm/sec, 50 cm/sec

Table 2.3d. Cases approved by the Ministry of Construction (4)

Item	(9) Shibuya Shimizu Building No. 1	(10) Fujita Industries No. 6 Laboratory
1	2	3
Designed by	Obayashi Corporation	Fujita Industries
Design requirements	Protect the main building and OA equipment installed therein	Protect the main building and equipment stored therein such as laboratory equipment, computers
Appraisal No.	BCJ Men9	BCJ Men10
Year of Appraisal	February 1987	February 1987
Year of approval; No.	March 13, 1987; Tok 52	May 14, 1987; Kana 23
No. of Stories	+5, -1	+3
Total floor area, m^2	560.30	102.21
Occupancy	Office	Research laboratory
Structure	RC	RC
Foundation	Concrete in-situ raft (earth-drilling method)	PHC pile (type A, B) Cement milk method
Isolator: Dimensions, mm	5.0 thick x 620 dia (50 layers); 6.0 thick x 740 dia (45 layers)	4.0 thick x 450 dia (44 layers)
Numbers	20	4
Bearing capacity	100 - 150 t : 620 dia 200 - 250 t : 740 dia	
Damper	Elasto-plastic damper using mild steel bars (108 Nos.)	
Base-shear coefficient used in design	0.15 : Basement, 1st floor; 0.183 : 3rd floor; 0.205 : 5th floor	0.15 : 1st floor, 0.17 : 2nd floor; 0.20 : 3rd floor

Fundamental period at: Small deformation	X = 1.30 sec; Y = 1.24 sec	1.35 sec
Large deformation	X = 2.99 sec; Y = 2.97 sec	
Input seismic waves	El Centro 1940 (NS) Taft 1952 (EW) Hachinohe 1968 (NS) Hachinohe 1968 (EW) SDKANR1G Man-made SDKANT1G seismic SDANSR1G waves	El Centro 1940 (NS) Taft 1952 (EW) Hachinohe 1968 (NS) Hachinohe 1968 (EW) ARTM79L00 (simulated seismic wave)
Input level	25 cm/sec, 50 cm/sec	25 cm/sec, 50 cm/sec

Table 2.3e. Cases approved by the Ministry of Construction (4)

Item	(11) Inorganic Material Research Institute, Vibration-free Wing	(12) Shimizu Corporation Tuchiura Branch Building
1	2	3
Designed by	Secretariat of the Ministry of Construction, Planning Bureau, Obayashi Corporation	Shimizu Corporation
Design requirements	Protect the main building and research equipment stored therein	
Appraisal No.	BCJ Men11	BCJ Men12
Year of Appraisal	June 1987	June 1987
Year of approval; No.		
No. of Stories	+1	+4
Total floor area, m^2	8,341 (old -- 7,725; new -- 616)	170.366
Occupancy	Research laboratory	Office, dormitory
Structure	RC	RC

Foundation	PHC raft (type A) Blast method	PHC raft (type B, C) using earth auger method
Isolator: Dimensions, mm	3.2 thick x 420 dia (62 layers)	6.0 thick x 450 dia; 6.0 x 500; 6.0 x 550 (31 layers)
Numbers	32	14
Bearing capacity	65 t (max 80 t)	51 - 165 t
Damper	Elasto-plastic damper using mild steel bars (48 Nos.)	Lead plug inserted in the center of laminated rubber
Base-shear coefficient used in design	0.15	All floors 0.15
Fundamental period at:		
Small deformation	X = 1.17 sec Y = 1.17 sec	X = 0.77 sec Y = 0.77 sec
Large deformation	X = 2.26 sec Y = 2.26 sec	X = 2.33 sec Y = 2.33 sec
Input seismic waves	El Centro 1940 (NS) Taft 1952 (EW) Hachinohe 1968 (NS) Hachinohe 1968 (EW) Tsukuba 1985 (NS) Tsukuba 1985 (EW) Tsukuba 1986 (NS) Tsukuba 1986 (EW)	El Centro 1940 (NS) Taft 1952 (EW) Hachinohe 1968 (NS) Ibaragi 606 1964 (NS)
Input level	25 cm/sec, 50 cm/sec	25 cm/sec, 50 cm/sec

2.3.3. Cases approved by the Ministry of Construction

More than ten base isolation structures using laminated rubber have been approved by the Ministry of Construction, Yachiyodai Apartments being the first. These are listed in greater detail in Table 2.3.

2.3.4. Trends in other fields

So far we have discussed proposals for response-control structures mainly in building construction: examples of buildings constructed using these techniques and some cases approved by the Ministry of Construction. We now review the trends in the field of civil construction and mechanical engineering in Japan and the directions of future technological developments and current norms in other countries.

1. **Trends in Japan in other fields**

    1. National Railways

        In 1961, chloroprene rubber pads were used to support the girders in the railway bridge on Kinugawa River on the Tohoku trunk route. In 1972, a book on the use of rubber shoes on the concrete railway bridge was published; this is widely referred to for bridges on the conventional trunk lines as well as the Shinkansen (Bullet train) track. In addition, a book called <u>Construction of Railway Bridge Supports</u> has also been prepared.

    2. Road Bridges

        The Japan Roads Association has published such books as <u>Bearing Handbook</u> and <u>Standard Design for Road Bridge Bearings</u> to promote the design of rubber bearings. There are many examples of the use of rubber supports as pads. Studies continue on base isolation structures for road bridges by the Public Works Research Institute of the Ministry of Construction and Road Corporation. Presently, studies on laminated rubber bearings have just been completed at the Public Works Research Institute.

    3. Electric Power Supply Industries

        i) Denryoku Central Research Laboratory

        *Study on "lead plug" is in progress jointly with EPRI;

        *Conducted forced-vibration tests on base isolation buildings of Okumura Inc. and Oiles Industries (1986, 1987);

        *Base isolation floor is being developed;

        * Base isolation method for machinery is being developed.

ii) Electric Power Supply companies, (nine companies) and Japan Nuclear Power Co.

*Phase I (April 1985-March 1987) of joint studies by electric power supply companies (mentioned above) is over and Phase II will start;

*Studies on the application of base isolation technique to transformer are in progress;

*Studies about base isolation structure for FBR-type atomic furnaces are underway. Cases of Super Phoenix FBR base isolation building in France etc. are referred. Prof. Shibata and Assistant Prof. Fujita of the Institute of Industrial Science at Tokyo University are in charge of these studies.

*Others

Development of devices and components and application tests are underway in such fields as machinery, pipelines, boiler structure, building structures and tanks.

2. Trends overseas

1. USA

Guidelines for base isolation design (proposed) are being prepared in North California, but this is considered a local document. These guidelines are being prepared by the Seismology Committee of the Association of Structural Designers, North California. Persons such as J.M. Kelly are also invited to participate. The document intends to consider specifications in great detail.

2. New Zealand

The design standard for reinforced concrete structure briefly discusses the base isolation structure. According to this standard, there is not much scope for future development of this technique and as such cursorily mentions its merits or the relationship between the input level and the behavior of the entire structure. It notes that some standardization can be expected as the number of such buildings increases.

3. Examples of response-control structures against wind

There are many examples of controlling vibrations due to wind. The City Corp Center in New York is one such example. Response-control against winds is also done in civil engineering structures and machinery. The list of examples of response-control against winds compiled by Matsuo Tsuji is given in Appendix 2 for reference.

CHAPTER 3

POSSIBLE APPLICATIONS OF RESPONSE-CONTROL STRUCTURES

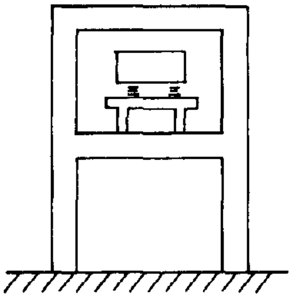
3.1. Improvement in Building Design by Using Response-control Techniques

3.1.1. Areas of Application

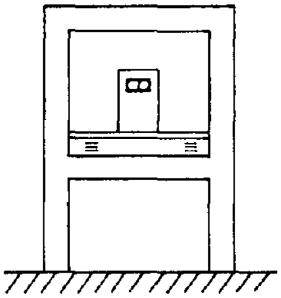
Damper techniques may be used for the entire building or for the equipment placed inside the building. The response-control technique may be employed for the following broad categories:

1. Instruments or equipment kept inside the building.
2. Structural elements (such as floors or beams).
3. The entire structure.

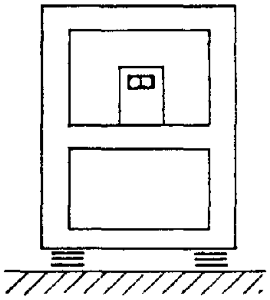
The concept or response-control may be explained schematically for all these cases as shown below:



Response-control
of
equipment



Response-control
of
floors



Response-control
of
the entire structure

3.1.2. External turbulence as objectives of response-control

The response-control technique can be used for both types of external turbulence: vibrations due to natural phenomena and vibrations due to anthropogenic phenomena. These can be further classified according to the amplitude and direction of the vibrations.

1. Types of Vibrations

    a Microtremor (continuous or frequent vibrations of small amplitude due to traffic, vibrations due to people walking or working, machine vibrations, and vibrations due to construction activity).

   b. Normal wind.
   c. Moderate earthquake.
   d. Typhoon.
   e. Severe earthquake.

2. Direction of vibrations
   a. Horizontal.
   b. Vertical.

The range of permissible vibrations generated in a public building due to different types of external forces or the level of vibrations in special purpose buildings such as the "clean room" in a semiconductor-manufacturing plant is shown in Fig. 3.1. Here the vertical axis represents the horizontal acceleration due to external force while the horizontal axis shows the fundamental frequency of buildings.

3.1.3. Improvement in the quality of design

The response-control technique restricts or controls the response of buildings to external vibrations. The response to be restricted or controlled is for acceleration, velocity and displacement. It is possible to control or restrict the stresses developed in structural material by controlling the above responses.

