

# Passive and Active Control of Structures

by

Julio Cesar Maldonado-Mercado

Submitted to the Department of Civil and Environmental  
Engineering

in partial fulfillment of the requirements for the degree of  
Master of Science in Civil and Environmental Engineering

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May 1995

© Julio Cesar Maldonado-Mercado, MCMXCV. All rights reserved.

The author hereby grants to MIT permission to reproduce and  
distribute publicly paper and electronic copies of this thesis  
document in whole or in part, and to grant others the right to do so.

Author .....  
Department of Civil and Environmental Engineering  
May 19, 1995

Certified by .....  
Eduardo A. Kausel  
Professor, Department of Civil and Environmental Engineering  
Thesis Supervisor

Accepted by .....  
Joseph M. Sussman  
Chairman, Departmental Committee on Graduate Students

MASSACHUSETTS INSTITUTE  
OF TECHNOLOGY

JUN 27 1995

LIBRARY Barker Eng

# **Passive and Active Control of Structures**

by

**Julio Cesar Maldonado-Mercado**

Submitted to the Department of Civil and Environmental Engineering  
on May 19, 1995, in partial fulfillment of the  
requirements for the degree of  
Master of Science in Civil and Environmental Engineering

## **Abstract**

Conventional design practice permits inelastic action in buildings, providing significant energy dissipation, but often resulting in important damage to structural members and non-structural elements when the building is subjected to dynamic loads such as earthquakes and wind. In response to these shortcomings several counter-measures have been developed, among which are the passive and active control systems. In the future, it is expected that a hybrid of these two mechanisms may be developed.

The aim of this thesis is to examine the present available devices for the passive and active control of buildings and to evaluate their stages in research, development and commercialization. From this analysis, guidelines are proposed to select adequate devices in specific situations. Different guidelines are developed depending on whether the device is at a present practical reality, or only at an early development stage.

To conduct this study, the basic theory of passive and active devices is first explained. Different analytical, experimental and actual devices applications are then examined. In addition methods that integrate these devices into practical designs are described.

Results from this study indicate that passive devices have not been used extensively by civil engineers due to lack of guidelines and economic incentives on the part of the governments. Research on new materials and devices has opened the possibility of applying active control to significantly reduce the effect of structural damage due to earthquakes and wind in the near future.

Thesis Supervisor: Eduardo A. Kausel

Title: Professor, Department of Civil and Environmental Engineering

# Acknowledgments

I would like to thank Professor Eduardo Kausel for his advice and direction of this work.

I would like also to thank the Faculty, staff and friends of the Civil Engineering Department with whom I share an important time in my life.

I would like to acknowledge CONACYT (Consejo Nacional para la Ciencia y la Tecnologia) for its financial support.

I would like to thank my friends from Ashwdown House and around MIT with whom I share a lot of unforgettable experiences.

Finalmente, dedico este trabajo a mis papas (Luz Maria y Mario), que siempre me han apoyado para conseguir mis metas en la vida. Tambien se lo dedico a mis hermanos Mario, Cesar Rafael y Cesar Octavio.

# Contents

|          |   |           |
|----------|---|-----------|
| <b>1</b> | <b>Introduction</b>   | <b>10</b> |
| 1.1      | Base Isolation . . . . .  | 10        |
| 1.1.1    | General Characteristics . . . . .                                   | 10        |
| 1.1.2    | Advantages and Disadvantages . . . . .                              | 13        |
| 1.2      | Supplemental damping . . . . .                                      | 14        |
| 1.2.1    | General Characteristics . . . . .                                   | 14        |
| 1.2.2    | Advantages and Disadvantages . . . . .                              | 16        |
| 1.3      | Tuned Mass Dampers . . . . .  | 17        |
| 1.3.1    | General characteristics . . . . .                                   | 17        |
| 1.3.2    | Advantages and Disadvantages . . . . .                              | 19        |
| 1.4      | Active Control . . . . .  | 20        |
| 1.4.1    | General Characteristics . . . . .                                   | 20        |
| 1.4.2    | Advantages and Disadvantages . . . . .                              | 22        |
| <b>2</b> | <b>Passive Damping Devices</b>                                      | <b>24</b> |
| 2.1      | Introduction . . . . .  | 24        |
| 2.2      | Friction Dampers . . . . .  | 25        |
| 2.3      | Viscous and Viscoelastic Dampers . . . . .                          | 26        |
| 2.4      | Hysteretic Damper . . . . .   | 28        |
| 2.5      | Nitinol Shape-Memory-Alloy Dampers . . . . .                        | 29        |
| 2.6      | Basic Design Issues for supplemental damping applications . . . . . | 30        |
| <b>3</b> | <b>Base Isolation</b>   | <b>34</b> |

|          |   |           |
|----------|---|-----------|
| 3.1      | Introduction . . . . .  | 34        |
| 3.2      | Theory and Design . . . . .   | 34        |
| 3.3      | Worldwide Activity . . . . .  | 38        |
| 3.4      | Economic feasibility . . . . .  | 41        |
| 3.5      | Problems related to the Implementation of Seismic Isolation . . . . . | 43        |
| 3.6      | Seismic Isolation Projects . . . . .                                  | 46        |
| <b>4</b> | <b>Active Mass Damper</b>   | <b>48</b> |
| 4.1      | Introduction . . . . .  | 48        |
| 4.2      | Active Structural Control . . . . .                                   | 48        |
| 4.3      | AMD Control Operation . . . . .                                       | 50        |
| 4.3.1    | Feasibility of AMD Control . . . . .                                  | 51        |
| 4.4      | Experimental Studies . . . . .  | 53        |
| 4.5      | Applications of Active Mass Dampers . . . . .                         | 54        |
| 4.5.1    | Buildings with AMD in Japan . . . . .                                 | 54        |
| 4.6      | HMD System . . . . .  | 58        |
| <b>5</b> | <b>Control of buildings</b>   | <b>61</b> |
| 5.1      | Introduction . . . . .  | 61        |
| 5.2      | General Definitions . . . . .   | 62        |
| 5.3      | Sensing System . . . . .  | 64        |
| 5.4      | State Equation . . . . .  | 65        |
| 5.5      | Optimal Control . . . . .   | 67        |
| 5.6      | Example . . . . .   | 69        |
| <b>6</b> | <b>Conclusions and Recommendations</b>                                | <b>71</b> |
| 6.1      | Summary . . . . .   | 71        |
| 6.2      | Recommendations . . . . .   | 73        |
| <b>A</b> | <b>Tables</b>   | <b>76</b> |
| <b>B</b> | <b>Figures</b>  | <b>78</b> |



# List of Tables

|     |  |    |
|-----|--|----|
| A.1 | The Building and AMD Properties: Sendagaya INTES (Higashino, 1993) | 76 |
| A.2 | The Building and AMD Properties: Hankyu Chayamachi . . . . .       | 77 |

# List of Figures

|      |  |    |
|------|--|----|
| B-1  | Pall friction device . . . . .   | 79 |
| B-2  | Deformed configurations of a Pall Friction Device . . . . .                | 79 |
| B-3  | Friction slip device (Aiken, et.al.,1993) . . . . .                        | 80 |
| B-4  | Section view of friction damper (Sumitomo) . . . . .                       | 80 |
| B-5  | Friction dampers installed in model(Sumitomo) . . . . .                    | 81 |
| B-6  | A viscoelastic damper (Chang, et.al.,1993) . . . . .                       | 81 |
| B-7  | VE dampers in model (Aiken, et.al.,1993) . . . . .                         | 82 |
| B-8  | ADAS element (Aiken, et.al.,1993) . . . . .                                | 82 |
| B-9  | Superelasticity (Aiken, et.al.,1993) . . . . .                             | 83 |
| B-10 | Building elevation: uniform damper distribution (Scholl,1993) . . . . .    | 83 |
| B-11 | Building plan: uniform damper distribution (Scholl,1993) . . . . .         | 84 |
| B-12 | Foothill Communities Law and Justice Center (Buckle,1990) . . . . .        | 84 |
| B-13 | Salt Lake City and County Building (Buckle,1990) . . . . .                 | 85 |
| B-14 | Isolation scheme for nuclear power plants(Electricite De France) . . . . . | 86 |
| B-15 | Various mechanical energy dissipators developed in New Zealand . . . . .   | 87 |
| B-16 | Active Tuned Mass Damper Mechanism . . . . .                               | 88 |
| B-17 | AMD Equipped Kyobashi Seiwa Building (Soong, 1990) . . . . .               | 88 |
| B-18 | Active Dynamic Damper System (Inove, 1993) . . . . .                       | 89 |
| B-19 | Section and Mode Shapes: Sendagaya Intes (Higashino, 1993) . . . . .       | 89 |
| B-20 | AMD Elevation: Sendagaya Intes (Higashino, 1993) . . . . .                 | 90 |
| B-21 | Cross Section: Hankyu Chayamachi Building (Higashino, 1993) . . . . .      | 90 |
| B-22 | Duox System Concept (Sakamoto,1993) . . . . .                              | 91 |
| B-23 | Open Loop Control System Flow Chart . . . . .                              | 91 |



|   |    |
|---|----|
| B-24 Close Loop Control System Flow Chart . . . . . | 92 |
| B-25 Model frame . . . . .                          | 92 |
| B-26 Displacements . . . . .                        | 93 |
| B-27 Control Force . . . . .                        | 93 |

# Chapter 1

## Introduction

Passive Control Mechanisms operate without using any external energy supply; they use the energy generated by the structures' response to supply the control forces. However, these systems become very costly when satisfying more rigorous requirements than those required for optimum design.

Active Control Mechanisms operate by using an external energy supply where the control forces are applied to the structure by means of actuators. In theory they can control the structure for a broader range of loadings, provided it is technically feasible and one supplies the required amount of energy.

The following innovative techniques have been suggested to control the vibrations of structures subjected to dynamic loads: a) Base isolation, b) Supplemental damping in the form of friction, viscoelastic, viscous fluid or hysteretic dampers, c) Tuned mass dampers and d) Active control devices.

### 1.1 Base Isolation

#### 1.1.1 General Characteristics

Base isolation is an effective approach in mitigating the seismic forces transmitted to the superstructure. In recent years, different base isolation systems have been installed in various new and existing buildings, including office buildings, computer

centers, buildings for high technology industries, emergency and communication centers. One of such systems uses laminated high-damping rubber and steel shim plates vulcanized into a solid bearing.

Earthquakes are one of the most destructive phenomena. Major earthquakes such as the one in Mexico City in 1985 have caused catastrophic destruction and great loss of lives. Generally, structures are designed with codes whose criteria are based on structural collapse prevention. This approach allows the effects of the whole ground motion to be transmitted to the structure and relies only on the strength and ductility of the structure to resist these ground motions. Large accelerations, therefore, could occur at the upper floors of the structure, and they may cause severe damage to the building. Seismic isolation changes the response behavior of the structure by allowing the ground to undergo relatively large displacements without transmitting forces into the isolated structure. In fact, in most isolation designs, the structure generally moves as a rigid body. This means that the accelerations which pass through the isolators are relatively constant over the height of the entire structure. Thus, the top floors are subjected to accelerations which differ slightly from those at the lower elevation.

Seismic isolation devices can be grouped into two categories: active and passive. A third category in the future may be a hybrid of the above two. All of these devices aim at insulating the structures from the ground's motion, resulting in some cases in large relative displacements between the isolated structure and the ground. Therefore additional devices are used to increase the damping of the system. These devices can be mechanical hysteretic dampers, lead extrusion energy absorbers, viscous dampers, tuned mass absorbers, or viscoelastic dampers.

Isolation systems, such as high-damping rubber bearings, have enough energy-dissipating capability in themselves and do not require any additional damping devices. A typical bearing consist of a layer of high-damping rubber laminated with steel shim plates. Rubber damping could reach 15% or higher. Relative displacement can thus be kept within the allowable without any other damping devices. The steel plates are used to increase the effective vertical stiffness and to withstand the vertical loads. Recently, high damping rubber bearings were used to isolate the Foothill

Communities Law and Justice Center in a city in California.

In Base Isolation technique, flexible elements are added to the structure to elongate its fundamental natural period to a value far enough from the dominant periods of the expected earthquakes. These flexible elements are usually located at the base of the structure, taking much of the deformation produced by the earthquake while the structure tends to move as a rigid body. The basic components of a base isolation system are:

1. Flexible elements that elongate the natural period of the structure.
2. A damper or an energy dissipation mechanism to control the deflection of the flexible elements to the desire level.
3. A mechanism to provide the building with the necessary rigidity to limit the vibration of the structure under wind and small magnitude earthquakes.

There are several base isolation systems but only two have been used in the isolation of actual structures: a) systems based on elastomeric bearing, b) sliding system.

#### **Elastomeric Bearing System**

The system based on elastomeric bearings combine laminated rubber bearings with an external or internal damping mechanism. A laminated bearing consists of thin sheets of steel and rubber built up in layers bonded together by vulcanization. They have a large vertical load bearing capability and horizontal deformability.

Hysteretic or viscous dampers are sometimes used as damping mechanisms. Some systems integrate the damping mechanism into the rubber by including lead rubber bearings and high damping rubber bearings. A lead rubber bearing has a lead plug at the center of the laminated rubber, and this lead plug takes the role of the damper. A high damping rubber bearing has damping characteristics imparted to the rubber itself through the addition of carbon.

#### **Sliding system**

In sliding systems a sliding mechanism is provided to let the structure slide under lateral loads.

### 1.1.2 Advantages and Disadvantages

Base isolation reduces the earthquake response of a structure and its design seismic forces. It reduces floor accelerations and thus the damage. A base isolation system is easy to install and it can be used in new as well in to retrofit existing structures.

The disadvantages of base isolation are that it is only suitable for buildings with short period, founded on soils which do not produce long period motion and wind loads are not significant. Also, a base isolation system requires an isolation gap to allow for the free lateral displacement of the isolators. Little is known about the effects of aging and long-term creep in the isolators of a base isolation system and how the chemical and physical properties change over time. The integrity of a base isolated structure depends on the integrity of its isolator. The coefficient of friction in sliding isolators can not be determined with certainty after a long period of inactivity (Villaverde,1990). For seismically isolated buildings, the fundamental torsional frequency may be closer to the fundamental translational frequency than if the same structures was on fixed-base. Also, the stick-slip processes inherent to base-isolation system may elicit high frequency pulses which would excite the higher modes of thebuilding.

Present base isolated structures are more expensive that fixed-base structures. In general, it has been found that there is not enough saving, in the design of the superstructure, to offset the cost of the isolators, the double basement slab and walls, and the special details need to provide for the flexibility of the utilities. On the average, the cost of a base isolated structure is about 5% more expensive than the cost of a similar fixed-based structure. The exception is for structures which must warrant the safety of its non-structural components.

## 1.2 Supplemental damping

### 1.2.1 General Characteristics

In the supplemental damping technique, dampers or other energy absorbing devices are added to a structure with the purpose of increasing its damping and reduce its response to dynamic loadings. Using this technique, it is possible to dissipate most of the energy transmitted to a structure by a strong earthquake while keeping the structure undamaged. Most of the research and actual implementation has been focus on:

1) Friction dampers. 2) Viscoelastic dampers. 3) Viscous fluid dampers. 4) Hysteretic dampers.

1) Friction dampers are those which exhibit rectangular hysteresis loop characteristic of Coulomb friction. One type of friction damper that has been implemented in buildings is the device design by Pall (Pall, 1993). These friction dampers consist of brake lining pads between two mild steel plates. These are clamped together with fast strength bolts, but are allowed to slip under a predetermined load. They are typically installed in conjunction with steel cross braces or a base isolation scheme. After they slip, they dissipate large amounts of energy by friction. When strategically located within a building, they enhance the resistance of the building under small and moderate excitations and increase its energy absorption capabilities during a severe one. Their performance is not affected by temperature, velocity or aging. They are designed to slip before any yielding takes place in the structure.

2) Viscoelastic dampers are devices which use the deformation of viscoelastic materials as a means to dissipate energy. Viscoelastic materials exhibit the features of an elastic solid as well as those of a viscous liquid. Because of these characteristics, they return to their original shape after deformation, but with a certain amount of energy lost as heat.

A double layer, shear damper with a viscoelastic copolymer material developed by the 3M company is described by Mahmood. The stiffness and damping properties of the viscoelastic polymers are influenced by the level of shear deformation in the

material, its temperature, and the loading frequency. Viscoelastic dampers require a significant relative motion between the parts of a structure to make the dampers work. The design of lateral forces for a structure is affected by the presence of viscoelastic dampers since they contribute to its stiffness and change its natural periods.

The 3M damper consists of viscoelastic material bonded to steel plates (Nielsen, 1993). Dampers do not contribute to the load carrying capability of structures, but rather are designed to help dissipate vibrations in them. They are passive installations in the buildings until vibrations generated by forces, such as wind and seismic events, induce their actions. Viscoelastic dampers are suitable for both retrofit and new construction.

3M viscoelastic dampers have been installed in several tall buildings to reduce wind-induced building vibrations for improved human comfort. For example, the two World Trade Center Towers in New York have dampers located in the lower chord of trusses that support the floors. There are 100 dampers per floor located from the 10th to the 110th floors, for a total of 10,000 dampers per building.

3) Viscous fluid dampers are devices that utilize the flow of a fluid through orifices as a means to dissipate energy. One viscous fluid damper is described by Constantinou (1993). In this particular design, the damper is filled with silicon oil. Its operational temperature ranges between  $-40^{\circ}\text{C}$  to  $70^{\circ}\text{C}$ . Also, below a set cut-off frequency, this damper essentially behaves as a linear viscous damper. As a result, the damping forces it generates are proportional to velocity, so that it has no effect on the static stiffness of the structure. Viscous fluid dampers do not introduce in-phase axial forces when used in conjunction with diagonal braces, as is the case with other types of dampers.

4) Hysteretic dampers use the hysteretic properties of metals in their inelastic range of deformation as energy dissipating mechanism. Under moderate earthquakes, a hysteretic damper acts as a stiff member which helps to resist structural deformation, while under severe earthquakes it acts as an energy absorber. When the hysteretic dampers are incorporated at strategic locations in a building, they increase the structure's earthquake resistance. Some are designed to deform in bending, some in torsion and some in shear. The more common are:

1. Rolling-bending U-strip.
2. Torsional beam.
3. Flexural beam.
4. Flexural plate.
5. Lead extrusion devices.
6. X-shaped plate (added damping and stiffness or ADAS).
7. Triangular plate (triangular added damping and stiffness or TADAS).

In general, hysteretic dampers show a stable behavior largely unaffected by the number of loading cycles, show insignificant age effects, and have an adequate resistance to environmental and temperature factors.

