Chapter 1

Introduction

1.1 Background to this Research

I got my BEng degree in 1989 in Civil Engineering at the Durango Institute of Technology (Durango, Mexico). Through the three and a half years that my career lasted, I became interested in the analysis and design of building structures. As a matter of fact, my BEng thesis deals with the plastic analysis and design of steel industrial buildings.

With the aim of learning more about analysis and structural design, from 1991 to 1992 I studied all the subjects of the MEng with a major in Structural Engineering at the Autonomous University of Chihuahua (Chihuahua, Mexico). During that period I became involved with the structural dynamics and the numerical methods used to solve the equations of motion of SDOF and MDOF systems. By that time (1991) I started to work as a part time lecturer at the Chihuahua Institute of Technology (Chihuahua, Mexico) teaching *Solid Mechanics* and *Strength of Materials*, and from 1993 to 1995 I also worked as a structural designer in a company devoted to the design and erection of steel building structures.

However, the experience I gained as a structural designer was not enough to satisfy my curiosity about the appropriate modelling of structures subjected to dynamic loads different than those induced by wind. For this reason by the beginning of 1997 I applied for two fellowships: one offered by the National Council of Science and Technology (*CONACYT*) of Mexico and other one offered by the Spanish Agency of International Cooperation (*AECI*). Such grants are oriented to graduate students willing to get a Master or a PhD degree. Fortunately, I earned both grants.

By the middle of 1997 I contacted Prof. Lluís Pujades, Coordinator of the Doctorate Program in Earthquake Engineering and Structural Dynamics at the Technical University of Catalonia. He accepted me as a new PhD student so I decided to come to Barcelona and to enroll myself in this doctorate program. From October 1997 to September 1998 I completed the subjects (credits) required to get the academic authorization to start my PhD Thesis.

Then I had the opportunity to talk with Prof. Francesc López Almansa who kindly agreed to become my Thesis Director and since then, I've been working on this thesis along with him and other researchers.

By the middle of 2002 Prof. López Almansa and I applied to participate in a European project and to get financial support to carry out laboratory tests in Bristol, UK as a part of my research. The project was approved, so we earned this grant and during September 2002 and from January 2003 through March 2003 I worked along with Prof. Colin Taylor from the University of Bristol. I participated in the design of the scale models, their testing on a shaking-table and the final processing of the obtained results.

With the experience gained and the results obtained through five years and a half, I wrote this thesis, which is intended to be a small contribution to the current knowledge of the dynamic behavior of building structures equipped with friction energy dissipation devices subjected to seismic loads and other inputs.

1.2 Overview of Structural Control

1.2.1 Introduction

When designing the majority of buildings and other civil engineering structures, the main actions to consider are those due to gravitational effects. These loads are always present and therefore they must be resisted throughout the entire life of the building. The magnitude of such loads can be quickly determined based on the self-weight and the occupancy requirements. Neglecting the variation through time of these loads, a static idealization is considered for the design of the structures. This idealization greatly simplifies the structural design, and, as a matter of fact, allowed our ancestors to design and to build amazing constructions before the developing of rational scientific principles.

On the other hand, when dealing with lateral actions, there is a natural trend to manage these forces with the same methods used for gravitational loads. For example, wind gusts and earthquakes are often idealized as 'equivalent' static loads of certain magnitude that must be resisted by the structure. This approach has given the bases for a number of design codes since the beginning of the 20^{th} century, and the results have been quite satisfactory so far in many cases [1, 2]. However, considering the dynamic characteristics of the horizontal loads, important improvements can be made. In fact, as a result of this dynamic point of view, many innovative approaches for structural protection have been proposed. A widely considered strategy consists of incorporating external elements to the structure to mitigate (i.e., *to control*) its dynamic response. The branch of Structural Engineering that deals with such concepts is called 'Structural Control' [3, 4, 5].

In Fig. 1.1 the protective structural systems studied by the structural control are classified. The three major groups shown in this figure (passive, active and semi-active and hybrid

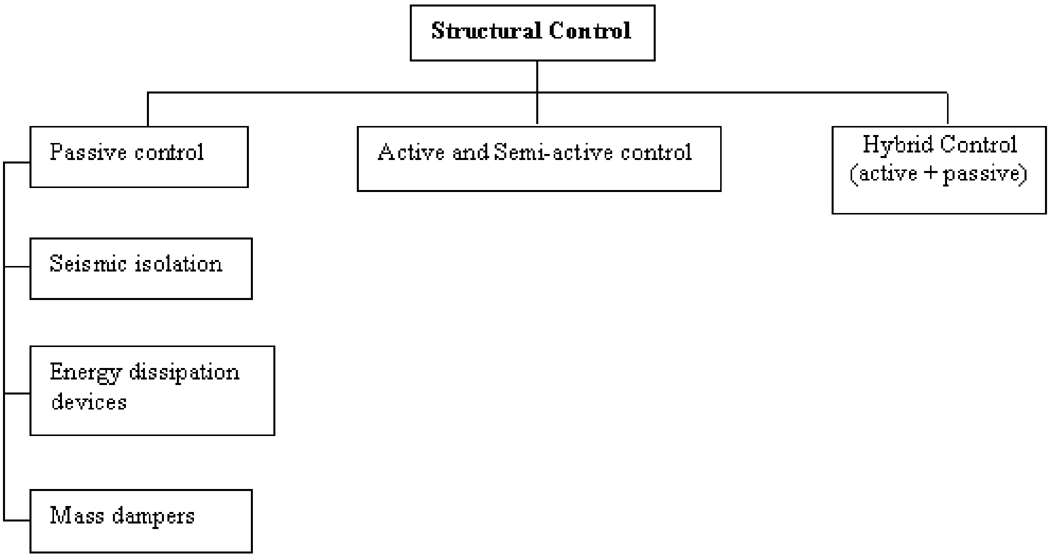


Figure 1.1 Structural Control systems

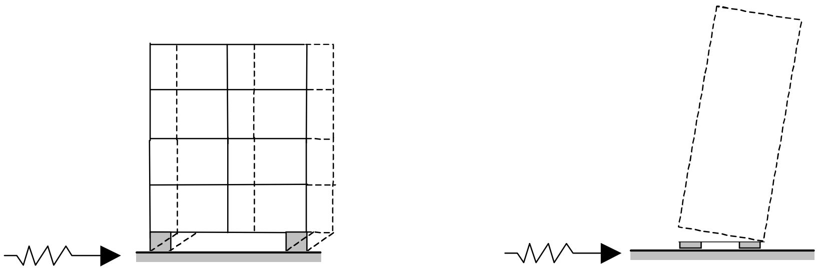
control) are discussed next.