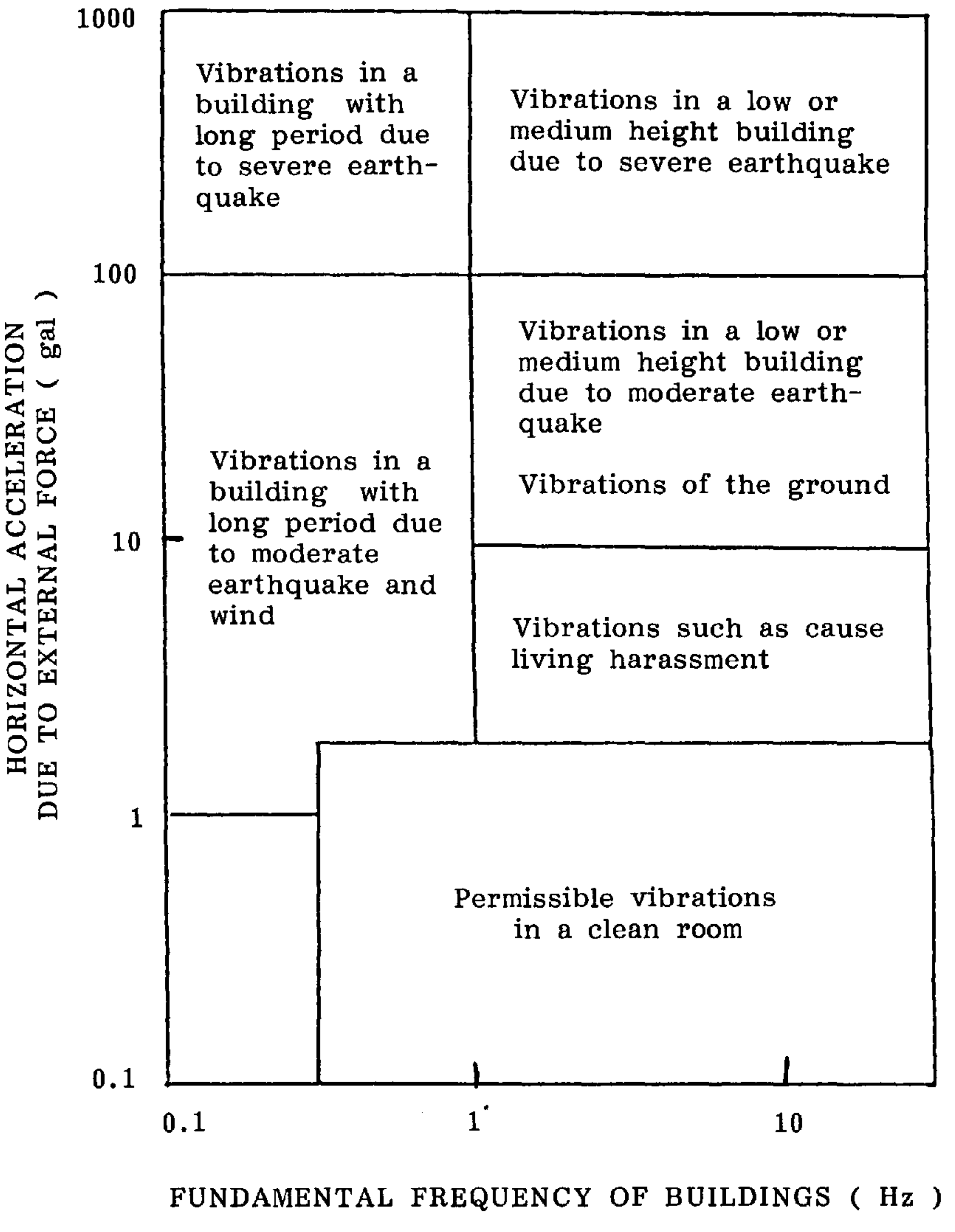


Fig. 3.1. The range of vibrations developed in a building due to external forces and the vibration sensitivity range for buildings in different applications.

The extent of restriction or control of response of buildings to external forces using response-control techniques can be set at any level, unlike in earlier wind and earthquake-resistant structural design methods. As a result, the response-control technique is most effective in solving the technical problems encountered during design, which are mentioned below:

1. Ensuring safety of structures under emergency conditions.
2. Reduction in the cross-sectional area of structural elements
3. Preventing vibrations, sliding or rolling of furnitures.
4. Preventing damage or peeling of nonstructural elements.
5. Restricting uncomfortable vibrations.
6. Maintaining nonerratic performance of machines and gadgets.

Earlier such design had to be carried out under several technological constraints. If response-control technique is used judiciously in the design of a building, safety, economy, machine performance, working comforts, living comforts in buildings can easily be ensured. Today it is possible to design a building having much of those added profits.

3.2. Applications of this Technique

As mentioned in Section 3.1, the response-control structure can be used to overcome various technical problems. Accordingly, it increases the value (utility) of the building structure. Applications of the response-control structures and the major problems therein are listed in Table 3.2.

The public buildings or building used at a time of disasters should be particularly safe with respect to earthquakes. When art galleries or museums house valuable exhibits, adequate protection must be provided.

In the case of a nuclear power plant, lifeline facilities or modern industrial facilities, the safety of a building and it contents against earthquakes is very essential. Also, if there is a possibility of hazardous discharge,then the response-control structure can be used to control such discharge. Particularly in modern industrial facilities such as an IC manufacturing factory, it is necessary to restrict the normal vibrations to very low levels and the response-control structure, in this case, can be used to ensure proper functioning.

Table 3.2. Performance requirements and merits in various applications of response control structures in buildings

Effect/ Technical theme	Housing	General office building	Public building	Building essential at hazardous conditions	Art gallery/ museums facility	Atomic power facility	Life line facility	Leading-edge industrial facility
1	2	3	4	5	6	7	8	9
1. Ensure safety of building structure	Safe	Safe	Safe	Safe	Safe	Safe	Safe	Safe
2. Flexibility in design of structural elements	Economy, design flexibility	Economy, design flexibility						
3. Prevent vibrations, sliding, rolling of contents	Safe	Satisfactory performance	Satisfactory performance	Satisfactory performance	Protect the exhibits	Protect the contents. Satisfactory performance. Prevent hazardous discharge	Protect the contents. Satisfactory performance. Prevent hazardous discharge	Satisfactory performance. Prevent hazardous discharge
4. Prevent damage to non-structural elements	Safe, economy, design flexibility	Safe, economy, design flexibility	Satisfactory performance	Satisfactory performance	Satisfactory performance	Satisfactory performance	Satisfactory performance	Satisfactory performance
5. Restriction of uncomfortable vibrations	Satisfactory living conditions	Satisfactory living conditions	Satisfactory living conditions					
6. Maintain proper functioning of machinery, equipment, etc.	Satisfactory performance	Satisfactory performacne	Satisfactory performance					

CHAPTER 4

VARIOUS ASPECTS OF RESPONSE-CONTROL STRUCTURES

In this chapter we discuss those problems which need to be solved so that the response-control technique can be fully developed as a practical technique in the future and widely accepted. In Section 4.1, we discuss the technical aspects and in Section 4.2, the statutory aspect. The following points are covered in Section 4.1.

1. External turbulence
2. Methods of dynamic analysis
3. Design methods
4. Equipment
5. Construction
6. Maintenance

The structures reviewed in this section are basically response-control structures. However, our discussion of the six main points will lay more stress on Menshin structures using base isolation. Current progress of technical development or the results of application of these techniques to actual buildings are also considered.

4.1. Topics for Future Technical Development

1. External Turbulence

1. Evaluation of seismic ground motion

   The earthquake resistance of a response-control structure depends on the precision and reliability in controlling its response to earthquakes. Evaluation of these properties depends on the correct evaluation of seismic ground motion which is assumed during design of an oscillating system. Therefore how to suppose the level and dynamic properties of incident seismic ground motion is the most important part of the design process. Here we shall discuss the problems in fixing the level and properties of such seismic ground motion during the design of a base isolation structure.

   Recently, the Building Center of Japan has published a report entitled Seismic Motion for Dynamic Analysis of Multistoried Buildings in which the views of the High-rise Building Technical Appraisal Committee about the guideline for seismic response analysis in seismic design of multistoried buildings are mentioned. According to the Committee's report:

1. The intensity of an earthquake to be used in seismic response analysis of high-rise buildings should be set in two stages, Level 1 and Level 2. While designing a building which is supported on Tokyo's gravelly soil layer, the maximum velocity of seismic ground motion, under each level, should be assumed to be 25 cm/sec and 50 cm/sec, respectively.

2. In the case of seismic response analysis, the wave form of seismic ground motion should be of more than three types, including at least one each of: (a) the standard waveform (El Centro (NS), Taft (EW); (b) the waveform considering the soil properties at and around the site of construction (for example, Tokyo 101, Osaka 205); and (c) the waveform incorporating a long-period component (Hachinohe, etc).

3. The main structural frame should be in the elastic range for the Level 1 seismic ground motion, while in case of the Level 2 seismic ground motion there can be no such damage to the structure, which may cause injuries to human beings.

Presently, construction of base isolation buildings must be approved by the Ministry of Construction after the design is evaluated by the Building Center of Japan (BCJ). The BCJ usually insists that the design of a base isolation structure be carried out in accordance with the guideline mentioned above for high-rise buildings.

However, the base isolation structure shows totally different behavior than that of high-rise buildings although its fundamental period may be similar. The major difference is that the response displacement is concentrated in the base isolation device and any propagation of energy to the upper portion is restricted. Accordingly, it seems desirable to study the seismic ground motion for the base isolation structure design and to look again at the design guideline.

While considering the incident seismic ground motion, we must note that the displacement is concentrated in the region of the base isolation device. In addition, we must consider the seismic ground motion with a comparatively long period and the effect of difference in the properties of the foundation strata. Also, we should consider the effect of vertical seismic motion on these buildings. And we must also consider that the direction of seismic ground motion does not necessarily coincide with the principal axis of the structure.

2. Evaluation of Wind Effects

The wind is broadly divided into two categories: mild breeze which flow every day (hereafter referred to as normal wind) and strong winds, for example typhoons with an average wind velocity of 20 m/sec or higher. In the normal wind, the sway of a building may be a problem in terms of comfortable living conditions, while for strong winds such as typhoons, the sway may be a problem in terms of structural safety.

