



ESCUELA TÉCNICA SUPERIOR DE INGENIEROS
INDUSTRIALES Y DE TELECOMUNICACIÓN

INGENIERÍA TÉCNICA INDUSTRIAL MECÁNICA

**THE DESIGN OF AN EARTHQUAKE IMMUNE
MOUNTING SYSTEM FOR A BUILDING**

Nekane Aldasoro Manero

Dr. Pablo Sanchis Gúrpide

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1 INTRODUCTION

Historically, earthquakes have caused death and devastation to humanity, and serious economic dislocation as a result of damage to buildings and the environment.

Earthquakes are among the most traumatic experiences caused by natural phenomena. In a short period of time, the firm foundation of Mother Earth begins to shake in a terrifying way and can cause physical devastation associated to lasting psychological effects. The statistics dictate that in the last century more than 50 million people died by earthquakes and around 450.000 have done between 2000 and 2010.

It is of global concern, therefore, to find solutions that can reduce these effects and socio-economic implications. This requires a joint effort between seismologists, geologist, structural engineers, architects, economists...

Seismologists and engineers work together to develop new seismic designs. The first challenge that they have to cope with is to determine in advance the characteristics of earthquakes expected in an area that will affect on the buildings during their lifetime. These characteristics will be introduced in the dynamic calculations of the structures taking into account construction codes and earthquake-resistant legislation.

Moreover, the estimate of the response of the structure to a particular input motion is the second problem that arise the earthquake-resistant design.

With the aim of resolving the above problems, a new engineering is born, "Seismic Engineering" that emerges as an interdisciplinary branch of engineering, a link between earth sciences (seismology) and civil engineering oriented primarily to mitigate the seismic hazard.

This new engineering has been gaining relevance in recent years and the work methods become more refined over time, given its importance to the recommendation of appropriate earthquake-resistant criteria in the construction of new buildings.

2 AIMS OF PROJECT

The focus of the project is to provide the reader with insight into the influence of earthquakes on buildings, and show how, over time, seismologists and engineers have developed designs and insulations to reduce significantly the effects produced by earthquakes. To provide that vision, the project will consist on several parts where different concepts will be explained.

- Introduction to earthquakes

To understand the influence of earthquakes on structures, in the first part it will be explained some basic concepts about these phenomenon; what are, why they occur, measures and scales, records, effects and consequences....

- Theoretical design considerations in conventional construction and design problems

In this section will be mentioned the criteria of construction, the importance of the lateral resistive system in seismic structural design, types of lateral structures, materials... as well as potential problems that may arise in the construction of buildings.

- Research programs, simulations and latest seismic technologies

In this point it will be explained the research programs, simulations and will be submitted the latest seismic technologies that are a set of technical means aimed to mitigate seismic impacts in buildings and non-buildings structures.

- Calculations, results and discussion

In the last section, the structural analysis methods will be explained, and four buildings designed in two different ways (with conventional construction and with a damping system) will be calculated and compared.

3 REVIEW OF LITERATURE

3.1 Introduction to earthquakes

3.1.1 Earthquakes

Regarded as endogenous risks, produced inside the Earth, earthquakes are caused by the accumulation of stress deformation of the layers of the Earth, being released abruptly.

Are broken masses of rocks that are subjected to great pressure and these materials are reordered, with the release of enormous energy that shakes the Earth.

The focus of onset is known hypocenter and can be located at different depths, even the deepest being located 700 kilometres. From this focus, the energy is released in waves that are generated and propagated in all directions concentrically, reaching the epicentre, which is the point on the nearest vertical surface, where they arrive with maximum intensity.

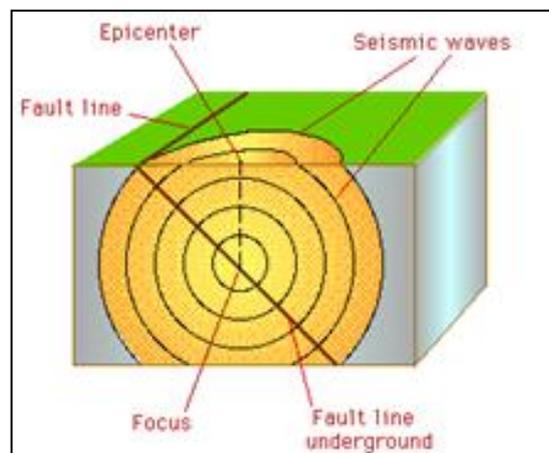


Figure 3.1: Origin of earthquakes

Earthquakes are especially common near the edges of tectonic plates that make up the crust or lithosphere.

Seismic waves are thus propagating waves, for transmitting the force generated in the seismic focus to the epicentre in proportion to the intensity and magnitude of the earthquake.

3.1.2 Seismic waves

Seismic waves are waves of force that travel through the Earth or other elastic body, for example as the result of an earthquake, explosion, or some other process that imparts forces.

There are two types of seismic waves, body waves and surface waves.

1. Body waves: Waves that travel through the interior of the Earth. They follow ray paths bent by the varying density and modulus (stiffness) of the Earth's interior. The density and modulus, in turn, vary according to temperature, composition, and phase. This effect is similar to the refraction of light waves.

There are two types of body waves:

- P-waves (primary waves): Longitudinal or compression waves. In solids, these waves generally travel almost twice as fast as S waves and can travel through any type of material. In air, these pressure waves take the form of sound waves; hence they travel at the speed of sound. When generated by an earthquake they are less destructive than the S waves and surface waves that follow them, due to their smaller amplitudes.
- S-waves (Secondary waves): Transverse or shear waves that cause the ground move perpendicularly to the direction of propagation. In the case of horizontally polarized S waves, the ground moves alternately to one side and then the other. S waves can travel only through solids, as fluids (liquids and gases) do not support shear stresses. Their speed is about 60% of that of P waves in a given material. S waves arrive second in a seismic station because of their slower speed. S waves are several times larger in amplitude than P waves for earthquake sources.

2. Surface waves: Analogous to water waves and travel just under the Earth's surface. They travel more slowly than body waves. Because of their low frequency, long duration, and large amplitude, they can be the most destructive type of seismic wave.

- Rayleigh waves: Surface waves that travel as ripples with motions that are similar to those of waves on the surface of water. They are slower than body waves, roughly 90% of the velocity of S waves for typical homogeneous elastic media.
- Love Waves: Surface waves that cause horizontal shearing of the ground. They usually travel slightly faster than Rayleigh waves.

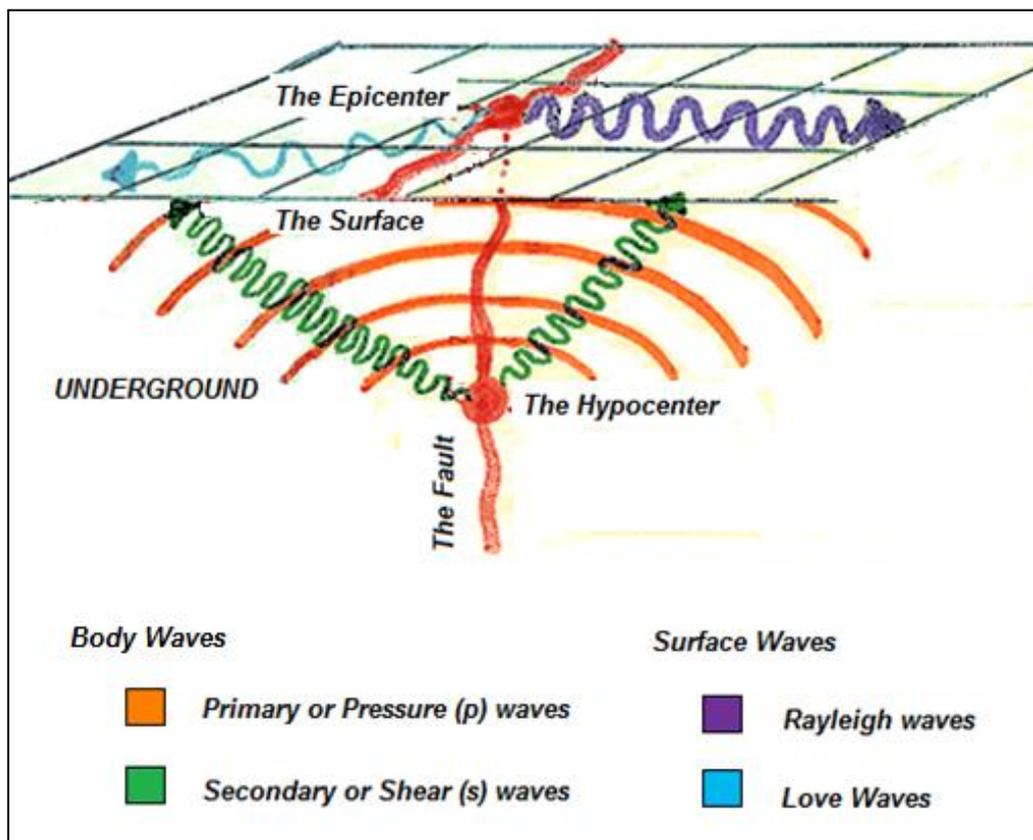


Figure 3.2: Seismic waves

3.1.3 Measures in earthquakes

There are several measurable parameters. Magnitude describes the size of the earthquake, expressed in amount of energy released. The scale is referred in the Richter scale, so that each increases of one unit; it releases 33 times more energy. This release may depend on the fault rupture and the spread of the movement.

It is also measurable intensity, as the effects of tremor or the extent of damage in a specific area. The intensity depends on the magnitude of the earthquake and vibration time, the amount of energy released, and the distance from the affected area to the epicentre or the geology of the area.

To measure it is used the Mercalli scale, which has 12 categories of intensity of movement, expressed in Roman numerals. This scale has its drawbacks as subjectivity, because it depends on personal interpretation and quality in the buildings in the affected area.

Richter Magnitudes	Description	Earthquake effects	Frequency of occurrence
< 2.0	Micro	Micro earthquakes, not felt.	About 8,000 per day
2.0-2.9	Minor	Generally not felt, but recorded.	About 1,000 per day
3.0-3.9		Often felt, but rarely causes damage.	49,000 per year (est.)
4.0-4.9	Light	Noticeable shaking of indoor items, rattling noises. Significant damage unlikely.	6,200 per year (est.)
5.0-5.9	Moderate	Can cause major damage to poorly constructed buildings over small regions. At most slight damage to well-designed buildings.	800 per year
6.0-6.9	Strong	Can be destructive in areas up to about 160 kilometres (100 mi) across in populated areas.	120 per year
7.0-7.9	Major	Can cause serious damage over larger areas.	18 per year
8.0-8.9	Great	Can cause serious damage in areas several hundred miles across.	1 per year
9.0-9.9		Devastating in areas several thousand miles across.	1 per 20 years
10.0+	Epic	Never recorded	Extremely rare (Unknown)

Table 3.1: Typical effects of earthquakes of various magnitudes near the epicenter

3.1.4 Recording the effects of earthquakes

Following a major earthquake, it is usually possible to retrace its complete history through the recorded seismic shocks over an extended period. This period may cover several weeks, or even years, and the record will usually show several shocks preceding and following the major one. Some of the minor shocks may be of significant magnitude themselves, as well as being the foreshocks and aftershocks of the major quake.

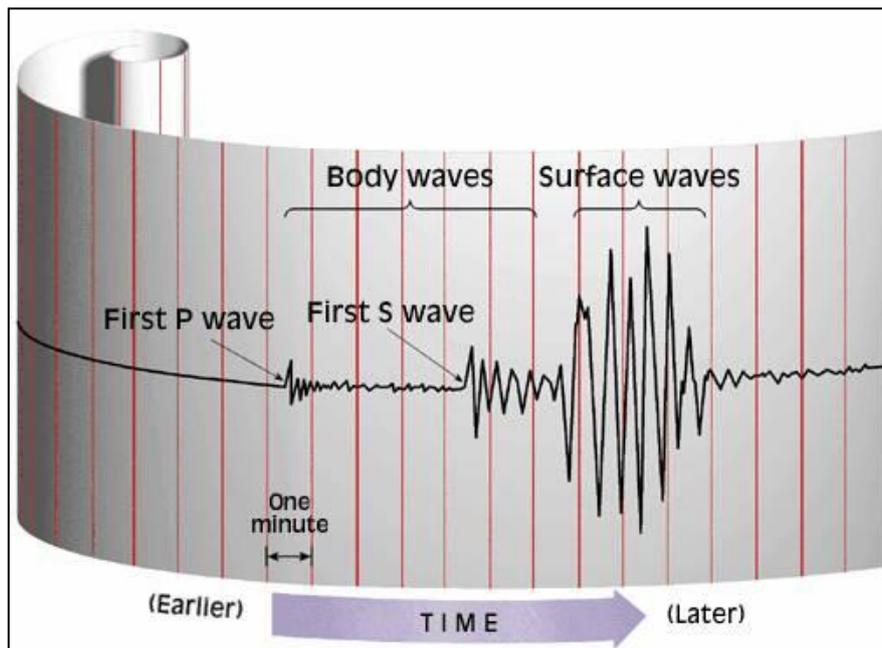


Figure 3.3: Seismograph - recording earthquake shockwaves

A major earthquake is usually rather short in duration, often lasting only a few seconds and seldom more than a minute or so. During the general quake, there are usually one or more major peaks of magnitude of motion. These peaks represent the maximum effect of the quake.

Although the intensity of the quake is measured in terms of the energy release at the location of the ground fault, called the epicentre, the critical effect on a given structure is determined by the ground movements at the location of the structure.

Modern recording equipment and practices provide us with representations of the ground movements at various locations, thus allowing us to simulate the effects of major earthquakes.

The graphics represent particular aspects of motion of the ground as recorded or as interpreted from the recordings for an earthquake. The graphics are plotted in terms of the acceleration of the ground in one horizontal direction as a function of elapsed time.

Nowadays, records of actual quakes may be "play back" on structures in order to analyze their responses. These playbacks are used in research and in the design of some major structures to develop criteria for design of lateral resistive system.

3.1.5 Predicting earthquakes

It is difficult to tell when an earthquake will occur because the earthquake prediction is a long term goal, and obviously it is impossible to change the nature of this natural phenomenon.

However, earthquake prediction is considered a formal one in which indicates the time of occurrence, the site of occurrence and at what depth and the magnitude of the event to occur, including all these parameters with an indication of error in each given value. The time of occurrence is usually provided as the most probable range of occurrence of the event.

3.1.6 Natural disasters produced by earthquakes

Seismic activities can produce lot of deaths because of the disastrous effects like direct movement of structures, demolish structures as buildings, bridges and dams, tidal waves, ground surface faults, violent vibratory motions, explosions, flooding, fires... The natural disasters produced by earthquakes can be the following:

3.1.6.1 Shaking and ground rupture

Shaking and ground rupture are the main effects created by earthquakes, principally resulting in more or less severe damage to buildings and other rigid structures.

The severity of the local effects depends on the complex combination of the earthquake magnitude, the distance from the epicentre, and the local geological and geo-morphological conditions, which may amplify or reduce wave propagation. The ground-shaking is measured by ground acceleration.

Ground rupture is a visible breaking and displacement of the Earth's surface along the trace of the fault, which may be of the order of several meters in the case of major earthquakes. Ground rupture is a major risk for large engineering structures such as dams, bridges and nuclear power stations and requires careful mapping of existing faults to identify any likely to break the ground surface within the life of the structure.

3.1.6.2 Landslides and avalanches

Earthquakes, along with severe storms, volcanic activity, coastal wave attack, and wildfires, can produce slope instability leading to landslides, a major geological hazard. Landslide danger may persist while emergency personnel are attempting rescue.

3.1.6.3 Fires

Earthquakes can cause fires by damaging electrical power or gas lines. In the event of water mains rupturing and a loss of pressure, it may also become difficult to stop the spread of a fire once it has started.

3.1.6.4 Tidal forces

Research work has shown a robust correlation between small tidally induced forces and non-volcanic tremor activity.

3.1.6.5 Soil liquefaction

Soil liquefaction occurs when, because of the shaking, water-saturated granular material (such as sand) temporarily loses its strength and transform from a solid to a liquid. Soil liquefaction may cause rigid structures, like buildings and bridges, to tilt or sink into the liquefied deposits. This can be a devastating effect of earthquakes.

3.1.6.6 Tsunami

Tsunamis are long-wavelength, long-period sea waves produced by the sudden or abrupt movement of large volumes of water. In the open ocean the distance between wave crests can surpass 100 kilometres, and the wave periods can vary from five minutes to one hour. Such tsunamis travel 600-800 kilometres per hour, depending on water depth.

Large waves produced by an earthquake or a submarine landslide can overrun nearby coastal areas in a matter of minutes. Tsunamis can also travel thousands of kilometres across open oceans and wreak destruction on far shores hours after the earthquake that generated them.

Most destructive tsunamis are caused by earthquakes of magnitude 7.5 or more on the Richter scale.

3.1.6.7 Floods

A flood is an overflow of any amount of water that reaches land. Floods occur usually when the volume of water within a body of water, such as a river or lake, exceeds the total capacity of the formation, and as a result some of the water flows or sits outside of the normal perimeter of the body.

However, floods may be secondary effects of earthquakes, if dams are damaged. Earthquakes may cause landslips to Dam Rivers, which then collapse and cause floods.