### **1.2.2 Advantages and Disadvantages**

In general, friction, viscoelastic viscous fluid, and hysteretic dampers reduce the seismic response of structures and minimize structural and non-structural damage. They are easy to install and do not impact the foundation design. They are attractive for the upgrading of existing buildings. The problems are the following: first, they are effective only for flexible structures, that may be subjected to large deformations. Also, they encumber the design procedure and make it more expensive. For instance, several alternatives have to be considered to find their optimum number and location. The addition of the viscous fluid damper to a structure changes its stiffness and affects its lateral force design. Besides, since the dampers typically exhibit a nonlinear force-displacement behavior, the design of buildings which use them requires a nonlinear analysis. In the case of friction and hysteretic dampers, another problem is the selection of the appropriate yield or slip level. Since these devices start working only after the yield or slip level is exceeded, if the level is set too high, there is the danger of some structural and nonstructural damage before they actually start working. On the other hand, if the yield level is set too low, any small disturbance would make



the dampers yield and set the structure into vibrational motion. Besides there are other important issues related: a) the introduction of high frequency components of motion due to the stick-slip behavior of the device, b) the possibility of a permanent offset after an earthquake, and c) the stability of the hysteresis loops under repeated post-elastic deformations d) the possibility of a premature fatigue failure in the case of the hysteretic dampers.

## **1.3 Tuned Mass Dampers**

### **1.3.1 General characteristics**

A tuned mass damper is a relatively small device composed of a mass, a spring, and a viscous damper which is installed near the top of a building with the purpose of reducing its response to dynamic loadings. The natural frequency of the device is always chosen to match one of the natural frequencies of the vibratory system. Its mass must be placed on a smooth surface to minimize friction forces and allow its free movement. In this way the device may react to and be effective under low levels of excitation. The principle of a tuned mass damper is based on the fact that by setting its natural frequency equal to one of the natural frequencies of the structure, its mass always opposes the motion of the structure and hence suppresses or reduces the structure's vibratory motion. It is accepted that a tuned mass damper can be effective in reducing the response of structural systems subjected to harmonic excitations and to wind forces. But in regard to reducing the effects of seismic loads there has not been a general agreement.

The tuned mass dampers (TMD's) have been found effective in reducing the wind-induced response of tall buildings (Chowdhury, 1985). The effectiveness of tuned mass dampers under transient type ground excitation, such as earthquakes, has been studied widely. It has been found that, as the frequency of the tuned mass damper approaches the frequency of the primary structures, it becomes effective in reducing the displacement and acceleration response of the primary structure. Results show

that the acceleration has sharp tuning when the mass ratio  $\mu$  is small and has broad tuning when the ratio of the mass of the TMD to the mass of the primary structure is large.

As the first mode response contributes more than 80% to the total seismic response of a tall buildings, the tuned mass damper is generally tuned to the fundamental frequency of the primary structure. So the seismic effectiveness of such tuned mass damper will vary from mode to mode.

Chowdhury and Iwuchukwu (1985) have studied the effect of tuned mass dampers on the modal response of the primary structure subjected to earthquake motions and they found the following:

1. A tuned mass damper tuned to the fundamental frequency of the primary structure is less effective in reducing the response of the primary structure caused by the higher modes; the response due to the high modes will, in fact, increase.
2. At all modes, the peak modal response ratio (peak response ratio =  $y_{tmax}/y_{max}$ , where  $y_{tmax}$  and  $y_{max}$  are the maximum relative displacements at top floor of building with and without the tuned mass damper) of the primary structure decreases as the generalized modal mass ratio increases (The generalized mass ratio is defined as the ratio of the generalized modal mass of tuned mass damper to generalized modal mass of the primary structure).
3. An increase of the damping of the primary structure increases its peak modal response ratio at all modes.
4. An increase of the damping of the tuned mass damper increases the peak modal response ratio of the primary structure but decreases the motion of the mass damper relative to the primary structure.
5. A mass damper tuned to the fundamental frequency of an elastic primary structure is even less effective on the inelastic response of the primary structure
6. Passive tuned mass dampers can not be relied upon for seismic control.

Some examples of actual implementation are: the 60-story John Hancock tower in Boston, which is implemented with powered dual tuned mass dampers to reduce transverse and torsional sway in high winds. Tuned mass dampers were also installed in the 919 feet tall Citicorp Center in New York City to control wind oscillations (1977).

### **1.3.2 Advantages and Disadvantages**

Tuned mass dampers seem to be an effective way to add damping to a structure and to control its response to dynamic loads. Their impact on the design of the structure is minimum since a structure with this type of device does not require special design procedures. They are easy to design and construct. Its construction requires only putting together a mass, a spring and a dashpot at localized points of the structure, without the need of sophisticated hardware. Other advantages are:

1. They do not depend on an external power source for their operation.
2. They do not interfere with the principal vertical and horizontal load paths of the structure.
3. They can respond to small level of excitation.
4. Their properties can be adjusted in the field.
5. They can be considered in new design as well as in upgrading work.
6. A single unit can be effective in reducing vibrations induced by small earthquakes, wind and traffic.
7. They require low maintenance.
8. They can be cost effective.

Their disadvantages are:

1. A large mass is needed for their effectiveness or a large space is needed for their installation.

2. The amount of travel of a tuned mass damper is by design large and therefore room is needed to accommodate for such mass travel. At the same time, stops or other constraints are needed to limit the amount of this mass travel in case the design allowance is exceeded.
3. Their effectiveness depends on the accuracy of their tuning. Since the natural frequencies of a structure cannot be predicted with great accuracy, tuned mass dampers require field adjustment at the time of their installation and periodic adjustments thereafter.
4. A tuned mass damper is only effective to control the response of a structure in one of its modes. Several dampers are needed, thus, when the response of the structure is important in more than one mode.
5. The effectiveness of a tuned mass damper is constrained by the maximum weight that can be practically placed on top of the structure
6. Friction limits the effectiveness of a tuned mass damper to react to low level excitations. So special features are needed if a damper is to control such low level excitations.

## **1.4 Active Control**

### **1.4.1 General Characteristics**

An active control system is a protective system that controls or modifies the motion of a structure through the action of some external control forces. A control system is composed of four elements:

1. a structure.
2. sensors.
3. a computer or controlling unit.

#### 4. actuators.

The sensors detect the response of the structure as well as the characteristics of the ground motion that excites it. The computers process the information from the sensor, compute according to a given algorithm the necessary control forces, and activate the actuators.

The actuator, powered by an external energy source, induces the required control forces to counteract the earthquake forces or change the dynamic characteristics of the structure. Until now, two major types of structural control systems have been proposed.

a) In the first, the external control forces are used directly to balance the earthquake forces. Examples of this type are the “active mass dampers”. In the active mass damper system a control force is applied to an auxiliary mass with the purpose of counteracting the seismic forces on the structure by means of the inertia of this auxiliary mass. In the active tendon system, the control force is applied through braces in the structure (Soong, 1990). In this system, the response of the structure is controlled by controlling the tension in these braces.

b) In the second type, the control forces are used to change the dynamic properties of the structure so that resonance of the structure with the ground motion is avoided at all times. An example of this is the “active variable stiffness system” in which by continuously changing the stiffness of the structure, resonance is avoided and the response of the structure is minimized.

Besides these two types, there is a “hybrid” type which combines the features of the active and passive systems. It reduces the force requirements and, therefore, the needed actuator capacity and power supply. Examples of this type are the “Active Tuned Mass Damper” and the “Active Base Isolation System” developed by Kajima Corp. (Kobori, 1990).

Only in Japan, have active control devices been implemented in buildings:

1. the 11-story Kyobashi Seiwa building in Tokyo, in which the active control system used is an active mass driver.

2. A 3-story building at the Kajima Institute of Construction Technology compound in Tokyo. The control system implemented is an active variable stiffness system.
3. The 70-story Land Mark tower in Yokohama, in which the control system implemented is an active tuned mass damper.

### **1.4.2 Advantages and Disadvantages**

In principle, a control system continuously monitors the characteristics of the excitation and the structural response, so its effectiveness may be independent of the characteristics of the excitation and site conditions and it is just limited by the capacity of the actuators. Also it may be effective to reduce the vibrations induced by excitations of small, moderate, or large intensity. But it has some disadvantages as well:

1. Because a sophisticated equipment is used, it is very expensive.
2. Maintenance of an active control system is very important because the system will be used only occasionally.
3. It depends on a power supply for the activation of the system. But power supply systems are vulnerable to severe earthquakes and thus may fail at the time when they are needed most. A back-up power supply on the basis of accumulators has been suggested to overcome this problem, but it is also expensive.
4. The control of civil engineering structures requires large control forces applied at high velocities. Therefore such active control may require excessively large actuators with large strokes.
5. Because actuator response and the computational time required to determine the force in the actuators, there is a time delay between the reading of information from the sensor and the application of the actuator forces. An active

control system may thus lead to an unstable structure, if such actuator forces are applied at the wrong times.

# Chapter 2

## Passive Damping Devices

### 2.1 Introduction

Conventional seismic design practice permits a reduction in the design forces on the premise that inelastic action in a suitably designed structure will provide that structure with significant energy dissipation and enable it to survive a severe earthquake without collapse. This inelastic action is typically intended to occur in specially detailed critical regions of the structure, usually in the beam shear or adjacent to the beam-column joints. Inelastic behavior in these regions, while capable of dissipating substantial energy, also often results in significant damage to the structural members and non-structural elements, such as in-fill walls, partitions, doorways and ceilings.

As a response to the shortcomings in conventional seismic design, a number of innovative approaches have been developed. One of these approaches involves adding energy absorbers to a structure that it is to be built in a seismic zone. The aim is to concentrate devices characterized by inelastic behavior in specially designed and detailed regions of the structure and to protect by this deflection of forces, structural elements that carry primary gravity load. Many types of energy-absorbing devices have been proposed for this purpose. Most of the research and actual implementation has resulted in a variety of damping devices; friction dampers, viscoelastic dampers, viscousfluid dampers, hysteretic dampers, nitinol shape-memory-alloy dampers. Each of these devices will be discussed in detail.



## 2.2 Friction Dampers

Friction dampers generate rectangular hysteresis loops, typically produced by Coulomb friction. The following describes some types of these devices.

1. Pall Friction Devices were developed in 1982 by A.S. Pall. This device has been implemented in three buildings in Canada. The details of the friction damper are shown in Figure B-1. It consists of diagonal brace elements with a friction interface at their intersection point; these elements are connected by horizontal and vertical links. These links ensure that when the load applied to the device via the braces is sufficient to initiate slip on the tensional diagonal, then the compression diagonal will also slip an equal amount in the opposite direction. Deformation fields of the damper are shown in Figure B-2.

Utilization of this type of geometric deformation in the cross-bracing of a building frame that it is likely to be displaced laterally has been proposed as a way to permit substantial controlled energy dissipation (Aiken, et.al., 1993). The friction resistance of the device is activated by a normal force that passes through a bolt at the intersection of the diagonal arms and reaches the sliding interface.

2. Friction-Slip Devices (FSD) consist of two U-shaped steel casings and a sliding piece located between the casings (Figure B-3). The interface between the inner and outer pieces is filled with a high-permanence brake-pad material, and the normal force to the friction surface is absorbed by prestressed bolts. The factors that affect the performance of the FSD are variation in bolt preload, temperature, rate of sliding, and misalignment.
3. Flour Daniel Energy-Dissipating Restraints (EDR) were originally developed as seismic restraint devices for the support of piping systems in nuclear power plants. The mechanism of the EDR uses sliding friction through a range of motion with a stop at the end of that range. The features of the device are its self-centering capability, which would tend to reduce permanent offsets if the structure were deformed inelastically; its proportionality in this design; friction

force and thus energy dissipated proportionally to the displacement. For these reasons EDR can be effective at low levels of seismic input or for wind loading, while also being effective at high seismic inputs. Several different types of hysteretic behavior are possible, depending on the spring constant of the core, the initial slip load, the configuration of the core, and the gap size. In addition, when the slip load increases, use of EDR will result in consistent decreases in interstory drifts and displacements. Acceleration trends are not as well defined (Aiken, et.al., 1993).

4. Sumitomo Friction dampers were designed and developed by Sumitomo Metal Industries, Ltd, in Japan. The damper is a cylindrical device with friction pads that slide directly on the inner surface of the steel casting of the device (Figure B-4). These friction devices can be attached to the underside of the floor beams and be connected to a chevron brace assemblage (Figure B-5). The device was originally developed as a shock absorber in railway rolling stock. Before 1991, this type of friction damper had already been incorporated in a 31- and a 22-storey building in Japan.

## 2.3 Viscous and Viscoelastic Dampers

Although the intrinsic characteristics of damping have not been identified, civil engineers make use of energy-dissipation devices to reduce building vibration. For a linear response analysis of a typical building, a range of 2 to 5% of the critical damping is commonly considered.

According to Hanson(1993) increasing damping has an important effect on the dynamic response of the system only when the excitation frequency is in the  $\pm 20\%$  range of the natural frequency of the system. It means that the addition of dampers only will be effective if the excitation is in that range.

### Viscous devices

These devices follow the linear viscous damping assumptions. The maximum forces developed in these devices depend on the damping coefficient,  $c$ , and the max-

imum relative velocity.

### Viscoelastic devices

The maximum forces developed in these devices depend on the stiffness, maximum relative displacement of the device, the device effective damping and the maximum relative velocity. A Viscoelastic (VE) damper is shown in Figures B-6 and B-7.

### VE Damper properties

According to Chang(1993), the stress-strain relationship of a viscoelastic damper under harmonic loads can be expressed by:

$$\sigma = \gamma_0(G' \sin\omega t + G'' \cos\omega t) \quad (2.1)$$

where  $G'$  and  $G''$  are defined as the shear storage modulus and the shear loss modulus, respectively, of the VE dampers and  $\gamma_0$  is the strain amplitude. The two parameters  $G'$  and  $G''$  determine the energy capacity of VE dampers.  $G'$  determines the storage stiffness of the dampers as:

$$K' = \frac{G'A}{\lambda} \quad (2.2)$$

where  $A$  is the total shear area and  $\lambda$  is the thickness of the VE layer. The ratio of  $G''$  to  $G'$  is the loss factor ( $\eta$ ). The structural equivalent damping of a viscoelastically damped structure depends on  $K'$  and  $\eta$ . Other factors that influence the behavior of VE dampers are ambient temperature, vibration frequency, number of loading cycles and range of deformation. For example, if the ambient temperature of VE dampers increases, their efficiency decreases. Besides, if the vibrational frequency increases, the values of  $G'$  and  $G''$  also become larger. There is no variation in the loss factor when there are moderate changes in frequency and ambient temperature.

### Modal Strain Energy Method

Chang (1993) discussed the modal strain energy method, which can be used to simulate a viscoelastic damped structure. The structural damping ratio is the principal parameter to be obtained for analysis or design.

The response of viscoelastically damped structures can be simulated using a lin-

early viscous damping model. The damping ratio for the  $i$ th mode of vibration of the structure with added VE dampers can be expressed as:

$$\xi_i = \frac{\eta}{2} * \left(1 - \frac{\phi_i^T K \phi_i}{\phi_i^T K_S \phi_i}\right) \quad (2.3)$$

where  $\phi_i$  is the  $i$ th mode shape vector of the viscoelastically damped structure,  $K$  is the stiffness matrix of the structure without adding VE dampers,  $K_S$  is the structural stiffness matrix with the addition of VE dampers, and  $\eta$  is the loss factor of the VE dampers. If the change of mode shapes can be neglected due to the added dampers. Equation 2.3 can be further simplified to:

$$\xi_i = \frac{\eta}{2} * \left(1 - \frac{\omega_i}{\omega_{S_i}}\right) \quad (2.4)$$

where  $\omega_i$  and  $\omega_{S_i}$  are the  $i$ th natural frequencies corresponding to the structures with and without added dampers, respectively.

### Design Recommendations

During an earthquake, the maximum forces developed in different types of dampers are not the same. In viscous/viscoelastic dampers maximum force is independent of maximum relative displacements and velocities. On the other hand in friction/yielding devices, maximum force depends on the design friction force or yielding force plus the strain hardening (Hanson,1993).

## 2.4 Hysteretic Damper

Added Damping and Stiffness (ADAS) elements are designed to dissipate energy through the flexural yielding deformation of mild-steel plates.

A research program at the Earthquake Engineering Research Center of the University of California at Berkeley was undertaken to investigate the behavior of individual ADAS elements under dynamic loading, and to propose improvements to a three-story ductile steel moment-resisting frame (MRF) upgraded with ADAS elements and subjected to shake table earthquake ground motion table (Aiken, et. al., 1993).

ADAS elements consist of multiple X-shaped mild steel plates configured in parallel between top and bottom boundary connection (Figure B-8). The ADAS elements used in the test were made from ASTM Grade A-36 steel and consisted of either four, six, or seven plates.

The particular advantage of an X-plate is that, when deformed in double curvature, the plate deformation is uniform over its height, and when deformed into its plastic regime, the yielding will be distributed. A rectangular plate when deformed plastically in double curvature will yield only at its ends. This concentration is particularly undesirable both in terms of the amount of energy that can be absorbed by such a deformation pattern and by the inherent lack of stability and by repeatability in the plastic range.

The primary factors affecting ADAS element behavior are; device elastic stiffness ( $K_e$ ), yield strength ( $R_y$ ) and yield displacement ( $\Delta y$ ).

The tests made by Aiken (1993) showed that: ADAS elements are capable of sustaining more than 100 loading cycles at a deformation amplitude of  $3\Delta y$  with stable response and no signs of degradation; ADAS elements can safely be designed for displacement ranges up to about  $10 \Delta y$ . The failure of one ADAS element was induced by 15 cycles of loading at an amplitude of  $14 \Delta y$ . The test also indicated the importance of rigid boundary connections for successful performance of ADAS elements.

The performance of an ADAS element is influenced by the degree of restraint at its head and base, and the design of these connection details must take this factor into consideration.

## 2.5 Nitinol Shape-Memory-Alloy Dampers

The shape memory effect in metals was first observed in the 1930s. In 1962 researchers at the Naval Ordnance Laboratory observed the phenomenon in Nickel-Titanium (Niti or Nitinol). Shape-memory alloys (SMA's) can undergo large strains and subsequently recover their initial configurations. The basis for this behavior is

that, rather than deforming in the usual manner of metals, shape-memory alloys undergo transformations from the austenitic to the martensitic crystal phase (Aiken, et.al.,1993).

In most current commercial applications the phase change is temperature induced, however it can be stress induced at room temperature if the Nitinol has the appropriate formulation and treatment. This stress-induced phase change phenomenon is referred to as superelasticity. Figure B-9 illustrates the theoretical behavior of Nitinol as it is loaded in tension. The key characteristic is that if the strain is less than  $\epsilon_{el}$  there is no permanent deformation. Aiken tested Nitinol wire which was incorporated in series as part of a cross-bracing system in a model. In this configuration, the Nitinol was loaded only in tension, which allowed the full volume of the Nitinol to effectively dissipate energy. One desirable feature of the Nitinol is that its strength increases when  $\epsilon_{ei}$  is exceeded. This means that if the predicted earthquake excitation were to be exceeded, the structure would stiffen rather than soften.