The response control for living comforts must be studied from various perspectives such as studying the properties of normal wind, methods of modelling building structure, methods of response analysis, and evaluation of living comforts.

The properties of wind force differ from those of the seismic force. Therefore, it is meaningless to consider the incident wind wave in a time domain. Hence the analysis as well as evaluation have to be made in the frequency domain. For the evaluation criteria for living comforts, various proposals have been offered such as the ISO standard wherein evaluation is made on the basis of response acceleration in the frequency domain. All these proposals should be reviewed.

3. Evaluation of Microtremor

It has been reported that base isolation structures using laminated rubber bearings are effective even in eliminating microtremor of ground.

Various factors cause microtremor: traffics, construction works, etc. The amplitude of such vibrations ranges from a few tens of µm to few hundred µm when there are several sources of vibrations. If there are only a few sources, the amplitude of vibration is small, a few µm. The frequency range is wide: 0.2- 0.5 Hz to about 100 Hz. It used to be comparatively easy to damp high-frequency vibrations above 10 Hz, but vibration of 1 - 10 Hz frequency were not easy to eliminate. In a base isolation structure, since the fundamental frequency is 0.3 - 1 Hz, damping of these microtremors is easy between 1 and 10 Hz. However, the microtremor of very low frequency (0.3 - 1 Hz) cannot be eliminated.

For the purpose of designing a base isolation structure, problems arise in methods for measurement and analysis of microtremor in the low frequency region, methods for the damping of microtremor of very low frequency, methods for evaluation of energy dissipation at a surface between foundation and subsoil, etc.

Such a technique for restricting or controlling the external microtremor is useful not only for improvement of living conditions but for production facilities which do not allow for microseisms. When applying such a technique to production facilities, it is necessary to reexamine the properties of microtremor related to the requirements of the production facilities in addition to the problems mentioned above.

2. Dynamic Analysis Method

1. Analytical model of structures

i) Base isolation structure

In case of a base isolation structure, the stiffness of the device portion is much less than the stiffness of the upper structure. Hence, the dynamic properties of the base isolation structure generally conform to the dynamic properties of a rigid body supported on a spring. It is thus possible to represent the base isolation structure as a nonlinear multi-degree-of-freedom single-mass system. Using this model, we can study the variation in response quanta by changing the parameters such as: a) nonlinear properties of various types of dampers; b) torsional vibrational properties; c) response properties to multidimensional inputs; and d) rocking response considering vertical stiffness of laminated rubber.

The response of such a nonlinear system can be evaluated in terms of an equivalent linear model. If we could know the universal method for supposing such an equivalent linear model, it would be very useful for the design of base isolation structures.

Further studies on the effect of nonlinearity in stiffness and damping of base isolation devices on the response of base isolation structures will be necessary to get such methods.

ii) Response-control structures (excluding the base isolation structures)

The response characteristics of response-control structures (excluding the base isolation structures) can roughly be inferred from the properties of fundamental mode of oscillation of simplified structure models.

For example, in case of added-mass type response-control structures, we can assume a two-mass system model, where the added mass is supposed to be one of the two masses. Analyzing this model, we can know the effect of the added-mass damper: in case of a tuned-mass-damper system, the effect can be evaluated in terms of the equivalent damping force of the total system, and in case of an active-mass-damper system, it is evaluated in the same way assuming the control force supplied to the system is equivalent to damping force.

In case of structures equipped with dampers using nonlinear mechanical properties of materials, friction resistance, etc., we can analyze their response by assuming that those dampers have damping properties proportional to the accumulated strain energy, and then we can know the effect of dampers in terms of the equivalent damping force.

Since the response-control structures under consideration appeared more recently than the base isolation structures did, knowledge and data on their effect are not yet complete. Therefore, in designing response-control structures, analyses on such simplified models as stated above will be useful to obtain rough knowledge on the effect of major factors before making detailed analyses on full structures.

2. Techniques for dynamic analysis on wind effects

Current practical methods for wind-resistant design do not adequately evaluate the effect of spatio-temporal fluctuation in wind pressure. To restrict or control the response to strong winds when using response-control techniques, it is necessary to consider the spatio-temporal fluctuation in wind pressure. While estimating the relationship between wind pressure and building structure response, we cannot determine the response in the time domain as in the case of earthquake response analysis: it is also necessary to study the response using statistical methods in the frequency domain which include the consideration on aerodynamical and structural properties of the building. In that case, a particular consideration should be taken on the fact that the time (instant) at which the maximum wind pressure is generated at each point on the wall surfaces of a structure is not simultaneous.

3. Design Method

1. Specifying the design criteria

The design criteria include the information on controlling the vibrations of a building to a particular level. These vibrations are generated in response to temporary external force, such as a severe earthquake or typhoon, or other normal external forces such as traffic vibrations, normal winds or small earthquakes. The level is determined according to the use, type of structure and location of the building. Establishment of guidelines for specifying the design criteria would be a significant contribution to the promotion of development of this technique.

In conventional buildings, structures are so designed that moderate earthquakes which occur at a higher frequency cause no damage and the structure may suffer some damage under the impact of a severe earthquake, but this damage should be so controlled that human life is not endangered. On the other hand, in the case of response-control structures, the design criteria must be established so that not only are any damages to the building structure avoided, but the entire building, including the things or equipment inside, is protected. Furthermore, the additional design criteria for normal turbulence should be set after considering various aspects such as living comforts and the operation of precision instruments.

2. Static design methods for structures

The main object of the response-control structure is to reduce the seismic response acceleration so that the seismic force to be assumed for structural design purposes is reduced. However, under the present regulations, we cannot reduce the level of seismic force by more than 75% of the seismic force level to be assumed for ordinary buildings. In the case of Menshin structures, using base isolation, it is possible to greatly reduce the acceleration response of structures and hence a review of the above cited lower limits is needed.

If it is possible to greatly reduce the seismic force by providing a base isolation device, it will be possible to construct new types of buildings such as high-rise, long-span reinforced concrete buildings, high-rise masonry buildings, etc.

3. Accuracy in response prediction

The mass of the actual structure, its dynamic properties or the various properties of devices used may not be the same as those assumed during the design state. It is therefore necessary to consider all possible uncertainties in the elements constituting an oscillating system. In any case, the development of a simple method for designing response-control or base isolation structures wherein the consideration on the uncertainty are minimized as much as possible is required to make this technique popular.

4. Design methods for non-structural elements and equipment

Use of the response-control structure generally reduces the response acceleration and relative story displacement of the structure. As a result, the force acting on the non-structural elements and equipment is decreased and in addition difference in the amount of forces acting them at each story becomes small. We can expect, thus, to rationalize the design of these elements and equipment . In the case of Menshin structures using the base-isolation method, however, a relative displacement of about 20 to 30 cm between the earth's crust and the structure can occur during a severe earthquake. In this case the design of non-structural elements and equipment has to allow for deformation. Adequate technology has not yet been developed but is clearly needed.

Safeguarding the equipment/instruments installed inside a building, beyond simply avoiding physical damage due to rolling during an earthquake, is essential when it is important to ensure that there is no error developed during the operation and that their performance is unaffected. It thus becomes necessary to evaluate the seismic response of such instruments as well as of the floor slabs to understand these aspects. Simultaneously, it is necessary to develop sophisticated analytical techniques.

5. Evaluation of the ultimate condition

Considering that the input seismic motion used in design does not represent the full nature of incident earthquakes, the evaluation of the ultimate safety of response-control or base isolation devices is difficult. Today, in the case of Menshin structures using the base-isolation method, the ultimate safety is evaluated assuming earthquake ground motions of the same magnitude and property as that considered during design of very tall buildings. However, there is currently no uniform approach for determining the ultimate condition during an earthquake with intensities higher than those assumed during design.

In ordinary buildings, the structure is made strong enough to ensure safety even at higher loads. What part of the response-control structures correspond to this extra power? Many proposals have been offered for safer design. They include assuming a higher level of seismic forces during design or installing fail-safe devices or backup devices. However, this topic needs immediate further study.

4. Response-Control Device

1. Structural properties of the device

Physical properties

Certain experiments can be conducted to objectively evaluate properties of a device. Since these devices are complex bodies with different structures, the experiments should reveal first the properties of raw materials, the performance and characteristics of each element and finally the characteristics of devices taken as a whole. More specifically, deformation properties and deformation-stiffness properties or energy-absorption properties can be evaluated. Evaluation of these parameters should ensure the safety of response-control structure.

Development and standardization of testing methods

The properties and characteristics of response-control devices will vary according to the type. Accordingly, some variety in test methods is necessary to test different properties. Some common standards must be established to ascertain the performance on these devices.

2. Evaluation methods for durability of devices

Evaluation and methods

Various methods of evaluation can be used. Some items can be evaluated according to a method specified by the Japanese Industrial Standards, some according to other evaluation methods. Anyway, we must select adequate evaluation items and evaluation methods based on common standards to guarantee the desired performances.

Desired performance

The desired performance, as far as the durability of the component parts of the devices is concerned, is not the same for all devices. A guideline, considering life, period of replacement and cost effectiveness, needs to be established depending on the design assumptions for a response-control building.

3. Evaluation of fire-proofing or fire-resistance

The response-control device operates during an earthquake and reduces the response of the building. It is thus an important device in terms of structural safety. Many existing response-control devices use inflammable materials such as laminated rubber supports. Presently, studies on their performance during a fire or thereafter are not enough. It is therefore necessary to study the performance of various response-control devices during a fire or thereafter.

At present, we have no guidelines for the necessary performance level nor any evaluation methods to appraise the fire-resistance or fire-proofing of the response-control device. These must be established as soon as possible. The evaluation method has to consider the fire resistancy of the device itself during a fire or thereafter, the structural role played by the device, the level of fire hazard of the building occupancy, the position where the device is installed, etc. For example, the required fire-resistance or fire-proofing of the device will vary depending on whether the device is installed at the foundation where little temperature rise is envisaged due to fire, or it is installed in a place where the fire hazard level is very high. Similarly, the required fire-resistance or fire-proofing will vary if the device is subjected to constant vertical load such as that due to various supports. We must establish a method for evaluating fire-proofing and fire-resistance of the device which is compatible with the design for fire-proof or fire-resistant buildings after considering the above factors.