3.1.6.8 Human impacts

Earthquakes may lead to disease, lack of basic necessities, loss of life, higher insurance premiums, general property damage, road and bridge damage, and collapse or destabilization (potentially leading to future collapse) of buildings. Earthquakes can also precede volcanic eruptions, which cause further problems.

3.1.7 Effects of earthquakes

Seismic activities produce various disastrous effects, including direct movement of structures, tidal waves, ground surface faults, violent vibratory motions, explosions, flooding, fires...

Earthquakes are the last effect for which are design the lateral bracing systems for buildings, dealing mostly with the horizontal aspect of the ground motion. This activity cannot be fully understood in terms of static force alone, however, as dynamic aspects of both the ground motion and the building response must be considered.

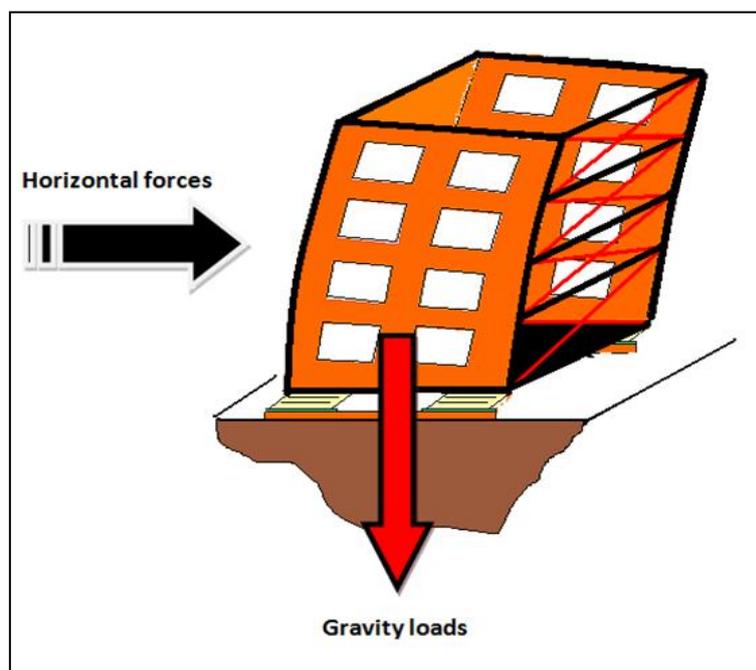


Figure 3.4: Building subjected to horizontal forces

For the analysis of direct motion of structures, it is necessary to provide some degree of dynamic stability (general resistance to shaking) and some quantified resistance to energy loading of the structure. The force effect caused by motion is generally directly proportional to the dead weight borne by the structure.

The other major influences on the structure's response are its fundamental period of vibration (determined by the mass, stiffness and size of the structure) and its efficiency in energy absorption (determined by elasticity of the structure).

A relationship of major concerns is that which occurs between the period of the structure and that of the earthquake. To analyse this relation can be use the spectrum curve that represent this relationship as derived from a large number of earthquake "playbacks" on structures with different periods.

The general interpretation of the spectrum effect is that the earthquake has its major direct force effect on buildings with short periods. These tend to be buildings with stiff lateral resistive systems, such as shear walls and X-braced frames, and buildings that are small in size and/or squat in profile.

For flexible structures, such as tall towers, the fundamental period may be so long that the structure develops a whiplash effect. Analysis for this behaviour requires the use of dynamic methods.

3.2 Theoretical design considerations in conventional construction

The objective in construction design is not only to maintain buildings without overthrow, but also provide them sufficient stand time, to have the possibility to dislodge people before the collapse of the building. Other aim is to construct buildings capable to withstand ground movements with a maximum stipulated.

3.2.1 Lateral resistive structure

The principal concern in structural design for earthquake forces is the lateral resistive system of the building. In most buildings this system consists of some combination of horizontally distributing elements and vertical bracing elements. Failure of any part of this system, or of connections between the parts, can result in major damage to the building, including the possibility of total collapse.

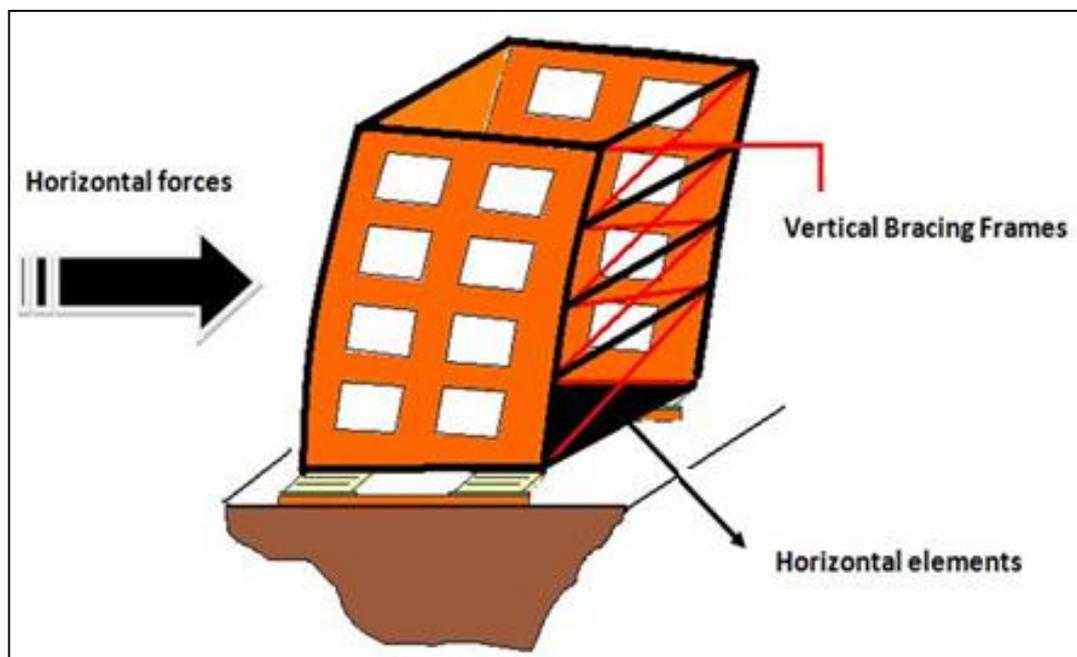


FIGURE 3.5: Lateral resistive system for a building

The detailing of construction connections is a major part of the structural design for earthquake resistance. In some cases it is desirable to allow for some degree of independent motion of parts of the building.

This is especially critical in situations where a secure attachment between the structure and various non-structural elements can result in undesired transfer of force to the non-structural elements. In these cases use must be made of connecting materials and details that allow for the holding of the elements in place while still permitting relative independence of motion. The connections that allow for some degree of independent movement of the parts are seismic separation joints.

A major problem in designing for lateral effects is simply that of determining the magnitudes of the loads. Precise prediction of potential ground movements caused by some hypothetical earthquake at a specific site and estimating the effects of the building's response and any site/structure interaction are conjectures of ethereal proportions.

Otherwise, to understand how a building resists the lateral load effects of wind and seismic force it is necessary to consider the manner of application of the forces, and then to visualize how these forces are transferred through the lateral resistive structural system and into the ground.

Seismic loads are actually generated by the dead weight of the building construction. In visualizing the application of seismic forces, it has to look at each part of the building and consider its weight as a horizontal force.

The weight of the horizontal structure, although actually distributed throughout its plane, may usually be dealt with in a manner similar to the edge loading caused by wind (a direct horizontal pressure is assumed to act on this plane). In the direction normal to their planes, vertical walls will be loaded and will function structurally in a manner similar to that for direct wind pressure.

The above figure shows a simple rectangular building under the effect of wind normal to ones of its flat sides.

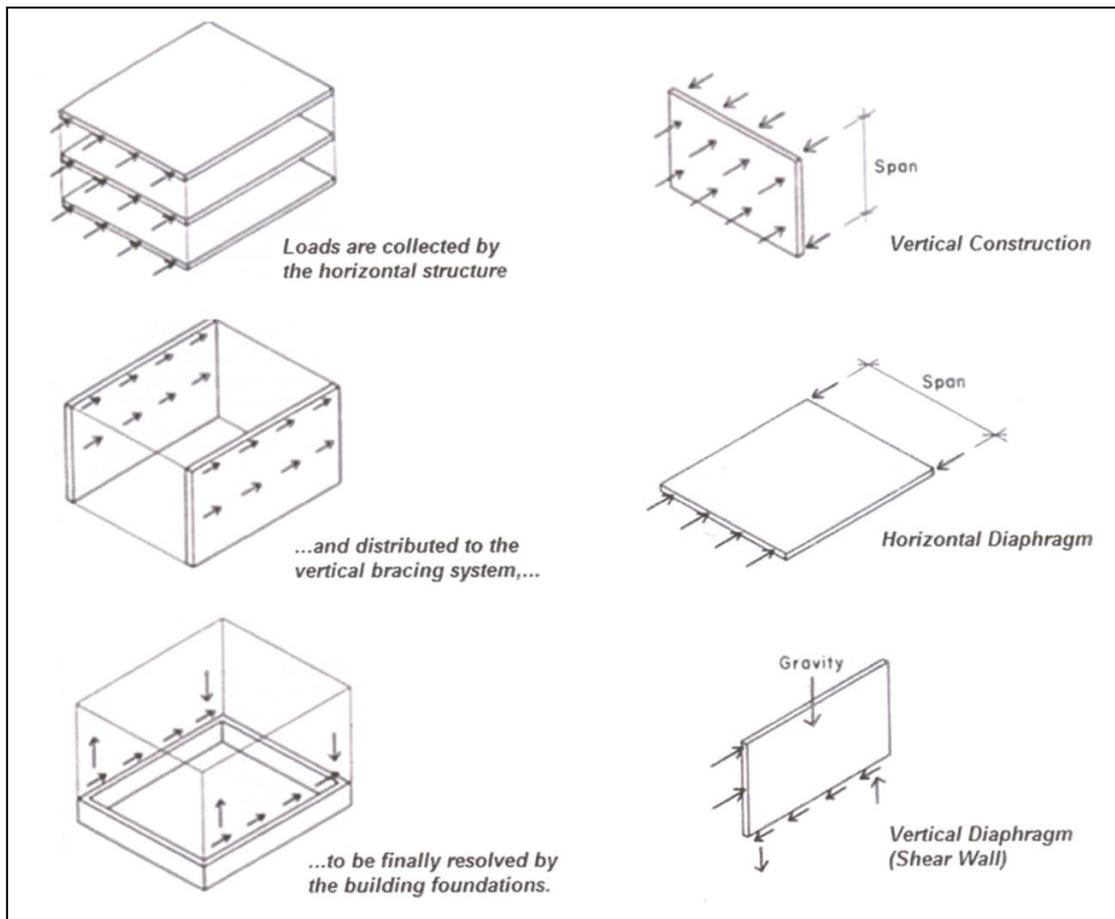


FIGURE 3.6: Propagation of wind force and basic functions of elements in a box building

The lateral resistive structure that responds to this loading consists of the following:

- Wall surface elements on the windward side are assumed to take the total horizontal pressure and are typically designed to span vertically between the roof and floor structures.
- Roof and floor decks, considered as rigid planes, receive the edge loading from the windward wall and distribute the load to the vertical bracing elements.
- Vertical frames or shear walls, acting as vertical cantilevers, receive the loads from the horizontal diaphragms and transfer them to the building foundations.
- The foundations must anchor the vertical bracing elements and transfer the loads to the ground.

If a wall is reasonably rigid in its own plane, it tends to act as a vertical cantilever for the seismic load in the direction parallel to its surface.

Thus, in the example building, the seismic load for the roof diaphragm would usually be considered to be caused by the weight of the roof and ceiling construction plus only those walls whose planes are normal to the direction being considered.

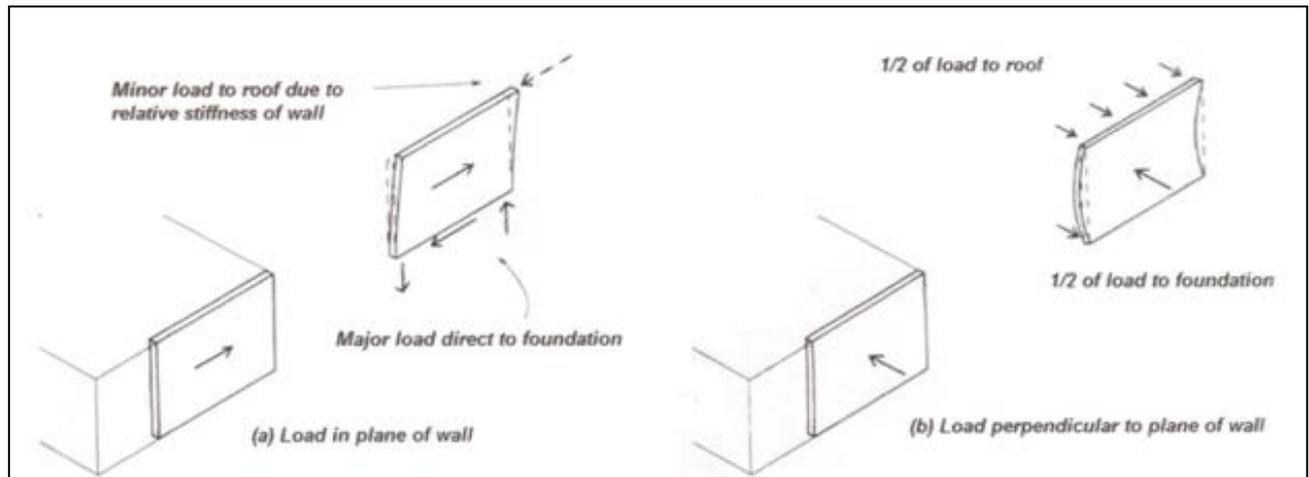


FIGURE 3.7: Seismic loads caused by wall weight

If this assumption is made, it will be necessary to calculate a separate seismic load in each direction for the building.

For determination of the seismic load, it is necessary to consider all elements that are permanently attached to the structure. Ductwork, lighting and plumbing fixtures, supported equipment, signs, and so on, will add to the total dead weight for the seismic load.

3.2.2 Types of lateral resistive systems

The choice of the type of lateral resistive system must be related to the loading conditions and to the behaviour characteristics required. It must also be coordinated with the design for gravity loads and with the architectural planning considerations.

Many design situations allow for alternatives, although the choice may be limited by the size of the building, by code restrictions, by the magnitude of lateral loads, by the desire for limited deformation, and so on.

The types of lateral resistive system are the following:

3.2.2.1 The box or panelized system

The box or panelized system consists of some combination of horizontal and vertical planar elements.

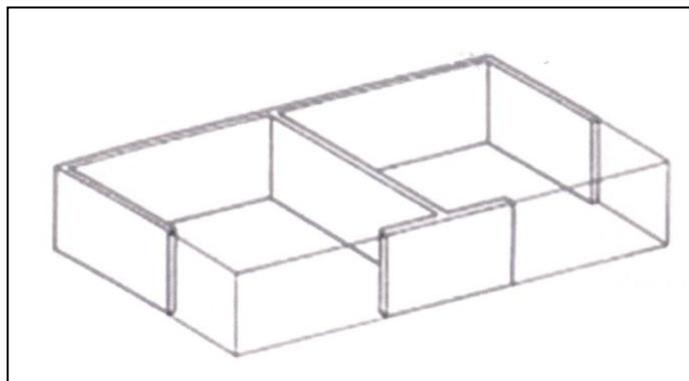


FIGURE 3.8: The box or panelized system

3.2.2.2 Internally braced frames

The typical assemblage of post and beam elements is not inherently stable under lateral loading unless the frame is braced in some manner. Shear wall panels may be used to achieve this bracing, in which case the system functions as a box even though is a frame structure.

It is also possible, however, to use diagonal members, X-bracing, knee braces, struts, and so on, to achieve the necessary stability of the rectangular frame. The term braced frame usually refers to these techniques.

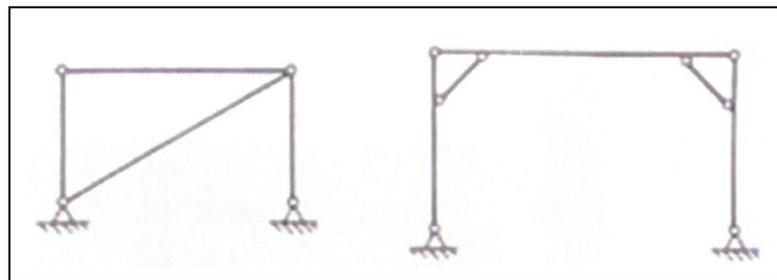


FIGURE 3.9: Internally Braced Frame

3.2.2.3 Rigid frames

Although the term rigid frame is a misnomer since this technique usually produces the most flexible lateral resistive system, the term refers to the use of moment resistive joints between the elements of the frame.

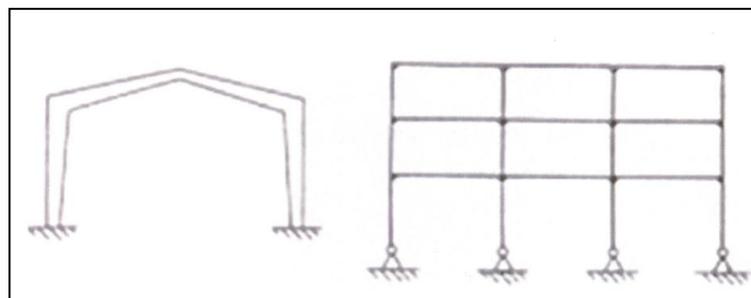


FIGURE 3.10: Rigid frames

3.2.2.4 Externally braced frames

The use of guys, struts, buttresses... that are applied externally to the structure or the building results in externally braced frames.