1.2.2 Passive control

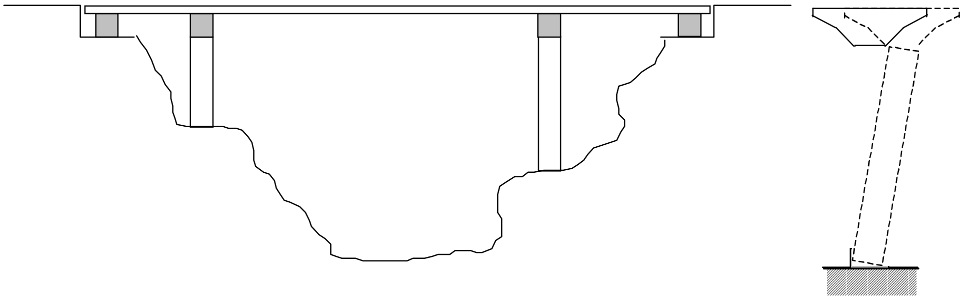
This approach consists of incorporating 'passive' (i.e., nor powered neither 'smart') devices to the structure, whose motion is to be controlled, to modify its dynamic parameters (basically, damping and stiffness) in order to reduce its response when facing the expected inputs. This group can be broadly divided into three subgroups: *seismic isolation, energy dissipation* and *mass dampers.*

1.2.2.1 Seismic isolation

The seismic isolation, mainly considered for buildings and bridges, consists in setting a device which is flexible in the horizontal direction and very stiff in the vertical direction. As indicated in Fig. 1.2, an isolation system is generally located between the foundation and the main structure in the case of buildings (see Figs. 1.2a and b), and between the piles and the slab in the case of bridges (see Figs. 1.2c and d). Mostly, isolators are used to increase the horizontal flexibility (Figs. 1.2a and c) or less frequently, to increase the rocking stability (Figs. 1.2b and d). In the case of buildings, since the isolators are significantly more flexible in the horizontal direction than the superstructure, they add a new mode of vibration to the



(a) Horizontal flexibility in buildings (b) Rocking stability in buildings



(c) Horizontal flexibility in bridges (d) Rocking stability in bridges

Figure 1.2 Types of seismic isolation

main structure, causing the lengthening of its fundamental period and keeping this period apart from the main period contents of the input. This new mode does not involve significant interstory drifts (Fig. 1.2a) and its participation factor of is very high. The upper modes are similar to those of the non-isolated structure, however the period of the first ones is shortened.

The main objective of the seismic isolation is to 'release' the structures from the influence of ground accelerations using foundations that are flexible in the horizontal direction. The isolation system absorbs partially some the input energy before this energy can be transmitted to the structure. The net effect is a reduction of the energy dissipation demand of the structural system, resulting in an increase of its performance. A simple scheme that classifies the superstructure (main structure), isolation system (isolators), substructure (foundation) and soil is shown in Fig. 1.3.

Fig. 1.4 shows some types of isolators used currently in structural engineering [6]. Fig. 1.4a shows an elastomeric bearing, which represents a common mean of introducing flexibility into an isolated structure. It consists of thin layers of natural rubber which are vulcanized and bonded to steel plates. Fig. 1.4b shows a lead rubber bearing (LRB), which is constructed of low damping natural rubber with a pre-formed central hole. A lead core is press-fitted in

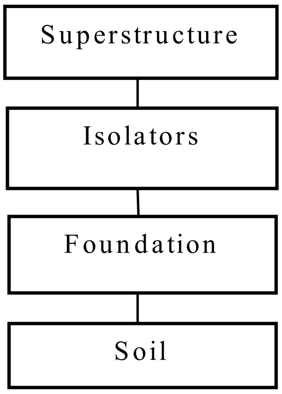


Figure 1.3 Basic components of a stucture with an isolation system

that hole. Under horizontal motions, the lead core deforms in almost pure shear, yields at low level of stress and produces hysteretic behavior which is usually stable over a number of cycles.

Sliding bearings represent another means of providing the base elements of an isolation system. One or the most used isolators of this type is the friction pendulum system (FPS) bearing (Fig. 1.4c). This consists of an articulated slider on a spherical surface which is covered with a polished stainless steel overlay. The slider is faced with bearing material, typically a self-lubricated high bearing capacity composite. The restoring force is generated by the rising of the structure along the spherical surface, while energy is dissipated by friction.

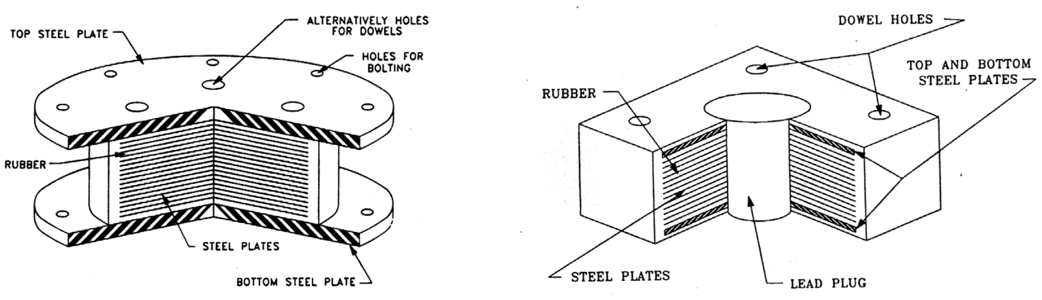
Seismic isolation is also effective when other type of vibrations are transmitted trough the ground (e.g., traffic), but it is not useful against vibrations induced by the wind, conversely isolators should possess the minimum initial stiffness required to avoid yielding under wind loads.