Nitinol has demonstrated a special ability to “yield” repeatedly and not lose its preload. Aiken demonstrated that the damping in the structure increased from 0.5 to 3.0% and all of the structural responses were reduced, when Nitinol is used.. A nitinol energy dissipator has the particular advantages of being mechanically simple and reliable.

## **2.6 Basic Design Issues for supplemental damping applications**

The aim of incorporating damping devices in a structure is to reduce its earthquake response (forces and deformations).

Structural engineers must address the following questions when they consider supplemental damping for a project (Scholl, 1993):

1. Is the building suitable for supplemental damping?
2. How much damping should be provided?

### 3. How should the dampers be distributed in the building?

#### **Suitable structures for supplemental damping**

Two major factors have to be considered in selecting supplemental damping as a solution. First, the type of structural system including its dynamic characteristics (mass, stiffness and damping) is important. The second factor is the characteristics of the expectable ground motion that will affect the building (amplitude, frequency content and duration of motion).

Supplemental damping devices require some form of relative deformation in the structure to activate the damper. Typically relative deformations in buildings are measured in terms of interstorey drift (ISD). The magnitude of ISD produced by an earthquake in a building is a good indicator of whether the use of damping is a good solution for a particular building. Damping will be effective if the magnitude of ISD is enough to activate the dampers and if ISD will be greater than the drift capacities of critical moments of the buildings. The aforementioned things are very important, because if the deformation demand exceeds the ultimate ISD, dramatic failure can occur. For example, the ultimate ISD ratio for unreinforced infill masonry walls is about 0.003. Thus, for a 10 foot high infill, the ultimate ISD is  $(0.003) \times (10 \text{ ft}) \times 12 \frac{\text{in}}{\text{ft}} = 0.36 \text{ inches}$ . (Scholl,1993). A limit of  $\frac{1}{3}$  inch of ISD is difficult to achieve for typical buildings during severe earthquakes, even with the supplemental damping devices now available. Supplemental damping devices can be applied to flexible frame buildings that can tolerate ISD of about 0.01 without important damage. Supplemental damping can be used for masonry buildings with some modifications.

#### **Amount of supplemental damping.**

The amount of supplemental damping is based on three factors: the actual response of damped flexible structure, the damper hardware costs, and the desired structural response performance.

#### **Distribution of Dampers in Structures**

The addition of dampers to a structure directly influences the lateral stiffness of a building. For example in a moment frame structure, additional dampers increase lateral stiffness. On the other hand, in a braced frame structure additional dampers

reduce its lateral stiffness. Other characteristics that influence the behavior of a building are the connection bracing and the applied ground motion.

Before deciding whether or not to use these devices, a site response spectra must be obtained. This spectra can show how damping and period shift affects the response displacements and accelerations.

The distribution of dampers in a building is based on how to handle the damper forces, which like all the lateral forces produced, must be transferred to the ground. The configuration of the dampers is chosen based on the first mode because the response of a building is mostly in the first mode.

As Scholl(1993) states, dampers should be distributed throughout a structure to ensure:

1. Plan stiffness regularity.
2. Elevation stiffness regularity.
3. Redundancy.

An example of uniform damper distribution in a building is shown in Figure B-10 and Figure B-11. This building has a symmetric and regular frame. With the addition of dampers on all its floors except the first one, elevation stiffness regularity is conserved. At each floor, the dampers are placed symmetrically so that the building stiffness regularity is conserved.

Regular distribution is important for friction and yielding devices because if one place has more stiffness than another, the displacements would be different and the dampers would work at different values. For example, in an extreme case of a very stiff zone, with very small displacements, a damper would do little or no work. On the other hand, if a damper is placed in a very deformable zone, it will have large displacements until its high level is reached and then it will fail.

### Design procedure

For designing structures with dampers, some changes must be made in the common design procedure. For example, Chang(1993) explains how to incorporate viscoelastic dampers in the design procedure. Selection of the design parameter, in this



case the damping ratio, is important. One of the methods to evaluate the damping ratio is the “Modal strain energy method” described before.

In general design is an iterative process. The following steps proposed by Chang et. al. (1993) must be updated in each cycle:

1. Determine structural properties of the building and perform structural analysis.
2. Determine the desired damping ratio.
3. Select desirable and available damper location in the building.
4. Select damper stiffness (  $K'$  ) and loss factor (  $\eta$  ).
5. Calculate the equivalent damping ratio using the modal strain energy method.  
The selection of the damping ratio can be a trial and error procedure or only consider that the added stiffness due to the damper is proportional to the storey stiffness of the structure.
6. Perform structural analysis using the designed damping ratio.

In general, if the specifications are not met, one can change damper properties, locations or damper dimensions. When the desired damping ratio and the structural performance criteria are satisfied, the design is complete. All these considerations are based on a linear elastic structure. If inelastic deformation is allowed in the structure, everything must be changed.

# Chapter 3

## Base Isolation

### 3.1 Introduction

Base isolation, also called seismic isolation, is intended to prevent earthquake damage to buildings and their contents. Base isolation systems are load bearing cylinders, called isolators, made of high damping rubber vulcanized to steel plates separating a structure from its foundation. They are designed to lower the magnitude and frequency of seismic shock, and provide energy absorbing characteristics. Seismic isolation can only be used in buildings up to 10-15 stories high, and only where soil conditions permit it (Buckle, et. al.,1990).

### 3.2 Theory and Design

Low and medium rise buildings have a fundamental frequency of vibration that is in the range of frequencies where earthquake energy is strongest. As a consequence, the ground vibration is amplified in the building, and accelerations and displacements increase to the top. The accelerations at each floor can cause damage to the building as well as their contents (Kelly, 1990).

One way to solve the vibration problem is by making the building more rigid, so in this way, the building does not experience an acceleration greater than the ground acceleration. However, this method is not only impractical and expensive, but the

ground acceleration can be high enough to damage the building. The other way is by making the building very flexible. This way is less expensive than the previous one, but it can cause damage to the non-structural components.

In a low to medium rise building, one way to achieve that flexibility is to concentrate it at the foundation level. But a device is needed between the source of disturbance and the building to protect it. This device is base isolation. But the building needs protection only from the horizontal components of the earthquake ground motion, because this is the one which causes damage to the building. In the vertical direction, accelerations are not usually a problem for most buildings.

Since much of the deformation is concentrated in the isolation bearings, this deformation can produce instability problems. For this reason damping elements must be added. But this influences the behavior of the entire system, because the accelerations can cause high frequency response in the building.

### **Basic Elements**

The basic elements of a practical base isolation system are:

1. A flexible mounting so that the period of vibration of the total system is lengthened enough to reduce the force response.
2. A damper or energy dissipator so that the relative deflections between the building and ground can be controlled to a practical design level
3. A means of providing rigidity under low (service) load levels such as wind and minor earthquakes.

### **Types of base isolation**

#### **a) Flexible Mounting systems**

1. Unreinforced rubber blocks.-The rubber from which the isolators are made is a highly filled natural rubber with mechanical properties that make it ideal for a base isolation system. The shear stiffness of this rubber is high for small strains but decreases by a factor of about four or five as the strain increases, reaching a minimum value at a shear strain of 50%. For strains greater than

100% the stiffness begins to increase again. Thus, for small loading caused by wind or low-intensity seismic loading the system has high stiffness and a short period, and as the load intensity increases, the stiffness drops. For very high load, say above the maximum credible earthquake, the stiffness increases again, providing a fail-safe action. The damping follows the same pattern but less dramatically, decreasing from an initial value of 20 % to a minimum of 10% and then increasing again. In the design of the system, the minimum values of stiffness and damping are assumed and the response is taken to be linear. The high initial stiffness is invoked only for wind load design and large strain response only for fail-safe action.

2. Elastomeric bearings (reinforced rubber blocks).-One of the most highly developed energy dissipators to date is the lead-rubber device in which a cylinder of lead is enclosed in an elastomeric bearings. It combines in one physical unit the flexible element and the energy dissipation. In this application, the lead is forced to deform plastically in shear by the shim plates. The lead plug produces a substantial increase in damping from approximately 3% of critical damping in the available rubber to about 10-15%. New developments include the replacement of the lead core with a confined column of granular material. Interparticle friction can then be generated during shearing deformations of the bearing and dissipated energy levels approach that of the lead-filled bearing.
3. Sliding plates. The sliding plates are used in regions of high or moderate seismicity. There the coefficient of friction between the plates is chosen so that small to moderate earthquakes are accommodated by the elastic deformation of the bearing pad. Severe earthquakes are accommodated by both the elastic deformation and slip on the frictional surface. This results in additional damping to that available from the elastomeric bearings alone. The damping force in this case acts in series with the shear stiffness of the bearing. In one system, the friction mechanism consists of a lead-bronze alloy plate bonded to the bearing and a stainless steel plate embedded in the superstructure. Tests have shown

that this device provides a fairly constant coefficient of friction (0.2) under a wide range of vertical pressures and relative velocities of the surfaces.

4. Roller and/ or ball bearings.-While the roller bearing system is ideal for limiting the transmission of force into the structure, it is not practical by itself due to the resulting displacements which, in the ideal case of frictionless bearings and a level surface, would be equal to the earthquake ground displacement. Hence, the roller bearings by themselves represent a system in which the forces in the structure are minimized but the displacements of the structure relative to the foundation are maximized. Also, the structure must have some lateral resistance so that it does not displace under the action of small lateral forces, such as wind and small earthquakes. On the other hand, the structure that is fixed to the foundation represents a system in which the forces in the structure are maximized and the displacement relative to the foundation is minimized . The solution for optimal earthquake performance requires a judicious combination of these two extremes: design a structure to resist lateral forces, but limit these forces by allowing the structure to move within acceptable limits relative to the foundation.

In the isolation system considered in this section, separation between the structure and the foundation is assumed to be provided by a cluster of frictionless ball bearings which are contained between steel plates. It is recognized that this is a simplification of the actual condition in that some amount of friction must be present. The bearing capacity of a system of this type is generally greater than the bearing capacity of the concrete foundation, therefore, it does not impact the foundation design and provides a direct transfer of the axial load in the column to the foundation (Anderson,1990).

5. Sleeved piles.-A twelve-story building has been constructed in Auckland, New Zealand, on a base isolation system called the sleeved pile system. This uses 12 m long bearing piles with cylindrical sleeves, allowing a certain amount of lateral movement, in this case 15 cm. The isolation period on the piles is 4

seconds, and resistance to wind loading would be inadequate with this system alone. In addition the damping would be very low. To improve the behavior of the system, energy absorbing devices in the form of mild steel tapered plate beams are included in the structure and these lower the period to around 2 seconds.

The sleeve pile concept is similar to the soft first-story design concept but without the risk of collapse due to excessive first story lateral deflections. If the structure should exceed the design lateral displacements, the sleeve itself will control the displacement, providing a fail safe action for the system . Although piles are an expensive foundation system they must be used if soil conditions make the use of footings unacceptable. When circumstances dictate the use of piles it may be cost effective to use the sleeved-pile concept and provide a substantial reduction in the lateral force requirements for the superstructure.

6. Cable suspension systems.- Each column has a isolation system in which the column is suspended by cables combined with energy dissipators.

### **3.3 Worldwide Activity**

What follows is a brief description of the advances of base isolation systems throughout the world, as reviewed by Buckle. Seismically isolated structures have been built in at least 17 countries. The total number of isolated structures built is only about 102. This number includes 38 buildings, 51 bridges, 6 nuclear power-related structures and 7 miscellaneous structures. But it does not include 136 bridges in Japan and Italy known to be partially isolated for seismic loads. Partial isolation(i.e., isolation in a horizontal direction only) has been used for bridges in several countries.

#### **United States**

In the USA, a total of 15 base isolated projects have been completed or are under construction. The first base-isolated building in the United States was the Foothill Communities Law and Justice Center located in the municipality of Rancho Cuca-

monga in San Bernardino County (Figure B-12). This building is four stories high, with a full basement and a sub-basement for the isolation system. It is 415 ft x 110 ft in plane. The building, completed in 1986, sits on 98 isolators which are multi-layer natural rubber bearings reinforced with steel plates. The superstructure of the building has a structural steel frame stiffened by braced frames in some bays. The building is sited within 4 miles of the San Andreas Fault and within 2 miles of the Sierra Madre Fault. It is therefore in a region of high seismicity. It is designed for the maximum credible earthquake for that site, an 8.3 Richter magnitude earthquake.

Although base isolation has been proposed and used for new construction, the concept is readily applied to the rehabilitation of older buildings of architectural and historic merit, which at present do not comply with building codes. A rehabilitation scheme using base isolation has been carried out for a ninety-two year old building in Salt Lake City (Figure B-13). The building is an unreinforced brick and sandstone structure, is badly weathered and its strength has deteriorated substantially. It is located close to an active fault and has been damaged by past earthquakes. Base isolation is the latest of several rehabilitation schemes that have been considered for the building. Conventional seismic strengthening designs, involved extensive use of shotcrete walls and other strengthening methods have been considered, but Base Isolation was chosen because it reduced the need for such strengthening measures by decreasing the seismic loads to the building.

### China

A simple low cost isolation system to protect brick houses on a trial basis has been conceived and implemented in China by Li in 1984. The load bearing walls of these structures are isolated from the foundation grade beam by a slip plane. Two sheets of terrazzo, separated by grains of clean sand 1 to 1.2 mm in diameter, make up the slip mechanism. A dynamic friction coefficient of 0.2 has been obtained by shaking table testing of the system and this effectively limits seismic forces in these earthen and straw buildings to less than 0.2g.

### France

Two very significant developments have taken place in France in the field of seismic

isolation. First is the use of standard elastomeric bearings, for protecting low rise, light weight structures (such as houses and schools) from earthquakes, and second, the use of much larger elastomeric bearings (with and without frictional sliding plates) to isolate complete nuclear power plants. In an attempt to standardize the design of nuclear power plants, the Electricite de France commissioned Spie-Batignolles to develop a seismic isolation system which would give similar seismic design forces regardless of the seismicity of the construction site. An elastomeric bearing in series with an optimal sliding plate is shown in Figure B-14. To date, 4 nuclear plants (8 units) have been built or are under construction which use this design concept. The construction costs for this system are very high, but are justified because it allows a standardized plant to be built at any site without additional costs for redesigning, strengthening and reclassifying of components.

### Japan

There has been a great interest in isolation in Japan. There are now at least twenty completed base-isolated buildings in Japan, with many other under construction or in the design phase. Most Japanese isolation system involve natural rubber multilayer bearings, usually with the addition of damping enhancing components, including lead plugs, high damping rubber, straight and coiled steel bars, viscous plates, and oil dampers. The largest of the trial structures, is Oiles Technical Center (Miyazaki,1982). This 5-story, reinforced concrete frame building is 36 x 30 m in plan, with column grid lines at 6 m and 9 m centers. It has a floor area of 4800  $m^2$  and a total weight of 7500 tons above the isolators. Thirty-five lead-filled elastomeric isolators support the structure with diameters ranging from 65 cm to 80 cm. Lead plugs range from 13 cm to 16 cm in diameter. All bearings are 36 cm high. The building was required to be conservatively designed using a base shear coefficient of 0.2, which is the same as that required for a conventional building. No economy was, therefore, possible in the design; the reason for construction was improved seismic safety, damage-free performance in major earthquakes, and as a prototype building.

### New Zealand

To date 41 structures, which use seismic isolation systems, have been built or



are under construction in New Zealand. In the 1970s, New Zealand researchers were developing practical and economical energy devices to dissipate a significant amount of seismic energy and control displacements (Skinner et. al., 1975). These are shown in Figure B-15. The devices all depend for their primary hysteretic energy dissipation on the cyclic yielding of steel components or on the cyclic deformation or extrusion of lead. When installed between the ground and the inertia mass of the structure (e.g. at the base of a building), they act by yielding to curtail the seismic shear forces between the main structure and the foundations or ground, much as would a yielding column or beam system. In parallel with suitably flexible supports, the devices can therefore be used with the advantage that even under design earthquake conditions, yielding is limited to the devices. The remain structure is designed to remain elastic or to experience only limited ductile behavior under severe shaking. The devices are generally used in parallel with centering springs (e.g. elastomeric bearings acting in shear, or, in some cases, with flexible sleeved foundation piles) and hence the likelihood of long term permanent set is reduced. The devices are installed to be replaceable if the need arises after a severe shaking, although tests have shown their capacity for cyclic loading far exceeds that necessary for several major events.

#### Soviet Union

Three isolated apartment buildings of 5,8 and 9 stories, respectively were built in Sevastopol from 1972-1976. Clusters of ellipsoid-shaped steel bearings were used to support these structures and all survived the 1977 Sevastopol earthquake without damage.

### **3.4 Economic feasibility**

The economic feasibility of seismic isolation, as any other construction project, depends on the evaluation of the cost-benefits. According to Mayes (1990) there are four factors that affect the selection of base isolation. These factors are:

1. Construction costs.

2. Earthquake insurance.
3. Earthquake damage.
4. Disruption cost due to building and contents damage.

It is important to notice that these factors have different characteristics depending on whether the building is constructed with traditional methods (following the construction codes) or by innovative methods, in this case Base isolation. The only exception is in nuclear power plants, which require equivalent performance characteristics regardless of the method of construction.

### Construction Costs

The factors that increase the cost of base isolation are the base isolation system itself, architectural details that are needed to locate the system, as well as special mechanical and electrical details. But the base isolation system also brings savings in the structural system, curtain walls and nonstructural component bracing. All these things happen due to the reduction in the design force level compared with a conventional design.

Comparing the savings and cost increases, it has been found that in some special structures where the requirements are very strict, such as in hospitals or fire stations, the savings are enough to offset the additional cost of the isolators and the ground floor slab needed for the base isolation system (Mayes, 1990). But in common buildings using a construction code, for example the Uniform Building Code (UBC), there is not enough savings.

### Earthquake insurance

Earthquake insurance is getting more expensive in seismic regions like California. The insurance companies have a deductible of 10% of the total building value and annual premiums in the range of  $\frac{1}{2}$  to  $\frac{3}{4}$  % of the total building value (Mayes, 1990).

So for example if a building value is \$ 10 million, it will have at the moment it is insured, a deductible of \$ 1 million and annual premiums of \$ 50,000 to \$ 75,000 per year. So if the owner invests in a base isolation system, he will save the insurance premium, which will help to amortize the initial cost of base isolation.

### Earthquake damage

The factors that cause non-structural damage in a building are the interstory drift and the floor accelerations. The utilization of base isolation can be a solution of both factors.

### Business disruption cost

This is the cost related to building and contents damage, such as loss of things like rent, revenue, productivity and also the potential liability to occupants for their losses and injuries.

### Construction cost studies of buildings

Mayes reviewed the special situation of the first U.S. project to incorporate base isolation: Foothills Community Law and Justice Center. The total construction cost increase for using base isolation was 4% on a \$ 30 million project. Almost half of that was due to the need for a structural basement floor slab not considered before and the double concrete walls that were required around the retaining wall basement area of the building. But there were also cost reductions, such as in steel costs from changing the moment frame to a braced frame, and in material and labor from eliminating all moment connections needed for the original fixed-base design.