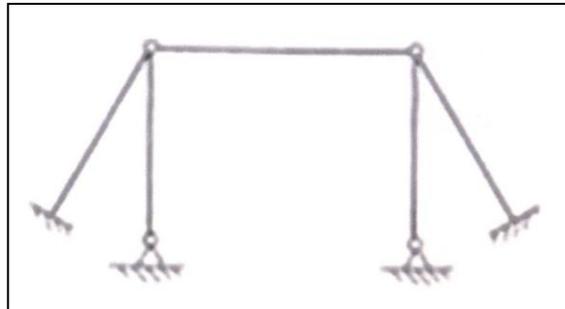


FIGURE 3.11: Externally braced frames

3.2.2.5 Self-Stabilizing elements and systems

Retaining walls, flagpoles, pyramids, tripods, and so on, in which stability is achieved by the basic form of the structure. Each of these systems has variations in terms of materials, forms...

An important property of these elements is the relative stiffness or resistance to deformation, which is of particular concern in evaluating energy effects, especially for response to seismic loads.

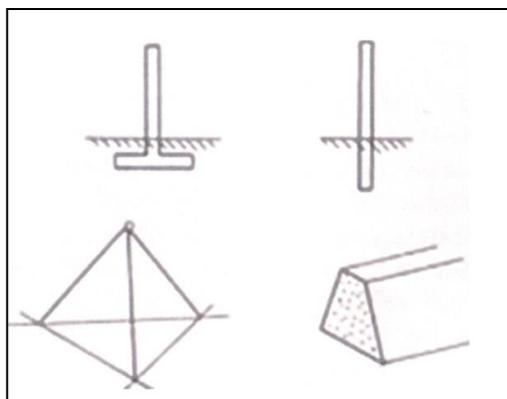


FIGURE 3.12: Self-Stabilizing elements and systems

In seismic analysis these properties are used to modify the percentage of the dead weight that is used as the equivalent static load to simulate the seismic effect.

Elements of the building construction developed for the gravity load design, or for the general architectural design, may become natural elements of the lateral resistive system. It is also possible, that the building developed may not have the necessary attributes for lateral load resistance, thus requiring some re-planning or the addition of structural elements.

The next illustration shows various situations in which the lateral bracing of the building is achieved by partial bracing of the system.

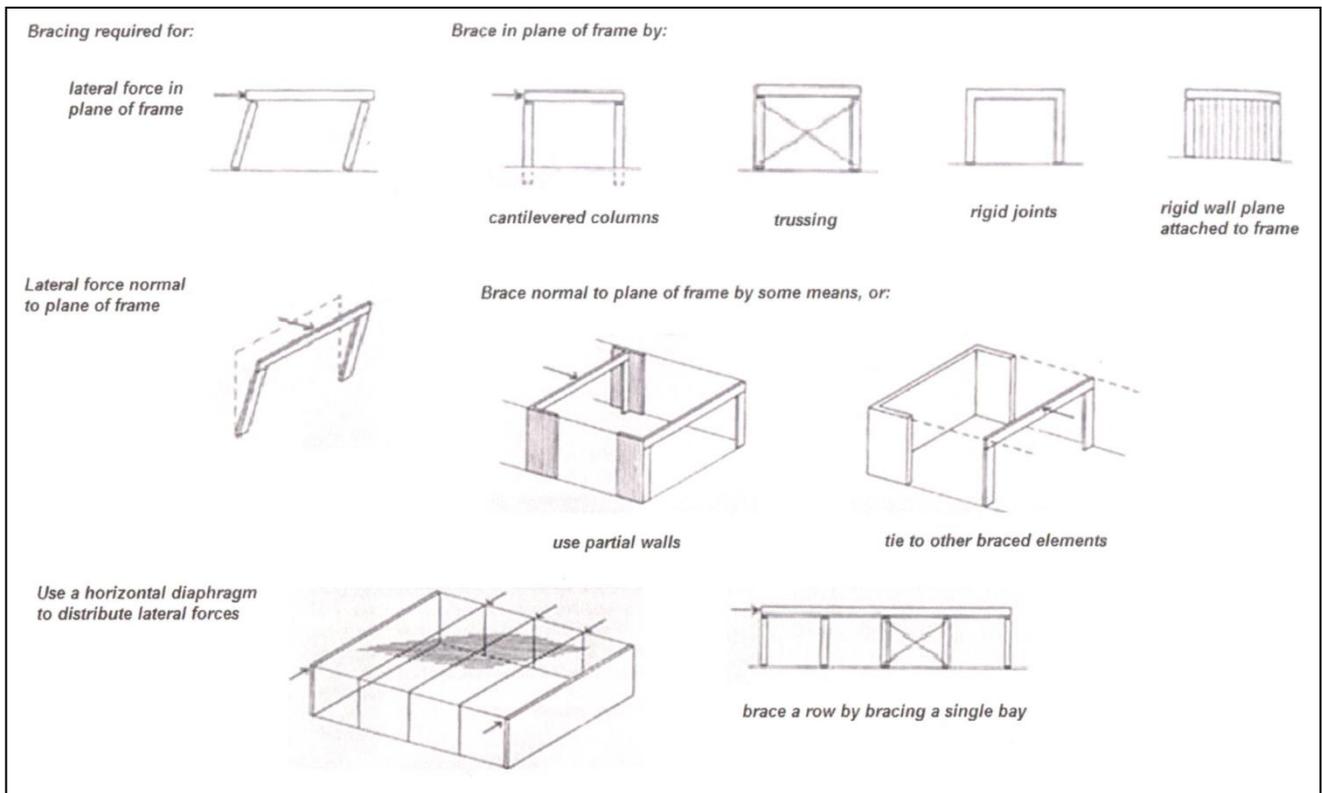


FIGURE 3.13: Bracing of framed structures for lateral loads

There is a possibility that some of the elements of the building construction that are not intended to function as bracing elements may actually end up taking some of the lateral load.

What can happen in these cases is that the stiffer finish materials take the load first, and if they are not strong enough, they fail and the intended bracing system then goes to work.

Although collapse may not occur, there can be considerable damage to the building construction as a result of the failure of the supposed non-structural elements.

3.2.3 Lateral resistance of ordinary construction

Buildings are built having into consideration that they will have some natural capacity for lateral force resistance. Below are showed the different lateral resistant of ordinary constructions:

3.2.3.1 Wood frame construction

Wood structures can be categorized broadly as light frame or heavy timber. In most cases the frames are covered on both surfaces by some type of surfacing material that give them a quantifiable capacity for diaphragm resistance. Thus, most light wood frames can be made resistive to lateral forces through the use of a combination of horizontal and vertical diaphragms.

Many of the ordinary elements of light wood frames can be utilized as parts of the lateral resistive system. Wall studs, posts, sills and plates, and roof and floor framing members, occurring naturally in the structures, are often able to be utilized for these functions.

Alterations necessary to make them more functional are often limited to moderate increases in sizes or to the use of some additional fastening or anchoring.

In recent times, there has been a trend toward the extensive use of sheet metal fastening devices for the assemblage or light wood structure. In general, these tend to increase resistances to lateral loads because the continuity of the frame is greater and the anchorage of members is more positive.

There is a considerable range in the diaphragm shear capability of various surfacing materials.

- Plywood: This may be used as the structural backup for a variety of finishes or may be used with an especial facing as the complete surfacing. Most plywood offer considerable potential for shear resistance.

- Board Sheathing: Capacities are nowhere near that of plywood, so that this type of structural covering is not much used at present.
- Plaster: Portland cement plaster, applied over wire reinforced backing and adequately secured to the framing, produces a very stiff diaphragm with load capacities equal to that of the thinner plywood.
- Miscellaneous Surfacing: Gypsum drywall, gypsum plaster, non-structural plywood, and particleboard can develop some diaphragm capacity that may be sufficient for low stress situations. Stiffness is minimal, thus narrow diaphragms should be avoided.

Some of the problems encountered in developing seismic resistance with light wood frame construction, are the follow.

1. Lack of adequate solid walls to serve as shear walls: This may be due to the building planning, with walls insufficient at certain locations or in a particular direction.
2. Lack of adequate diaphragm surfacing: Many types of surfacing have rated capacities for shear. Each, however, has its limits and some materials are not rated for code-acceptable loadings.
3. Lack of continuity of framing: Because it is often not required for gravity load conditions, members may consist of separate pieces that are not spliced for tension or compression continuity.
4. Lack of adequate connections: Load transfers may not be possible without modification for the construction details, involving additional framing, increases nailing, or use of special anchorage devices.

Wood post and beam structures can sometimes be made to function as braced frames or moment resistive frames. A problem of this construction is often the lack of ability for load transfers between members required for resistance to lateral loads. At present this is less the case due to the increasing use of metal framing devices for beam seats, post caps and bases, and so on.

3.2.3.2 Structural masonry

Structural masonry walls have considerable potential for utilization as shear walls. There are, however, a number of problems that must be considered.

1. Increased Load: Due to their weight, stiffness, and brittleness, masonry walls must be designed for higher lateral seismic forces.
2. Limited stress capacity. The unit strength must be adequate for the required stress resistances. In addition, both vertical and horizontal reinforcing is required for major shear wall functions.
3. Cracks and bonding failures. Walls not built to the specifications usually used for seismic resistive construction often have weakened mortar joints and cracking. These reduce seismic resistance, especially in walls with minimal reinforcing.

Anchorage of masonry walls to their supports is usually simply achieved. Resistance to vertical uplift and horizontal sliding can typically be developed by the usual doweling of the vertical wall reinforcing. The anchorage of horizontal diaphragms to masonry walls is another matter and typically requires the use of more "positive" anchoring methods than are ordinarily used when seismic risk is low.

3.2.3.3 Reinforced concrete construction

Poured concrete elements for most structures are ordinarily quite extensively reinforced, thus providing significant compensation for the vulnerability of the tension weak material. This form of constructions has considerable natural potential for lateral force resistance.

Structures consisting of poured concrete columns used in combination with various concrete spanning systems require careful study for the development of seismic resistance as rigid frame structures.

The following are some potential problems:

1. Weight of the structure: This is ordinarily considerably greater than that of wood or steel construction, with the resulting increase in the total seismic force.
2. Adequate reinforcing for seismic effects: Of particular concern are the shears and torsions developed in framing elements and the need for continuity of the reinforcing or anchorage at the intersections of elements.
3. Ductile yielding of reinforcing: This is the desirable failure, even for gravity load resistance. With proper design it is a means for developing a yield character in the otherwise brittle.
4. Detailing of reinforcing: Continuity at splices and adequate anchorage at member intersections must be assured by careful layout of reinforcing installation.
5. Tying of compression bars: column and beam bars should be adequately tied in the region of the point joint.

In masonry structures, considerable cracking is normal in poured concrete structures, due to shrinkage, temperature expansion and contraction... Under the back and forth swaying actions of an earthquake, these cracks will be magnified, and a grinding action may occur.

The grinding action can be a major source of energy absorption but can also result in progressive failures or simply a lot of pulverizing and flaking off of the concrete. If reinforcing is adequate, the structure may remain safe, but the appearance is sure to be affected.

3.2.3.4 Steel frame construction

Structures with frames of steel can often quite readily be made resistive to lateral loads, usually by producing either a braced (trussed) frame or a moment resistive frame. Steel has the advantage of having a high level of resistance to all types of stress and is thus not often sensitive to multidirectional stresses or to rapid stress reversals. In addition, the ductility of ordinary structural steel provides toughness and a high level of energy absorption in the plastic behaviour mode of failure.

The high levels of stress obtained in steel structures are accompanied by high levels of strain, resulting often in considerable deformation. The analysis for deformations is often a critical part of the design of steel structure, especially for moment resistive frames.

The ordinary post and beam steel frame is essentially unstable under lateral loading. Frames must be made self stable with diagonal bracing or with specially designed moment resistive connections or be braced by shear walls.

The trussed steel structure is typically quite stiff, in a class with the wall braced structure. This is an advantage in terms of reduction of building movements under load, but it does mean that the structure must be designed for as much as twice the total lateral force a moment resistive frame.

3.2.3.5 Precast concrete construction

Precast concrete structures present unique problems in terms of lateral bracing. Although they share many characteristics with poured in place concrete structures, they lack the natural member to member continuity that provides considerable lateral stability.

Precast structures must therefore be dealt with in a manner similar to that for post and beam structures of wood or steel. This problem is further magnified by the increased dead weight of the structure, which results in additional lateral force.

Separate precast concrete members are usually attached to each other by means of steel devices that are cast into the members. Sometimes precast concrete spanning members are often also pre-stressed rather than simply utilizing ordinary steel reinforcing. Under lateral load all connections will likely be required to transfer shear, tension, bending, and torsion. Thus for seismic resistance many of the typical connections used for gravity resistance alone will be inadequate.

Because of their weight, precast concrete spanning members may experience special problems due to vertical accelerations. When not sufficiently held down against upward movement, members may be bounced off their supports (a failure described as dancing).

3.2.3.6 Foundations

Where considerable below grade construction occurs, the below grade structure as a whole usually furnishes a solid base for the above grade building. Not many extra details or elements are required to provide for seismic actions. Of principal concern is the tying together of the base of the building, which is where the seismic movements are transmitted to the building. If the base does not hold together as a monolithic unit, the result will be disastrous for the supported building. Buildings without basements or those supported on piles or piers may not ordinarily be sufficiently tied together for this purpose, thus requiring some additional construction.

3.2.3.7 Freestanding structures

In freestanding structures (exterior walls, large signs, water towers, stair towers...) the principal problem is usually the large overturning effect. Rocking and permanent soil deformations that result in vertical tilting must be considered. It is generally advisable to be quite conservative in the design for soil pressure due to the overturning effects. When weight is concentrated at the top the dynamic rotational effect is further increased.

3.3 Design problems

In the developing of resistance to seismic forces is kept in mind throughout the entire process of the building design besides materials, systems and construction details. Some of the major issues that should be kept in mind in the early planning stages are:

- 1) The need for some kind of lateral bracing system. The particular system to be used should be established early, although it may require considerable exploration and development of the options in order to make an informed decision.
- 2) Implications of architectural design decisions. When certain features are desired, it should be clearly understood that there are consequences in the form of problems with regard to lateral design. Some typical situations than commonly cause problems are the following:
 - General complexity and lack of symmetry in the building form.
 - Random arrangement of vertical elements (walls and columns), resulting in a haphazard framing system in general.
 - Lack of continuity in the horizontal structures due to openings, multi-plane roofs, split level floors, or open spaces within the building.
 - Building consisting of aggregates of multiple, semi-detached units, requiring considerations for linking or separation for seismic interaction.
 - Special forms (curved walls, sloping floors...) that limit the performance of the structure.
 - Large spans, heights, or wall openings that limit placement of structural elements and result in high concentrations of load.
 - Use of non-structural material and construction details that result in high vulnerability to damage caused by seismic movements.

- 3) Allowance for lateral design work. Consideration should be given to the time, cost, and scheduling for the lateral investigation and design development.
- 4) Design styles are not developed with seismic effects on the mind. In many situations the design styles of architecture or features are initially developed in areas where seismic effects are not of concern. When these are imported to regions with a high risk of seismic activity, a mismatch often occurs. Various aspects of building form and types of problems that are experienced will be described then.

Despite the complexity of the form of the buildings, investigation for seismic response may often be simplified by the fact that the investigation deal mostly with those elements of the building that are directly involved in the resistance of lateral forces, what it is known as the lateral resistive system.

Thus, most of the building construction, including parts of the structure that function strictly for resistance of gravity loads, may have only minimal involvement in seismic response. These non-structural elements contribute to the load (generated by the building mass) and may offer damping effects to the structure's motion, but may not significantly contribute to the development of resistance to lateral force.

A discussion of the issues relating to building form must include consideration of two separate situations: the form of the building as a whole and the form of the lateral resistive system.

The whole building, including window walls, canopies... must be considered in determining the building mass for the lateral load, but the naked structure must be visualized in order to investigate the effects of lateral forces.

Development of a reasonable lateral resistive structural system within a building may be easy or difficult and for some proposed plan arrangements may be next to impossible. In addition to planning concerns, the vertical massing of the building has various implications on its seismic response.

It needs to keep in mind that dead load is in general a disadvantage in earthquakes, because the lateral force is directly proportional to it. Care should be exercised in developing the construction details and in choosing materials for the building in order to avoid creating unnecessary dead load. This load it is only useful to overturn resistance and is a necessity for the foundations that must anchor the building.

3.3.1 Potential response

The three building profiles represent a range of potential response with regard to the fundamental period of the building and the concerns for lateral deflection.

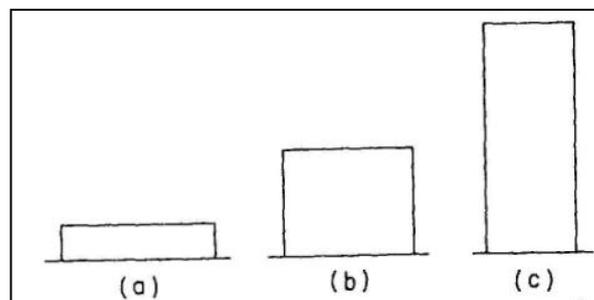


FIGURE 3.14: Potential responses

The short (a), stiff building tends to absorb a larger jolt from an earthquake because of its quick response (short period of natural vibration).