A number of isolators have been used in buildings and bridges all over the world [7, 8, 9].

1.2.2.2 Energy dissipation devices

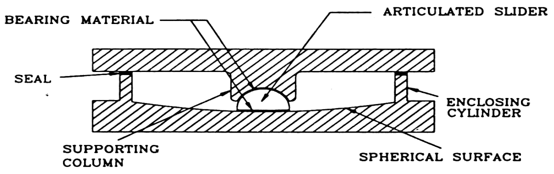
These elements consist of relatively small devices installed in buildings to dissipate energy. They are generally located between the main structure and the bracing system. Fig. 1.5 shows a building structure composed of two independent substructures: the 'main frame' and the 'lateral-load resistant system' (or bracing + dissipators assembly). The lateral-load resistant system denotes the braces plus certain devices acting as dampers [10]. The main function of these energy dissipation devices is to absorb or to deviate part of the input energy, therefore, this action reduces the energy dissipation demand of the main structure and minimizes the structural damage.

There are basically three types of energy dissipators: *metallic dampers, friction dampers* and *visco* or *visco-elastic dampers.* Fig. 1.6 shows three typical devices belonging to each of



(a) Elastomeric bearing

(b) Lead-rubber bearing



(c) Friction pendulum system (FPS) bearing

Figure 1.4 Different types of isolators [6]

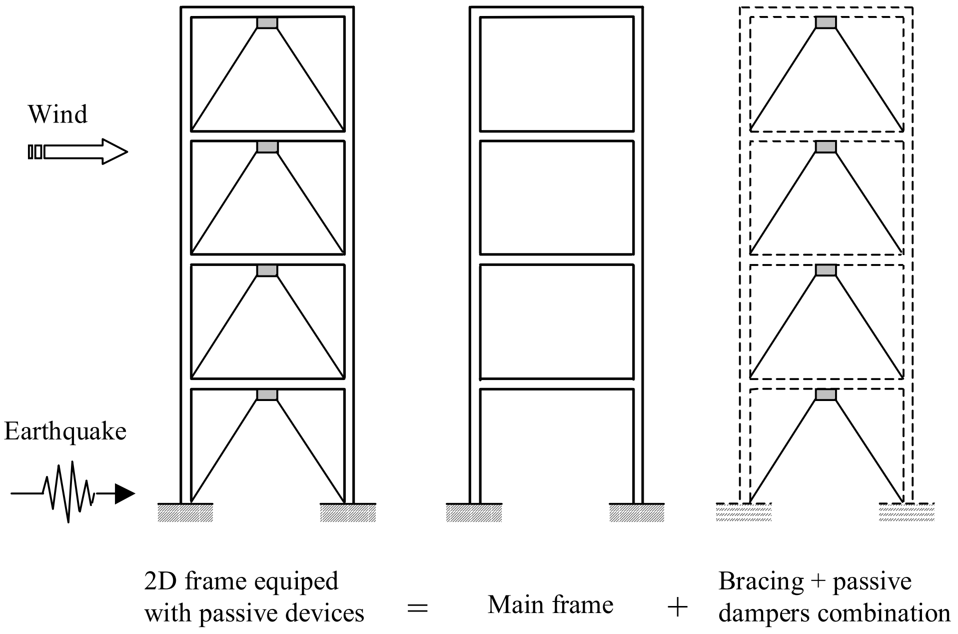


Figure 1.5 Building equipped with energy dissipation devices

these categories [11]. They are discussed next.

Metallic dampers. These devices are based on the ability of mild steel or other metals to sustain many cycles of stable hysteretic yielding behavior to dissipate the input energy. A wide variety of different types of devices that utilize flexural, shear, or longitudinal deformation modes into the plastic range have been developed. For instance, the so-called 'added damping and stiffness' (ADAS) device (see Fig. 1.6a), consists of multiple X-steel plates of the shape shown in Fig. 1.6a, installed as illustrated in the same figure. Shaking table tests of a 3-story model were carried out by Whittaker [12] and demonstrated that the ADAS elements improved the behavior of the moment-resisting frame to which they were installed by (a) increasing its stiffness, (b) increasing its strength and (c) increasing its ability to dissipate energy (added damping).

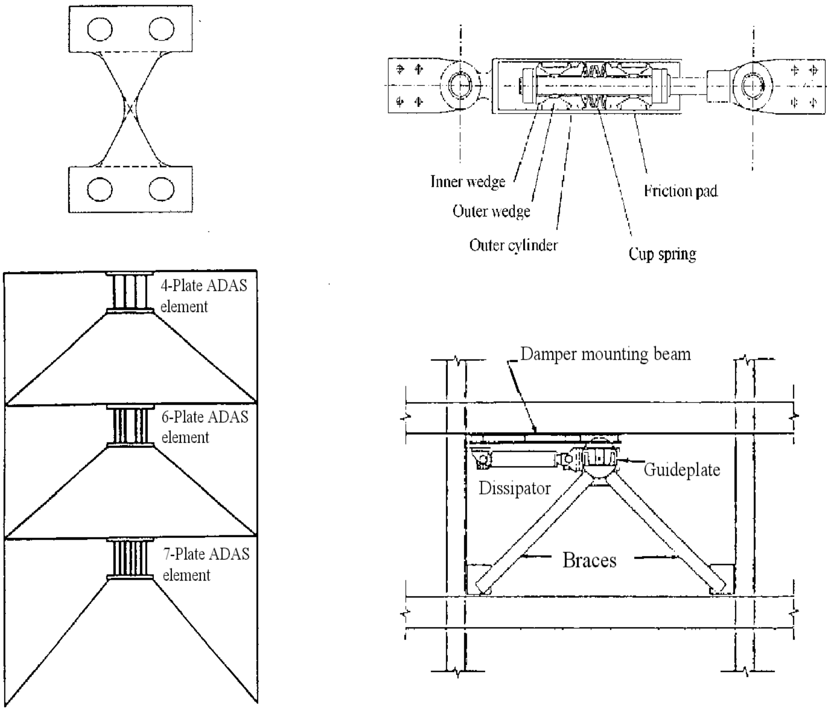
Friction dissipators. These devices use frictional forces to dissipate energy. As a representative example, Fig. 1.6b shows a Sumitomo friction damper [13]. It has copper alloy friction pads impregnated with graphite that slide along the inner surface of a cylindrical steel casing. The normal force on the contact surface is developed by a series of wedges which act under the compression of Belleville washer springs [14]. The purpose of the graphite is to lubricate the contact surfaces and to ensure a stable coefficient of friction and a silent operation.