5. Construction

Let us discuss the base isolation type vibration-isolator construction, most frequently used today.

1. Safety during construction

There are two types of construction methods. In the first, a superstructure and a foundation structure are made separately and laminated rubber is placed between the foundation and the superstructure. In another method, after the foundation is made, the laminated rubber is placed above it and then the rest of the structure is constructed.

In the former method, metal spacers are inserted temporarily in place of laminated rubber bearings during construction. After the completion of the structure, it is jacked up and the spacers are removed and are replaced with laminated rubber. The technological problem with this method is how to ensure the safety of the superstructure under construction. Presently, this method has never been used in the construction of very large buildings, but this problem will be great if large buildings are planned in this way. A study is also needed on the stresses that develop in foundation beams, etc. when the structure is jacked up from the foundation. When the jacking up operation is in progress, the laminated rubber is subjected to tension or compression. Effects of these stresses, however, have never posed serious problems, but some study is needed depending on the size of building (area and height) and the vertical stiffness of the laminated rubber.

Even in the latter method where laminated rubber is placed after completion of the foundation construction, the vertical stiffness of the laminated rubber may pose a problem. If the rubber is soft vertically, we need to determine the method of loading or the order in which the columns are to be cast so that columns do not sink in a nonuniform manner (differential settlement).

Another technological problem associated with these two methods is the development of machinery (tools for jacking up, measuring equipment, machinery for handling laminated rubber bearings) required for such construction.

2. Quality control

Three aspects of quality control must be considered during installation of base isolation devices (rubber laminates, dampers): (a) inspection before installation; (b) inspection during installation; and (c) inspection after completion of the building.

Standardization and specifications for the items to be inspected at each stage are essential for future technological development.

6. Maintenance

1. Maintenance methods

Once the building is in use, the device itself must be checked to make sure that under no circumstances is its functioning affected. Presently, various management systems, inspection methods, criteria for repair and replacement, and processing methods have been proposed to ensure normal operation of the device. However, the problems remain including the terms of agreement among the building user and the structural designer or terms of agreement between the manufacturer of the device and the construction company. Some legal measures, including the warranty period, must be established relating to the maintenance of laminated rubber bearings.

Particularly, in the case of rubber laminates, a specialist must participate in the inspection or repair of the devices. Training of those specialists and development of techniques related to maintenance are requested for this purpose.

2. Safety checks

   Presently, routine checking is the responsibility of the building user. The user must fully understand the points to be inspected for the proper functioning of the base isolation devices or peripheral equipment, their performance and properties. Such knowledge must be shared with the general public. The addresses of persons to contact in case of emergency and the address of the manufacturer should be clearly indicated. It is also necessary to form a service agency which can undertake repairs if faults are detected during routine inspection. Such an agency could be the agency for maintenance, inspection and repairs of base isolation buildings.

   Checks on the condition of base isolation devices after severe earthquakes are also necessary. Criteria for such temporary inspection must be developed and decision should be taken on whether to make them obligatory. On the other hand, the development of devices which will not require such detailed inspection is eagerly awaited.

4.2. Suggestions for the Future

To ensure the smooth development of response-control structures in the future, the construction industry should note the following points:

1. Encouragement for technical development

   It is not sufficient to establish the specifications for response-control structure: it is also necessary to encourage the new technological development required for this purpose. To do so, positive efforts must be made to implement the suggestions in Section 4.1. The development of devices related to the response-control/base isolation structure, however, should be entrusted to private industries.

2. Simplification of permission for buildings

   Although it is necessary to carry out safety checks thoroughly, there must be no inordinate delay in conducting these checks or the procedures involved, as this would hamper technical development. To popularize the use of the response-control structure, it may be necessary to develop standard specifications for the commonly used devices and also to establish a system to authorize the performance of these devices.

3. Options for designers and developers

   Instead of laying a fixed standard, a guideline may be laid so that designers and developers can exercise professional options.

4. Encouragement of high-level technology

   Buildings constructed with high-level technology should be carefully evaluated and reviewed so that active technical development is encouraged.

5. Exchange and collection of technical information

   The exchange, collection and active application of technical information should be promoted so that technical development proceeds in the building industry.

   Efforts should be made to compile experimental data and measurements in the case of actual buildings, and feedback should be promoted for further technical development.

6. Preparing an optimum evaluation method for effectiveness of response-control structures

   The effect of reducing the response of the response-control structure to external turbulence should be evaluated from various angles so that the effectiveness of such structures is correctly evaluated by the general public and the social atmosphere is created for complete development of response-control structures.

CHAPTER 5

EVALUATION OF EFFECTIVENESS OF RESPONSE-CONTROL AND BASE ISOLATION TECHNIQUES

From among the many types of response-control structures available we shall restrict our discussion in this chapter to Menshin technique using base isolation.

In Section 5.1, "Points for Effectiveness Evaluation," the following five points are considered for evaluation:

1. safety;
2. living comforts;
3. performance;
4. economy; and
5. design freedom.

For the purpose of building administration these items should be evaluated from the two points of view.

The first is evaluation from the legal point of view. In any case, when a comparatively new and still developing technique like base isolation structure, is used for buildings before obtaining proof of safety, some special considerations should be taken in order to prevent accidents or damage. This is an important factor in the safety evaluation mentioned above. This point is considered by the Ministry of Construction while approving buildings based on the technology according to the regulations. However, this evaluation of safety as specified in the building regulations is of the lowest level. In addition to this lowest level of safety evaluation, there are other factors to be considered such as opinions of designer, building owner, and general public.

The other aspect is related to the promotion of healthy development of this technique by suggesting the objective evaluation method for the effect of the response reduction. Evaluation points (2) - (5) correspond to this.

Based on these considerations, Section 5.1 deals with these five items and major points to be discussed.

Among the above aspects of safety evaluation, the items and methods used for evaluation by the Ministry of Construction for statutory approval of buildings, particularly those directly related to the safety of the structure during an earthquake, are discussed in Section 5.2.

Many of the above points can be used for response-control and base isolation (Menshin) techniques in addition to the base-isolation technique.

While preparing guidelines for evaluation and approval of these structures in the future, the suggestions contained in Section 5.2 will serve as a valuable reference.

5.1. Points for Effectiveness Evaluation

The performance of the base isolation technique can be classified in three ways as shown in Fig. 5.1.

The most fundamental aspect is "dynamic properties." For example, we can include such basic dynamic properties as reduction in the response acceleration, relative story displacement and stress in each member or increase in relative displacement between the earth's crust and the foundation. The effects that can be observed according to dynamic properties include prevention of sliding or rolling of things stored in the building, prevention of damage to the non-structural members, reduction in the cross sectional area of structure members and reduction of vibrations felt by inhabitants. On the other hand, the need for external piping or the need for countermeasures to safeguard deformation in piping are among the adverse effects of using such means.

These effects in total will result in improving the quality of the building in terms of safety, living comforts, performance, and economy.

- Dynamic properties
  - Reduction in
    - response acceleration
    - response relative displacement
    - response material stress
  - Increase in relative displacement between the foundation and the earth's crust

- Effect
  - Prevention of sliding or rolling of objects in a building
  - Prevention of damage to non-structural members
  - Reduction in the cross-sectional area of structural members
  - Reduction in vibrations felt by inhabitants
  - Measures to counter the deformation of piping and external wiring

- Add advantage in
  - Safety
  - Living comforts
  - Performance
  - Economy

Fig. 5.1. Points for evaluation of effectiveness.

In evaluating the effectiveness of the base isolation structure advantages and disadvantages are revealed, and all these aspects must be evaluated to determine the actual added value of a base isolation structure. In practice, however, the points to be evaluated may vary according to the factors contributing to each technology; naturally, the weight attached to each factor will also vary.

Evaluation in terms of the public safety should be based on the safety factor as specified in the regulations mentioned at the beginning of this chapter and other aspects related to technological development.

Below we discuss evaluation of usefulness on the basis of the added value of buildings with base isolation structure in comparison with buildings without base isolation structures.

1. Safety

Safety during an earthquake includes the safety of the structure and the safety of objects other than the structures.

Among these, if safety of the structure is hampered for any reason, the threat of hazard to human life is very great and damage to the structure could cause dislocation in other public services. Accordingly, investigations by state agencies must ascertain that safety above a certain norm has been maintained based on the Building Standard Law.

There is no theoretical contradiction between the base isolation structure and conventional earthquake-resistant structures. Both have common aims, but the standard of achieving them are different. Compared to conventional earthquake-resistant structures, experiences with base isolation structures during earthquakes are few. It is therefore not possible to apply the same methods of evaluation of safety standards as applied in conventional earthquake-resistant structures for which we have copious results and experience.

In the base isolation structure, the load on the upper structure is reduced, and is concentrated on the base isolation device (mechanism). Therefore, the reliability of the base isolation mechanism is important.

Ensuring the safety of items other than the structure includes checking whether there is any damage to the non-structural elements, or whether there is any sliding, rolling or falling of the equipment or the contents of the building. The non-structural elements include stores of hazardous materials, flammable materials, transport equipment or external walls or the signboards on these walls. Any damage to these items may endanger human life or cause other public hazards; they cannot be ignored during a safety evaluation.

In either case, for safety evaluation, it is necessary to accurately evaluate the dynamic performance of the base isolation structure under the conditions for which it is intended.

2. Living Comforts

The improvement in the living comforts of the building with the use of a base isolation device is due to reduction in response acceleration since the vibration characteristics of the base isolation structure have a long period of oscillation. Even vibrations caused by factors other than earthquakes (traffic, construction, operating machinery) are reduced as a result of the base isolation device. However, swaying due to such external forces as winds with considerably longer periods of vibration may increase. Even during an earthquake, if the vibrations continue for long periods the sway may increase and residents may suffer from symptoms like sea sickness.

Body sensitivity to vibrations can be ignored to a limit. Quantitative evaluation of this limit is possible for vibrations of comparatively short periods. However, since the data for long-period vibrations is not adequate, such quantitative evaluation cannot be done.