The tall (c), slender building, on the other hand, responds slowly, dissipating some of the energy of the seismic action in its motion. However, the tall building may develop some multimodal response, a whiplash effect, or simply so much actual deflection that it may have problems of its own.

3.3.2 Symmetry and forms

Investigation of the seismic response of a complex building is a difficult problem. Anything done to simplify the investigation will not only make the analysis easier to perform but will tend to make the reliability of the results more certain.

Thus, from a seismic design point of view, buildings with relatively simple forms and with some degree of symmetry usually have the lowest requirements for elaborate or extensive bracing or for complex connections for lateral loads.

When symmetry does not exist, a building tends to experience severe twisting as well as the usual rocking back and forth. The twisting action often has its greatest effects on the joints between elements of the bracing system. Thorough investigation and careful detailing of these joints for construction are necessary for a successful design.

Most buildings are not symmetrical, being sometimes on one axis, often not on any axis. However, real architectural symmetry is not necessarily the true issue in seismic response.

Of critical concern is the alignment of the net effect of the building mass (or the centroid of the lateral force) with the centre of stiffness of the lateral resistive system - most notably the centre of stiffness of the vertical elements of the system.

3.3.3 Stability

The overall inherent stability of a building may be implicit in its vertical massing or profile. The structure (d) has considerable potential for stability with regard to lateral forces, whereas the structure in (e) is highly questionable. Of special concern is the situation in which abrupt change in stiffness occurs in the vertical massing.

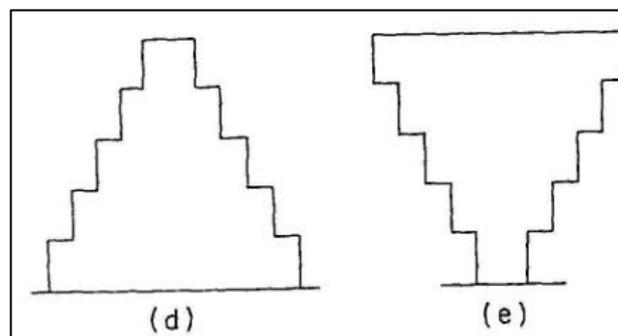


FIGURE 3.15: Potential for stability

3.3.4 Multimassed buildings

When a building is not architecturally symmetrical, the lateral bracing system must either be adjusted so that its centre of stiffness is close to the centroid of the mass or it must be designed for major twisting effects on the building. As the complexity of the building form increases, it may be necessary to consider the building to be multimassed.

Many buildings are multimassed rather than consisting of a single geometric form. Under lateral seismic movement the various parts of this building will have different responses. If the building structure is developed as a single system, the building movements will be very complex, with extreme twisting effects and considerable strain at the points of connection of the discrete parts of the mass.

If the elements of the buildings are separated in parts, the independent movements of these will be different due to their difference in stiffness. It may be possible to permit these independent movements by providing structural connections that are detailed to tolerate the type and magnitude of the actual deformations. Thus, the twisting effects on the building and the strain at the joints between the elements of the mass may be avoided.

There is also the potential for difference in response movements of the different parts of the building. The separation may be created at this connection of the masses to eliminate the separate parts.

However, it may not be feasible or architecturally desirable to make the provisions necessary to achieve either for the types of separation described. The only other option is therefore to design for the twisting effects and the dynamic interactions that result from having a continuous, single structural system for the entire building. The advisability or feasibility of one option over the other is often difficult to establish and may require considerable study of alternate designs.

3.3.5 Linking element

When a building is separated, the linking element that joints the parts, although contiguous with the parts, is unlikely to be capable of holding them together under seismic movements. If it cannot, there are various forms of differential movement that must be provided for. In addition to providing for these movements, it is also necessary to consider the bracing of the linkage element.

If it is not capable of being independently braced, it must be attached to one or the other of the larger elements for support, making for a quite complex study of actions at the connection of the masses. When individual parts of multimassed buildings are joined, there are many potential problems that are described below:

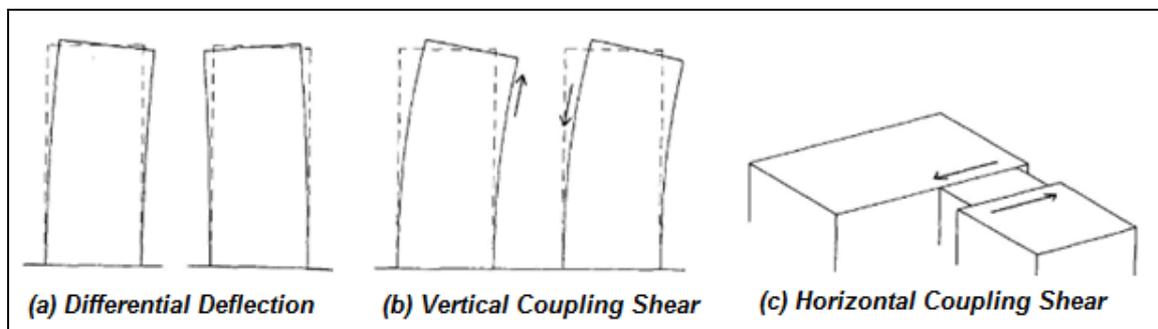


FIGURE 3.16: Types of action for structures

- If the separate masses move at the same time, it is necessary to provide a dimension of separation to prevent them from bumping each other (called battering or hammering). If they are not actually separated, their independent deflections may be a basis for consideration of the forces that must be considered in preventing them from being torn apart.
- If the building is separated in parts, involves a shearing action on the joint similar to that which occurs in laminated elements subjected to bending. For the vertically cantilevered elements, the shear and lateral deflection effects vary from zero at the base to a maximum at the top.
- The horizontal shearing effect is a common type of problem that must be dealt with, as it occurs frequently in one story structures, whereas the vertical shear and lateral deflection problems are usually severe only in taller structures.

3.3.6 Tag along technique

Individual joined masses are sometimes so different in size or stiffness that the indicated solution is to simply attach the smaller part to the larger and let it tag along. In some instances the tag along relationship may be a conditional one. The greater contact area between the parts, the attachments will support better the efforts.

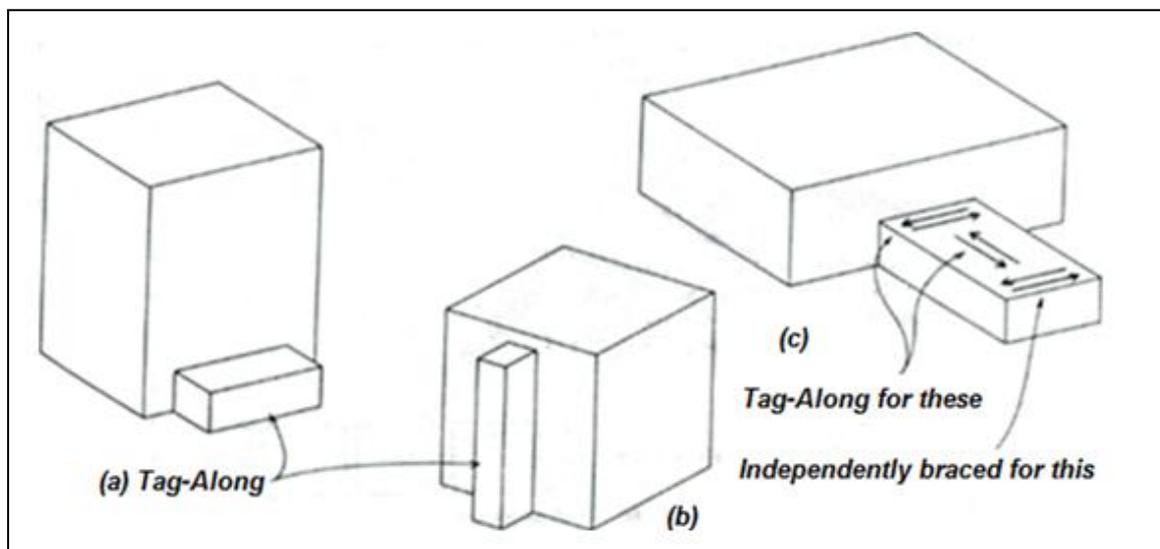


FIGURE 3.17: Tag along technique

The tag along technique is often used for stairs, chimneys, entries and other elements that are part of a building, but are generally outside the main mass. It is also possible to consider the total structural separation of such elements in some cases.

3.3.7 Propagation of loads

The most difficult aspect of visualizing the propagation of loads due to seismic activity is that it is essentially a three dimensional problem. Forces applied to buildings must flow with some direct continuity through the elements of the structure, be transferred effectively from element to element (columns, bearing walls), and eventually be resolved into the ground. Where there are interruptions in the normal flow of the forces, problems will occur.

A common type of discontinuity is that of openings in horizontal and vertical diaphragms. These can be a problem as a result of their location, size, or even shape.

Another discontinuity that must sometimes be dealt with is that of the interrupted multi-store shear wall. It is sometimes possible to redistribute the shear force from an interrupted wall with walls that are sidestepped rather than in the same vertical plane of the upper wall.

Again, the overturn on the upper wall must be accommodated by continuing the structure at the ends of the wall down to the foundation. Sometimes, the uses of individual panels of X-bracing are sufficiently similar in function to the individual panels of the shear wall to make the situation have the same general options and requirements for a solution.

When building is important to consider the subsurface conditions, the topographic situations, the instability conditions and site structure that increases interaction during seismic motion effects on buildings. That is why the ground must be considered to be an element of the lateral resistive system.

3.3.8 Vulnerable elements

There are many commonly used elements of buildings that are especially vulnerable to damage due to earthquakes. Most of these are non-structural, that is, not parts of the structural system for resistance of gravity or lateral loads. Some typical situations are the following:

- **Suspended ceilings:** These are subject to horizontal movement. If not restrained at their edges, they can swing and bump other parts of the construction. Another common failure consists of the dropping of the ceiling due to downward acceleration if the supports are not resistive to a jolting action.

- Cantilevered elements: This elements should be designed (codes criteria) for significant seismic force in a direction perpendicular to the cantilever.
- Miscellaneous suspended objects: Items that are supported by hanging should be studied for the effects of pendulum like movements. Supports should tolerate the movements or should be designed to restrain it.
- Piping: Building movements during seismic activity can cause the rupture of piping that is installed in a conventional manner.
- Stiff weak elements: Any parts of the building construction that are stiff but not strong are usually vulnerable to damage (window glazing, wall and floor tile, masonry...). Reduction of damage and of hazard to occupants requires careful study of installation details for attachment.

3.3.9 The soft story

Any discontinuity that constitutes an abrupt change in the structure is usually a source of some exceptional distress. This is true for static load conditions as well, but is especially critical for dynamic loading conditions.

Any abrupt increase or decrease in stiffness will result in some magnification of deformation and stress in a structure subjected to energy loading. Openings, notches, necking-down points and other form variations, produce these abrupt changes in either the horizontal or vertical structure. An especially critical situation is the called soft story.

The soft story can occur at an upper level. However, it is more common at the ground floor level between a rigid foundation system and some relatively much stiffer upper level system.

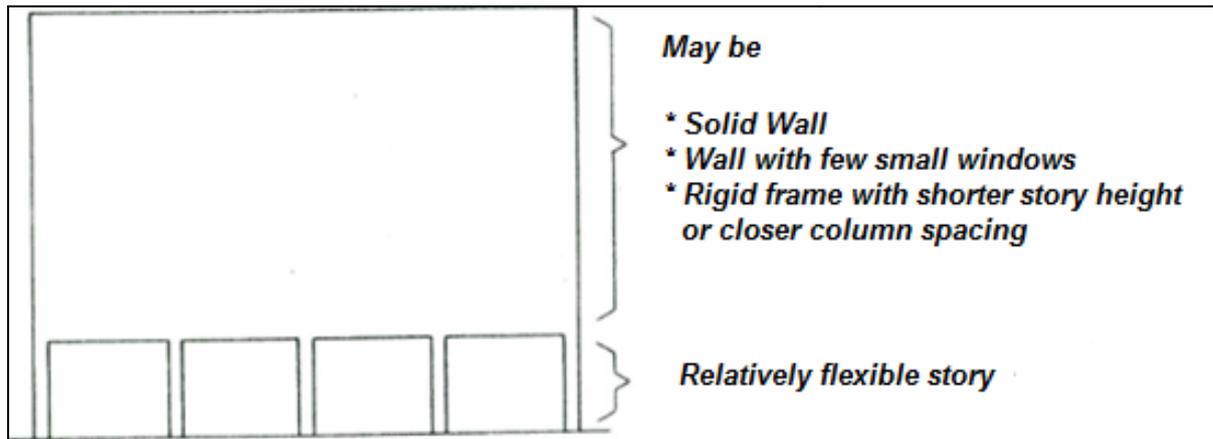


FIGURE 3.18: The soft story

The soft story presents a strong case for a true dynamic analysis or at the least a very conservative design with the static load method.

In the building of the image if it is necessary the open ground floor, there are some possibilities to reduce the soft-story effect.

- Bracing some of the open bays (a).
- Keeping the building plan periphery open while providing a rigidly braced interior (b).
- Increasing the number and/or stiffness of the ground-floor columns for an all rigid frame structure (c).
- Using tapered or arched forms for the ground floor columns to increase their stiffness (d).
- Developing a rigid first story as an upward extension of a heavy foundation structure (e).

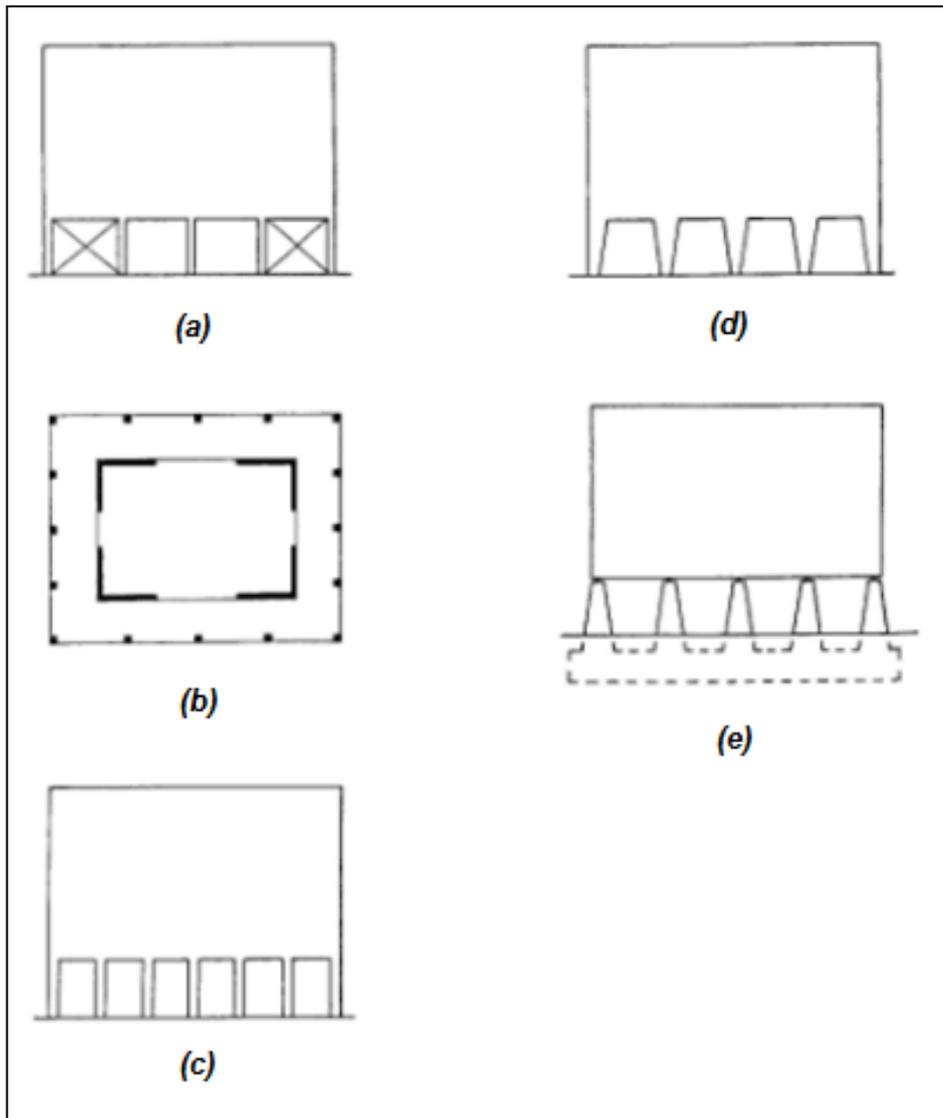


FIGURE 3.19: Some remedies for the soft story

The soft story is actually a method for providing critical damping or major energy absorption, which could be a positive factor in some situations. However, the major stress concentrations and deformations must be carefully provided for, and a true dynamic analysis is certainly indicated.

3.4 Research programs, simulations and latest seismic technologies

3.4.1 Research programs

Research for earthquake engineering covers the following fields: analytical investigation or experimentation intended for discovery, scientific explanation of earthquake engineering related facts, revision of conventional concepts in the light of new findings, and practical application of the developed theories.