Viscous and viscoelastic dampers. These dampers are basically made of viscous fluids, copolymers or glassy substances which dissipate energy when subjected to shear deformation. A typical viscoelastic damper is shown in Fig. 1.6c which consists of a viscoelastic layer bonded to steel plates [15]. When mounted in a structure, shear deformation and hence energy dissipation takes place when the structural vibration induces relative motion between the outer steel flanges and the center plate.

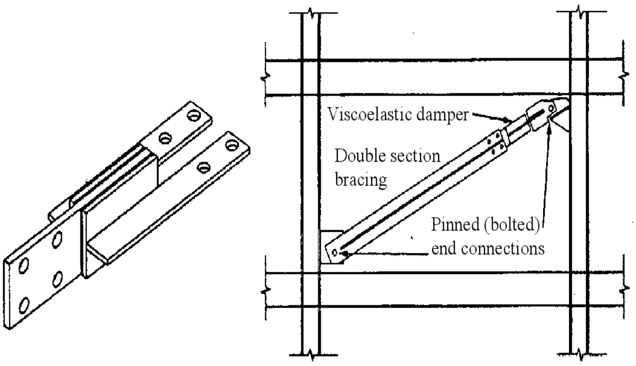
A certain number or energy dissipation devices have been installed in structures all over the world [16, 17].

1.2.2.3 Mass dampers

They consist of massive elements connected elastically to the main structure. Such connection must allow the relative motion between the mass damper and the structure so the big inertia forces involved partially cancel the external forces on the structure. To do this, the natural period of the added mass must be close to the fundamental period of the structure. This is the principle of the *tuned mass dampers* (TMD). These elements have been mostly proposed to reduce horizontal vibrations of tall and/or slender constructions (skyscrapers, TV towers, chimneys, etc.). Mass dampers are usually more effective when installed on the top of the construction to control the first mode, as shown in Fig. 1.7. For the case of multi-story buildings or other tall structures, however, more than one TMD could be installed on different levels to control several modes of vibration. Fig. 1.8 shows some types of mass



(a) ADAS element and installation detail (b) Sumitomo friction damper and installation detail



(c) Viscoelastic damper and installation detail

Figure 1.6 Energy dissipators used in structural engineering [11]

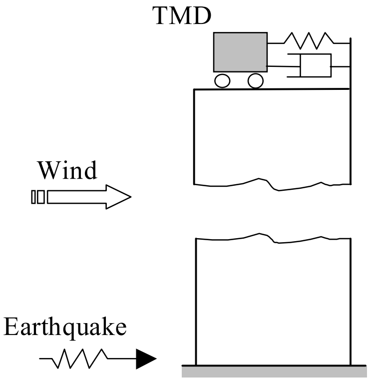
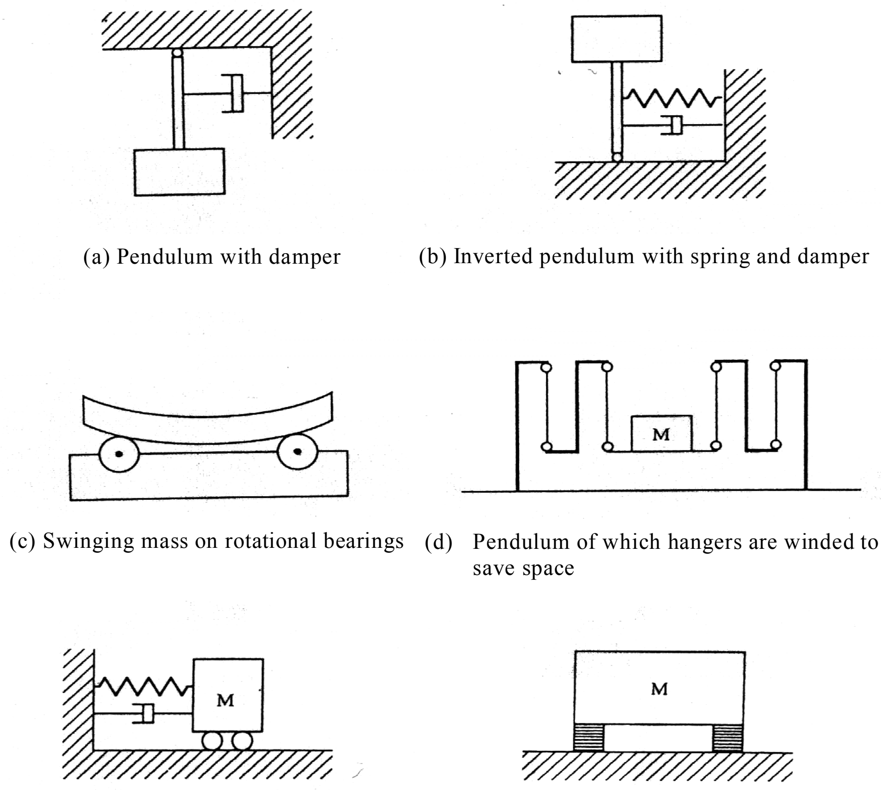


Figure 1.7 Tuned mass damper (TMD) located on the top of a building



(a) Pendulum with damper

(b) Inverted pendulum with spring and damper

(c) Swinging mass on rotational bearings

(d) Pendulum of which hangers are winded to save space

(e) Sliding mass with spring and damper

(f) Mass on rubber bearing

Figure 1.8 Different types of mass dampers [18]

Desirable features	**Isolation system**	**Energy dissipators**	**Mass dampers**
Low initial cost		■	
Effective to resist wind forces		■	■
Reliability	■	■	
Long durability	■	■	■
Low cost of maintenance		■	
Low cost of replacement		■	
Effective against severe earthquakes	■	■	
Effective when used with flexible structures or soils		■	■

Table 1.1 Comparison between the passive control systems

dampers that can be used for structural purposes [18].