The importance attached to living comforts, as well as the structural aspects, have emanated from the current trend in building technology toward improvement in the quality of environment. Evaluation of living comforts is done by the owner, occupier, or designer and statutory provisions need not be incorporated unless social problems arise.

It is in the interest of the owner, occupier and designer to establish some rational and objective method for such evaluation.

3. Performance

With the inclusion of the base isolation structure and the resultant reduced response acceleration, sliding or rolling of equipment or their faulty operation is avoided; the buildings for emergency operation, production management, or information processing have the advantage of keeping their functions.

Buildings with conventional antiseismic structures also possess these properties. The criteria for deciding which method to choose vary with each case. It is difficult to determine a common manner in which to evaluate the effectiveness of performance, and a method must be evolved which considers the type of building and type of construction. In doing so the requirements from the building and its construction can be specified for the desired performance against vibrations and then accordingly a method of evaluation is established. This will be very useful for proper development of the base isolation structure.

4. Economy

Table 5.1 shows the cost of the base isolation structure compared with the cost of conventional earthquake-resistant structure in qualitative terms. The cost comparison is made by dividing the cost into factors, namely, physical factors such as increased variety of construction materials, and the process factors from design to construction and subsequent maintenance.

Since the seismic force and the relative story displacement of a building are reduced in a base isolation structure, the deadweight (mass) of the upper floors decreases, and the installation methods for equipment and instruments becomes simple. The cost due to physical factors is therefore less. On the other hand, the cost increases due to using a base isolation device (e.g., double foundation), the necessity of using flexible joints in piping to overcome relative displacement between the ground and the building, increased length of piping and others.

The main process factor is concerned with manpower. During the design process, the cost increases if dynamic analysis is considered necessary. During construction, the cost generally increases since the quantity of work, the period of construction and materials to be managed all increase. The maintenance must also be carried out with more precision than in case of conventional buildings, and hence the cost increases.

Table 5.1. Cost comparison of base isolation and conventional structures

Item	Cost	Reasons
1	2	3
I. Physical factors		
a) Structural part		
Superstructure	Less	Mass is reduced since seismic force is reduced
Foundation or base isolation mechanism	More	Double foundation and addition of mechamism
Base isolation mechanism	More	Absent in non-base isolation building
b) Non-structural part		
Finishing material, equipment, instrument piping	Less	Fitting procedure is simplified since aceleration and interfloor displacement are reduced and mass is also reduced
External piping or wiring	More	Counter measure for relative displacement such as flexible joint and longer route, etc., are required
II. Process factors		
Design	More	Dynamic analysis
	Less	Only if standardization is possible
Construction	More	Volume of work, duration of work, and items of quality control increase
Maintenance	More	Point check, protection is required

To correctly estimate costs, all factors should be considered with proper weight. In many cases the cost of the base isolation structure is higher than that of conventional structure.

However, the costs vary according to the type of building or the prevalent economic conditions. One should also consider the residential comforts, performance and other activities. It is not possible to evaluate the structure undimensionally.

5.2. Evaluation of Safety

The various viewpoints related to the evaluation of the base isolation structure are mentioned in Section 5.1. Here, we shall discuss the safety parameters, particularly those considered by the Ministry of Construction or the Building Center of Japan for building approval.

The safety of the base isolation structure is mainly determined from the dynamic performance and can be broadly divided in two types: normal behavior and the behavior during earthquake. Such behavior depends on the structural performance of the base isolation device, design specification, design method, reliability of the construction and maintenance.

We shall discuss each point in detail.

1. Design Criteria

During the design of the base isolation structure, first the design load has to be set and design criteria for that load have to be determined after considering the application and importance of the building.

1. Types of loads and external forces

   The types of loads and external forces may be the same as those for conventional antiseismic structure. These include dead load, live load, snow load, wind load, seismic force, soil pressure, water pressure, and other loads or external forces.

   The values of these loads and external forces, specified in Building Standard Law or structural calculation standards of Architectural Institute of Japan, are based on past experience and results obtained from conventional non-base isolation structures and are considered more as promises made by designer based on engineering conclusions. Thus, during the design of base isolation structures, while evaluating load and external forces, it may be necessary to reconsider some actual phenomena, such as strong winds or earthquakes.

   Among these actual phenomena, the seismic force is determined as a result of the seismic response of the building. The seismic force for a base isolation building, should be evaluated carefully, taking its longer fundamental period and nonlinearity into account.

2. Uses and importance of the building

   Understandably, the design targets are set according to the uses and importance of the building. For a base isolation structure, as a basic rule of design, the condition of the seismic response is studied in detail through dynamic analysis, and the results are used in the design.

   In this case, it is possible to set the criteria related to structural safety or those related to the performance of the building in more detail than in the case of a conventional building.

   Clearly, with this assumption, the seismic motion which is likely to be incident at the building needs to be evaluated properly.

   Presently, since analysis of performance of actual available construction is limited even during the design of an ordinary office building, the same level of seismic motion is assumed as for a multistory building. This practice should be reviewed considering the current norms and design practices for earthquake-resistant buildings of the same size and uses.

3. Response criteria

The response criteria of buildings to various loads and external forces are as follows:

1) In the case of vertical loads such as dead loads, live loads or snow loads, the building should not sink non-uniformly nor should there be excessive sinking. This is not limited only to base isolation structures. For base isolation structures particularly, the foundation structure plays an important role. If it does not perform in the specified manner, then the base isolation structure will not be workable; it is therefore necessary for design against vertical loads to be more precise than in conventional buildings.

2) In the case of wind loads, the stresses in the structure, developed in response to the wind loads, should be kept within the elastic limits which conform to the specification in Building Standard Law. It may be necessary to study the vibrations due to wind load in terms of living comforts. As far as a general base isolation structure is concerned, this need not be considered as a criterion for safety.

3) The behavior of buildings in response to an earthquake may be considered separately from conventional buildings and multistoried buildings taller than 60 m.

According to the code regulation, there are two types of considerations for ordinary buildings, as follows:

i) During the course of its life, a building may be subjected a few times to earthquakes of moderate strength (of the order of 80-100 gal on the ground surface). On those occasions, the performance of buildings should be problem free. Damage may be minor and restored easily.

ii) Very strong earthquakes (of the order of 300-400 gal on the ground surface), which are quite rare, may never strike a building during its life. However, even if the structure is severely damaged, it should not collapse. Nonetheless, this is not sufficient security for important buildings such as emergency operation center, and other measures are carried out. For such buildings, the performance has to be maintained even under severe earthquake conditions.

For multistoried buildings taller than 60 m, the Technical Appraisal Committee for multistoried structures in the Building Center of Japan has listed criteria under the title "Seismic Motion for the Dynamic Analysis of Multistoried Buildings" and published them in The Building Letter, June, 1989.

i) The building should withstand without damage against an earthquake ground motion which is likely to strike the site of the building more than once during its life. The main building structure should exhibit response mostly in the elastic region. Seismic motion of this intensity is called seismic motion of level 1.

ii) The building should withstand, without any threat to human life such as collapse of main structures or exterior walls, against the earthquake which is considered to be the highest amongst the seismic motion recorded in the building site in the past or which is likely to strike the area in future. Seismic motion of this intensity is called seismic motion of level 2.

For buildings constructed on the gravelly soil of Tokyo, the maximum velocity of the seismic wave, used for dynamic analysis of the upper structure with a basement and foundation, is as follows:

Seismic motion of level 1 ... more than 25 cm/sec
Seismic motion of level 2 ... more than 50 cm/sec.

Even in the case of base isolation structures, most of the safety norms for earthquakes are common to those in conventional buildings. The period of vibrations is longer in the base isolation structures and similar to that for multistoried buildings. The maximum value of the seismic wave for dynamic analysis is specified in terms of the maximum velocity. The intensity of an earthquake is designated as level 1 (25 cm/sec) or level 2 (50 cm/sec), similar to that for multistoried buildings.

As mentioned before, there is some room for review of the design criteria of earthquake-resistant buildings and of the uses and importance of buildings.

Table 5.2 shows the proposed design criteria of base isolation buildings with this understanding.

Table 5.2. Seismic response criteria of base isolation structures

Level	External force level	Building	Base isolation devices
I	Weak earthquake, about 30-50 gal	Elastic	Elastic
II	Moderate earthquake about 80 - 100 gal	Below permissible stress	Elasto-plastic below permissible deformation**
III	Severe earthquake once in 50 years or corresponding to 25 kine	Below yield strength	Elasto-plastic below critical deformation**
IV	Very severe earthquake once in 100 years or corresponding to 50 kine	Below permissible ductility	Elasto-plastic below critical deformation**
V	Mega earthquake*	Without collapse	Collapse permitted

*Mega earthquake is the maximum earthquake likely to strike the building site.

**Laid according to the properties of the Menshin mechanism. Permissible deformation < Critical deformation.

2. Seismic Motion for Design

The following points must be considered while prescribing the seismic motion for design purposes.

1. Maximum amplitude

   The maximum amplitude of seismic motion to be used for design is decided in accordance with the design criteria. Since, the Menshin structure with base-isolation usually has long period vibrations, the maximum amplitude should be determined in terms of the maximum velocity. However, while laying the maximum amplitude of a small to medium earthquake, it is more meaningful to consider the acceleration than the velocity. If we consider earthquake resistance of conventional building structures, the criteria may be laid according to the level of the earthquake as shown in Table 5.2. There is another method in which both velocity and acceleration values are considered.

   The conventional method in deciding the maximum amplitude of vibrations is quite simple. Here, the standard value is first determined and then multiplied by the zonal coefficient according to the regional activity (probability and intensity) of the earthquake. If we consider that in base isolation structures, componental response of longer periods may be predominant, and that the investigations about the earth's crust and response analysis may be conducted in detail, it is probably more suitable to calculate the amplitude after considering the level of seismic activity in and around the building site or the dynamical properties of ground motion of that area.

2. Waveform

In the case of buildings taller than 60 meters, three types of seismic waveforms have been used for dynamic analysis of the building: the standard seismic waveform, the seismic waveform representing the zonal properties, and the seismic waveform incorporating the long-period component (after Japan Building Center's article "Seismic Motion for the Dynamic Analysis of Multistoried Buildings" published in The Building Letter, June, 1989).