Nowadays, there are many universities, laboratories and institutes in the world that work in earthquake research. Among them can be emphasize the NSF (National Science Foundation) and EERI (Earthquake Engineering Research Institute).

The National Science Foundation (NSF) is the main United States government agency that supports fundamental research and education in all fields of earthquake engineering. In particular, it focuses on experimental, analytical, and computational research on design and performance enhancement of structural systems.

The Earthquake Engineering Research Institute (EERI) is a leader in dissemination of earthquake engineering research related information both in the U.S. and globally.

3.4.2 Earthquake simulation

The first earthquake simulations were performed by statically applying some horizontal inertia forces based on scaled peak ground accelerations to a mathematical model of a building. With the further development of computational technologies, static approaches began to give way to dynamic ones.

Dynamic experiments on building and non-building structures may be physical, like shake-table testing, or virtual ones.

In both cases, to verify a structure's expected seismic performance, some researchers prefer to deal with so called "real time-histories" though the last cannot be "real" for a hypothetical earthquake specified by either a building code or by some particular research requirements.

Therefore, there is a strong incentive to engage an earthquake simulation which is the seismic input that possesses only essential features of a real event.

Sometimes, earthquake simulation is understood as a re-creation of local effects of a strong earth shaking.

The simulation can be done by the earthquake shaking table that is a device for shaking structural models or building components with a wide range of simulated ground motions, including reproductions of recorded earthquakes time-histories. Modern tables typically consist of a rectangular platform that is driven in up to six degrees of freedom (DOF) by servo-hydraulic or other types of actuators.



FIGURE 3.20: World's largest earthquake shake table test

Video: <http://www.youtube.com/watch?v=c25HuZeQsyo&feature=related>

Test specimens are fixed to the platform and shaken, often to the point of failure. Using video records and data from transducers, it is possible to interpret the dynamic behaviour of the specimen. Earthquake shaking tables are used extensively in seismic research, as they provide the means to excite structures in such a way that they are subjected to conditions representative of true earthquake ground motions.

3.4.3 Structure simulation

Theoretical or experimental evaluation of anticipated seismic performance mostly requires a structure simulation which is based on the concept of structural likeness or similarity.

Similarity is some degree of analogy or resemblance between two or more objects. The notion of similarity rests either on exact or approximate repetitions of patterns in the compared items.

In general, a building model is said to have similarity with the real object if the two share geometric similarity, kinematic similarity and dynamic similarity.

The most effective type of similarity is Kinematic; when the paths and velocities of moving particles of a model and its prototype are similar.

The ultimate level of kinematic similarity is kinematic equivalence when, in the case of earthquake engineering, time-histories of each story lateral displacements of the model and its prototype would be the same.

3.4.4 Vibration control technologies

Earthquake analysis and design of a structure is commonly performed assuming the structure remains elastic (the design neglects the effects of damage), though inelastic analyses (which takes into account material inelasticity) are increasingly used.

For ordinary design, the actual earthquake forces are reduced by a response modification factor that varies depending on the assumed inherent ductility of the structure, based on its lateral force-resisting system (moment frame, braced, shear wall...) and material (wood, steel, concrete...). This force reduction, along with appropriate safety factors, is combined with gravity and other loads in the design of the overall structure.

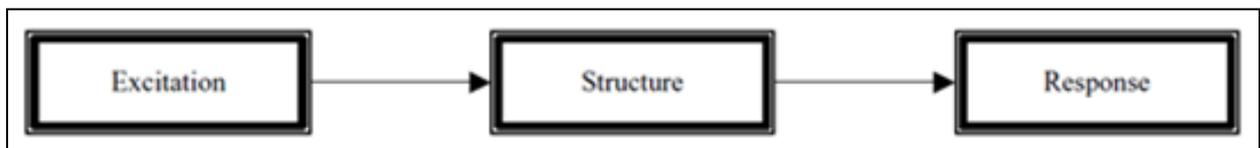


FIGURE 3.21: Conventional structure

Conventional seismic design attempts to make buildings that do not collapse under strong earthquake shaking, but may sustain damage to non structural elements and to some structural members in the building.

This may render the building non-functional after the earthquake, which may be problematic in some structures which need to remain functional in the aftermath of the earthquake.

Special techniques are required to design buildings such that they remain practically undamaged even in a severe earthquake. Buildings with such improved seismic performance usually cost more than normal buildings do. However, this cost is justified through improved earthquake performance.

Seismic vibration control is a set of technical means aimed to mitigate seismic impacts in building and non-building structures. All seismic vibration control devices may be classified as passive, semi-active, active or hybrid.

3.4.4.1 Passive control techniques

Passive control devices have no feedback capability between them, structural elements and the ground.

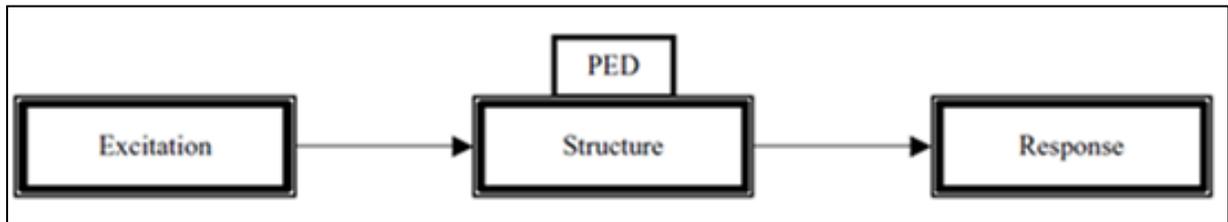


FIGURE 3.22: Structure with passive energy dissipation (PED)

In this section will be mentioned the base isolation, the supplemental damping and the tuned mass damper.

➤ Base isolation

This is the most widely used method against earthquake damage. A base isolated structure is supported by a series of elements which are placed between the building and the building's foundation in such a way that earthquake motions are not transmitted up through the building, or at least greatly reduced.

The isolators are often designed to absorb energy and thus add damping to the system. This helps in further reducing the seismic response of the building.

A careful study is required to identify the most suitable type of device for a particular building. Also, base isolation is not suitable for all buildings.

Most suitable candidates for base-isolation are low to medium-rise buildings rested on hard soil underneath; high-rise buildings or buildings rested on soft soil are not suitable for base isolation.

There are 3 main types of base isolation:

- **Frictionless rollers**

When the ground shakes, the rollers freely roll, but the building above does not move. Thus, no force is transferred to the building due to shaking of the ground; simply, the building does not experience the earthquake.

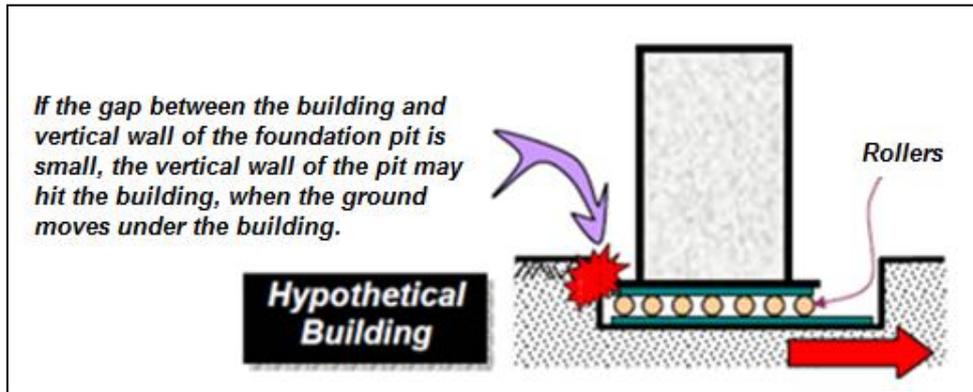


FIGURE 3.23: Frictionless rollers

- **Flexible pads**

If the same building is rested on flexible pads that offer resistance against lateral movements, then some effect of the ground shaking will be transferred to the building above.

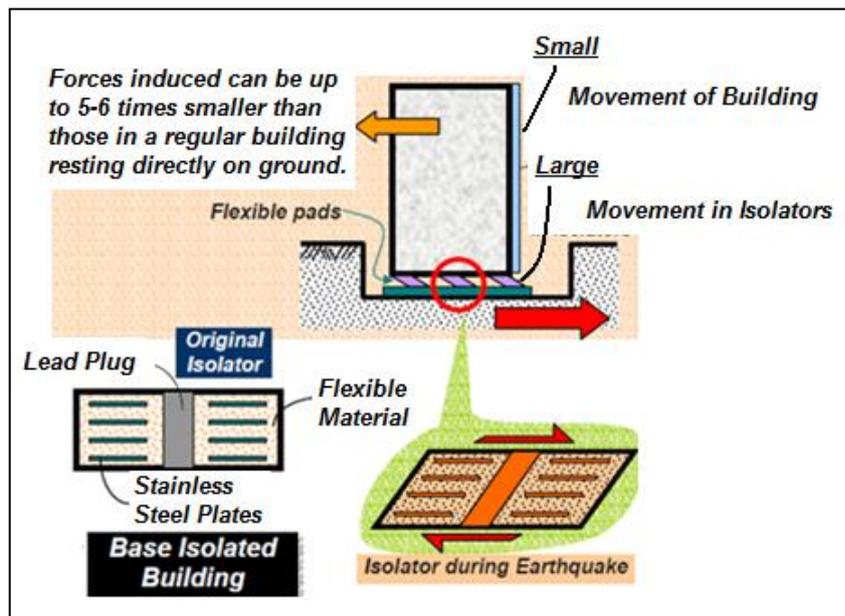


FIGURE 3.24: Flexible pads

If the flexible pads are properly chosen, the forces induced by ground shaking can be a few times smaller than that experienced by the building built directly on ground, namely a fixed base building.

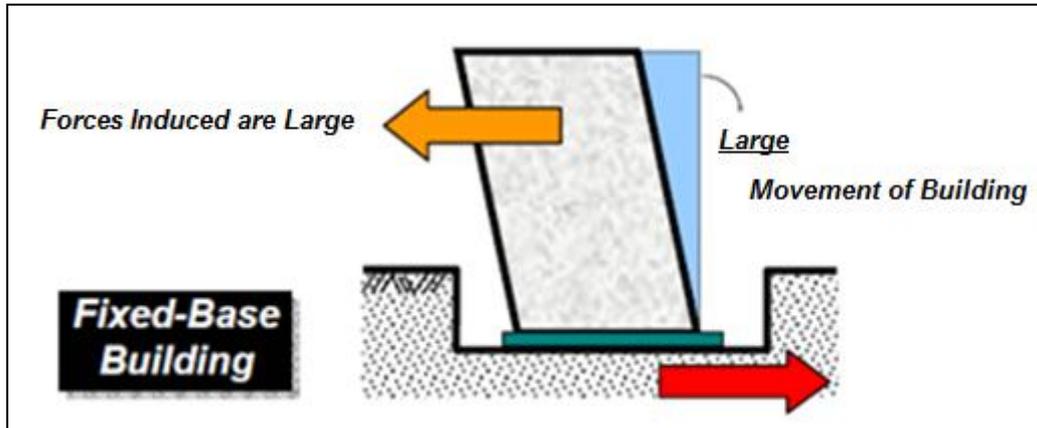


FIGURE 3.25: Fixed-Base building

A flexible pad system is the lead rubber bearing (LRB). This system is made from layers of rubbers sandwiched together with layers of steel. In the middle of the bearing is a solid lead "plug." On top and bottom, the bearing is fitted with steel plates which are used to attach the bearing to the building and foundation. The bearing is very stiff and strong in the vertical direction, but flexible in the horizontal direction.

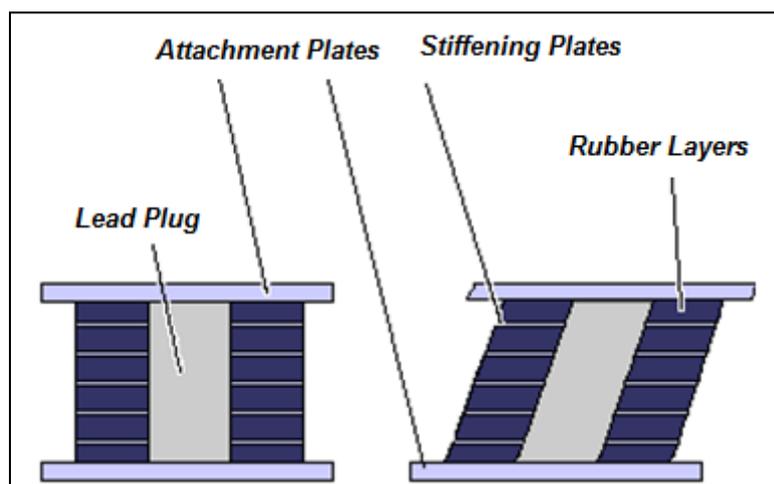


FIGURE 3.26: Lead rubber bearing system

The next figure shows how this isolation system works. As a result of an earthquake (ground moving to the left), the ground beneath each building begins to move. Each building is undergoing displacement towards the right, which is due to inertia.

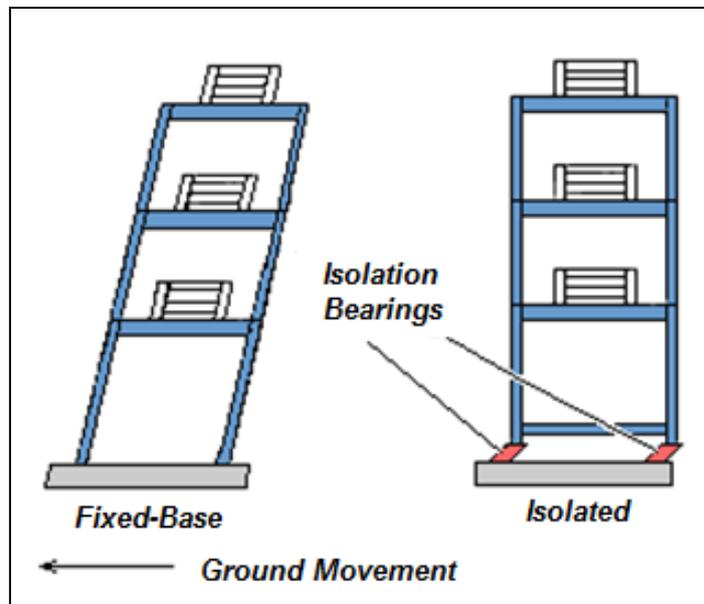


FIGURE 3.27: Comparative between buildings

In addition to displacing to the right, the un-isolated building is also changing shape into more of a parallelogram from a rectangular. This is the process of deforming. And of course, the primary cause of earthquake damage is deformation which the building goes through as a result of inertial force acting on it.

The base-isolated building, though still displacing, retained its original rectangular shape. Only the lead-rubber bearings supporting the building are deformed. The base-isolated building escaped the deformation and damage, which shows that the inertial forces acting on the base-isolated building have been reduced.

Experiments and observations of base-isolated buildings in earthquakes have been shown to reduce building accelerations to as little as 1/4 of the acceleration of fixed-base buildings.

Since the rubber isolation bearings are highly elastic, they don't suffer any damage. The lead plug in the middle of the example bearing experiences the same deformation as the rubber.

However, it also generates heat as it does so. In other words, the lead plug reduces, or dissipates, the energy of motion (kinetic energy) by converting that energy into heat. And by reducing the energy entering the building, it helps to slow and eventually stop the building's vibrations sooner, in other words, it damps the building's vibrations.

- **Spherical sliding isolation**

The building is supported by bearing pads that have a curved surface and low friction.

During an earthquake, the building is free to slide on the bearings. Since the bearings have a curved surface, the building slides both horizontally and vertically.

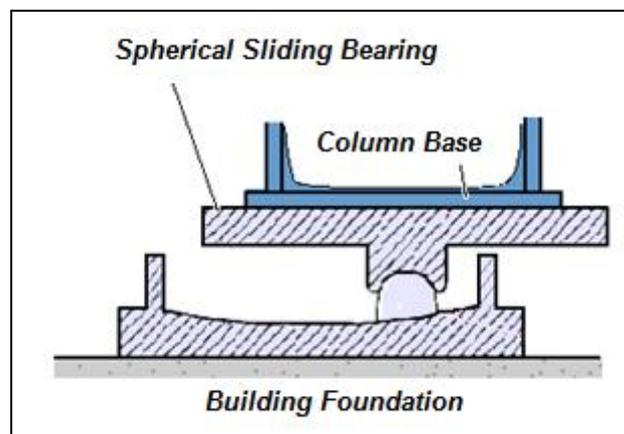


FIGURE 3.28: Spherical sliding isolation

The force needed to move the building upwards limits the horizontal or lateral forces which would otherwise cause building deformations.

Also, by adjusting the radius of the bearing's curved surface, this property can be used to design bearings that also lengthen the building's period of vibration.

➤ **Supplemental dampers**

Typical structures may possess 1% to 5% inherent structural damping. This damping may be contributed from architectural components such as partition walls, ceiling, exterior cladding, and mechanical ducts etc.

Dampers directly provide an additional damping to the structure in the form of discrete devices. Dampers have been designed to provide 5% to 50% of critical damping for many existing and new structures. Dampers are introduced to reduce or eliminate structural yielding and architectural damage.

For both new and existing structures, dampers can provide better and more reliable performance than conventional construction.

Many devices have been thoroughly tested and a rational design procedure is available. Dynamic response calculations are commonly performed to analyze the damped structure. Many damped structures with 20% damping or higher will keep the structure elastic.