Base isolation can also be used in retrofit projects to improve the earthquake behavior of a building. But these projects face more present constraints such as the need for basements or piled foundations to locate the base isolation. When this solution is possible, it helps to interfere with the original structure as little as possible.

## **3.5 Problems related to the Implementation of Seismic Isolation**

The problems facing civil engineers who are implementing base isolation are very complex with many interrelated factors. The more significant ones are summarized as follows by Mayes, (1990):

1. Cost comparisons. Cost comparisons must be made on an equivalent basis between a conventional fixed base design and an isolated building design. An isolated structure will generally have a greater initial cost. The cost of earthquake damage insurance and of possible disruption of work must be included in the life cycle cost comparison.
2. Design philosophy of current codes. Many owners do not realize what performance characteristics are implicit in the design of a standard fixed-based building, and many believe they have an “earthquake proof” building when in fact the main issue addressed by the building code is prevention of collapse. In other words, standard buildings are designed to behave in the following manner:
  - (a) To resist minor earthquakes without damage.
  - (b) To resist moderate earthquakes without structural damage but with some nonstructural damage.
  - (c) To resist major earthquakes without collapse but with structural and non-structural damage.
3. Earthquake insurance. Currently there are no insurance cost benefits offered for the use of improved mitigation measures, such as seismic isolation .
4. Codes. The lack of codes that specifically address the use of seismic isolation has been a handicap because codes provide a key step in the implementation of any new technology, a consensus on requirements that should be used.
5. Government leadership. The government can provide leadership in many forms. These may include tax incentives, and legislative mandates, but could also offer an example through the use of innovative mitigation technologies in government buildings.
6. Construction Research and Development. Investment by the U.S construction industry has been small, compared to that of the Japanese construction industry in research and development. In the early 1970s, the Japanese government

required all contractors who wished to bid on federally funded projects to expend 1% of their gross income on research and development. As a result, the top 5 Japanese construction companies are spending \$ 15-20 million per year in research and have begun a 5-year plan to construct 50 new isolated buildings and 50 isolated bridges. By contrast, the reluctance of the U.S. construction industry to spend money on research has had a negative impact on the development of this technology.

### **Some solutions**

1. Development of different levels of performance criteria.-Codes and/or performance criteria that provide increasing levels of resistance to earthquake need to be developed
2. Implementation of seismic isolation codes. The new codes, particularly those introducing the technology of base isolation should be promoted in construction practice.
3. Public and professional awareness of new technologies. Expanding understanding of the new technologies will facilitate their use.
4. Economic incentives. Either tax breaks or reduced insurance premiums for improved seismic performance would accelerate utilization of this anti-seismic measures.
5. Government leadership. The government can give legislative support for application of this system and can provide an example in its own construction projects.
6. Development of Design Aids. Universities and engineering associations should develop aids to promote the application within the industry.
7. Funding research and development. The construction Industry should be required to set aside 1% of its gross income for research and development, if they wish to bid on government-funded projects.

## 3.6 Seismic Isolation Projects

The following phases must be considered in a seismic isolation project (Sharpe,1990):

1. Conceptual design.
2. Seismic isolation system only.
3. Complete structural system including seismic isolation.
4. Complete building including structural, architectural, mechanical and electrical systems, and seismic isolations.

### 1) Conceptual design.

All the factors that affect a base isolation project must be analyzed. For example, if the site soils are soft, the predominant frequencies of the ground motion could be similar to those of the base isolation system. The concept used to integrate the isolation system with the structural framing is important. Connections between the isolators and the frame and the foundation must support major horizontal displacements expected and possibly vertical uplift. Nonstructural components must be able to resist very large differential displacements.

### 2) Seismic Isolation System.

The basic performance parameters required for the system should be compared to those offered by the vendor. The system should be tested before dynamically on a shaking table or other dynamic testing equipments. The system must produce the results require such as base shear reduction, effective damping and attenuation of high frequency motion. It must be analyzed the extreme case when the system fails. The past history of each proposed isolator system should be evaluated.

### 3) Combined Structural/Isolation System.

The frequency characteristics of the structural and isolation systems should be compared. If the two predominant frequencies are close, there may be some resonant amplification of motions. The structure should be considerably stiffer (higher fundamental frequency) than the isolation system.

#### 4) Complete Building.

The effects on structural components and systems must be analyzed, as well as, the details at the interfaces between adjacent soils/foundations and structure. The provisions for large differential displacements at architectural elements such as entrance, exterior walls, flashings, partitions and elevator shafts need careful evaluation. A basic concern is that the nonstructural elements and systems can respond without damage or within allowable limits to the differential seismic displacements transmitted through the isolation system.

#### Types of Data reviewed

The following information related to the project should be obtained (Sharpe,1990):

1. The owner/client's performance criteria and its background.
2. Reports on geotechnical, soil bearings and tests, seismicity, and other potential hazards.
3. All data on the proposed isolator system including prior applications test data on isolator components and materials, performance criteria and vendor back-up service capability.
4. All design calculations, drawings and sketches for isolator systems, building or structure supported, and interfaces between structure/isolators/foundations.
5. Cost estimates for construction including all testing required for isolator systems.
6. Correspondence and reports relating to the concept and design.

The data should be reviewed to ensure that it is applicable to the project, has been interpreted and applied properly.

# Chapter 4

## Active Mass Damper

### 4.1 Introduction

A tuned mass damper is a passive type of device that can suppress a structure's vibration by transmitting it into an auxiliary mass. Thus, until the vibration energy is transmitted to and is dissipated by the auxiliary mass, and the vibration develops and becomes stationary, reduction of the main structural vibration is small. In general, passive tuned mass dampers are tuned to the first fundamental frequency of the structure. This is effective for building control only when the first mode is dominant. However, this may not be the case when a structure is subjected to earthquake-type loads in which the vibrational energy is spread over a wider frequency band (Soong, 1990). In contrast, the Active Mass Damper (AMD) can even from the beginning of the response suppress the vibration of strong winds and earthquakes with its instantaneous application of control forces.

### 4.2 Active Structural Control

Active control is characterized by:

1. A sensor to detect changes in the system.



2. A central processing computer to analyze the sensor inputs, compare them with pre-set quantitative models, and select a desired course of action.
3. An actuator to generate a real-time action that will modify the system's behavior or performance.

Numerous control algorithms have been developed since the 1970's to determine the value of the control forces that should be generated. On the other hand, very little progress has been made in terms of devices and mechanisms for implementing the desired course of action. To date, active control schemes are implemented using active mass dampers, variable stiffness devices and active bracing or tendon systems, all of which are driven by electro-hydraulic servo-mechanisms which are still slow to respond and require extensive maintenance.

Dynamic excitations of a structural system are classified into three types:

1. Environmental vibrations (machinery vibration, traffic noise, etc).
2. Wind forces.
3. Earthquake ground motions.

These excitations are very different from each other in frequency range, spectral characteristics, amplitude, duration, stationary conditions, etc. The purpose of structural response control is to provide living comfort and structural safety.

The procedures of structural response control are as follows (Kobori,1990):

1. Suppressing the input energy from the disturbance.
2. Isolating the structure's natural from the predominant power components of the disturbance.
3. Providing non-linear structural characteristics and establishing a non-stationary state and a nonresonant system.
4. Supplying control forces to suppress the structural response induced by disturbances.

5. Utilizing an energy absorption mechanism.

### 4.3 AMD Control Operation

“Admitting that it is impossible to precisely predict the ground motion in case of a major future earthquake, it is reasonable to adjust the structure itself. The basic concept of seismic response control, therefore, is the artificial adjustment of the building’s dynamic properties such as stiffness and damping” (Kobori, 1993).

Studies have shown that tall buildings subject to wind, usually oscillate at their own fundamental frequencies. One common scheme, used to correct this situation, is the Tuned Mass Damper. Figure B-16 shows a model of a structure-TMD system with a one degree of freedom model of mass ( $m_1$ ), damping constant ( $c_1$ ) and spring constant ( $k_1$ ), which represent the first-mode modal mass, damping, and stiffness of the building, whereas  $m_2$ ,  $c_2$  and  $k_2$  are the corresponding quantities associated with the TMD. The dynamic absorber theory shows that when the natural frequency of mass  $m_2$  (with a fixed mass  $m$ ) is made to match the natural frequency of mass  $m_1$  (with mass  $m_2$  absent) then the vibration of the primary mass is reduced.

The equations of motions of the system can be written in the form:

$$m_1\ddot{y}_1(t) + c_1\dot{y}_1(t) + k_1y_1(t) = c_2\dot{z}(t) + k_2z(t) + f(t). \quad (4.1)$$

$$m_2\ddot{z}(t) + c_2\dot{z}(t) + k_2z(t) = -m_2\ddot{y}_1(t). \quad (4.2)$$

in which  $z(t) = y_2(t) - y_1(t)$  is the displacement of  $m_2$  relative to  $m_1$  (Chang, et.al., 1986).

The aforementioned analysis presupposes that only the first vibration mode is of concern, thereby justifying the use of a one degree of freedom model. However, in many cases, the wind load also excites the higher modes of vibration of the building and might make one of those higher modes the dominant one. Yet, by adjusting  $m_2, k_2$  and  $c_2$ , mass, stiffness and the TMD damping coefficient, respectively, it is

only possible to “tune” the TMD to one frequency which is usually the building’s first fundamental mode .

For example, when more modes need to be reduced, more masses have to be used. The Tuned Mass Damper, as a system, is only capable of reducing the single frequency excitation that was calculated to be dominant under the expected loading conditions and is ineffective at other frequency excitations.

To increase the frequency where TMD’s are effective, it is necessary to be able to adjust each natural frequency to match the building’s dominant frequency as it changes in real time. It is difficult to change the mass of the TMD’s natural frequency to be able to control its associated stiffness  $k_2$ . With this capability to change the stiffness  $k_2$ , it is possible to implement a closed loop active control scheme using an active tuned mass damper, to reduce the vibration of the building at any dominant frequency within a specified range. A set of sensors would first be used to determine the accelerations and displacements of the building at every level. This information would then be processed to find the dominant mode of building vibration with its associated frequency and mode shape. The central control mechanism would then calculate the spring stiffness required to match the TMD natural frequency to the dominant building frequency, as well as the power necessary to be delivered to the spring so that it can undergo the desired stiffness change.

### **4.3.1 Feasibility of AMD Control**

The feasibility of active control can be established by considering the following aspects (Abdel-Rohman, 1985):

1. Time delay effect on the controlled response. In an ideal system, the assumption is made that all operations can be performed instantaneously. In reality, however, time is consumed in processing measured information, in performing on-line computation, and in executing the control forces as required. Thus, time delay causes unsynchronized application of the control forces, which not only renders ineffective, but may also cause system instability.

2. Effectiveness of the control mechanism in suppressing the vibration. As active control is only used to counter large environmental forces, it is likely that the control system will be infrequently activated. The reliability of a system operating largely in a standby mode and the related problems of maintenance and performance qualification become an important issue. Furthermore, an active mass damper system relies on external power sources which, in turn, rely on all the support utility systems. These systems are most vulnerable at the precise moment when they are most needed. The scope of the reliability problem is thus considerably enlarged.
3. Uncertainties in structural parameters. Controlled systems performance is in general function of structural parameters such as masses, stiffnesses, and damping ratios. In reality, structural parameters of as-built structures cannot be identified precisely and the parameter values used in control design may deviate significantly from their actual values. Thus parameter uncertainties are practical concerns. A sensitivity approach must be done to estimate the amount of parameter variability that can be tolerated for a prescribed level of performance. For example a variation of 40% in stiffness, in an eight-story structure with an active mass damper leads to a maximum of 5% change in the maximum top floor relative displacement and base shear according with Soong (1990).
4. Size of actuators required to achieve the designed control law. Active control requires the generation of large control forces, for which a new generation of actuators and control systems will be required.
5. Limited number of sensors and actuators. From an economical and practical point of view, the number of sensors and actuators is severely limited for structural applications and this is particularly true in the case of actuators. It is, therefore, important to know the minimum number of sensors and actuators required for the structure to be completely controllable and observable, and where these sensors and controllers should be positioned to produce maximum control benefit. For structural systems with no repeated modal frequencies, they can

be made controllable and observable by a single properly located sensor and actuator. It should be noticed, however, that practical considerations and computational requirements often need more sensors and controllers to be used than these minimum numbers. A criterion of optimality should be related to maximum state information, i.e. sensor locations should be chosen in such a way that they produce maximum information on the state of the structural system. Appropriate Control devices must be developed based on both technological and economic considerations.

## 4.4 Experimental Studies

The Takenaka Corporation has fabricated and tested several active mass dampers of different sizes. First, a small active mass damper was placed on top of a four story model frame. It was about 2 % of the structural weight. The model structure had dimensions of 1 x 1 x 2 m, it weighed 970 kg and was tested on a shaking table that provided a simulated earthquake type base motion. In 1984, a full scale AMD system was fabricated by Takenaka and was tested on top of a full-scale six-story structure. The biaxial AMD, with a fail-safe regulator, weighs 6 tons, approximately 1% of the structural weight, and has a maximum stroke of  $\pm 1$  m with a maximum control force of 10 tons. It can operate in two horizontal directions because it has two actuators set at right angles.

At the Kajima Corporation, an Active Mass Driver (operating under similar principles as an active mass damper) was placed on a 0.5 m (width) x 3m (height) three-story steel frame (Soong, 1990). This structure was also tested on a shaking table.

At the State University of New York at Buffalo, an active mass damper system was tested in conjunction with an active tendon system. Using a six-story 42,000 lb model structure, the AMD was placed on top of the structure, which could be operated under different conditions by changing its mass, its stiffness and the state of the regulator.

## 4.5 Applications of Active Mass Dampers

Active mass driver systems were applied for the first time in 1989. Since then, two different types of mass dampers have been used in actual buildings:

1. Active Mass Driver (AMD) Systems.
2. Hybrid Mass Damper (HMD) Systems: a small AMD combined with a conventional passive tuned mass damper (TMD).

### 4.5.1 Buildings with AMD in Japan

There are twelve buildings with an AMD in Japan (Izumi, et. al., 1993). These are sometimes called semi-active dampers or hybrid mass dampers by their developers. Izumi classifies the AMD according with the following characteristics:

**Mechanism.** An AMD mechanism may be any of the following types:

1. Friction Pendulum System (5 of 12 buildings with AMD). Bearings consists of an articulated slider in a concave spherical stainless steel surface. The slider is covered with a teflon layer to minimize the friction between the two surfaces in contact. Because of the friction between the contact surface, a structure supported on this type of bearings responds to low level forces like a conventional fixed-base structure. Hence, the structure can withstand wind, and small earthquake loads without appreciable motion. Once the friction forces are exceeded, however, the structure responds as a free pendulum with the dynamic response controlled by the natural period of this pendulum and its damping by the mobilized frictional forces. Similarly, as the slider rises and as it moves along the spherical surface, a gravity restoring force, which helps to bring the surface back to its position of equilibrium, is developed. In the pendulum system, multiple pendulums can be designed to elongate the primary natural period.
2. Multiple rubber bearings (7 of 12 buildings with AMD). The multistage rubber bearing consists of a number of stages (each stage comprising 3 or 4 laminated

rubber bearing elements) piled up with stabilizing plates between them. In the application to mass dampers, the multistage rubber bearings can support large-scale moving masses and provide horizontal movements without friction, although the natural frequencies of the mass dampers become the same ones in every horizontal direction.

**Mass ratio.** The mass ratio in AMD (the ratio of the added mass compared to the effective building mass) is about 0.5%. This is almost half of a TMD's because AMD's high efficiency as compared to a TMD.

**Actuator.** The types of actuators used were:

1. AC Servomotor Type. A moving mass supported by an XY-motion mechanism and each of 4 reaction walls, is connected by coil springs. In X and Y directions respectively, oil dampers are installed between the moving mass and the reaction walls. The driving mechanism in each direction consists of an AC servomotor, reduction gear, and a magnetic clutch and pinion on the same axis, which are mounted on the moving mass for easy maintenance. The pinion is in gear with a rack supported by the reaction wall and the moving mass.
2. Hydraulic Actuator. In a normal hydraulic system, the actuators are supplied with operating oil from the accumulators which accumulate the oil fed by the pumps and keep the pressure from exceeding the capacities of the accumulators and the pump. The pressure becomes lower and lower, until the accumulators finally become almost empty. In a normal active mass damper using hydraulic actuators, the hydraulic systems are also easily stopped by the controller, if it keeps working against strong winds and earthquakes beyond the capacity of the hydraulic system.

Actuators used for earthquakes and those used for wind are not distinguishable by maximum stroke length. However, the tendency is for the maximum stroke to be longer as the scale of the building increases and the mass ratio decreases. Also,

usually a larger control force is needed as mass increases. The ratio of the control force to the added mass is mainly 15-25 % for those used for earthquakes, and less than 10% for those used for winds.

**Kyobashi Seiwa Building.** In 1989, Kajima installed a full scale active mass driver system on the top floor of the eleven-story Kyobashi Seiwa Building in Tokyo. It was the first building in the world with an active control system. The active mass driver is a pendulum-type system with two masses capable of controlling torsional as well as lateral vibration of the slender structure in strong winds or moderate earthquakes. The overall composition of the system is shown in Figure B-17. The system consists of a driver part, a controller part and a monitoring part. Two units of weights that provide the control force are placed at the roof of the building i.e., one AMD of 4 ton placed in the center of the floor and other AMD of 1 ton at the edge of the floor to control the lateral and torsional vibrations, respectively. By the ceaseless engagement of the 1.5 kw pump and accumulator, instantaneous start up of the system is possible when an earthquake occurs. This means that conservation of electrical power is achieved under this system.

It was reported that the building has experienced several moderate earthquakes and strong winds during which ground acceleration, wind velocities and structural responses were measured. The measured responses during the earthquakes were compared with the simulated responses from numerical analyses of uncontrolled structures. Wind response observations were performed every 30 minutes with and without control. From these comparisons, a remarkable decrease in amplitude due to active mass driver system was confirmed.

**Sendagaya Intes** Figure B-18 shows a general view of an experimental version of an active vibration control system using a dynamic damper (Inove, et. al.,1993). An auxiliary mass installed on the top floor of a building model is driven by an actuator. An active dynamic damper has a ball-screw driving system equipped with an AC servo-motor.



Sendagaya Intes, completed in December 1991, is an eleven-story structure constructed with steel encased reinforced concrete and a steel frame with a two-story roof appendage. The vertical cross section of the building is shown in Figure B-19. The building is equipped with two masses to control the translation and torsion of the building. However, the two AMDs are designed only to move in the  $y$  direction because the concept of installation is to reduce the vibration from the north and south winds which induce the  $y$  direction translation and torsion. The properties of the building and its AMD are shown in Table A.1.