A similar consideration is suitable for base isolation structures. Summarizing the aspects from the viewpoint of the selecting the waveforms we find:

1) Typical waves in the past (standard seismic waveforms) such as:

   El Centro 1940
   Taft 1952
   Hachinohe 1968

2) Measured waveform near the construction site.

3) Simulated seismic waveform representing zonal properties, properties of the earth's crust.

4) Recorded waveforms incorporating the long-period component (or alternative seismic waveform incorporating the long-period component) such as:

   Hachinohe 1968
   Akita 1983.

In addition, we also have records of Mexico earthquake (1985) which has a seismic wave with prevalence of long-period component. However, its properties are exceptional and such an earthquake is not expected to occur even in Japan. There are doubts, therefore, about whether it should be used in Japan for design purposes. While studying local safety, the use of the resonant wave is suggested. This needs to be further studied.

3. Multi-dimensional inputs

   The principal axis (direction) of vibration of a base isolation structure is not as clear as in an ordinary building. It may, therefore, be useful to study safety assuming an incident input ground motion having components in both directions of the horizontal plane.

   It is assumed that there will be little effect due to vertical motion of the ground but this may need to be considered.

   For such multi-dimensional inputs, we can use recorded waveforms or simulated seismic waveforms, but at present we do not know what type of possible waveforms is critical in the design of base isolation structures. Future studies will be necessary about this problem.

3. Methods of Dynamic Analysis

The reliability of vibration analysis depends on

1) whether the factors governing actual response are made into an accurate model or not, and

2) whether constants used in the model reflect the actual structure or not.

We discuss these points here.

1. Dynamic-analysis model

   The model used in dynamic analysis of the base isolation structure should allow the motion of a building structure in at least one direction. Even then, if the structure above is stiff, we can use a single degree of freedom model. If it is not stiff, we cannot ignore the effect of higher mode of oscillation. Hence it is better to use the multi-degree of freedom system model.

   When the torsional oscillation is expected to occur or while studying the response to multi-dimensional inputs, we must use the multi-degree of freedom model considering these points.

   It is generally assumed that the correlative dynamic action between the base isolation building structure and the earth's crust is small, but sometimes we may require a model which considers this interaction.

2. Restoring-force characteristics

   The restoring-force characteristics of base isolation devices and building structures should be made into an optimum model which reflects the real situation.

For example, there is a limit up to which the deflection in rubber material can be considered as linear and hence analysis in the region beyond this limit has to be conducted with a nonlinear model. This is not limited only to the base isolation structure. Since there is some sort of fluctuation in the physical value of restoring-force characteristics, their effect on the response calculation should be studied.

3. Damping constant

The damping constant used for vibration analysis of base isolation structures may be determined separately for each structural element and can be laid differently for the base isolation device and the building structure. Previously, the damping constant was determined in gross for the fundamental mode of oscillation. In the case of base isolation structure, we expect no interaction between the building and the ground, and a special damping element is used for the base isolation device. Therefore, in this case we cannot use the conventional approach. When the upper structure is considered stiff, the damping properties of the entire structure are in line with those of the base isolation device and the conventional approach can be applied. According to recent studies, the value of damping constant or reinforced concrete buildings having cracks in structural elements is less than 3% excluding the damping properties of base isolation materials such as rubber, which can be ascertained experimentally.

4. Basic concept of structured design

1. Design process

Even for base isolation structures, the design for the vertical load is made first. The cross section of the upper structure in the base isolation building is smaller than that in a non-base isolation structure. There are no other differences in the design of structural members for vertical load. The base isolation supports act as supports for the upper part of the building; hence, care is needed to ensure that there is no nonuniform or excessive sinking of columns due to load.

The design for the horizontal force considers mainly the seismic force. Evaluation of the seismic force should be based on the consideration on the longer fundamental period and nonlinear properties of base isolation structure. According to the present seismic design code, the seismic shear coefficient for each floor should be determined on the basis of building height. This value can be decreased to 75% based on a proper analysis. This provision is used in the base isolation buildings approved so far by the Ministry of Construction where the shear coefficient of the first story is above 0.15.

It may be possible to further reduce the seismic force according to the results of vibration analysis but considering the uncertainty of seismic motion, the extent of reduction has been restricted in previous approvals.

The results of vibration analysis may be used for the distribution of the story shear coefficient in the vertical direction (Ai).

2. Confirmation of ultimate condition

   Even when safety at the design earthquake is ascertained, we cannot guarantee the result if an earthquake of higher intensity occurs. This is related to the intensity and properties of seismic ground motion assumed in the design. In the base isolation structure, it is necessary to estimate the ultimate condition and leave some safety margin for that design level. Sometimes the use of fail-safe mechanism is proposed to avoid the collapse of the building under ultimate condition. When such fail-safe mechanism is used, the mechanism must demonstrate its expected effect.

   Studies must determine whether fail-safe mechanisms are really needed. In the case of a jet passenger aircraft, the inertial guidance system and hydraulic system for stability control are designed to include three independent subsystems in order to prepare for the misoperation or the break-down. However, a situation in which all of them fail is not considered.

3. Design of foundation

   For the base isolation device to demonstrate its working, the foundation structure has to be perfect. It is so designed that there is no nonuniform or excess sinking of columns and that the foundation can withstand horizontal force.

   The horizontal seismic force for the design of foundation structures is the sum of the shear force of the upper structure as determined by vibration analysis and the inertia force on foundation structure itself. (However, when the shear resistance of the upper structure is designed stronger in spite of the results of analysis, that should be used in place of the shear force of the upper structure.)

4. Design of secondary elements and equipment.

   The secondary elements and equipment are so designed that they are safe at the maximum response and relative story displacement obtained through vibration analysis. The response acceleration and the relative story displacement of an upper structure decreases greatly compared to the non-base isolation structure. This facilitates the design process.

   On the other hand, since the relative displacement between the ground or neighboring buildings is greater than in ordinary buildings, arrangements must be made for piping, deformation of wiring and so on. Particularly for gas pipes which have a high hazard level, an alarm system must be provided. Proper safety arrangements must be made for fire hydrant pipes, which have to operate normally under the emergency.

5. Performance of the base isolation device

A base isolation device is the principal component of a base isolation structure. Accordingly, its dynamic properties, endurance properties and fire resistance should be ascertained experimentally.

The device may be promoted by issuing a certificate that the specified checks have been carried out or we can ensure the performance by setting adequate standard.

1. Dynamic performance

   It is necessary to ensure the following for the dynamic performance of a base isolation device:

   1) Load-deformation relationship

      This may vary according to operating conditions, but generally it should express the relationship between different types of forces such as compression, tension and shear with stiffness, resistance, deformability, creep characteristics and energy absorption properties.

   2) Damping properties

   3) Dependence of dynamic properties on temperature, deflection, frequency.

2. Durability

   This is closely related to maintenance. Change in the properties of materials due to aging so that the desired performance cannot be obtained must be arrested and corrected. The effects of weather, ozone, heat, cold, chemicals, oil, wear on the performance should be ascertained experimentally simulating operating conditions.

   It is useful to study the performance of this device even for uses other than in base isolation structures.

3. Fire resistance

   In case of base-isolation method, the base isolation element is often placed between the double layered foundations. Hence, fire resistance is not so essential but still should be ascertained.

   The space between double foundation could be used as a part of the building space but, after considering the level of fire hazard in that space or the fire hazard of the entire structure and the fire hazard due to earthquakes, the fire resistance required for the base isolation device should be evaluated. For diverse development of base isolation structures, these studies should be conducted immediately.

6. Construction

The most important aspect of construction of the base isolation buildings is the management to achieve the desired performance. Because the fundamental period and damping properties of the base isolation system should be realized more deliberately than in the case of conventional non-base isolation buildings, the importance of quality management is great. It may also be necessary to study the safety of the structure during construction.

The base isolation device may be considered an industrial product and the materials management may be carried out on the basis of quality, appearance, dimensions, and manufacturing method.

Quality control includes checking the standard developed for quality assurance during manufacture and some intermediate inspection, if required, as well as obligatory inspection on receipt of goods. Inward inspection includes checking the quantity, appearance, dimensions and results of materials inspection. The rejected goods are sent for repair or modification.

Quality control during construction aims at preventing damage and ensuring accuracy of fittings. This is checked at the time of receipt and after completion of the building.

The materials management methods may differ depending on whether the base isolation device is fitted at an earlier or later state in construction.

7. Maintenance

If after completion of the building, a fault develops in the base isolation device, which is the heart of the entire base isolation structure, the device will be of no use during earthquake. Continuous maintenance of these devices is therefore necessary to avoid such situations.

For proper maintenance, it is necessary to clearly specify the maintenance system, the periods of checking, the items to be checked, and the methods and procedures for emergency conditions.

Maintenance of structural performance is also necessary for conventional non-base isolation buildings, but this has been done successfully under the responsibility of the owner. On the other hand, in the case of base isolation structures, the behavior of a building during an earthquake is controlled by the mechanical part which is the base isolation device and, hence, maintenance should also include regular checks of the device. This is similar to the maintenance of elevators. Many points have to be studied while evaluating the safety of a building from the maintenance point of view.

CHAPTER 6

SUMMARY

During the first stage of this study, it was decided to explore the current status of the response-control structures and the possibility of using them. The topics of study for the methods of evaluation of response-control structures, particularly the base isolation structures, were broadly summarized. We find that more attention should now be paid to four points:

1. preparation of guidelines for evaluation and approval of base isolation structures;
2. preparation of guidelines related to the performance of base isolation devices;
3. facilities to encourage exchange, collection and dissemination of technical information on the response-control structure; and
4. study of methods of evaluation of performance of response-control structures.

Below, we offer some comments on these points.

1. Preparation of guidelines for evaluation and approval of base isolation structures

   All considerations in the evaluation of base isolation structure must be made in terms of safety point of view. Studies on the items discussed in Chapter 5 should therefore be carried out immediately.

2. Preparation of guidelines related to the performance of base isolation devices

   The development of various base isolation devices is generally done by private industries. Clarification of the performance to be guaranteed, the necessary specifications and standardization of devices can be done in the second stage of this study. The information about the devices given Section 4.1 of this report will be useful here.