There are currently a number of mass dampers installed in structures worldwide [19].

Table 1.1 summarizes the principal features of the passive control devices.

1.2.3 Active and semi-active systems

There are some important differences between the passive control and the active control: (1) instead of inert devices (isolators, dissipators or mass dampers) the active systems consist of mechanisms (actuators) highly powered by energy sources (while passive devices are 'dead' elements), therefore these devices are able to push the structure to counteract the input forces, (2) sensors are installed to know the status of the structure in real time and (3) this information is processed by a controller (typically a computer) which gives the precise orders to the actuators so they act properly on the structure to minimize its response.

The basic scheme of the active structural control is shown in Fig. 1.9 [20], while in Fig. 1.10 the elements of an active control loop are schematically shown [21]. An analogy of the elements of Fig. 1.10 with the human body is illustrated in Fig. 1.11.

Fig. 1.12 shows an active mass damper. It is basically the TMD depicted in Fig. 1.7. In this case, however, the functioning of the whole system is automatic (feedback control) since an actuator was added to govern the horizontal relative motion between the mass and the main structure. Another example of active control is shown in Fig. 1.13 [21].

Figure 1.14 shows a diagram of a tendon controller [21] which belongs to the mock-up depicted in Fig. 1.13. It is composed by four cables and one hydraulic actuator. The cables are braced to the upper floor by one of their ends while the other ends are attached to a horizontal rigid frame through four pulleys. The cables are connected to the piston rod of an hydraulic actuator whose motion is commanded by a servovalve proportionally to the difference between the analog signal from the D/A converter and the actual displacement of

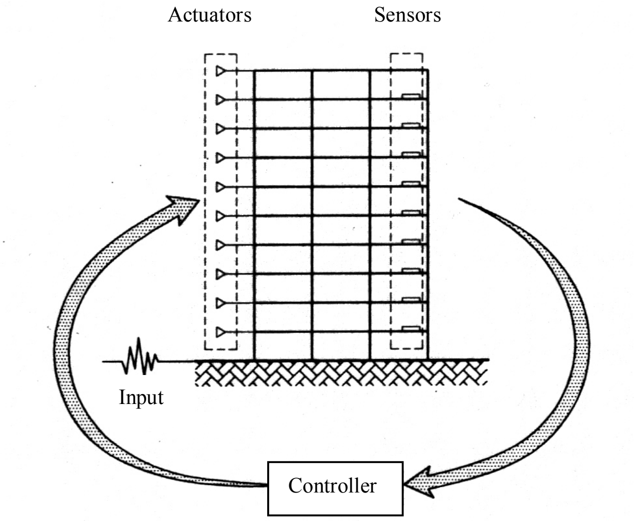


Figure 1.9 Active structural control scheme [20]

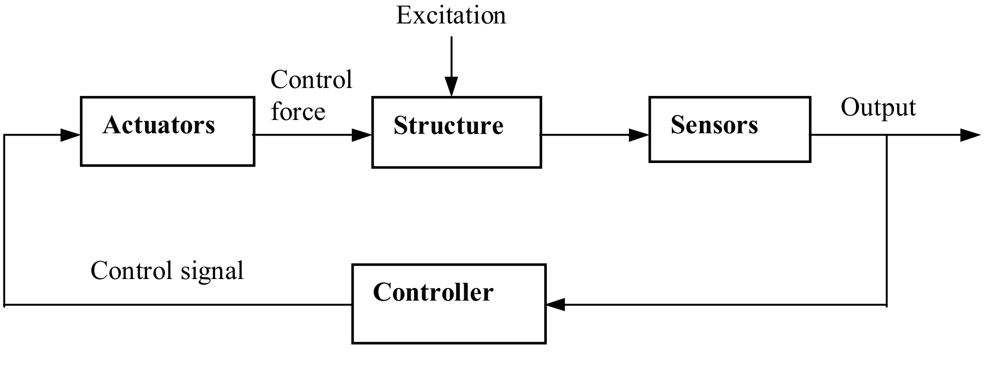


Figure 1.10 Basic elements on an active control loop [21]

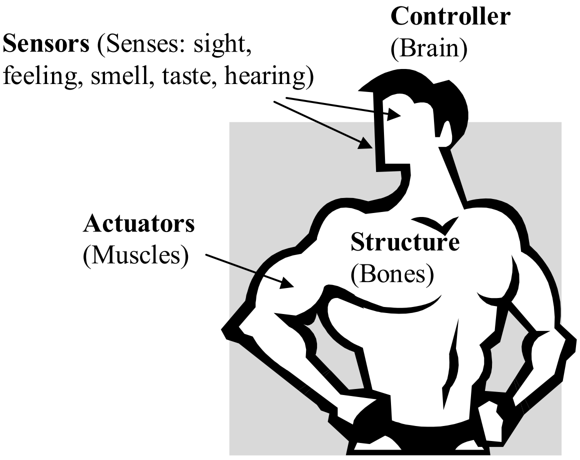


Figure 1.11 Analogy of an active control system with a human body (model: Servio)

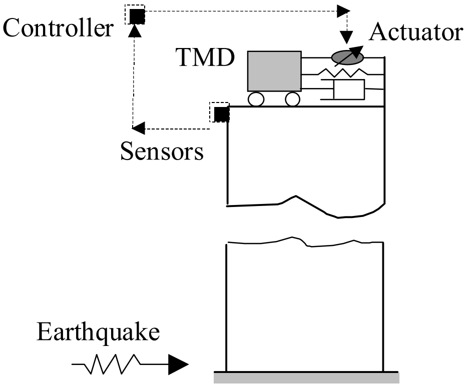


Figure 1.12 Active (or semi-active) control example (active mass damper)