Figure B-20 shows the elevation of the AMD used. The iced thermal storage tank used for the air conditioning system double as the mass of AMD, to avoid introducing extra weight on the building. Control commands are calculated by a microcomputer and sent to the analog servoamplifier, which drives the hydraulic actuators. The tank is supported by multistage rubber bearings to reduce the control energy consumed in AMD and to make the movement smooth by controlling small excitations. The stiffness of plumbing is increased to improve the reliability of the hydraulic actuators.

The response of uncontrolled state movements distributed from 0.5 to 1.1 cm/s were reduced to 0.2 - 0.4 cm/s with active control.

**Hankyu Chayamachi Building.** This building is located in Osaka, Japan and is used as an office, hotel and theater. The building is equipped at the top with a heliport for emergency use, and it is also utilized as the moving mass of the AMD system. The heliport weighs 480 tons and is 3.5% of the tower weight (14,000 ton). Figure B-21 shows the building cross section. The heliport is supported by six multistage rubber bearings. The natural period of the rubber and heliport system was set at 3.6 seconds, shorter than that of the building (3.8 seconds). The dimensions of the building and the AMD are summarized in Table A.2. The primary mode damping ratio of the building was 1.4% and this was increased to 10.6 % by AMD.

The AMD development has come to an application stage in Japan. But the current AMD's are not enough to improve the safety of the building during strong earthquakes. Because the mass stroke may be more than 1 meter, the development

of a new control algorithm is needed to minimize the stroke as much as possible. Another problem is that it is difficult to maintain the system for several years waiting for a large scale earthquake. AMD's lifetime is usually shorter than this.

## 4.6 HMD System

Response control systems of the passive type function are effective only after the structure begins to move, which means that it starts slowly. To solve this deficiency, trials to combine a passive control system with an active one are occurring. For example, research for the active tuned mass damper which combines a tuned mass damper with an actuator have been conducted.

The HMD System (Hybrid mass damper system, called DUOX) is a combination of an AMD system and a passive tuned mass damper (TMD). Although a slight time lag is recognized in the instantaneous start-up on occurrence of earthquakes, it possesses about the same control efficiency as the AMD system. Its special feature is that it only requires a small AMD device to be mounted on top of a conventional tuned mass damper. Consequently, a bi-directional control device can be easily made. The AMD weight is about 10-15 % of the TMD weight. The fundamental concept of the system is shown in Figure B-22. The system performs control as follows. First, the sensors detect the building velocity at the device location. Then, the relative displacement of the TMD with reference to the building and finally the relative displacement and velocity of that AMD with reference to the TMD. This information is backed to the controller for evaluating the optimum control gains in order to achieve the required control effect and to maintain the strokes of the AMD within allowable range. The control algorithm was verified by means of a shaking table test conducted on a model, and based on this test result, the actual system was developed. The practical application was made to Ando Nishikicho Building (located in Nishikicho, Kanda, Tokyo) which is a 14-story, 68 m high, office and residential building. This building structure has almost a square plan so that it needs universal vibration control effect and the system should work well under a disturbance ground motion as large as

intensity V (Japan seismic intensity level) or a wind disturbance as is expected once every 20 years. The response vibration at the top of the building was less than one third as compared with a non-controlled state. The passive auxiliary weight of DUOX is approximately 0.8 % or 20 ton of the total building weight above ground and the active portion auxiliary weight is as small as 0.08% or just 2.0 ton for each. Another feature of the system is that the whole device is upheld by hollowed laminated rubber bearings that provide the passive TMD with adequate lateral stiffness. The vibration energy is absorbed by the oil damper placed between the passive weight and the roof slab of the building. There are two identical small AMD's placed on the passive TMD so that the latter is controlled by the inertia forces generated by the AMD's.

**Absolute Vibration Control System** In this system, the entire building is supported by laminated rubber bearings and the foundation which are connected by springs to a drive system whose arms are extendible by hydraulic pressure. The damping force is transmitted to the building by springs, so by setting the spring rigidities, it is possible to dampen even small vibrations. Also the vibration-damping system actuator is installed on the ground and can cope with large earthquakes. Instead of applying the technique to an entire building, it is also possible to install the actuator inside the building and to dampen the oscillation of only one part. This provides a small-scale absolute vibration-damping system for only the necessary parts of a building.

#### **Vibration Control System Using Tuned Liquid Dampers (MOVICS-1,2)**

This is a vibration control system employing the common water-supply tanks on the top of high-rise buildings (Takeda, et. al., 1993). Each unit consists of two U-shaped tanks with an air chamber that can adjust the pressure and a rotary-frequency-adjustment mechanism to control the air flow installed above it. Each frequency-adjustment mechanism consists of a compact U-shaped water tank, a valve, the valve's axis, and a mechanical spring. A special feature of this vibration control system is its ability to perform frequency adjustments separately in two horizontal

directions.

**Vibration Control System Using Active Mass Dampers (AVICS-1)** An active mass damper has a ball-screw drive system equipped with an AC servo-motor. Control is based on optimal control theory involving feedback of actuator characteristics and various states and conditions. By guaranteeing a large stroke and improving operability the vibration control objectives can be achieved using a small added mass. At the same time, it is possible to control vibration through a wide frequency range including higher order vibration mode.

# Chapter 5

## Control of buildings

### 5.1 Introduction

An approximated method is used to estimate the modal response of the entire structure, based on incomplete measure data, in order to obtain necessary control forces using an optimal modal control technique (Yang, et. al., 1990). Optimal modal control forces are applied to control the dynamic behavior of the structure. To model properly the dynamic behavior of the civil engineering type of structures, such as high rise buildings, a sufficient number of degrees of freedom are usually needed.

A high rise building can be analyzed for simplicity as a shear beam model with only a horizontal degree of freedom at each floor. But the requirement of using enough number of sensors to accurately model the dynamic behavior of the high-rise shear beam model makes the control problem difficult. For a high rise building with many floors, it is impractical to allocate a sensor and an actuator for each degree of freedom even for a simple shear-beam model. So it is necessary to determine the proper locations for only limited numbers of sensors and actuators. The data collected from such a limited number of sensors are often called incomplete measured data.

Many control algorithms have been introduced for the control of civil engineering type of structure:

1. Optimal control algorithms.

2. Pole assignment method.
3. Modal control theory.

Modal control theory is the most useful for the control of high rise buildings. The responses of the structure under control are simulated by some of the lower vibration modes of the structure. Most of the studies assumed that the dynamic response of the building can be obtained exactly. This means that the measuring sensors were set for each of the degrees of freedom. But in reality, measured data can be obtained by setting measuring sensors only for some selected degrees of freedom, so measured data are incomplete.

Passive control with base isolation can reduce the displacements of the structure relative to the ground motion. This system can achieve great efficiency for relatively lower but more rigid buildings. On the other hand, active control devices, such as active tendon control, usually reduce the relative displacements or relative velocities between different storeys. This algorithm can be applied efficiently to flexible structures.

The efficiency of an active control system could be reduced due to limitations existing in the control devices, such as time delay, accuracy of the controller and maximum potential of the actuator. As a result, active control devices, such as an active tendon control, may not be enough to cope with the input of impact forces which simulate an earthquake excitation.

## 5.2 General Definitions

Some control terminologies:

**Open Loop Control** The control factors (control forces or control actions) are decided and added to the structure based on the sensing data collected from the behavior which are independent of the response of the structure. The flow chart in Figure B-23 shows the control system.

**Close Loop Control** The control factor (control forces or control actions) are decided and added to the structure based on the sensing data collected from the responses of the structure. The flow chart displayed in Figure B-24 shows the control system.

**Passive control** A control system which does not need any external input of energy. The passive control mechanism generates the necessary control forces even if the structure is disturbed or its response exceeds certain limits. Most of the passive control systems are in a close loop fashion. Passive control examples include:

1. Damping tendon devices.
2. Tuned mass damper devices.
3. Lead-rubber base isolation devices.
4. Frame with cross bracing cables.
5. Frame with hanging chain damper.

**Active control** A control system that has external energy supply function. An active control system may be operated in an open loop or in a closed loop fashion. In an open-loop active control system, the control action is determined from the initial state of the system. The control action is previously known from the information given by the configuration of the system, its initial state, and by the applied disturbance. In other words, the control action does not depend on the response of the structure.

In a closed-loop active control system, the control action is decided from the current state of the system. The feedback information from the responses of the structure is needed to determine the control actions.

Typical examples of active control devices:

1. Active control by mass absorber.
2. Active control by auxiliary damper.
3. Active control by tendons.

## 5.3 Sensing System

In a feedback control system, a sensing system is one of the essential components from which the control action can be triggered. Most of the control feedback for the civil structures are state responses with respect to displacements, velocities and accelerations. The output of the measured results for a linear system can be written in the form:

$$Y(t) = HX(t) \quad (5.1)$$

where  $X(t)$  is a  $2n \times 1$  vector describing the vibration state of the system;  $Y(t)$  is an  $m \times 1$  vector containing the measured results of the system;  $H$  is a  $m \times 2n$  matrix relating the measure results and the actual state of the system.

The measured results can be classified as those of complete measuring or as an incomplete measuring case. In the case of complete measuring, the dimension of  $Y(t)$  is equal to the dimension of  $X(t)$  i.e.,  $m = 2n$ . The entire state of the dynamic system can be measured through the sensing system. In this case, the dynamic state of the structure can be obtained by multiplying the measuring data by the inverse of matrix  $H$  :

$$X(t) = H^{-1}Y(t) \quad (5.2)$$

In the case of incomplete measuring, the dimension of  $Y(t)$  is smaller than the dimension of  $X(t)$ , i.e.  $m < 2n$ . The actual state of the dynamic system can not be obtained exactly through Eq. 5.2. So an approximate modal method is used, with the following assumptions:

1. Masses are lumped at the floors.
2. Stiffness of the horizontal beam and floor is much greater than the stiffness of the columns.
3. Foundation is rigid with infinite stiffness.
4. Linearly viscous damping is assumed.
5. Vibrations in both vertical and torsional directions are neglected.



## 5.4 State Equation

One horizontal degree of freedom is assigned to each of the floors. By taking each of the floors as a free body, the equation of motion of this n-story building can be obtained as follows:

$$m_j \ddot{D}_j + C_{j+1}(\dot{D}_j - \dot{D}_{j+1}) + C_j(\dot{D}_j - \dot{D}_{j-1}) + K_{j+1}(D_j - D_{j+1}) + K_j(D_j - D_{j-1}) = f_j + u_j \quad (5.3)$$

where  $c_{n+1} = k_{n+1} = 0$  and  $D_j, \dot{D}_j, \ddot{D}_j$  are the relative displacement, velocity and acceleration of the j-th story, respectively;  $m_j, c_j, k_j$  are the lumped mass, damping factor and stiffness of the j-th story respectively;  $f_j$  and  $u_j$  are the external horizontal force and the control force applied to the j-th story, respectively.

Equation 5.3 can be written in a matrix form:

$$[M][\ddot{D}] + [C][\dot{D}] + [K][D] = [F] + [U] \quad (5.4)$$

where  $[M], [C]$  and  $[K]$  are the matrices of order  $(n \times n)$  for masses, damping coefficients and stiffness, whereas,  $[D], [F]$  and  $[U]$  are the vectors of order  $(n \times 1)$  for displacements, external forces, and control forces, respectively.

There are in the following forms:

$$[M] = \begin{bmatrix} m_1 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 \\ 0 & 0 & \dots & 0 \\ 0 & 0 & 0 & m_n \end{bmatrix}$$

$$[C] = \begin{bmatrix} c_1 + c_2 & -c_2 & 0 & 0 & 0 \\ -c_2 & c_2 + c_3 & -c_3 & 0 & 0 \\ 0 & \dots & \dots & \dots & 0 \\ 0 & 0 & -c_{n-1} & c_{n-1} + c_n & -c_n \\ 0 & 0 & 0 & -c_n & c_n \end{bmatrix}$$

$$[K] = \begin{bmatrix} k_1 + k_2 & -k_2 & 0 & 0 & 0 \\ -k_2 & k_2 + k_3 & -k_3 & 0 & 0 \\ 0 & \dots & \dots & \dots & 0 \\ 0 & 0 & -k_{n-1} & k_{n-1} + k_n & -k_n \\ 0 & 0 & 0 & -k_n & k_n \end{bmatrix}$$

$$[D] = \begin{bmatrix} D_1 & D_2 & \dots & D_n \end{bmatrix}^T$$

$$[F] = \begin{bmatrix} f_1 & f_2 & \dots & f_n \end{bmatrix}^T$$

$$[U] = \begin{bmatrix} U_1 & U_2 & \dots & U_n \end{bmatrix}^T$$

Equation of motion Eq. 5.3 can be transformed into a set of first order linear simultaneous equations which is called the *state equation*, by defining the state variable as:

$$X(t) = \begin{bmatrix} D \\ \dot{D} \end{bmatrix}$$

the state equation can be written as:

$$\dot{X}(t) = AX(t) + BU(t) + W(t) \quad (5.5)$$

where  $X(t)$  is a  $(2nx1)$  vector representing the state variables of the system; the vector  $U(t)$  is of order  $(nx1)$  and represents the control force variable of the system; and  $[A]$  of order  $(2nx2n)$ ,  $[B]$  of order  $(2n \times n)$  and  $[W]$  of order  $(2nx1)$  are the coefficient matrices of the state equation in the forms of:

$$[A] = \begin{bmatrix} 0 & I \\ -[M]^{-1}[K] & -[M]^{-1}[C] \end{bmatrix}$$

$$[B] = \begin{bmatrix} 0 \\ M^{-1} \end{bmatrix}$$

$$[W] = \begin{bmatrix} 0 \\ M^{-1}F \end{bmatrix}$$

## 5.5 Optimal Control

An optimal control problem can be solved by finding the control law with the objective function:

$$J = \frac{1}{2} \int_{t_0}^{t_f} (X^T(t)QX(t) + U^T(t)RU(t))dt \quad (5.6)$$

is minimized when  $t_f$  approaches infinity under the constraint of the State Equation:

$$\dot{x}(t) = Ax(t) + BU(t) \quad (5.7)$$

According to Pontryagin's Optimal principle, the Hamiltonian of the problem can be written as:

$$H[X(t), U(t), \lambda(t), t] = \frac{1}{2}X^TQX + \frac{1}{2}U^TRU + \lambda^TAX + \lambda^TBU \quad (5.8)$$

where  $\lambda$  is the Lagrange multiplier. Letting the first derivative of the Hamiltonian with respect to  $U$  and  $X$  be zero, the optimal conditions can be obtained:

$$\frac{\delta H}{\delta U} = 0 = RU(t) + B^T\lambda(t) \quad (5.9)$$

$$\frac{\delta H}{\delta X} = 0 = -\dot{\lambda} = QX(t) + A^T\lambda(t) \quad (5.10)$$

with an end condition of:

$$\lambda(t_f) = \frac{\delta[\frac{1}{2}X^T(t_f)SX(t)]}{\delta X(t_f)} = SX(t_f) = 0 \quad (5.11)$$

From Eq. 5.9 one has:

$$U(t) = -R^{-1}B^T\lambda(t) \quad (5.12)$$

Assuming the solution of the Lagrange's multiplier to be in the form of:

$$\lambda(t) = P(t)X(t) \quad (5.13)$$

and substituting Eq. 5.13 into Eq. 5.10 give:

$$-\dot{P}(t)X(t) - P(t)\dot{x}(t) = QX(t) + A^T\lambda(t) \quad (5.14)$$

Substituting by Eq. 5.12 into Eq. 5.7 gives:

$$\dot{x}(t) = AX(t) - BR^{-1}B^TP(t)X(t) \quad (5.15)$$

Substituting Eq. 5.13 and Eq. 5.15 into Eq. 5.1 and eliminating  $X(t)$ , the Riccati equation can be obtained as:

$$-\dot{P}(t) = P(t)A + A^TP(t) - P(t)BR^{-1}B^TP(t) + Q \quad (5.16)$$

In the case where  $t_f$  approaches infinity,  $P(t)$  will approach a stable value, i.e.  $\dot{P}(t) = 0$ . Consequently the term including  $\dot{P}(t)$  in Eq. 5.16 can be eliminated. Thus one has:

$$-PA + A^TP - PBR^{-1}B^TP + Q = 0 \quad (5.17)$$

and the optimal control force can be obtained by substituting Eq. 5.13 into Eq. 5.12:

$$U(t) = -R^{-1}B^TPX(t) \quad (5.18)$$

## 5.6 Example

The two-story frame shown in Figure B-25 is subjected to a steady-state force at the floor levels. The frame's response is controlled against the dynamic forces using tendons. They are shown in Figure B-25(b). These tendons are arranged on X shapes in order to control the structure in either direction. The idea is that when one tendon works in one direction, the other does not. So the resultant control force can be considered as a lateral one, applied at each floor level.

The structural properties were assumed as follows: masses  $m_1 = 108 \frac{lb*s^2}{in}$  and  $m_2 = 99 \frac{lb*s^2}{in}$ ; rigidity  $EI = 0.5 \times 10^{10} lb * in^2$ ; and length  $L = 15$  ft.

This example was modeled in the Matlab program, by means of which it is possible to solve linear differential equations. This model was also studied by Abdel-Rohman (1979) in the context of a general approach to active structural control.

The forcing functions used by Abdel-Rhoman are assumed to be dynamic forces with two sinusoidal components, whose frequencies coincide with the structure's frequencies.

$$F_1 = 200\sin 7.88t + 600\sin 22.2t \quad (5.19)$$

$$F_2 = 3000\sin 7.88t + 600\sin 22.2t \quad (5.20)$$

The principal reason for using active control in buildings are to ensure the safety of the occupants and well as human comfort, both at the smallest cost possible. Therefore the following general constraints should be used to control the structure:

- Safety can be ensured by imposing constraints on the maximum allowed deflection or acceleration at some points of the structure. This was considered in the current example by taking:
  - Displacement = 0.002 of the height of the structure
- Human comfort can be satisfied by imposing constraints on the acceleration at

each level for example.

– Acceleration =  $6 \frac{in}{s^2}$  (1.5% of g)

- The cost control can be expressed as a function of control forces' magnitude. This was not considered.

Figure B-26 shows both the uncontrolled and controlled response of the deflection at the second floor.

Figure B-27 shows the control force in the second floor required to minimize the displacement. It is interesting to note that this force is very high since the objective is to control the displacements, without considerations of the level of control force required.

# Chapter 6

## Conclusions and Recommendations

### 6.1 Summary

Conventional design practice permits inelastic action in buildings, providing significant energy dissipation, but often resulting in important damage to structural members and non-structural elements when the building is subjected to dynamic loads such as earthquakes and wind. In response to these shortcomings several counter-measures have been developed, among which are the passive and active control systems. In the future, it is expected that a hybrid of these two mechanisms may be developed.