3. Facilities to encourage smooth exchange, compilation and dissemination of technical information on response-control structure

Section 4.2 deals with the development of new techniques in response-control structures and their improvements. Due protection must be provided for various claims about innovations (patents) and information related to safety has to be circulated among developers, users and government officers. During the second stage of our study, we should consider developing an agency for this purpose. The present arrangement in the aircraft industry, to ensure the exchange of information among manufacturers of aircraft, airlines companies and governments, may be used for guidance.

4. Study of methods of evaluation of performance of response-control structures

   Response-control structures reduce the response of a building to external turbulence and improve its performance. Hence, to promote the development of response-control structures, we should establish some fair and objective method of evaluation of the extent of reduction in the response of any building to external turbulence using these response-control structures.

APPENDIX 1

VARIABILITY OF THE PERFORMANCE OF RESPONSE-CONTROL STRUCTURES

We shall not review here the reliability of response-control devices but the uncertainties or variability of loads and structural properties assumed in the design of response-control structures. The effect of the variability on the overall reliability of the system will also be considered.

It is quite clear that the vibration levels assumed in the design of response-control structures, and the corresponding variability, varies depending on different sources of vibrations. The variability of external turbulence levels assumed in the design, which is due to natural phenomena such as earthquakes or stormy winds, is in many cases caused by differences in modeling those phenomena.

Seismic ground motions assumed in the design are calculated by analyzing historical data, simulated seismic activity models, etc., where the upper limit of earthquake magnitude is supposed to exist or not. The variability of those seismic ground motions assumed varies depending on the method of analysis or modeling of earthquake phenomena. The coefficient of variation reported is 140% (Ref. 1), irrespective of the return period, which is a considerably larger value among those values reported, or 100% for the return period of 100 years and 50 to 70% for the return period of 50 years (Ref. 2), which are smaller values compared with others. The uncertainty in evaluating the ground motion magnification in subsoil layers can be expressed by the coefficient of variation of acceleration response spectrum on ground surface except in case of extremely complex subsoil conditions. According to Ref. 3 values of the coefficient are 20 to 30%. As far as the subsoil properties are estimated adequately, the coefficient of variation of incident seismic ground motions assumed in the design can be considered as large as those stated above.

While studying variations in wind load evaluation, Ref. 4 has cited the variation of gust response of high-rise buildings. If we assume that shape factors and surface roughness of the building site are evaluated with some accuracy, we can consider that the variation of wind load is caused mainly by the suitableness of a probabilistic model of strong winds. According to Ref. 4, coefficient of variation in wind load evaluation is 50% and 40% for return period of 100 and 50 years, respectively (Ref. 5).

For mechanical vibrations or those due to traffic, if the properties of the vibration source are determined accurately, the variation should be much less than for an earthquake or strong winds.

Evaluation of variations in input forces is quite useful for setting the vibration limits over which the damping effect can be expected in a linear as well as non-linear system. It is also important to determine the level of reliability of control when vibrations are within the design specifications.

In evaluating the effect of the response-control structure, it is also important to accurately determine the fundamental periods of vibration and the damping of the proposed building. The accuracy of these two factors causes some effects on the performance of response-control devices more or less depending on the type of those devices. Some devices may be easily adjusted for their properties, while some may not. Below we mention the general accuracy of performance prediction.

The fundamental periods of vibration may now be determined quite accurately using the analytical approach. However, they are related to the evaluation of the effect of secondary elements and earth's crust. In many cases, analyses of fundamental periods of vibration do not include this effect and, therefore, the accuracy may be in a similar level as that of a simple approximate calculation based on the number of stories or building height. Ref. 6 has pointed out that the detailed method of predicting fundamental periods of buildings may sometimes include an error up to 50%. If the vibration records are available for a similar building, a certain level of accuracy can be maintained by making proper corrections. Even then, we must remember that the fundamental periods of oscillation will vary according to vibration levels or the history of previous seismic shocks.

It is not easy to determine the damping constant of a structure by the analytical approach. It is generally set between 2 and 5% except when damping is evaluated on the basis of interaction between the earth's crust and the structure. A method to estimate the damping constant based on the fundamental periods and amplitude of target vibrations has also been proposed (Ref. 7), but even there the error cannot be controlled within 50%. Accuracy in estimating the damping constant can be improved if the results of the seismic measurements for similar structures are available, as in the case of fundamental periods of vibration. For the microtremor level, Ref. 7 reports that, with enough accuracy, damping constant in % is equal to the value of fundamental period of ground oscillation in Hz. The fundamental frequency and damping constant of microtremor can be determined comparatively easily by actual measurements. However, an accurate estimate is not always possible during the design period and hence, evaluation of the effect of the damper device, assuming some variation in the system properties, is necessary.

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APPENDIX 2

EXAMPLES OF RESPONSE CONTROL AGAINST WIND

Table 1. Mechanical means for suppressing wind-induced vibration of structures

Source: Nippon Kazekogakkai-shi (Journal of Japan Wind Engineering Association), No. 20, June 1984

Countermeasures for suppressing wind-induced vibrations from structural dynamic viewpoint by Matsuo Tsuji

Method of response control	Precedent	Applications and wind-induced vibrations considered or observed	Highlights of methods, devices and effects	Occurrence of wind-induced vibration		Measures taken		Wind tunnel test	Remarks, other examples
				A	B	C	D		
1	2	3	4	5	6	7	8	9	10
A. Increase stiffness	0								
A1: Mutual inter-connection between members)		Mukojima Bridge (span 118m Langer girder bridge completed in 1968) tension members of 17m long H-section (170 x 368) was subjected to vortex-induced vibrations and it became unstable at a wind velocity of 25-30 m/sec, leaving some fatigue damage at ends	The ends of tension members were reinforced (1970). Longer members were tied with each other with horizontal wire ropes at height of 7.9m		0		0	0	Damaged during Typhoon No. 10 in 1970
	0	Burton Bridge (arch type) 10-22m long H-section (221 x 455) suspenders having holes in web to reduce vortex-induced vibrations, were subjected to vortex-induced vibrations under construction when wind speed exceeds 9 m/sec	Horizontal strut of channel-shaped steel was fitted at a height of 5.9m. 19mm dia wire rope fitted horizontally at the height of 6.7m and 18.6m. Another 19mm dia wire rope fitted diagonally at height of 13.4m.	0	0		0	0	

1	2	3	4	5	6	7	8	9	10
	0	Rokkaku Bridge (double deck truss cable-stayed bridge 90+220+90m). Stay cables at 5th level (PWS 85 dia) were subjected to wind-induced vibrations.	Cables were interconnected with wire ropes		0		0		
	0	Heavy water plant, Port Hawkesburry. 2 slender cylindrical towers out of 6 (3m dia, 70 and 75m height, gap 9m) vibrated with an amplitude of 0.3-0.6m when wind speed is 11-25 m/sec	The tops of two cylindrical towers are tied with horizontal plane truss	0	0		0	0	La Prade Heavy Water Plant. Al-can Alumina Plant
	0	Multi-conductor electric power line	Flexible spacer (damping action)		0	0		0	
	0	Onomichi Bridge (Cable stay bridge 85 + 215 + 85m). Vibrations due to aerodynamical interaction observed on ropes (54-70 dia) set in a parallel way.	The number of spacers are increased		0		0		
A2: Increasing stiffness of members	0	Bronx-Whitestone Bridge (suspension bridge, central span 701m, 1939). Stiffening girder made of plate girders. Frequent vibrations during strong wind	Stiffening with additional trusses (center tie and tower stay also present)		0		0		
	0	Golden Gate Bridge (suspension bridge, central span 1280m, 1937). If the wind speed at right angles to the bridge axis exceeds 13 m/sec there is torsional vibration. In December 1951 at wind speed of 3 m/sec there was a mixture of torsional and flexural vibrations	Since some damage was caused to accessories, stiffening trusses were changed into a closed cross section		0		0		

1	2	3	4	5	6	7	8	9	10
A3: Stay cable	0	Deer Isle Bridge (suspension bridge, central span 329m, 1939). In December, 1942 at wind speed of 32 m/sec, the amplitude of flexural vibrations was 3.8m	Cable stay were added		0		0		Thousand Islands, others
B. Mass addition									
B1: Rubble, sand filling method	0	Zdakova Bridge (arch, effective span 330m, completed in 1967). Steel pipe supports 4.1m dia, t = 12 mm, 1 = 41.48m. Vortex-induced vibrations at V = 6-13 m/sec, resonance at 8 m/sec with an amplitude of 13cm	Rubble filled for 31m length. Resonance 5 m/sec, amplitude 1/20, f = 1.6 → 0.73 Hz δ= 0.0078 → 0.0195		0		0		Tjorn bridge (Arch, 1960)
B2: Water filled pipe method	-	Suspension Bridge. Counter-measure was applied against fluttering (torsional) during installation works of stiffening girder	By placing the water filled tubes facing the wind upstream, the center of torsional rigidity shifts toward the direction of wind, increasing V_{cr}	0					
C. Added damping (Type 1: Asynchronous type)									
C1: Visco-elastic material	0	World Trade Center (New York, 110 story building). Gust response vibrations	Visco-elastic material is inserted at connections between column faces and lower chord members of floor truss girders. Dimensions of visco-elastic material are 101.6 (w) x 254 (1) x 1.27 mm (t)						Pamphlet of 3M Inc. Columbia Center, Seattle
	0	Bybrua Bridge (Norway). Vibrations of stay cable	Rubber tubes placed at the lower end of stay cables for absorption of vibrations		0	0			