There are some groups of dampers that are used in current times. Each group of dampers has specific characteristics, advantages and disadvantages for structural applications.

Design engineers need to understand the static and dynamic behaviour of the device being used.

In this section will be mentioned the following systems:

- Fluid viscous dampers
- Viscoelastic dampers
- Friction dampers
- Metallic yielding dampers

- **Fluid viscous dampers (FVDs)**

FVDs have been widely used in aerospace and military applications since the early 1900's. After the end of the cold war, its technology became available for civilian usage.

Compressible silicon oil flows through orifices with high velocity, generating heat which is radiated into the surrounding air. This hydrodynamic process dissipates the seismic energy.

FVDs add viscous damping to the structure, and can reduce acceleration and displacement for the most of the frequency range.

FVDs are the most useful where engineers desire to reduce displacement without increasing the structure's frequency.

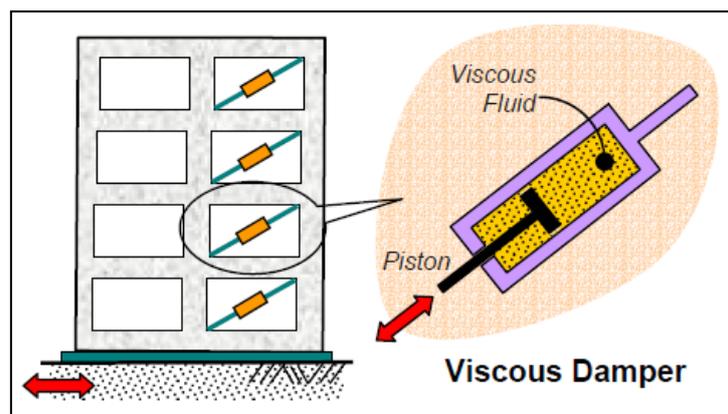


FIGURE 3.29: Viscous Damper

- **Viscoelastic dampers (VEDs)**

VEDs add both stiffness and damping to the structures using inelastic deformation of polymers in the joints between elements.

- **Friction dampers**

Friction Dampers consist of the friction surface clamped together by high strength bolts with slotted holes. Slip force is designed large enough that there is no sliding for wind forces.

However, it slips during large seismic excitations. Friction energy dissipates seismic energy through heat.

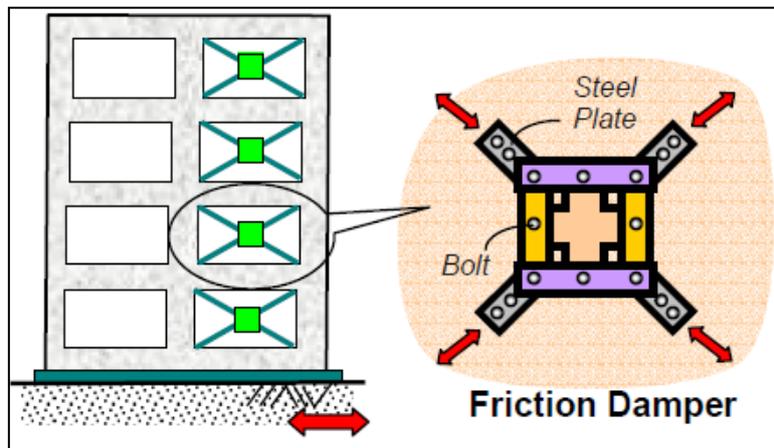


FIGURE 3.30: Friction damper

- **Metallic Yielding Dampers (MYDs)**

Metallic Yielding Dampers are probably the most familiar to structural engineers, since its concept is the same as typical steel seismic force resistive elements such as steel moment frames and braces.

Beam-column connections yield for steel moment frames to absorb the seismic energy. The braces also buckle to absorb the seismic energy. One type of MYD is the buckling restrained brace.

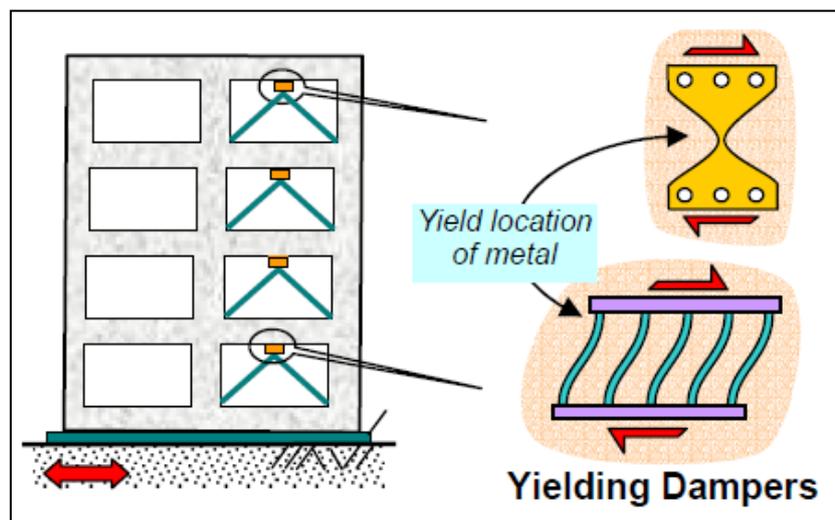


FIGURE 3.31: Yielding dampers

➤ **Tuned mass damper**

The dampers are huge concrete blocks or steel bodies mounted in skyscrapers or other structures, and moved in opposition to the resonance frequency oscillations of the structure by means of springs, fluid or pendulums mechanism. The main objective of the mass dampers is to absorb the resonant portions of the whole wave frequencies band.

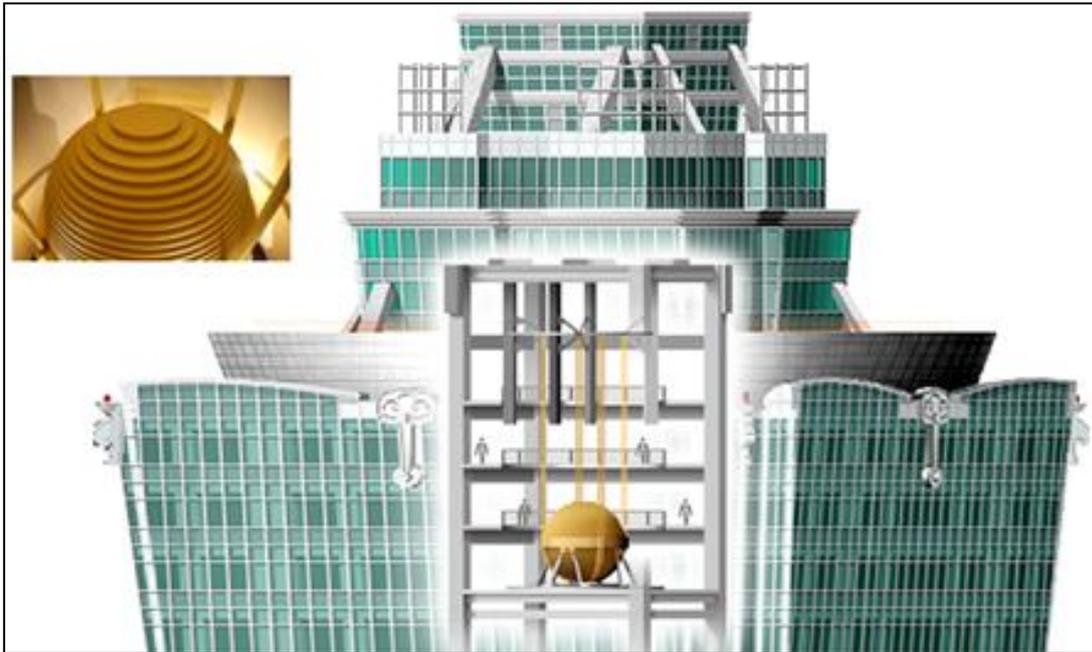


FIGURE 3.32: Tuned mass damper in Taipei 101

3.4.4.2 Active, Semi-active and hybrid control technologies

Active, semi-active and hybrid structural control systems are a natural evolution of passive control technologies such as base isolation and passive energy dissipation.

The possible use of active control systems and some combinations of passive and active systems, so called hybrid systems, as a means of structural protection against wind and seismic loads has received considerable attention in recent years.

Active/hybrid control systems are force delivery devices integrated with real-time processing evaluators/controllers and sensors within the structure. They act simultaneously with the hazardous excitation to provide enhanced structural behaviour for improved service and safety.

Remarkable progress has been made over the last twenty years. The First and Second World Conferences on Structural Control held in 1994 and 1998, respectively, attracted over 700 participants from 17 countries and demonstrated the worldwide interest in structural control.

This rapid growth of research interest and development of active/hybrid structural control systems is in part due to several coordinated research efforts, largely in Japan and US.

Indeed, the most challenging aspect of active control research in civil engineering is the fact that is an integration of a number of diverse disciplines, some of which are not within the domain of traditional civil engineering. These include computer science, data processing, control theory, material science, sensing technology, as well as stochastic processes, structural dynamics, and wind and earthquake engineering.

These coordinated efforts have facilitated collaborative research efforts among researchers from diverse background and accelerated the research to implementation process as one sees today.

➤ **Active structural control**

An active structural control system has the basic configuration as shown schematically in the figure:

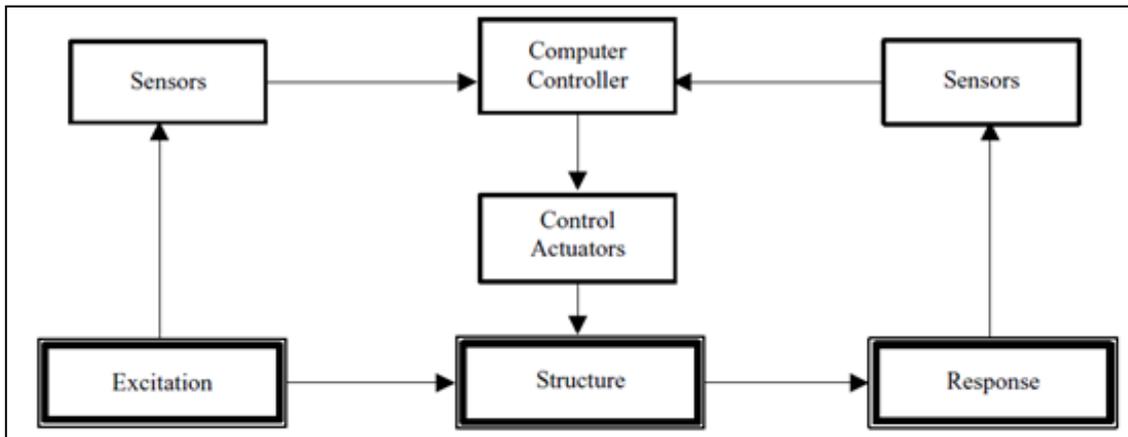


FIGURE 3.33: Structure with active control

It consists of sensors located about the structure to measure either external excitations, or structural response variables, or both; devices to process the measured information and to compute necessary control force needed based on a given control algorithm; and actuators, usually powered by external sources, to produce the required forces.

When only the structural response variables are measured, the control configuration is referred to as feedback control since the structural response is continually monitored and this information is used to make continual corrections to the applied control forces. A feed forward control results when the control forces are regulated only by the measured excitation, which can be achieved, for earthquake inputs, by measuring accelerations at the structural base.

In the case where the information on both the response quantities and excitation are utilized for control design, the term feedback-feedforward control is used.

In comparison with passive control systems, a number of advantages associated with active control systems can be cited; among them are;

- Enhanced effectiveness in response control. The degree of effectiveness is, by and large, only limited by the capacity of the control systems;
- Relative insensitivity to site conditions and ground motion;
- Applicability to multi-hazard mitigation situations; an active system can be used, for example, for motion control against both strong wind and earthquakes;
- Selectivity of control objectives; one may emphasize, for example, human comfort over other aspects of structural motion during noncritical times, whereas increased structural safety may be the objective during severe dynamic loading.

➤ **Semi-Active and hybrid structural control**

The term hybrid control generally refers to a combined passive and active control system as depicted in the figure:

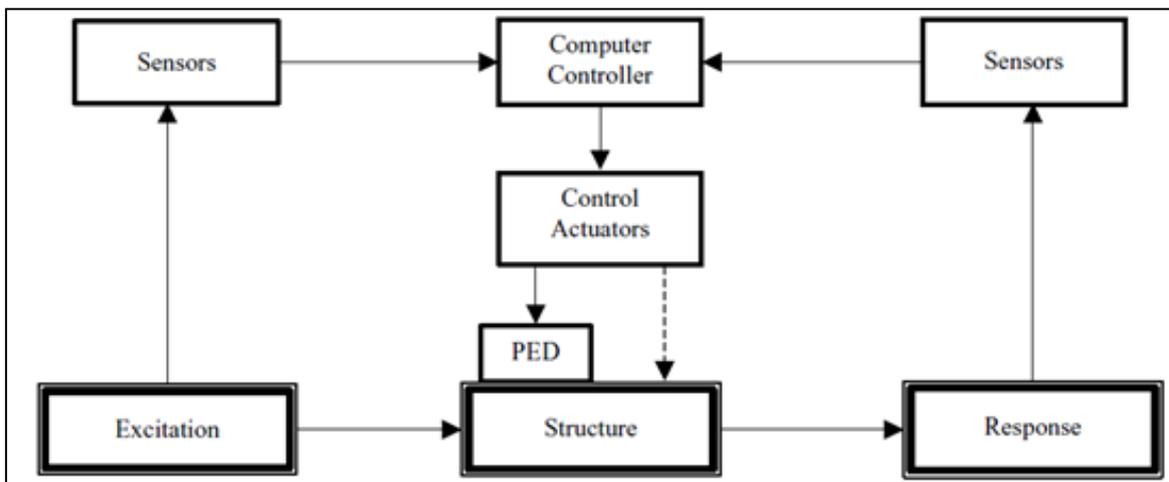


FIGURE 3.34: Structure with hybrid control

Since a portion of the control objective is accomplished by the passive system, less active control effort, implying less power resource, is required.

Similar control resource savings can be achieved using the semi-active control scheme sketched in the next figure:

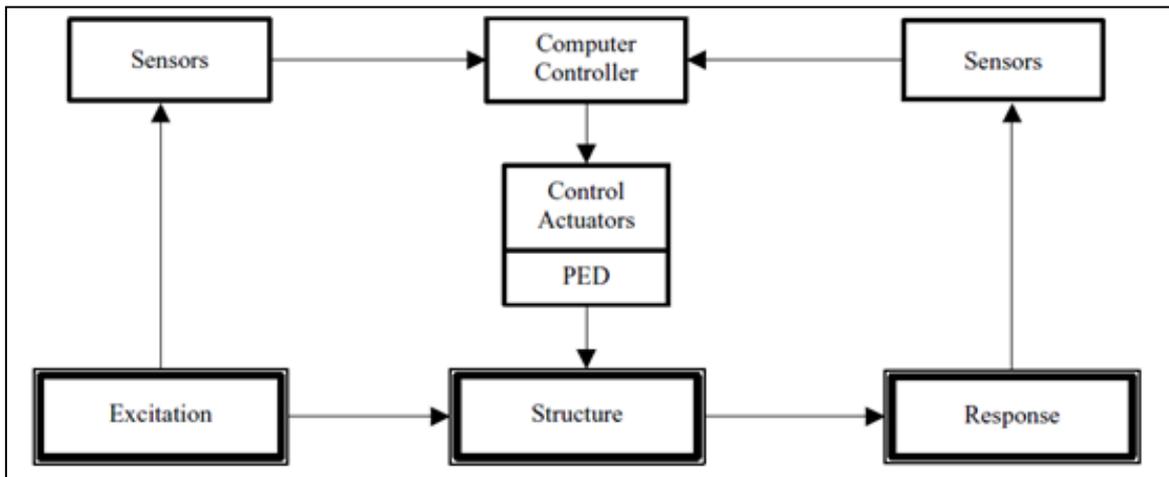


FIGURE 3.35: Structure with semi-active control

The control actuators do not add mechanical energy directly to the structure; hence bounded-input bounded-output stability is guaranteed. Semi-active control devices are often viewed as controllable passive devices.

A side benefit of hybrid and semi-active control systems is that, in the case of a power failure, the passive components of the control still offer some degree of protection, unlike a fully active control system.

In this section several systems will be mentioned:

- Hybrid mass damper systems
- Semi-active damper systems
- Semi-active controllable fluid dampers

- **Hybrid mass damper systems**

The hybrid mass damper (HMD) is the most common control device employed in full-scale civil engineering applications. An HMD is a combination of a passive tuned mass damper (TMD) and an active control actuator.

The ability of this device to reduce structural responses relies mainly on the natural motion of the TMD. The forces from the control actuator are employed to increase the efficiency of the HMD and to increase its robustness to changes in the dynamic characteristics of the structure.

The energy and forces required to operate a typical HMD are far less than those associated with a fully active mass damper system of comparable performance.

Design constraints, such as severe space limitations, can preclude the use of an HMD system. In these cases, the active mass damper is used.

- **Semi-active damper systems**

Control strategies based on semi-active devices combine the best features of both passive and active control systems. The close attention received in this area in recent years can be attributed to the fact that semi-active control devices offer the adaptability of active control devices without requiring the associated large power sources.

In fact, many can operate on battery power, which is critical during seismic events when the main power source to the structure may fail. In addition, as stated earlier, semi-active control devices do not have the potential to destabilize (in the bounded input/bounded output sense) the structural system.