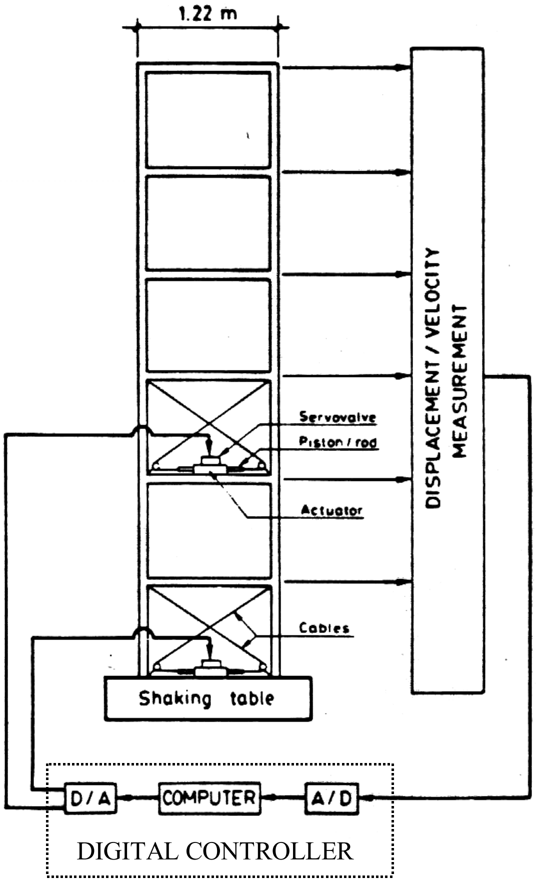


Figure 1.13 Experimental control loop [21]

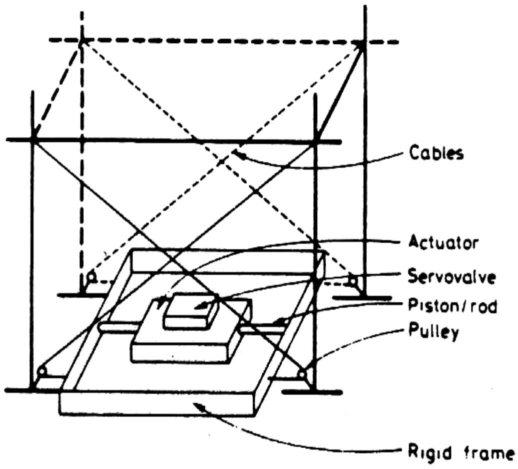


Figure 1.14 Active tendon controller [21]

the piston/rod. In this way the tensions of the cables are actively modified, which results in horizontal control forces on the structure.

On the other hand, the semi-active systems behave as the active ones, but the basic difference between them is that semi-active devices get only a small portion of energy, so they lack of the capacity to push the structure, rather they are only capable of stopping its motion (in other words, the semi-active systems can absorb but they cannot supply energy). These systems are simpler, more robust, more reliable and more economical than the active ones and its efficiency is only slightly lower (but superior compared to the passive control devices). Fig. 1.12 could also represent a typical semi-active system.

Active and semi-active systems have been installed in some structures worldwide [22, 23]

1.2.4 Hybrid systems

They consist of a series or parallel combination of an active (or semi-active) system with a passive one. The interest of this assembly lies on the sum of advantages of both systems: the passive devices can produce the major magnitude of reduction of the response while the active system can give the final adjustment, i.e., it is capable of minimizing displacements and accelerations (to protect sensitive equipment, for example). Fig. 1.15 shows an example of an actuator plus a base isolation system (the active system can be used to reduce vibrations of high frequency and low amplitude in the superstructure) and Fig. 1.16 shows a two-axis hybrid-type mass damper [22]. This one has been developed to reduce the vibration of tall bridge towers and high-rise building structures. A sliding mass shaped in an arc segment is combined with active control by an AC servo-motor. The movement of the arc segment on roller bearings is similar to that of a pendulum takin the role of a TMD. After some experiments were made with the tower structural model, it has been applied to actual bridge towers and high-rise buildings.

Since big control forces are not required, hybrid systems are more reliable and more economical than the active ones.

Hybrid systems have been installed in some structures worldwide [22].

1.2.5 Summary

It is important to notice that none of these systems is a part of the main structure (i.e., control systems are not designed to resist gravitational loads) and can be disassembled temporary for maintenance, reparation or substitution purposes. The only exception is the base isolation (still, there are special techniques to replace the isolators).

While these technologies play an important role in the structural design, passive systems are the simplest, most economical, robust and reliable of all the systems above mentioned; if designed properly, they are quite efficient when the structures that incorporate them

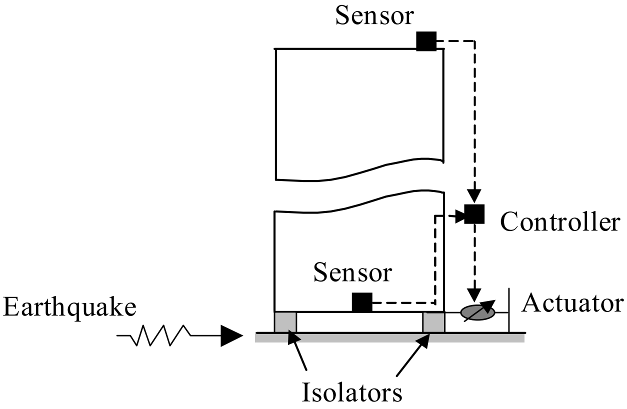


Figure 1.15 Combination of active (or semi-active) control with a base isolation system

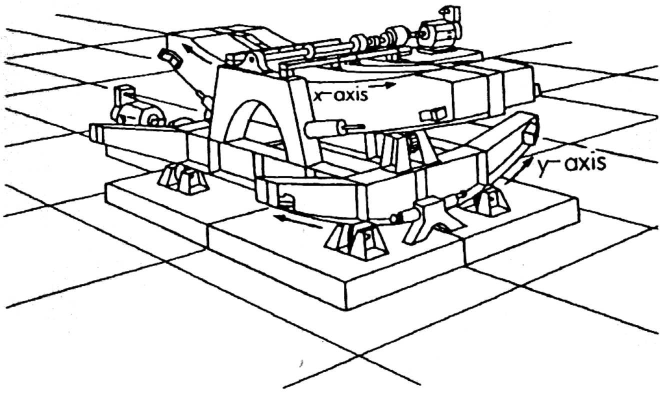


Figure 1.16 A two-axis hybrid-type mass damper [22]

are subjected to seismic motions. This is one of the reasons why these systems are more developed all over the world than the active and semi-active ones.