The aim of this thesis is to examine the present available devices for the passive and active control of buildings and to evaluate their stages in research, development and commercialization. From this analysis, guidelines are proposed to select adequate devices in specific situations. Different guidelines are developed depending on whether the device is at a present practical reality, or only at an early development stage.

To conduct this study, the basic theory of passive and active devices is first explained. Different analytical, experimental and actual devices applications are then examined. In addition methods that integrate these devices into practical designs are described.

Passive control is achieved by providing additional stiffness, damping and duc-

tility in the buildings. Passive control does not need any external input of energy to work. However, a main disadvantage is that it is unable to adapt to changing situations. Most of the research and implementation has until now resulted in a variety of damping devices, such as friction dampers, viscoelastic dampers, viscous fluid dampers, hysteretic dampers, and nitinol-shape-memory-alloy dampers. Each of these devices reduces the seismic response of the building and its structural and non-structural damage. These devices are easy to install, and do not interfere with the foundation. In addition, friction and hysteretic dampers are not affected by temperature changes, number of loading cycles or aging. However, friction and hysteretic dampers have several disadvantages. They are only effective for flexible structures, and they may be subjected to large deformations. These dampers complicate the design procedure, because several alternatives have to be considered in order to find the optimum number of dampers needed, and the places to situate these dampers. For friction and hysteretic dampers, a selection of an adequate yield or slip level must be made, because these dampers work only after the yield or slip level is exceeded. If the level is set too high, there may be structural and non-structural damages before these devices start to work. On the other hand, if the yield level is set too low, any small movement can activate the dampers, setting off vibrations in the buildings. There are two major factors to be considered in selecting a supplemental damping system: the type of structural system, and the expected ground motion to which the structure will be exposed.

Among the passive devices available to date we can cite Base Isolation. This system must be considered separately due to its special characteristics. It isolates the building from the horizontal components of earthquake ground movements so as to prevent damage to the structure. It can only be used in buildings of up to 10-15 storeys in height, and only when soil conditions permit. Furthermore, the stick-slip process, inherent to base isolation system, may elicit high frequency pulses which can excite the higher modes of the building and be detrimental to the building integrity. Base isolation is more expensive than fixed-base structure due to the cost of isolators, the double basement slab and walls, and the special details needed for the system.



The structures that may justify the expensive usage of base isolation method are buildings that warrant the safety of its non-structural components such as hospitals, nuclear reactors, and fire stations.

The idea of active control is innovative; it changes the way of seeing the structural design from a passive or static mode to an active or dynamic point of view, where its feedback system allows it to adapt to different situations. But this system also has a greater risk, because there are more uncertainties which make it important to have a redundant system. If something goes wrong, the safety of the building must never be affected. The maintenance of the system is very important because it may be used only occasionally. It also relies on an external power supply, and this power supply may fail during the earthquake. Control of buildings requires large control forces applied at high velocities. Therefore such active control may require large actuators with large strokes. There is also a problem with time-delay between reading the information from sensors and the application of the actuator forces. If these actuator forces are applied at the wrong times they may create an instability problem in the structure rather than solving one. The system is very expensive due to the use of modern technology, including computer, actuator and sensors. Several control algorithms have been developed since the 1970's to determine the value of the control force that should be generated. But very little progress has been made in terms of devices and mechanisms for implementation in actual buildings. To date, active control schemes are implemented using active mass dampers and active tendons which are all driven by electro-hydraulic servo-mechanisms. However, these actuators are slow to respond and require maintenance.

## **6.2 Recommendations**

There has been an increase in worldwide awareness on the part of civil engineers of the potential of passive and active devices for reducing the dynamic forces experienced by structures under wind or earthquakes. This thesis has reviewed some of these mechanisms, and has reached the following recommendations:

### Passive Control Devices.

- Ideally, these devices should be incorporated in the design of structures in seismic zones.
- It is important to select the most appropriate passive device for the type of building and the zone where it will be built.
- Guidelines for the design of passive devices and their integration into existing structures are needed.
- In the future, the development of shape-memory-alloys (SMA) or smart materials will increase the use of these devices.
- Economic incentives, either tax breaks or reduced insurance premiums for improved seismic performance, would accelerate utilization of mitigation measures that reduce the cost of earthquake damage.
- Research and development expenditure on the part of the construction industry is necessary.

### Active Control Systems.

- Development of new actuators and sensors are badly needed.
- Experimental research on proposed control systems is also needed. A test program involving small to large-scale tests is required, before full implementation in real structures can begin.
- Develop standards for structural control systems, including test procedures and performance criteria.
- Development of new materials.
- Development of advanced computer technology and systems specific for structural control applications.

- Study reliability of the systems under extreme circumstances.
- Practical methods and techniques for design, manufacturing, fabrication and implementation.

### Hybrid Control Systems

- Combined passive and active devices can be considered as a way of improving performance of one with the other, so more steps in this direction must be taken.

If the aforementioned recommendations are followed in the future, a building that is able to sustain minimal structural and non-structural damage can be realized within ten years. This design would be effective in curtailing the vibrations induced by dynamic forces of any kind and intensity.

# Appendix A

## Tables

| Building Properties           | Units                             | Value  |
|-------------------------------|-----------------------------------|--------|
| Mass                          | $\frac{t \cdot s^2}{cm}$          | 3.346  |
| Rotational Inertia            | $\frac{t \cdot cm \cdot s^2}{cm}$ | 19.610 |
| Natural Period of Translation | $s$                               | 1.700  |
| Natural Period of Torsion     | $s$                               | 1.600  |
| Dampting Ratio                |                                   | 0.010  |
| Eccentricity Distance         | $cm$                              | 50.000 |
| Active Mass Dampers (AMD)     | Units                             | Value  |
| Mass                          | $\frac{t \cdot s^2}{cm}$          | 3.346  |
| Natural Period                | $s$                               | 1.700  |
| Dampting Ratio                |                                   | 0.010  |
| AMD No. 1 Eccentricity        | $cm$                              | 1715   |
| AMD No. 2 Eccentricity        | $cm$                              | 1715   |

Table A.1: The Building and AMD Properties: Sendagaya INTES (Higashino, 1993)

| Building Properties       | Units                             | Value |
|---------------------------|-----------------------------------|-------|
| Mass                      | $\frac{t \cdot s^2}{cm}$          | 3.346 |
| Rotational Inertia        | $\frac{t \cdot cm \cdot s^2}{cm}$ | 6.302 |
| Natural Period (X)        | s                                 | 3.400 |
| Natural Period (Y)        | s                                 | 3.800 |
| Dampting Ratio            |                                   | 0.014 |
| Active Mass Dampers (AMD) | Units                             | Value |
| Mass                      | $\frac{t \cdot s^2}{cm}$          | 0.490 |
| Natural Period            | s                                 | 3.600 |
| Dampting Ratio            |                                   | 0.030 |

Table A.2: The Building and AMD Properties: Hankyu Chayamachi

# Appendix B

## Figures

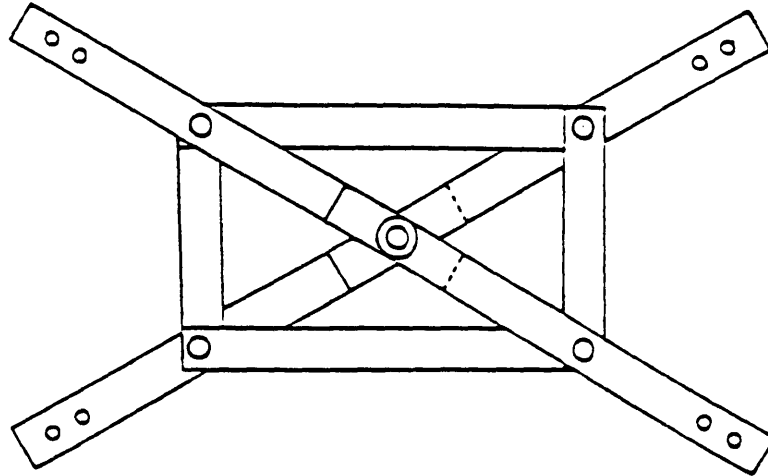


Figure B-1: Pall friction device

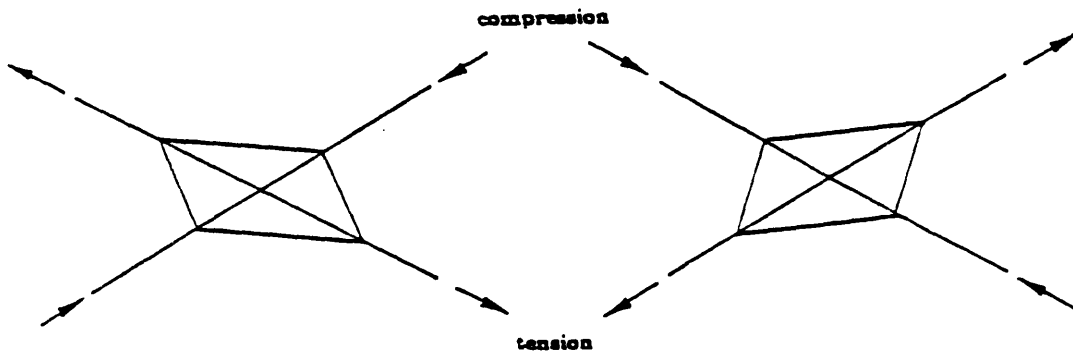


Figure B-2: Deformed configurations of a Pall Friction Device

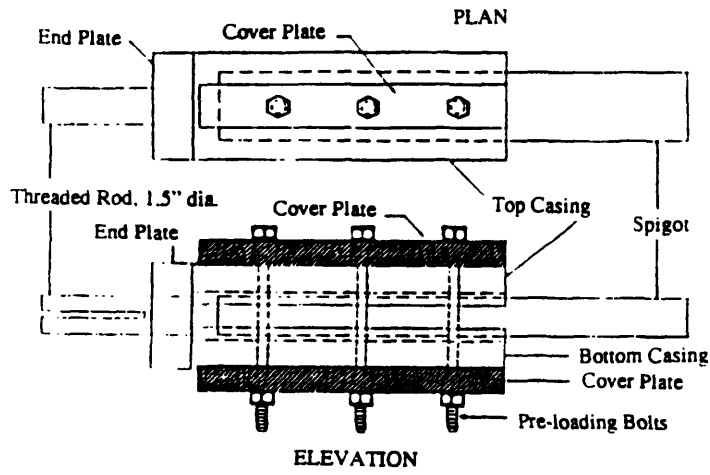


Figure B-3: Friction slip device (Aiken, et.al.,1993)

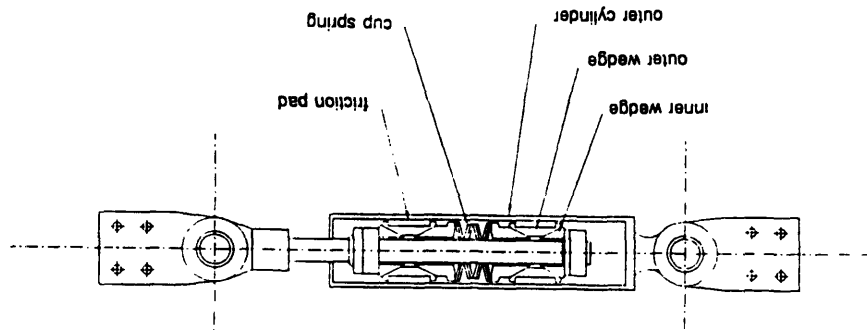


Figure B-4: Section view of friction damper (Sumitomo)



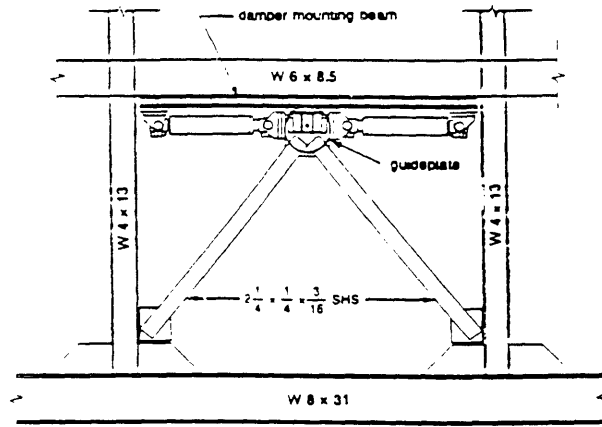


Figure B-5: Friction dampers installed in model(Sumitomo)

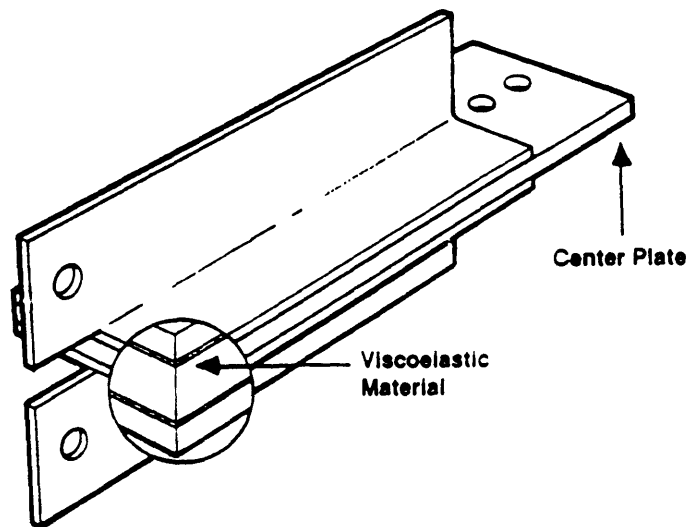


Figure B-6: A viscoelastic damper (Chang, et.al.,1993)

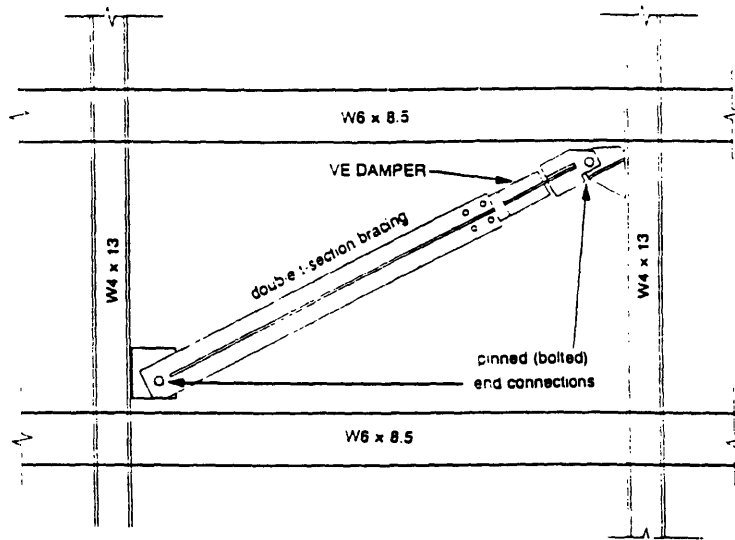


Figure B-7: VE dampers in model (Aiken, et.al.,1993)

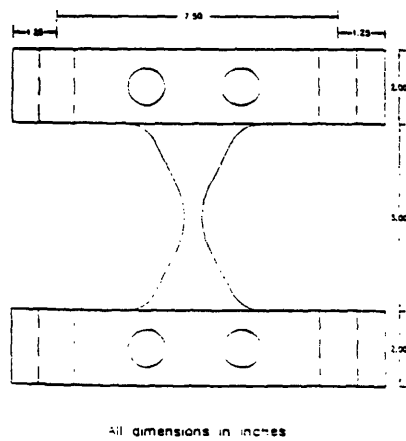


Figure B-8: ADAS element (Aiken, et.al.,1993)

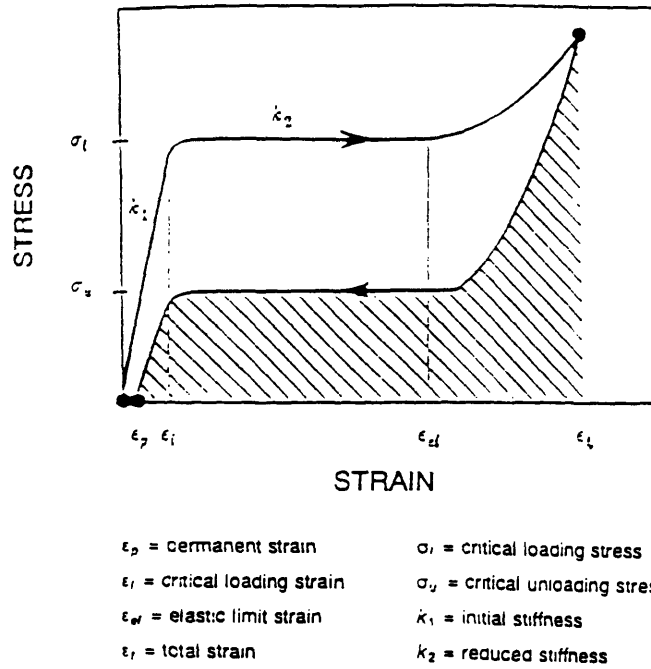


Figure B-9: Superelasticity (Aiken, et.al.,1993)

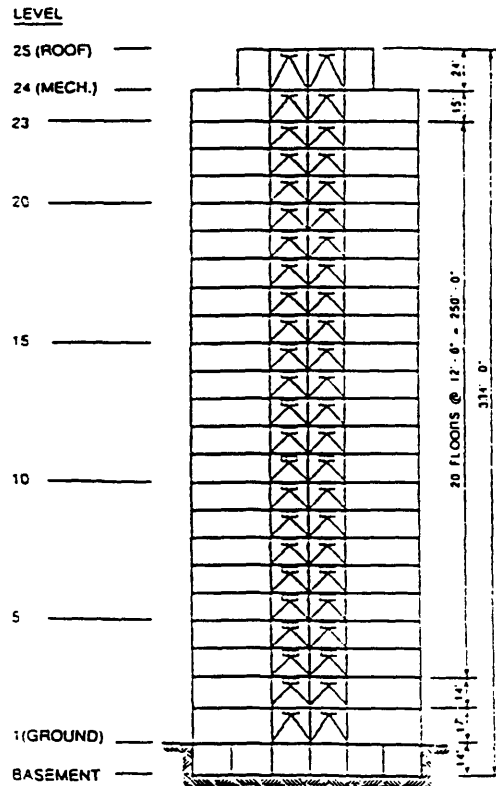


Figure B-10: Building elevation: uniform damper distribution (Scholl,1993)

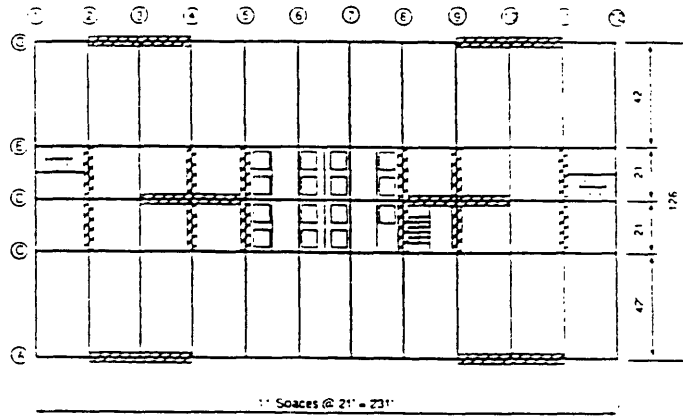


Figure B-11: Building plan: uniform damper distribution (Scholl,1993)