Extensive studies have indicated that appropriately implemented semi-active systems perform significantly better than passive devices and have the potential to achieve the majority of the performance of fully active systems, thus allowing for the possibility of effective response reduction during a wide array of dynamic loading conditions.

One means of achieving a semi-active damping device is to use a controllable, electromechanical, variable-orifice valve to alter the resistance to flow of a conventional hydraulic fluid damper.

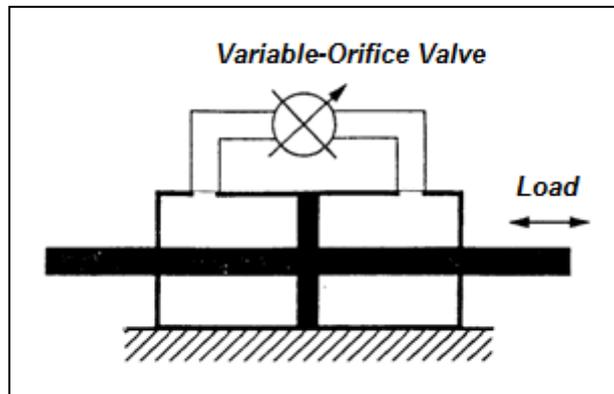


FIGURE 3.36: Semi-active damping

- **Semi-active controllable fluid dampers**

Another class of semi-active devices uses controllable fluids. In comparison with semi-active damper systems described above, an advantage of controllable fluid devices is that they contain no moving parts other than the piston, which makes them simple and potentially very reliable.

The essential characteristics of controllable fluids is their ability to reversibly change from a free-flowing, linear viscous fluid to a semi-solid with a controllable yield strength in milliseconds when exposed to an electric (for electro rheological (ER) fluids) or magnetic (for magneto rheological (MR) fluids) field.

In the case of magneto rheological fluids, they typically consist of micron-sized, magnetically polarisable particles dispersed in a carrier medium such as mineral or silicone oil.

When a magnetic field is applied to the fluid, particle chains form, and the fluid becomes a semi-solid and exhibits viscous-plastic behaviour. Transition to rheological equilibrium can be achieved in a few milliseconds, allowing construction of devices with high bandwidth.

While no full-scale structural applications of magneto rheological devices have taken place to date, their future for civil engineering applications appears to be bright.

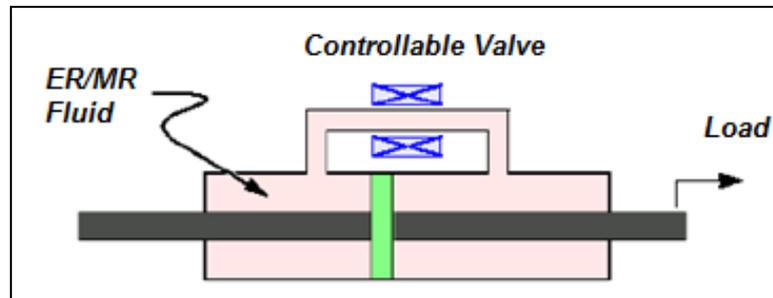


FIGURE 3.37: Controllable fluid damper

3.4.5 Performance based seismic design

The primary focus of most model building codes, including the recently released 2003 International Building Code, is to ensure life safety. Continued operation of a facility and reduction of economic losses associated with earthquake damage to the facility are secondary considerations, if they are considered at all during the design process.

Economic losses sustained in previous earthquakes have highlighted the need for a design methodology that allows the design team, which includes the building owner, architect, and engineer, to understand and choose a desired level of seismic performance for buildings and non-structural components when they are subjected to a specified level of ground motion.

Performance based seismic design allows the design team to work together to determine the appropriate levels of ground motion and performance objectives for the building and the non-structural components in order to meet the owner's expectations.

4 CALCULATIONS, RESULTS AND DISCUSSION

4.1 Buildings subjected to earthquakes

Seismic Analysis is a subset of structural analysis and is the calculation of the response of a building (or non-building) structure to earthquakes.

It is part of the process of structural design, earthquake engineering or structural assessment and retrofit in regions where earthquakes are prevalent.

As seen in the figure, a building has the potential to ‘wave’ back and forth during an earthquake (or even a severe wind storm). This is called the ‘fundamental mode’, and is the lowest frequency of building response. Most buildings, however, have higher modes of response, which are uniquely activated during earthquakes.

The figure just shows the second mode, but there are higher abnormal vibration modes. Nevertheless, the first and second modes tend to cause the most damage in most cases.

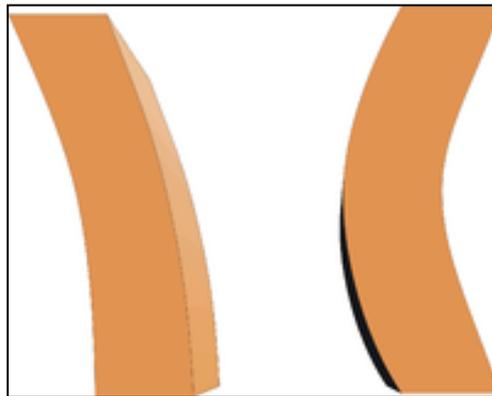


FIGURE 4.1: First and second modes of building seismic response

Structural analysis methods can be divided into the following five categories:

4.1.1 Equivalent static analysis

This approach defines a series of forces acting on a building to represent the effect of earthquake ground motion, typically defined by a seismic design response spectrum.

It assumes that the building responds in its fundamental mode. For this to be true, the building must be low-rise and must not twist significantly when the ground moves.

The response is read from a design response spectrum, given the natural frequency of the building (either calculated or defined by the building code).

The applicability of this method is extended in many building codes by applying factors to account for higher buildings with some higher modes, and for low levels of twisting.

To account for effects due to "yielding" of the structure, many codes apply modification factors that reduce the design forces (e.g. force reduction factors).

4.1.2 Response spectrum analysis

This approach permits the multiple modes of response of a building to be taken into account (in the frequency domain). This is required in many building codes for all except for very simple or very complex structures.

The response of a structure can be defined as a combination of many special shapes (modes) that in a vibrating string correspond to the "harmonics".

Computer analysis can be used to determine these modes for a structure. For each mode, a response is read from the design spectrum, based on the modal frequency and the modal mass, and they are then combined to provide an estimate of the total response of the structure.

Combination methods include the following:

- Absolute - peak values are added together
- Square root of the sum of the squares (SRSS)
- Complete quadratic combination (CQC) - a method that is an improvement on SRSS for closely spaced modes

It should be noted that the result of a response spectrum analysis using the response spectrum from a ground motion is typically different from that which would be calculated directly from a linear dynamic analysis, since phase information is lost in the process of generating the response spectrum.

In cases where structures are either too irregular, too tall or of significance to a community in disaster response, the response spectrum approach is no longer appropriate, and more complex analysis is often required, such as non-linear static or dynamic analysis.

4.1.3 Linear dynamic analysis

Static procedures are appropriate when higher mode effects are not significant. This is generally true for short, regular buildings. Therefore, for tall buildings, buildings with torsional irregularities, or non-orthogonal systems, a dynamic procedure is required.

In the linear dynamic procedure, the building is modelled as a multi-degree-of-freedom (MDOF) system with a linear elastic stiffness matrix and an equivalent viscous damping matrix.

The seismic input is modelled using either modal spectral analysis or time history analysis but in both cases, the corresponding internal forces and displacements are determined using linear elastic analysis.

The advantage of these linear dynamic procedures with respect to linear static procedures is that higher modes can be considered.

However, they are based on linear elastic response and hence the applicability decreases with increasing nonlinear behaviour, which is approximated by global force reduction factors.

In linear dynamic analysis, the response of the structure to ground motion is calculated in the time domain, all phase information is therefore maintained. Only linear properties are assumed. The analytical method can use modal decomposition as a means of reducing the degrees of freedom in the analysis.

4.1.4 Non linear static analysis

In general, linear procedures are applicable when the structure is expected to remain nearly elastic for the level of ground motion or when the design results in nearly uniform distribution of nonlinear response throughout the structure.

As the performance objective of the structure implies greater inelastic demands, the uncertainty with linear procedures increases to a point that requires a high level of conservatism in demand assumptions and acceptability criteria to avoid unintended performance. Therefore, procedures incorporating inelastic analysis can reduce the uncertainty and conservatism.

This approach is also known as "pushover" analysis. A pattern of forces is applied to a structural model that includes non-linear properties (such as steel yield), and the total force is plotted against a reference displacement to define a capacity curve. This can then be combined with a demand curve (typically in the form of an acceleration-displacement response spectrum (ADRS)). This essentially reduces the problem to a single degree of freedom system.

Nonlinear static procedures use equivalent SDOF structural models and represent seismic ground motion with response spectra. Story drifts and component actions are related subsequently to the global demand parameter by the pushover or capacity curves that are the basis of the non-linear static procedures.

4.1.5 Non linear dynamic analysis

Nonlinear dynamic analysis utilizes the combination of ground motion records with a detailed structural model, therefore is capable of producing results with relatively low uncertainty.

In nonlinear dynamic analysis, the detailed structural model subjected to a ground-motion record produces estimates of component deformations for each degree of freedom in the model and the modal responses are combined using schemes such as the square-root-sum-of-squares (SRSS).

In non-linear dynamic analysis, the non-linear properties of the structure are considered as part of a time domain analysis. This approach is the most rigorous, and is required by some building codes for buildings of unusual configuration or of special importance.

However, the calculated response can be very sensitive to the characteristics of the individual ground motion used as seismic input; therefore, several analyses are required using different ground motion records.

4.2 Calculate and compare buildings subjected to horizontal forces

Buildings with torsional irregularities, non-orthogonal systems or tall buildings can be calculated through a linear dynamic procedure.

By using this process, the building is modelled as a MDOF system with a linear elastic stiffness matrix and an equivalent viscous damping matrix.

The seismic input in the calculation of the building is modelled using modal spectral analysis and the corresponding internal forces and displacements are determined using linear elastic analysis.

In this section, buildings will be calculated in two different ways:

- Multi story building with no damping system (conventional construction)
- Multi story buildings with modal damping taking three different damping ratios ($\xi = 0.01$, $\xi = 0.03$, $\xi = 0.05$)

The calculations will be performed by using a mathematics program called “Mathematica 6.0”. Note that the processes of calculations can be consulted in Annex 1: Calculations, and that the graphics representations of the responses of each floor of the buildings can be consulted in Annex 2: Graphics.

4.2.1 The building

Consider a simple model of horizontal vibration of a four story building ($n=4$) subject to a force that gives the building an initial displacement of:

$$X(0) = [0.025, 0.020, 0.01, 0.001]^T$$

In modelling buildings it is known that most of the mass is in the floor of each section and that the walls can be treated as mass less columns providing lateral stiffness.

Some reasonable values for a building are $m_1 = m_2 = m_3 = m_4 = 4000\text{kg}$ and $k_1 = k_2 = k_3 = k_4 = 5000\text{N/m}$.

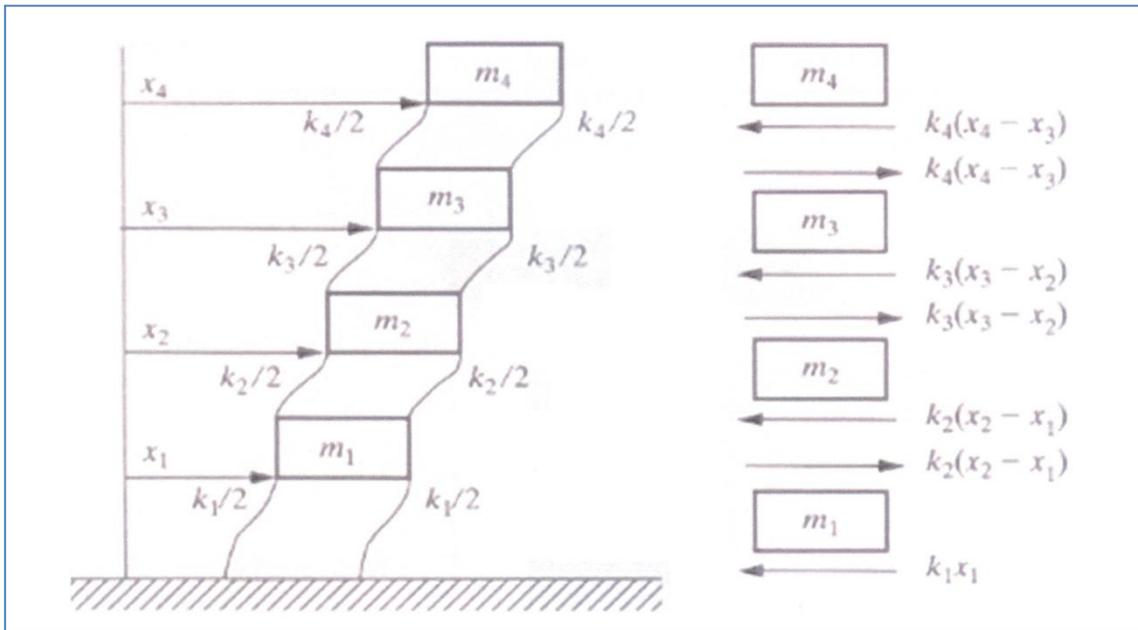


FIGURE 4.2: Four story building subjected to horizontal forces

4.2.2 Calculation of a multi story building with no damping system

The building designed without a damping system has been calculated by simple modal analysis.

In this case, the building can be represented as follows:

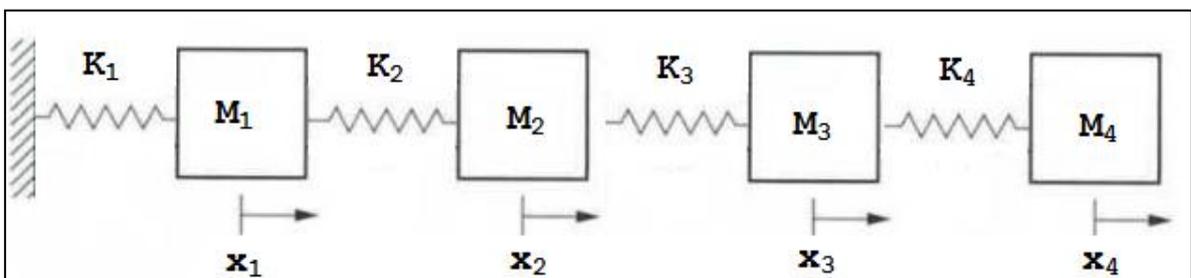


FIGURE 4.3: Four degree of freedom system with no damping

Natural frequencies, modal shapes, phase angle and modal participation factors obtained through “Mathematica 6.0” for the multi story building with no damping system are the following:

- Natural frequencies

Natural frequency for the first floor: $W_1 = 0.388289 \text{ rad/s}$

Natural frequency for the second floor: $W_2 = 1.11803 \text{ rad/s}$

Natural frequency for the third floor: $W_3 = 1.71293 \text{ rad/s}$

Natural frequency for the fourth floor: $W_4 = 2.10122 \text{ rad/s}$

- Modal shapes

Modal shape for the first floor:

$$U_1 = \begin{pmatrix} 0.114007 \\ 0.214263 \\ 0.288675 \\ 0.328269 \end{pmatrix}$$

Modal shape for the 2nd floor:

$$U_2 = \begin{pmatrix} 0.288675 \\ 0.288675 \\ 0. \\ -0.288675 \end{pmatrix}$$

Modal shape for the 3rd floor:

$$U_3 = \begin{pmatrix} 0.328269 \\ -0.114007 \\ -0.288675 \\ 0.214263 \end{pmatrix}$$

Modal shape for the 4th floor:

$$U_4 = \begin{pmatrix} -0.214263 \\ 0.328269 \\ -0.288675 \\ 0.114007 \end{pmatrix}$$

- Phase angle $\phi = 90^\circ$ or 1.57 rad .

- Modal participation factors

Modal participation factor for the first floor: $d_1 = 0.0414$

Modal participation factor for the second floor: $d_2 = 0.0508068$

Modal participation factor for the third floor: $d_3 = 0.0130164$

Modal participation factor for the fourth floor: $d_4 = -0.00625569$

The responses, displacements (m) respect time (sec), of the different floors of the building are expressed in the following equations:

$$x_1(t) = 0.0047 \cos(0.3883t) + 0.0147 \cos(1.1180t) + 0.0043 \cos(1.7129t) + 0.0013 \cos(2.1012t)$$

$$x_2(t) = 0.0089 \cos(0.3883t) + 0.0147 \cos(1.1180t) - 0.0015 \cos(1.7129t) - 0.0021 \cos(2.1012t)$$

$$x_3(t) = 0.012 \cos(0.3883t) + 0 \cos(1.1180t) - 0.0038 \cos(1.7129t) + 0.0018 \cos(2.1012t)$$

$$x_4(t) = 0.0136 \cos(0.3883t) - 0.0147 \cos(1.1180t) + 0.0028 \cos(1.7129t) - 0.0007 \cos(2.1012t)$$

4.2.3 Calculation of a multi story building with modal damping

Viscous energy dissipation can be introduced to the modal analysis done previously.

Viscous damping does provide an excellent model in many physical situations and represents a significant improvement over the undamped model.

The simplest method of modelling damping is to use modal damping, where a ratio assigned by experience or measurement is used, ξ_L .