1.3 Friction Dissipators

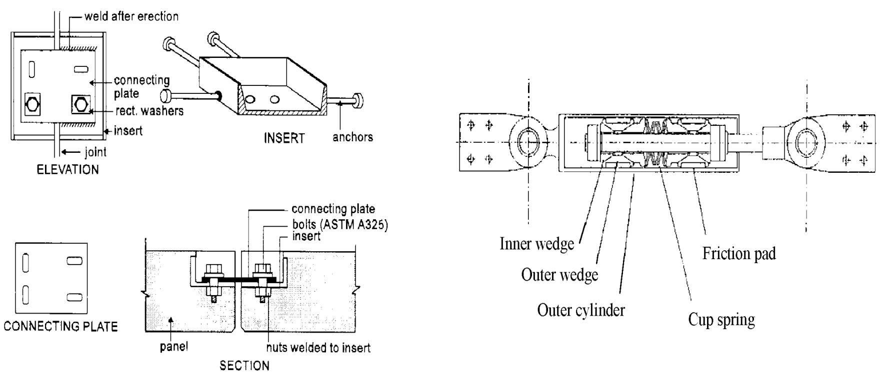
As discussed previously, among the various energy dissipators currently available, three major types are used: *dampers based on metal yielding, friction dampers* and *viscous* or *viscoelastic dampers*. This thesis deals with friction dampers, also called friction dissipators (FD).

Basically, a friction dissipator is a device that absorbs energy through friction forces. There is a variety of FD currently utilized for structural purposes, like those shown in Fig. 1.17. The device shown in Fig. 1.17a is a limited slip bolt (LSB) joint originated by Pall et al. [24]. The LSB incorporates brake lining pads between steel plates in order to provide a consistent force-displacement hysteresis loops, and is assembled with cross-bracing in framed structures (see Fig. 1.18c). As described previously in Paragraph 1.2.2.2, the Sumitomo friction damper (Fig. 1.17b) [13] has copper alloy friction pads that slide along the inner surface of the cylindrical steel casing. The required normal force is adjusted through the action of the spring against the inner and outer wedges. This dissipator is mounted as shown in Fig. 1.18a. Finally, Fig. 1.17c presents the energy dissipating restraint (EDR) described in [4]. In this case, dissipation occurs on the interface between bronze friction wedges and the steel cylinder wall. The combination of wedges, stops, and internal spring produces a frictional force proportional to the relative displacement of the device ends. This device is assembled with the diagonal braces as shown in Figs. 1.18c and d.

Besides the FD shown in Fig. 1.17 there is currently a wide variety of friction devices that have been proposed for the energy dissipation of the structures [5, 25, 26, 27]. All the friction systems, except one (the Fluor-Daniel EDR), generate rectangular hysteresis loops, typical of Coulomb's dry friction (see Fig. 1.19) [27, 28, 29].

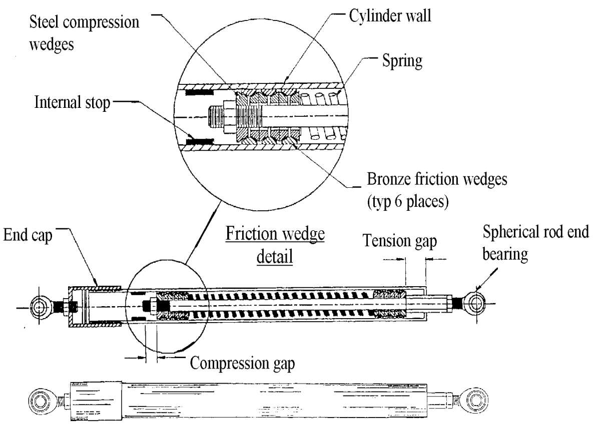
As said before, this Thesis focuses to the study of friction dampers. One of the reasons is that these devices have several advantages, such as:

- High energy dissipation capacity at a given amplitude (see Fig. 1.19).
- Controllable friction force through prestressing.
- Behavior not affected greatly by the load amplitude, the input frequency contents or the number of cycles.
- Virtually unlimited capacity of energy dissipation.
- No fatigue effects.



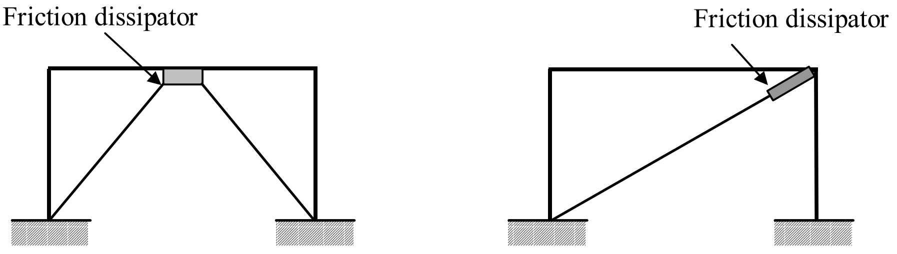
(a) Limited slip bolted (LSB) joint

(b) Sumitomo's friction damper



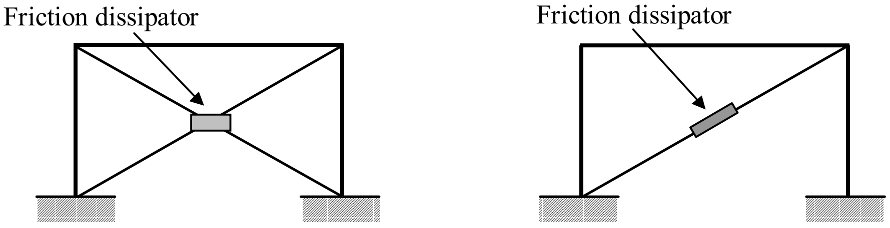
(c) Energy dissipating restraint (EDR)