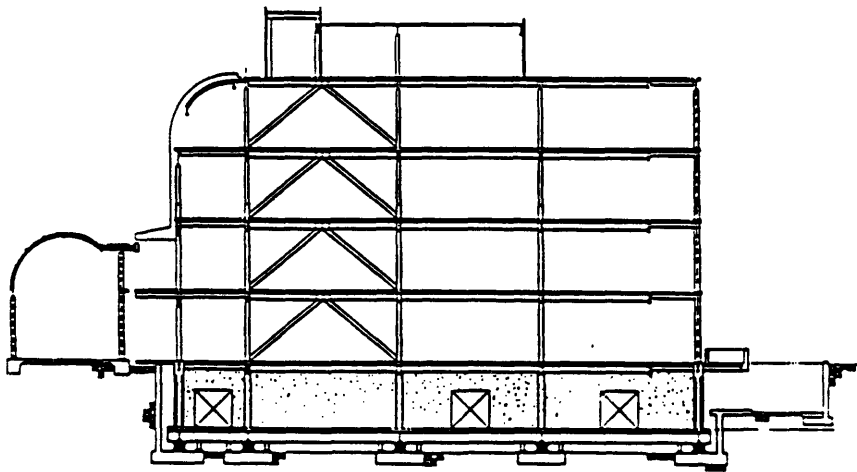
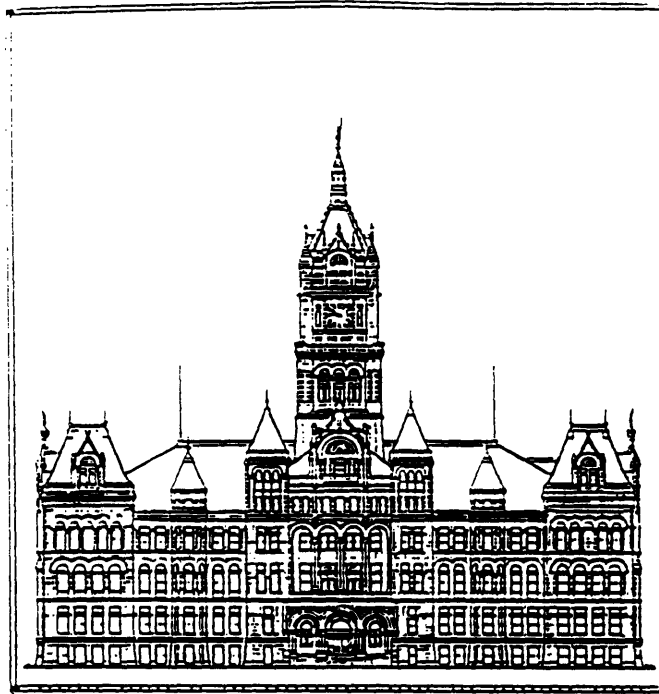
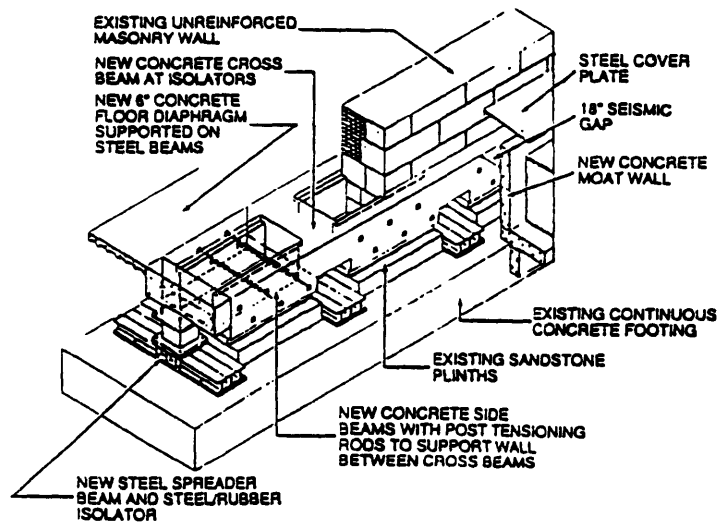


Figure B-12: Foothill Communities Law and Justice Center (Buckle,1990)

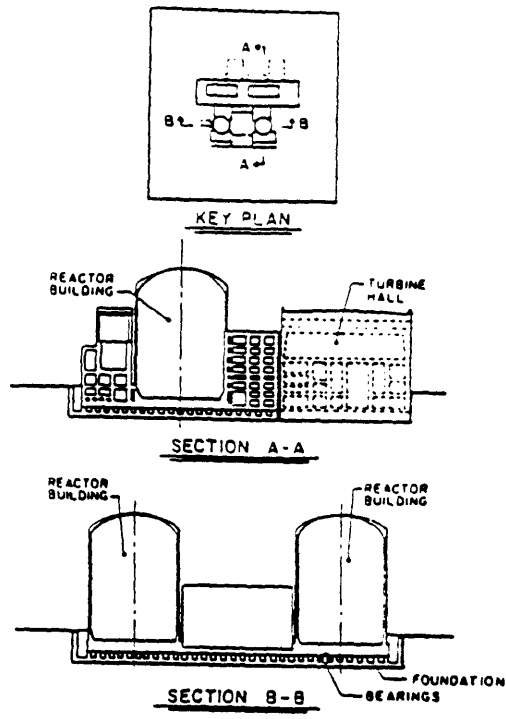


(a) East Elevation

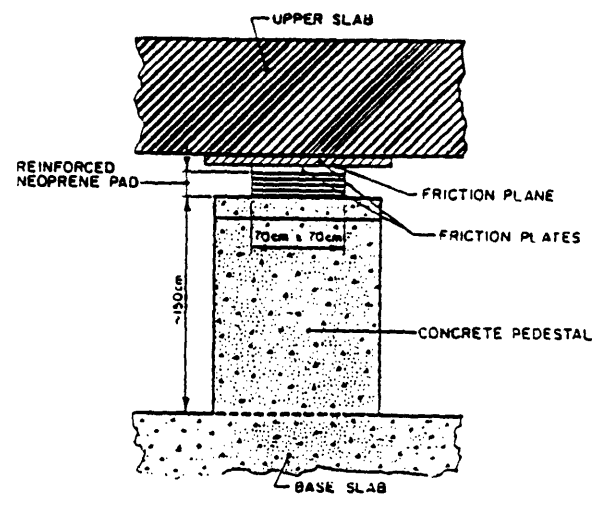


(b) Isolator installation under the exterior walls

Figure B-13: Salt Lake City and County Building (Buckle,1990)

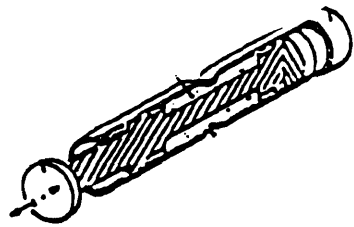


(a) Sectional views



(b) Detail of elastomeric bearing and friction plates

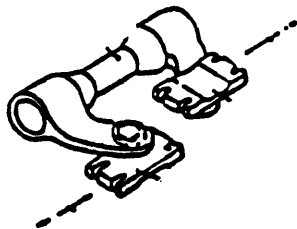
Figure B-14: Isolation scheme for nuclear power plants(Electricite De France)



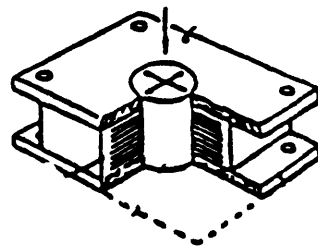
**Lead Extrusion Device**



**Flexural Beam Device**



**Flexural Beam Device**



**Lead-Rubber Device**

Figure B-15: Various mechanical energy dissipators developed in New Zealand

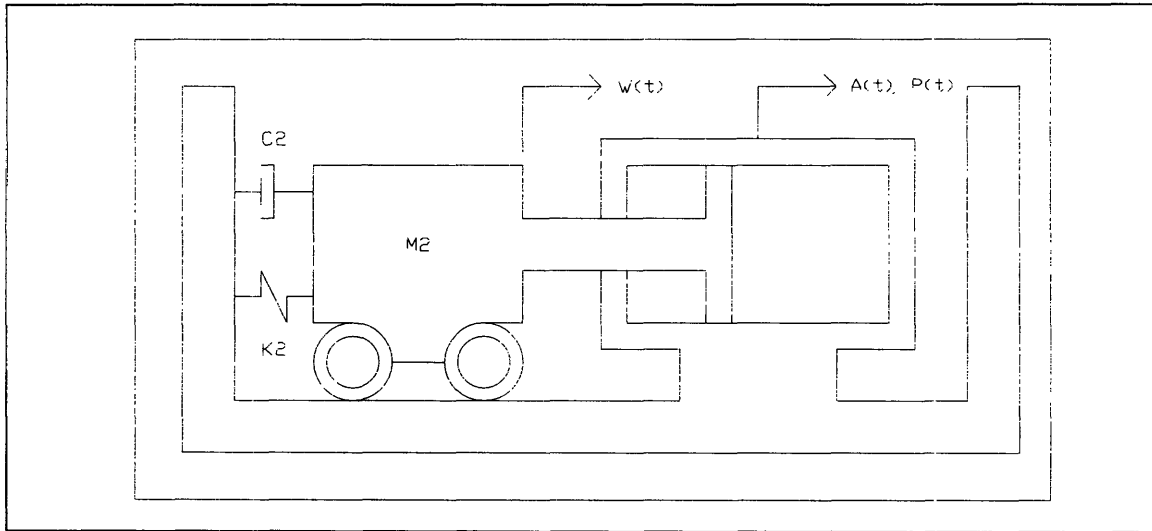


Figure B-16: Active Tuned Mass Damper Mechanism

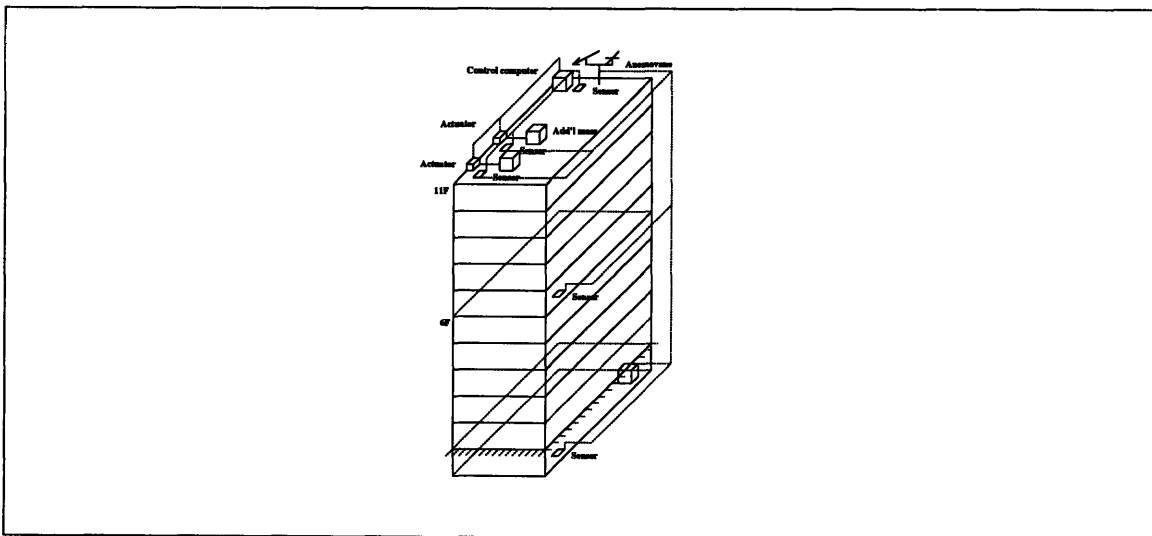


Figure B-17: AMD Equipped Kyobashi Seiwa Building (Soong, 1990)



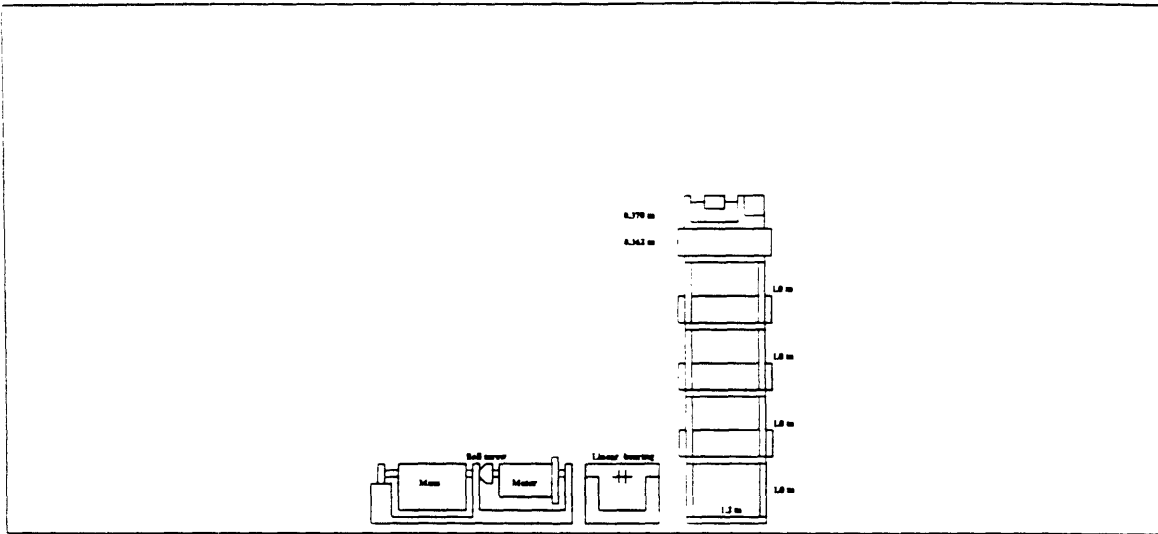


Figure B-18: Active Dynamic Damper System (Inove, 1993)

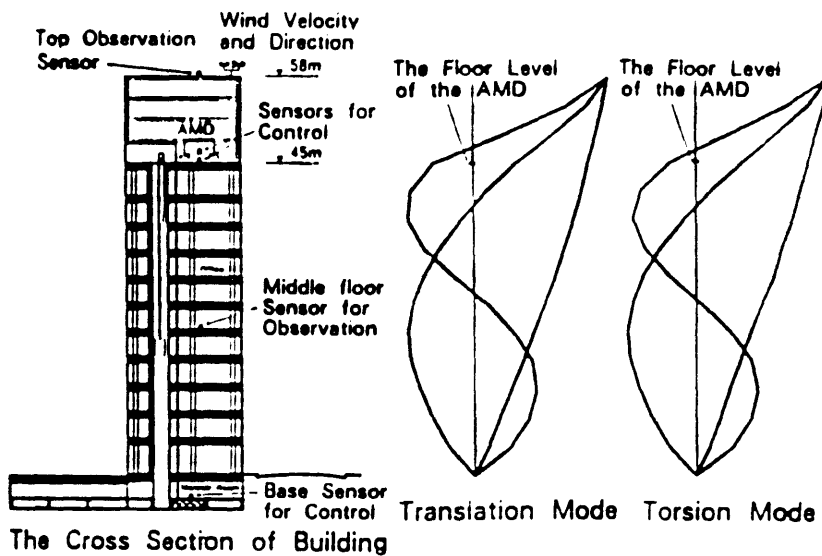


Figure B-19: Section and Mode Shapes: Sendagaya Intes (Higashino, 1993)

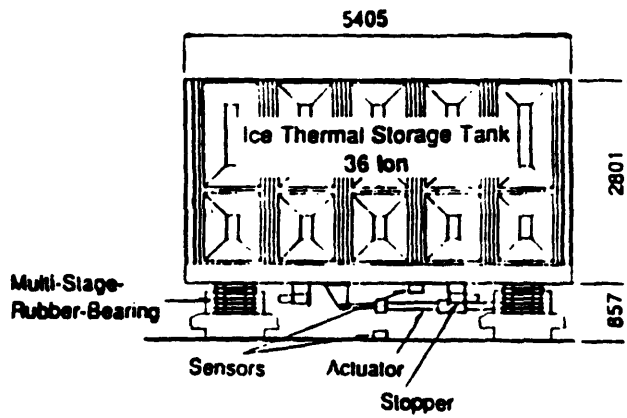


Figure B-20: AMD Elevation: Sendagaya Intes (Higashino, 1993)

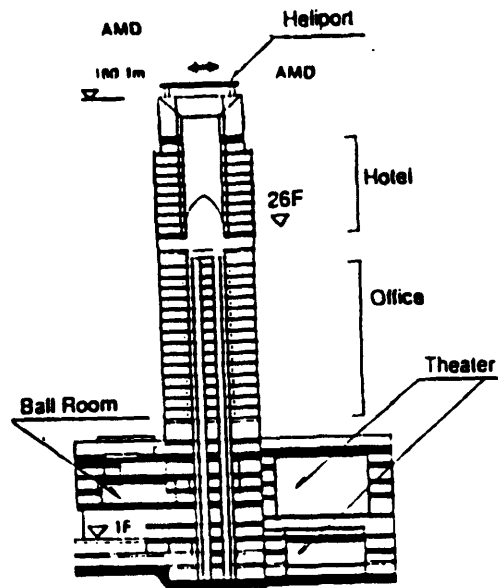


Figure B-21: Cross Section: Hankyu Chayamachi Building (Higashino, 1993)

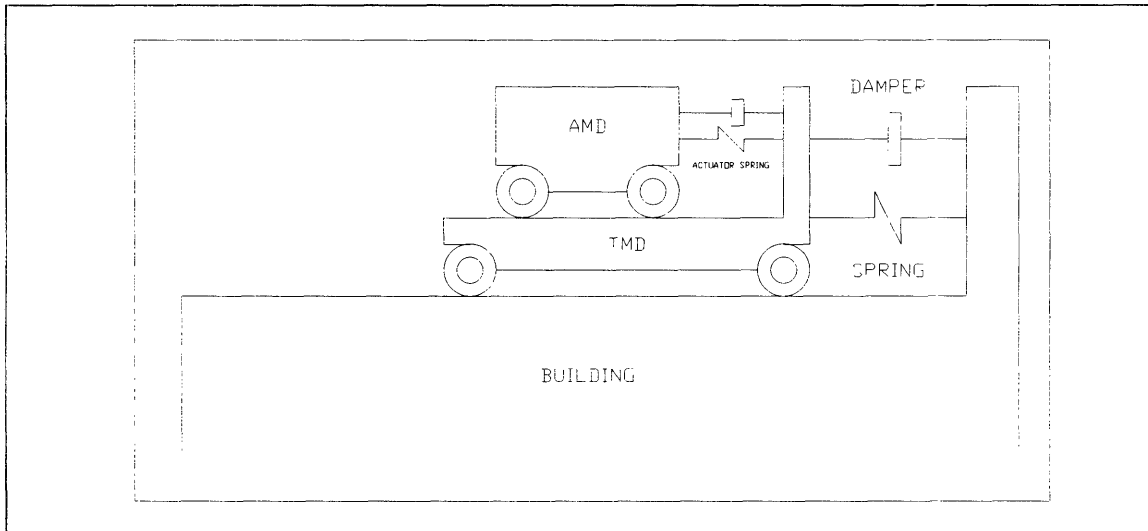


Figure B-22: Duox System Concept (Sakamoto,1993)