1	2	3	4	5	6	7	8	9	10
		Gymnasium. Aluminum sheet roofing on eaves was peeled off due to vibrations (0.8 mm thick)	Asphalt cover around the roof up to 5m width		0		0		
C2: Hydraulic damper method	0	Brotonne Bridge (France) Prestressed concrete cable stay bridge, central span 320m. The cables showed primary, secondary and third mode of vibrations when wind velocity in the direction of bridge axis ± 30 degree was 15 m/sec. In primary mode amplitude was about ± 30 cm.	Each cable was connected to two hydraulic dampers placed in an inverted V-shape at a height of about 2.5m above bridge surface to suppress vertical and horizontal vibrations		0		0		Completed in 1977. West Gate bridge New Tjorn bridge
	-	Suspension bridge, others. Flexural vibrations due to wind	Hydraulic dampers are introduced at each cable end.		0				
C3: Fluid-tank type	0	Tower type structures like chimney	Oil tank having number of horizontal separation plates is placed at the top (of tower) and viscous damping is achieved with oil motion		0	0			
	-	Elevated water tank	Number of baffle plates (vertical) placed in water tank		0				
C4: Wire rope method (Guy cable)	0	Severn Bridge (UK, suspension bridge, central span 988 m, 1966). Stability against wind improved with stiffening girders	Better damping effect due to tensile hysteresis of diagonal guy cables		0	0			Bosporus, Humber
	0	Vortex-shedding excitation of a construction tower at the time of erection of Severn bridge. Bending vibrations at about 9 m/sec, torsional vibrations at about 27 m/sec during wind tunnel experiment	35 x 2 wire rope were stretched from top of tower to anchorage thereby absorbing energy	0		0		0	Bosporus bridge set-back used

1	2	3	4	5	6	7	8	9	10
C5: Damper spring type (DS)	0	Steel chimney (welded), dia 5.m, height 90m. At wind speed of about 16 m/sec, cracks and buckling developed in steel plates due to vortex-shedding excitation	At the time of reconstruction, spring and damper were connected in series to the lower end of cable which extended from tower top downward		0		0		
C6: Sliding block type (SB)	0	Forth Road Bridge (UK, suspension bridge, central span 1006m, completed in 1964). Vortex shedding excitation of construction tower during erection. The swing of top of tower at a wind speed of about 9 m/sec was 2.3m	Wire rope was pulled from top of tower and connected to concrete block on an inclined sliding platform. The sliding friction of block is used to get damping effect.	0			0		Weight of block 16 t. In'noshima bridge, 3P tower. Kan'mon bridge, etc.
	0	Friarton Bridge (UK, 114 + 174 + 114 + 66 m, continuous box girder) vortex-shedding excitation while laying the projected girders of central span	Wire rope is pulled down from the center of girder joining both ends and connected to 6 t block placed on an inclined sliding platform	0		0			
C7: Damper and weight type (DW)	0	In'noshima Bridge (suspension bridge, central span 770m, completed in 1983). Vortex-shedding excitation of construction tower (2P) during erection. Resonance wind velocity 9-12 m/sec. Expected amplitude of transverse vibration at that velocity is 0.8m	Wire rope is pulled from the top of tower in an inclined manner and connected to hydraulic damper (having variable damping coefficient) and weight (5 t)	0		0			DW type on an inclined platform
	0	O'naruto Bridge (suspension bridge, central span 876m). Vortex-shedding excitation of construction tower during erection. Bending and torsional vibrations assumed	Combination of two such assemblies mentioned above. Damper stroke is reduced using balance. 20 t weight x 2 nos.	0		0		0	Seto Ohashi bridge, Shimotsui

1	2	3	4	5	6	7	8	9	10
C8: Block under water type (BW)	0	Nankai Bridge (central span 404m, tower height 60m). Vortex-shedding excitation of tower during construction. Resonance wind velocity is about 11 m/sec. In the absence of damping, the vibration amplitude of 0.5m is observed	Wire rope is pulled from the top in inclined manner. From the center, another rope is suspended in water with concrete block	0		0		0	Completed in 1972.
	0	Speyer Bridge (West Germany, cable stay bridge. 275 + 61 + 61 + 59m). Vortex-shedding excitation of girder during construction. Completed in 1975.	A steel frame was suspended into water from the girder using wire ropes during occurrence of vibrations	0					Situation where additional dampers were required did not arise
	-	Suspension bridge. Increase in critical wind velocity for fluttering while laying stiffener girder	A plate is suspended into water from the girder	0					
C9: Gyroscope type		Suspension bridge. Increase in critical wind velocity for torsional flutter	Gyromoment proportional to the torsion angular velocity has damping action and as a result, critical wind velocity is increased	0	0	0		0	
C10: Pendulum impact type	0	Chimney etc. or tower shaped structures	When the pendulum suspended from the top hits impact plate during its oscillations, energy is consumed (absorbed)	0	0	0	0		
D. Added Damping (Type 2. Synchronous type)									

1	2	3	4	5	6	7	8	9	10
D1: Damper for aerial transmission line		Low-speed wind vibrations: at 0.5 - 7 m/sec vertical vibrations of 3 - 150 Hz are produced	Energy absorption as a result of deformation of twisted wires		0	0			Also used for preventing the vibrations in suspenders of Severn bridge or Hamber bridge
Concentrated type	0	General area	Stock bridge damper, materials of better quality						
Distributed type	0	Special areas like river valleys, capes, mountain ridge line, icing-expected region, etc.	Bate damper, etc. Spliced wire type						
D2: Cantilever type	0	Commodore Barry bridge [cantilever (Gerber) truss, central span 501m]. H-section vertical member was damaged due to vibrations during construction. Bending and torsion vibration developed along both principal axes of the cross section at a wind speed of 17 - 25 m/sec during wind tunnel experiment	Total 920 dynamic absorbers were fitted to 258 members. Each absorber was made by fitting a weight to the lower end of rubber rod 10 cm square and 60 cm long (1976)	0	0		0	0	Bras D'or bridge. Antenna array
	-	Transport pipe bridge, vortex-shedding excitation	The shear deformation of visco-elastic material between the double layered beams is used		0				

1	2	3	4	5	6	7	8	9	10
D3: Pendulum type	0	Sydney Tower (tower height about 250m, completed in 1981). The design criteria for gust response is such that peak acceleration is within 0.02 g. Wind response measured during December 1980 - August 1982	One of the two sets of tuned-mass dampers (TMD) was placed above observatory for damping primary mode of vibration, where doughnut-shaped water tank (180 t) was used as a pendulum of 10m length and 8 dampers were connected to it tangentially. The other set of TMD for damping secondary mode of vibration was composed of a 40 t steel ring suspended with 1.2m rod in the intermediate ring and seven dampers		0	0		0	Antenna tower. Chimney
	0	Meiko West Bridge (cable stay bridge, central span 405m, tower height 122m). Vortex-shedding excitation of construction tower (P2) during construction (V = 13 m/sec, anticipated vibration amplitude about 1m). In absence of damper $\delta = 0.0078$	Shear deformation of visco-elastic members between 2 pendulums is used. Weight 3.2 t, adjustment of period possible. Placed at a height of 100m. δ is increased to 0.17	0		0		0	PD type
	0	Norderelbe Bridge (cable stay bridge 64 + 172 + 64 m, single plane suspension). Vibration of tower above the upper cable point was observed (30 m). Vibration frequency 1.93 Hz (X), 1.1 Hz (Y). $\delta = 0.02$	A pendulum weighing 490 kg (mass ratio 0.076) which can swing in both directions was placed within the tower after adjusting the frequency of oscillations to that of the tower. Damper provided. δ is increased to 0.1		0		0		The tower top cross section was 1.13m x 1.13m

1	2	3	4	5	6	7	8	9	10
D4: Spring mass type	0	Pedestrian Bridge (West Germany, cable stay bridge, 90 + 28 + 22 m) Flexural vibrations: Primary: 0.86 Hz: δ = 0.096; Secondary: 1.72 Hz; δ = 0.029	TMD was made from a 2700 kg plumb weight (primary mass ratio 0.0184) supported by coil spring. Damper provided. Primary δ = 0.38; Secondary almost doubled		0	0			Example of pedestrian bridge in West Germany: Kessock bridge
	-	Bronx-Whitestone Bridge (suspension bridge, central span 701m). Flexural vibrations of stiffening girder. Danger of damage at V > 31 m/sec	8 plumb weights, each 11 t were suspended inside the girder using springs		0		0		Information available only on proposed structures. Real structures are still awaited
D5: Hydraulic support Block type	0	Citi Corp Center (New York, 63 story building). Gust response. Vibration frequency of primary bending mode for two principal axes 0.145 Hz and 0.139 Hz. h= 0.01	373 t concrete block (mass ratio = 0.02) is supported hydraulically in horizontal direction along both axes and has stroke of 2.3m. Using the compression air spring, resonance adjustment in both directions is possible. h increased to 0.04		0	0			Equipped in February 1978. Trigger level is an acceleration of 0.003 g at 63rd floor
	0	John Hancock Tower (Boston 60 stories). Bending and torsional modes in east-west direction	Two 273 t lead boxes kept on 58th floor at a distance of 60m. The mechanism is the same as that at Citi Corp Center		0	0			Constructed in June 1977
E. Active Response Control									
E1: External force type	-	Tower-like structure	The controlling force is applied to structure by external means such as ropes, rods, springs, etc. The detection of vibrations and corresponding actuator drive control is essential		0				

1	2	3	4	5	6	7	8	9	10
E2: Internal force type		Cable stay bridge. Fluttering, gust response	Controlling force is generated using electro-hydraulic servo-actuators placed below cable ends. Critical wind velocity of fluttering increased. Gust response reduced.		0				
E3: Active TMD type	-	Multistoried building Gust response	An actuator is placed between TMD and structure such that optimum controlling force is exerted after vibrations are detected. Compared with passive TMD, the same effect can be achieved with smaller mass or shorter stroke		0				
E4: Semi-active TMD type	-	Multistory building. Gust response	A control valve is provided to the TMD damper making it a damper with variable coefficient of damping. Control for maximum damping is obtained after sensing the vibrations. While retaining the merits of active TMD, the power requirements are reduced thus simplifying the device.		0				

Notes: Precedent: Symbol 0 means that the method considered has never been applied to real structures.
Symbols: A--During construction; B--After completion; C--During construction; D--After completion; V--Wind velocity; V_{cr}--Critical wind velocity; f--Vibration frequency; δ--Logarithmic damping ratio; h--Damping constant; TMD--Tuned-mass damper. Mass ratio--Reduced mass ratio; Damper--Oil damper, vibration absorber, etc.

APPENDIX 3

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