Figure 1.17 Different types of friction dissipators used currently in structural control [13, 24, 25]



(a) Frame with the dissipator located between the braces and the upper slab

(b) Frame with the dissipator located between the brace end and the beam-column connection



(c) Frame with the dissipator located in the middle of the cross bracing

(d) Frame with the dissipator located in the middle of the diagonal brace

Figure 1.18 Location of friction dissipators

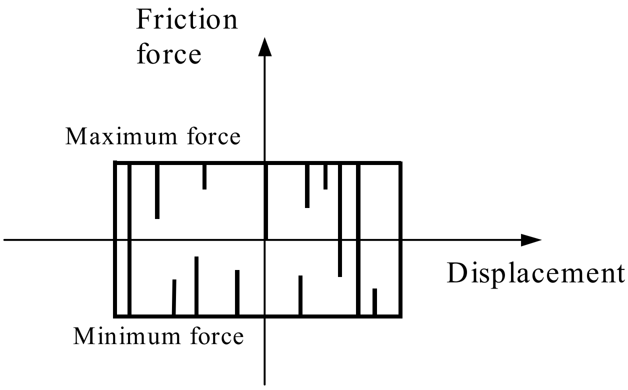


Figure 1.19 Rectangular hysteresis loops typical of dry friction

On the other hand, their dynamic behavior is highly nonlinear and, in consequence, their numerical simulation becomes a challenging issue. This is the main reason of the lack of reliable and accurate numerical models and it has also caused the arising of some controversial issues associated to these devices, such as the sudden coming up of high frequency responses or their efficiency under near-fault pulses [30]. Moreover, no specific design guidelines for friction dissipators have been reported.

It should be emphasized that friction dissipators are not useful for wind loads because their ability to reduce accelerations is limited as they tend to introduce high frequencies in the response. Therefore, this Thesis deals only with the seismic application of friction dissipators.

1.4 Motivation and Objective of this Research

As stated in Section 1.2, passive devices (friction dissipators included) are mostly considered to be incorporated to structures due to their reliability and economy (compared to active and semi-active systems). For this reason, this research deals with passive dampers, specifically with friction dissipators. These present several advantages (and some disadvantages) as seen in Section 1.3.

Moreover, there is currently a certain lack of accurate, reliable and computationally efficient numerical algorithms to simulate the dynamic behavior of buildings incorporating friction dissipators. This lack keeps certain questions unanswered, hence the seismic efficiency of friction dissipators is still a controversial issue. Besides, this situation is the main source of motivation to study the dynamic behavior of buildings equipped with friction dissipators.

The objective of this Thesis is to contribute to the evaluation of the efficiency of friction energy dissipation devices to reduce the seismic vulnerability of buildings. To reach this goal, the following research approach has been established:

- A numerical procedure has been developed and implemented into a computer code (ALMA program). This program simulates the dynamic behavior of building structures equipped with friction dissipators.

- A series of shaking-table tests has been carried out on scale models equipped with real friction dampers.

- The results of ALMA, those of the commercial package ADINA, and the results obtained from the laboratory tests have been compared to evaluate the accuracy and the reliability of the proposed algorithm.

- Finally, a methodology to perform a numerical parametric study to assess the efficiency of friction dissipators to reduce the seismic vulnerability of buildings is proposed. Preliminary calculations are carried out. Based on this study, the *optimal slip load* for buildings equipped with friction dissipators will be found as the main design parameter of friction devices.

1.5 Organization and Thesis Contents

This thesis is organized to make it easily understandable. For this reason, the chapters are written following a logical sequence, as described next:

- This first chapter deals with the general aspects of structural control with a special emphasis in friction dissipators which are included into the passive control approach.
- Chapter 2 gives a general overview of the state of the art regarding the principles of dry friction and the research and application of FD as well as their numerical simulations.
- The third chapter deals with the numerical solution of the equations of motion of structures modelled as single-story buildings equipped with FD. A solution is proposed and its algorithm (based on the linear acceleration method, i.e., Newmark's method) is described. The output from this algorithm is compared to the solution obtained using the commercial software package ADINA, which is based on the constraint function method. Some examples of solution of buildings subjected to different inputs are analyzed and the respective time-history responses are shown. The agreement between the proposed algorithm and ADINA is good.
- In Chapter 4, the proposed algorithm described in Chapter 3 is used as a basis to develop a general method to solve the equations of motion of multi-story buildings equipped with FD and a step-by-step numerical procedure is proposed and implemented into a computer code (ALMA program). Again, the results obtained by using this new algorithm are compared to the ADINA output. As in Chapter 3, the agreement between both programs is satisfactory.
- Chapter 5 describes the shaking-table testing of a two scaled-down models of a single-story building a two-story building, both equipped with FD. The numerical results (obtained with ALMA) are compared to the experimental ones. Good agreement is obtained.
- Chapter 6 proposes a methodology to carry out a numerical parametric study about the seismic efficiency of FD. This methodology aims to get the optimal values of the slip load for buildings equipped with FD. Preliminary calculations are performed.
- Finally, the seventh chapter contains a summary and the conclusions of this Thesis and some proposals for future research.

There are five appendices added up to this Thesis. Appendix A contains the basic principles of contact analysis, Appendix B deals with the numerical solution of equations of motion of SDOF and MDOF systems. This appendix is mostly related to chapters 3 and 4. Appendix C describes the solution of the equations of motion using the Lagrange multipliers. Appendix D describes the facilities, equipment and instrumentation used in the laboratory tests. The results of the tests and the comparison between them and those obtained using ALMA, are presented in Appendix E.