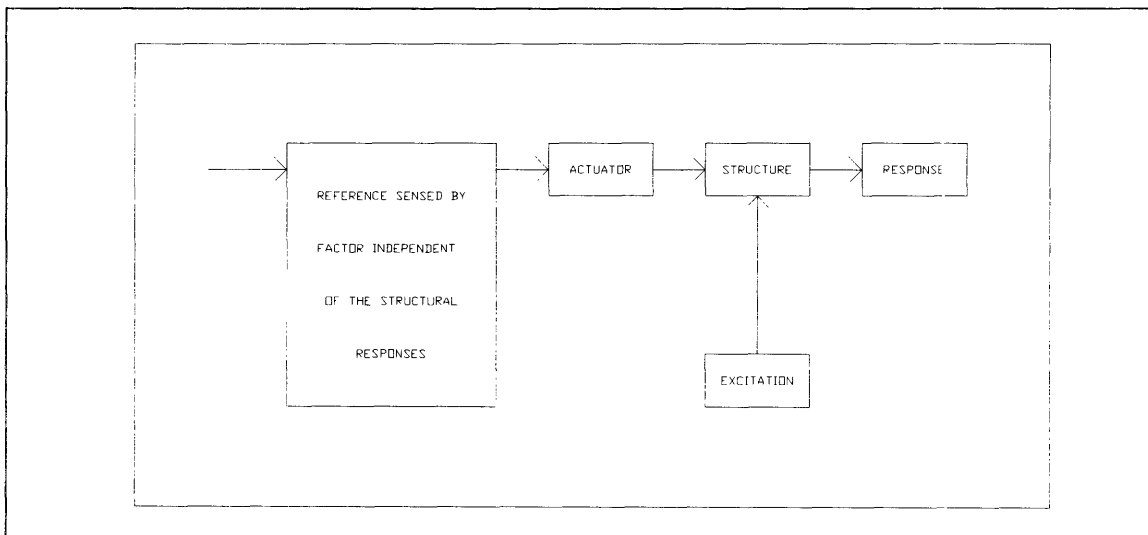


Figure B-23: Open Loop Control System Flow Chart

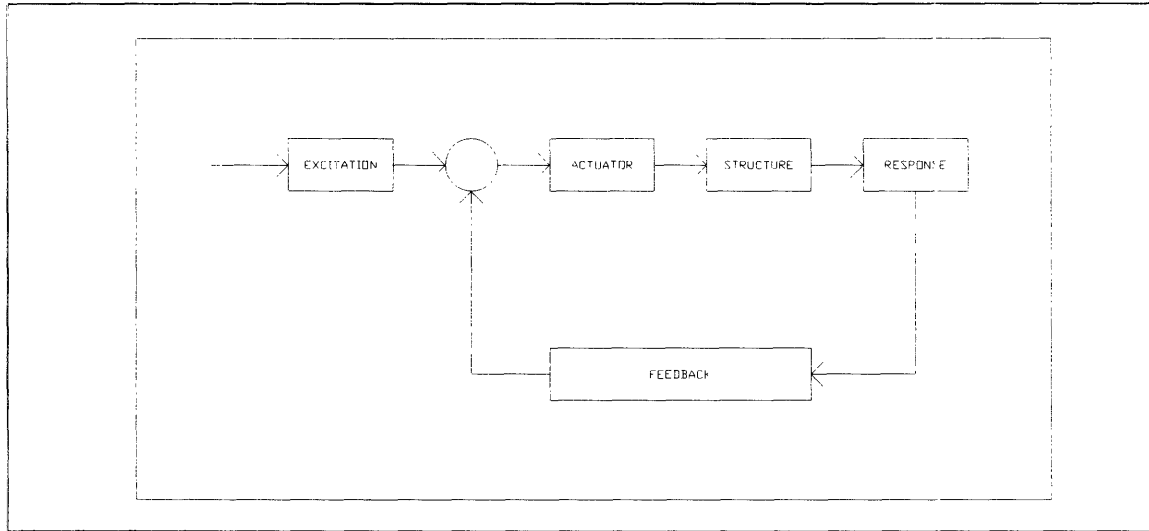


Figure B-24: Close Loop Control System Flow Chart

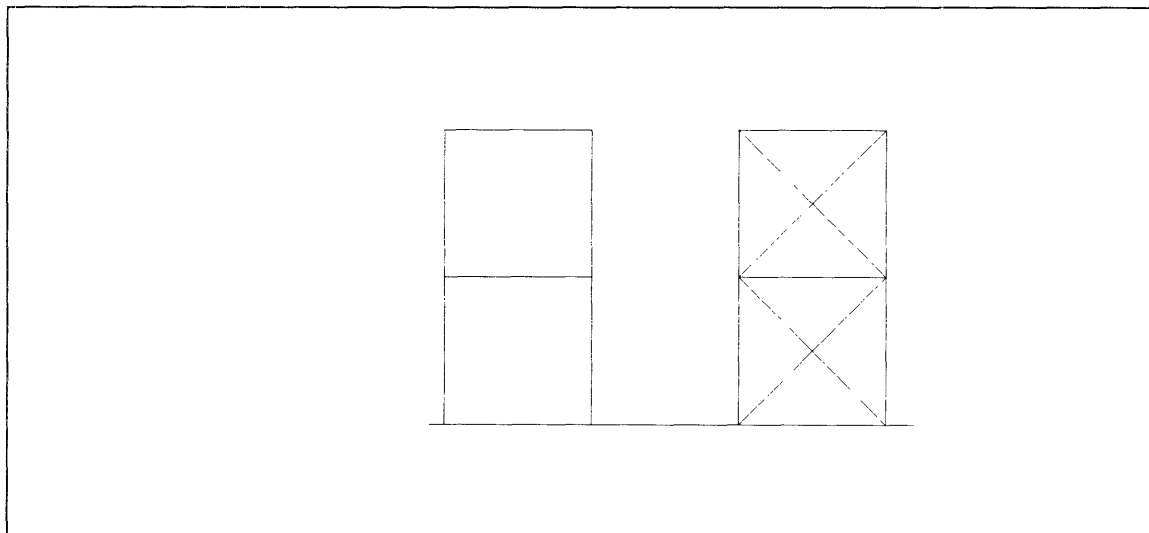


Figure B-25: Model frame

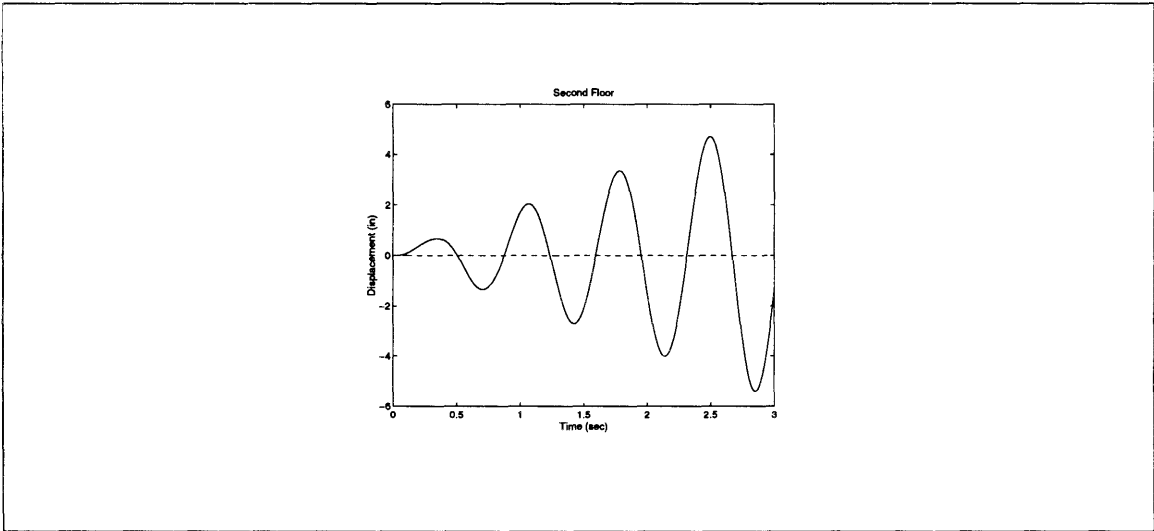


Figure B-26: Displacements

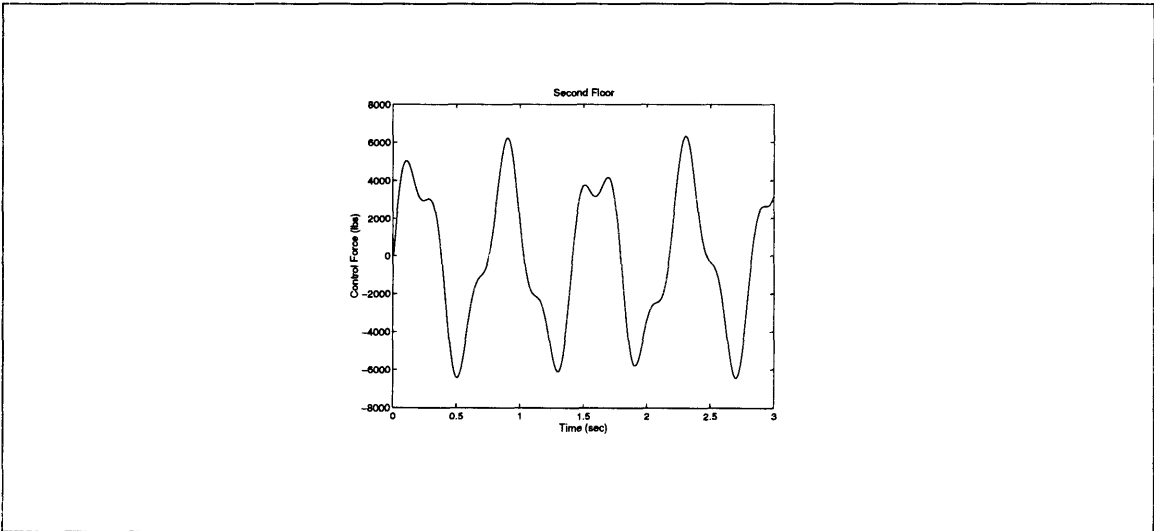


Figure B-27: Control Force

# Bibliography

- [1] M. Abdel-Rohman. The feasibility of active control of tall buildings. In *Structural Control: Proceedings of the Second International Symposium on Structural Control*, July 15 - 18, 1985 Symposium, University of Waterloo, Ontario, Canada, September 1985. Martin Mijhoff Publishers, Netherlands.
- [2] Ian D. Aiken, Douglas K. Nims, S. Whittaker, and James M. Kelley. Testing of passive energy dissipation systems. *Earthquake Spectra, Passive Energy Dissipation: Journal of the Earthquake Engineering Research Institute*. 9(3), 1993.
- [3] James C. Anderson. A slip surface isolation system for multi-story buildings. *Earthquake Spectra, Seismic Isolation (From Idea to Reality): Journal of the Earthquake Engineering Research Institute*, 6(2), May 1990.
- [4] David D. Bergman and Robert D. Wanson. Visco-elastic mechanical damping devices tested at real earthquake displacements. *Earthquake Spectra, Passive Energy Dissipation: Journal of the Earthquake Engineering Research Institute*, 9(3), 1993.
- [5] Ian G. Buckle. Seismic isolation: World application and performance - a world view. *Earthquake Spectra, Seismic Isolation (From Idea to Reality): Journal of the Earthquake Engineering Research Institute*, 6(2), May 1990.
- [6] K. C. Chang, T. T. Soong, M. L. Lai, and E. T. Nielsen. Viscoelastic dampers as energy dissipation devices for seismic applications. *Earthquake Spectra, Passive Energy Dissipation: Journal of the Earthquake Engineering Research Institute*, 9(3), 1993.

- [7] A. H. Chowdhury and M. D. Iwuchukwu. The past and future of seismic effectiveness of tuned mass dampers. In *Structural Control: Proceedings of the Second International Symposium on Structural Control*, July 15 - 18, 1985 Symposium, University of Waterloo, Ontario, Canada, September 1985. Martin Mijhoff Publishers, Netherlands.
- [8] T. Fujita. Hybrid mass dampers with convertible active and passive modes for vibration control of tall buildings. In *Structural Control: Proceedings of the International Workshop on Structural Control*, August 5 - 7, 1993 Symposium, Honolulu, Hawaii, August 1993.
- [9] M. Higasino and S. Aizawa. The application of active mass damper systems in actual buildings. In *Structural Control: Proceedings of the International Workshop on Structural Control*, August 5 - 7, 1993 Symposium, Honolulu, Hawaii, August 1993.
- [10] Y. Inove, E. Tachibana, and Y. Mukai. Recent developments in active structural control of buildings in japan. In *Structural Control: Proceedings of the International Workshop on Structural Control*, August 5 - 7, 1993 Symposium, Honolulu, Hawaii, August 1993.
- [11] James M. Kelley. Base isolation: Linear theory and design. *Earthquake Spectra, Seismic Isolation (From Idea to Reality): Journal of the Earthquake Engineering Research Institute*, 6(2), May 1990.
- [12] T. Kobori. Technology development and forecast of dynamical intelligent buildings (dib). In *Intelligent Structures: Proceedings of the International Workshop on Intelligent Structures*, July 23 - 26, 1990 Symposium, Taipei, Taiwan, July 1990. Elsevier Applied Science, London and New York.
- [13] Robert J. Kontz. Earthquake hazard mitigation: The need for human resources development and research. *Earthquake Spectra, Seismic Isolation (From Idea to Reality): Journal of the Earthquake Engineering Research Institute*, 6(2), May 1990.

- [14] Ronald L. Mayes, Lindsay R. Jones, and Ian G. Buckle. Impediments to the implementation of seismic isolation. *Earthquake Spectra, Seismic Isolation (From Idea to Reality): Journal of the Earthquake Engineering Research Institute*, 6(2), May 1990.
- [15] Ronald L. Mayes, Lindsay R. Jones, and Trevor E. Kelley. The economics of seismic isolation in buildings. *Earthquake Spectra, Seismic Isolation (From Idea to Reality): Journal of the Earthquake Engineering Research Institute*, 6(2), May 1990.
- [16] G. R. McKay, W. E. Chapman, and D. K. Kirkcaldie. Seismic isolation: New zealand applications. *Earthquake Spectra, Seismic Isolation (From Idea to Reality): Journal of the Earthquake Engineering Research Institute*, 6(2), May 1990.
- [17] E. Nielsen. Visco-elastic dampers for wind and seismic applications. In *Structural Control: Proceedings of the International Workshop on Structural Control*, August 5 - 7, 1993 Symposium, Honolulu, Hawaii, August 1993.
- [18] Robert A. Olson and W. Henry Lambright. Base isolation: What we need to know to diffuse this technology. *Earthquake Spectra, Seismic Isolation (From Idea to Reality): Journal of the Earthquake Engineering Research Institute*, 6(2), May 1990.
- [19] Avtar Pall, Serge Vezina, Pierre Proulx, and Rashmi Pall. Friction dampers for seismic control of the canadian space agency headquarters. *Earthquake Spectra, Passive Energy Dissipation: Journal of the Earthquake Engineering Research Institute*, 9(3), 1993.
- [20] M. Sakamoto and T. Kobori. Practical applications of active and hybrid response control systems. In *Structural Control: Proceedings of the International Workshop on Structural Control*, August 5 - 7, 1993 Symposium, Honolulu, Hawaii, August 1993.



- [21] Roger E. Scholl. Fundamental design issues for supplement damping applications. *Earthquake Spectra, Passive Energy Dissipation: Journal of the Earthquake Engineering Research Institute*, 9(3), 1993.
- [22] Ronald L. Sharpe. Independent engineer peer review for seismic isolation projects. *Earthquake Spectra, Seismic Isolation (From Idea to Reality): Journal of the Earthquake Engineering Research Institute*, 6(2), May 1990.
- [23] T. T. Soong. *Active Structural Control: Theory and Practice*. Longman Scientific and Technical. John Wiley and Son, Incorporated, New York, NY, 1990.
- [24] K. Tagawa. Several topics in active control research and implementation against strong earthquakes in japan. In *Structural Control: Proceedings of the International Workshop on Structural Control*, August 5 - 7, 1993 Symposium, Honolulu, Hawaii, August 1993.
- [25] T. Takenada, H. Okada, Y. Yasui, and A. Tamura. Mitigating seismic disasters and providing a vibration free environment. In *Structural Control: Proceedings of the International Workshop on Structural Control*, August 5 - 7, 1993 Symposium, Honolulu, Hawaii, August 1993.
- [26] M. Tzumi, T. Teigimoto, H. Kitamura, and Y. Shirasawa. Buildings with response control systems in japan. In *Structural Control: Proceedings of the International Workshop on Structural Control*, August 5 - 7, 1993 Symposium, Honolulu, Hawaii, August 1993.
- [27] R. Villaverde. Are vibration control techniques a competitive alternative for the seismic design of structures? In *Proceedings of the Mexican Society of Seismic Engineering, A. C.*, 1990.
- [28] Robert D. Wanson. Supplemental damping for improved seismic performance. *Earthquake Spectra, Passive Energy Dissipation: Journal of the Earthquake Engineering Research Institute*, 9(3), 1993.

- [29] J. Wirai, W. Abira, and E. Tsuji. Study on tuned active dampers for the control tower of kasai international airport. In *Structural Control: Proceedings of the International Workshop on Structural Control*, August 5 - 7, 1993 Symposium, Honolulu, Hawaii, August 1993.
- [30] T. S. Wu and Seidensticker R. W. Passive earthquake resistance through base isolation. In *Intelligent Structures: Proceedings of the International Workshop on Intelligent Structures*, July 23 - 26, 1990 Symposium, Taipei, Taiwan, July 1990. Elsevier Applied Science, London and New York.
- [31] W. Yang, D. Liaw, D. Wsu, and H. Fu. A simple model for optimal control of high rise buildings. In *Intelligent Structures: Proceedings of the International Workshop on Intelligent Structures*, July 23 - 26, 1990 Symposium, Taipei, Taiwan, July 1990. Elsevier Applied Science, London and New York.