The value of the ratio has to be between 0 and 1, but usually ξ_L , is small unless the structures contains viscoelastic material or a hydraulic damper in present. Common values are $0 \leq \xi \leq 0.05$.

In this case, the building can be represented as follows:

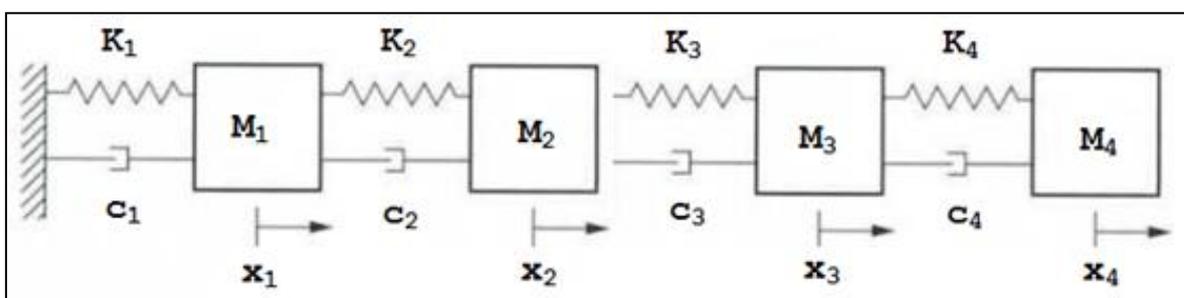


FIGURE 4.4: Four degree of freedom system with viscous damping

In this section, three buildings are going to be calculated, such that each building has a different damping ratio; $\zeta = 0.01$, $\zeta = 0.03$ and $\zeta = 0.05$.

4.2.3.1 Calculation of a building with modal damping ($\zeta = 0.01$)

For any value of damping ratio modal shapes are unchanged. As $\zeta = 0.01$, natural frequencies and modal participation factors can be considered the same as the building without damping system. The phase angle instead has to be calculated.

- Phase angle $\phi = 89.427^\circ$ or 1.56 rad.

The responses, displacements (m) respect time (sec), of the different floors of the building are expressed in the following equations:

$$x_1(t) = 0.0047 e^{-0.00388t} \sin(0.3883t + 1.56) + 0.0147 e^{-0.01118t} \sin(1.1180t + 1.56) \\ + 0.0043 e^{-0.01713t} \sin(1.7129t + 1.56) + 0.0013 e^{-0.02109t} \sin(2.1012t + 1.56)$$

$$x_2(t) = 0.0089 e^{-0.00388t} \sin(0.3883t + 1.56) + 0.0147 e^{-0.01118t} \sin(1.1180t + 1.56) \\ - 0.0015 e^{-0.01713t} \sin(1.7129t + 1.56) - 0.0021 e^{-0.02109t} \sin(2.1012t + 1.56)$$

$$x_3(t) = 0.012 e^{-0.00388t} \sin(0.3883t + 1.56) + 0 e^{-0.01118t} \sin(1.1180t + 1.56) \\ - 0.0038 e^{-0.01713t} \sin(1.7129t + 1.56) + 0.0018 e^{-0.02109t} \sin(2.1012t + 1.56)$$

$$x_4(t) = 0.0136 e^{-0.00388t} \sin(0.3883t + 1.56) - 0.0147 e^{-0.01118t} \sin(1.1180t + 1.56) \\ + 0.0028 e^{-0.01713t} \sin(1.7129t + 1.56) - 0.0007 e^{-0.02109t} \sin(2.1012t + 1.56)$$

4.2.3.2 Calculation of a building with modal damping ($\zeta = 0.03$)

For any value of damping ratio modal shapes are unchanged and modal participation factors can be considered the same as the building without damping system.

Natural frequencies and phase obtained through Mathematica for the multi story building with $\zeta = 0.03$, are the following:

- Natural frequencies

Natural frequency for the first floor: $W_1 = 0.38809$ rad/s

Natural frequency for the second floor: $W_2 = 1.11753$ rad/s

Natural frequency for the third floor: $W_3 = 1.71216$ rad/s

Natural frequency for the fourth floor: $W_4 = 2.10027$ rad/s

- Phase angle $\phi = 88.28^\circ$ or 1.54 rad.

The responses, displacements (m) respect time (sec), of the different floors of the building are expressed in the following equations:

$$x_1(t) = 0.0047 e^{-0.011648t} \sin(0.3883t + 1.54) + 0.0147 e^{-0.0335409t} \sin(1.11753t + 1.54) \\ + 0.0043 e^{-0.0513879t} \sin(1.71216t + 1.54) + 0.0013 e^{-0.0630388t} \sin(2.10027t + 1.54)$$

$$x_2(t) = 0.0089 e^{-0.011648t} \sin(0.3883t + 1.54) + 0.0147 e^{-0.0335409t} \sin(1.11753t + 1.54) \\ - 0.0015 e^{-0.0513879t} \sin(1.71216t + 1.54) - 0.0021 e^{-0.0630388t} \sin(2.10027t + 1.54)$$

$$x_3(t) = 0.012 e^{-0.011648t} \sin(0.3883t + 1.54) + 0 e^{-0.0335409t} \sin(1.11753t + 1.54) \\ - 0.0038 e^{-0.0513879t} \sin(1.71216t + 1.54) + 0.0018 e^{-0.0630388t} \sin(2.10027t + 1.54)$$

$$x_4(t) = 0.0136 e^{-0.011648t} \sin(0.3883t + 1.54) - 0.0147 e^{-0.0335409t} \sin(1.11753t + 1.54) \\ + 0.0028 e^{-0.0513879t} \sin(1.71216t + 1.54) - 0.0007 e^{-0.0630388t} \sin(2.10027t + 1.54)$$

4.2.3.3 Calculation of a building with modal damping ($\xi = 0.05$)

For any value of damping ratio modal shapes are unchanged and modal participation factors can be considered the same as the building without damping system.

Natural frequencies and phase obtained through Mathematica for the multi story building ($\xi = 0.05$) are the following:

- Natural frequencies

Natural frequency for the first floor: $W_1 = 0.3878$ rad/s

Natural frequency for the second floor: $W_2 = 1.11663$ rad/s

Natural frequency for the third floor: $W_3 = 1.71078$ rad/s

Natural frequency for the fourth floor: $W_4 = 2.09859$ rad/s

- Phase angle $\phi = 87.134^\circ$ or 1.52 rad.

The responses, displacements (m) respect time (sec), of the different floors of the building are expressed in the following equations:

$$x_1(t) = 0.0047 e^{-0.01941t} \sin(0.3878t + 1.52) + 0.0147 e^{-0.0559t} \sin(1.11663t + 1.52) \\ + 0.0043 e^{-0.085646t} \sin(1.71078t + 1.52) + 0.0013 e^{-0.105081t} \sin(2.09859t + 1.52)$$

$$x_2(t) = 0.0089 e^{-0.01941t} \sin(0.3878t + 1.52) + 0.0147 e^{-0.0559t} \sin(1.11663t + 1.52) \\ - 0.0015 e^{-0.085646t} \sin(1.71078t + 1.52) - 0.0021 e^{-0.105081t} \sin(2.09859t + 1.52)$$

$$x_3(t) = 0.012 e^{-0.01941t} \sin(0.3878t + 1.52) + 0 e^{-0.0559t} \sin(1.11663t + 1.52) \\ - 0.0038 e^{-0.085646t} \sin(1.71078t + 1.52) + 0.0018 e^{-0.105081t} \sin(2.09859t + 1.52)$$

$$x_4(t) = 0.0136 e^{-0.01941t} \sin(0.3878t + 1.52) - 0.0147 e^{-0.0559t} \sin(1.11663t + 1.52) \\ + 0.0028 e^{-0.085646t} \sin(1.71078t + 1.52) - 0.0007 e^{-0.105081t} \sin(2.09859t + 1.52)$$

4.2.4 Comparison of the multi story buildings

Previously, four buildings with the same mass and stiffness values, and subjected to the same horizontal forces have been calculated.

The first building is designed without a damping system (conventional construction), so that, the calculation has been done through simple modal analysis.

The other buildings are designed with a damping system, such that each building has a different damping ratio. In these cases the calculations have been done by modal damping analysis.

The responses of the different floors of the buildings can be consulted in Annex 2: Graphics.

Comparing one by one the graphics, where the responses of the buildings are represented, it is possible to reach the following conclusions:

The modal participations are the same for all the buildings and, as d_3 and d_4 are smaller than the factors d_1 and d_2 , mode one (w_1) and mode two (w_2) dominate the responses in all the buildings.

Is clearly seen in the graphics that the displacements increases when ascend in the floors of the building.

In buildings designed with the damping system, is clearly seen that the responses of the floors decrease when damping ratio increases. It is determined that buildings with this kind of systems suffer less under horizontal forces comparing with buildings designed only with conventional construction.

It is determined that the existing buildings should be designed with damping systems to prevent damages on the structures and even prevent the total collapse of the building, instead of designing them taking into account only conventional considerations.

5 CONCLUSIONS

Through this document has been highlighted the need to investigate and develop new seismic designs in order to reduce socio-economic effects and the countless deaths that produce earthquakes.

The objective in construction design is not only to maintain buildings without overthrow, but also provide them sufficient stand time, to have the possibility to dislodge people before the collapse of the building. Other aim is to construct buildings capable to withstand ground movements with a maximum stipulated.

Foresee the consequences that can produce earthquakes on buildings and evaluate their response to a particular input motion are problems that must be solved. So that, engineers and architects try to solve them and design buildings according to construction codes.

Nowadays there are various options to meet the targets set in construction design.

On the one hand, buildings can be constructed using conventional construction. Buildings are designed and dimensioned taking into account that earthquakes forces are reduced by a response modification factor that varies depending on the assumed inherent ductility of the structure, based on its lateral force-resisting system (moment frame, braced, shear wall...) and material (wood, steel, concrete...). This force reduction, along with appropriate safety factors, is combined with gravity and other loads in the design of the overall structure.

On the other hand, vibration control technologies can be used that are a set of technical means aimed to mitigate seismic impacts in building and non-buildings structures. Buildings with such improved seismic performance usually cost more than normal buildings do.

The seismic vibration control devices can be classified as passive, semi-active, active or hybrid systems.

These systems provide to conventional building a greater capacity to withstand vibration and reduce the seismic impact.

Semi-active and hybrid systems are the more important inside vibration control devices, since a portion of the control is accomplished by the passive system, so that, less active control effort (implying less power resource) is required.

A side benefit of hybrid and semi-active control systems is that, in the case of a power failure, the passive components of the control still offer some degree of protection, unlike a fully active control system.

In the section of calculations, four buildings have been calculated in two different ways. The first building has been designed only with conventional construction and the others with a damping system (passive control device), such that each building has a different damping ratio.

It is determined that buildings with this kind of systems suffer less under horizontal forces comparing with buildings designed only with conventional construction, and that the responses of the buildings decreases when damping ratio increases.

Summarizing the above information, it is concluded that the development of seismic design is really important to construct structures that could withstand the devastating effects of earthquakes.

6 RECOMMENDATIONS

Seismic engineering and structural engineering, continuously work to develop and improve seismic construction design and create new vibration control technologies.

It is possible to get a great variety of data and information through a tracing of earthquakes that occur in the world. In this way, a number of statistics can be done and even the earthquakes can be simulated on the shaking tables, with the aims to see their characteristics and the consequences that produce and accordingly, develop new construction codes and new earthquake-resistant legislations.

Earthquakes are natural phenomena that affect the entire world, so that, engineers, architects... not have to be the only ones that try to find solutions to reduce the earthquakes effects, but also implies the need for collaboration of governments and citizens.

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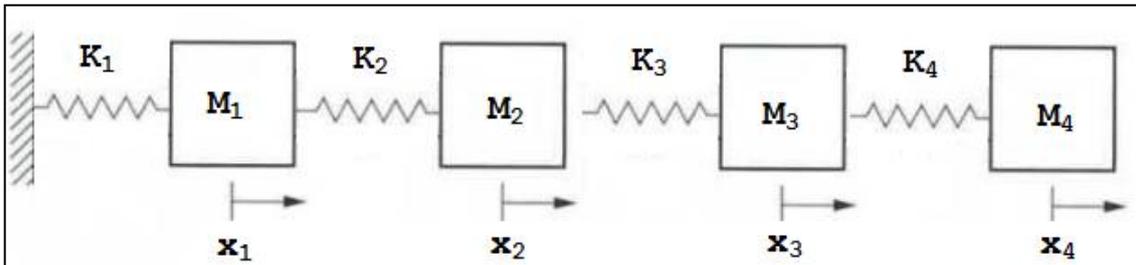
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ANNEX 1: CALCULATIONS

1.1. Calculation of a multi story building (Conventional construction)

- 1) For each mass in the system and/or for each degree of freedom, there corresponds a coordinate $x_i(t)$ describing its motion in one dimension; this gives rise to an $n \times 1$ vector $x(t)$, with $n \times n$ mass matrix M and stiffness matrix K satisfying,

$$m\ddot{x} + kx = 0$$



Develop the equations of motion for the building ($n=4$):

$$\begin{aligned} M_1 \ddot{X}_1 &= -K_1 X_1 - K_2 X_1 + K_2 X_2 \\ M_2 \ddot{X}_2 &= -K_2 X_2 + K_2 X_1 - K_3 X_2 + K_3 X_3 \\ M_3 \ddot{X}_3 &= -K_3 X_3 + K_3 X_2 - K_4 X_3 + K_4 X_4 \\ M_4 \ddot{X}_4 &= -K_4 X_4 + K_4 X_3 \end{aligned}$$

$$\begin{aligned} M_1 W_1^2 X_1 &= (K_1 + K_2) X_1 + (-K_2) X_2 \\ M_2 W_2^2 X_2 &= (-K_2) X_1 + (K_2 + K_3) X_2 + (-K_3) X_3 \\ M_3 W_3^2 X_3 &= (-K_3) X_2 + (K_3 + K_4) X_3 + (-K_4) X_4 \\ M_4 W_4^2 X_4 &= (-K_4) X_3 + (K_4) X_4 \end{aligned}$$

$$\ddot{X} = W^2 X$$

Expressing the terms in matrix form and substituting values:

MatrixForm [m]

$$\begin{pmatrix} k_1 + k_2 & -k_2 & 0 & 0 \\ -k_2 & k_2 + k_3 & -k_3 & 0 \\ 0 & -k_3 & k_3 + k_4 & -k_4 \\ 0 & 0 & -k_4 & k_4 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{pmatrix} = \frac{MW^2}{K} \begin{pmatrix} m_1 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 \\ 0 & 0 & m_3 & 0 \\ 0 & 0 & 0 & m_4 \end{pmatrix}$$

$$\begin{pmatrix} 10 \cdot 10^3 & -5 \cdot 10^3 & 0 & 0 \\ -5 \cdot 10^3 & 10 \cdot 10^3 & -5 \cdot 10^3 & 0 \\ 0 & -5 \cdot 10^3 & 10 \cdot 10^3 & -5 \cdot 10^3 \\ 0 & 0 & -5 \cdot 10^3 & 5 \cdot 10^3 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{pmatrix} = W^2 \begin{pmatrix} 4 \cdot 10^3 & 0 & 0 & 0 \\ 0 & 4 \cdot 10^3 & 0 & 0 \\ 0 & 0 & 4 \cdot 10^3 & 0 \\ 0 & 0 & 0 & 4 \cdot 10^3 \end{pmatrix}$$

STIFFNESS MATRIX MASS MATRIX

- 2) In this example the mass matrix is diagonal and the matrix square root, $M^{1/2}$, becomes simply,

$$M^{1/2} = \begin{pmatrix} \sqrt{m_1} & 0 & 0 & 0 \\ 0 & \sqrt{m_2} & 0 & 0 \\ 0 & 0 & \sqrt{m_3} & 0 \\ 0 & 0 & 0 & \sqrt{m_4} \end{pmatrix} = \begin{pmatrix} \sqrt{4} & 0 & 0 & 0 \\ 0 & \sqrt{4} & 0 & 0 \\ 0 & 0 & \sqrt{4} & 0 \\ 0 & 0 & 0 & \sqrt{4} \end{pmatrix} = 2 \mathbf{I} = 2 \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

The inverse of the diagonal matrix $M^{1/2}$, denoted $M^{-1/2}$, becomes simply,

$$M^{-1/2} = \begin{pmatrix} \frac{1}{\sqrt{m_1}} & 0 & 0 & 0 \\ 0 & \frac{1}{\sqrt{m_2}} & 0 & 0 \\ 0 & 0 & \frac{1}{\sqrt{m_3}} & 0 \\ 0 & 0 & 0 & \frac{1}{\sqrt{m_4}} \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{4}} & 0 & 0 & 0 \\ 0 & \frac{1}{\sqrt{4}} & 0 & 0 \\ 0 & 0 & \frac{1}{\sqrt{4}} & 0 \\ 0 & 0 & 0 & \frac{1}{\sqrt{4}} \end{pmatrix} = \frac{1}{2} \mathbf{I} = \frac{1}{2} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

- 3) Calculate K^* that is a symmetric matrix cause, $K^* = (M^{-1/2}K M^{-1/2})^T = M^{-1/2}K M^{-1/2}$.

Stiffness Matrix

$k = \{\{10, -5, 0, 0\}, \{-5, 10, -5, 0\}, \{0, -5, 10, -5\}, \{0, 0, -5, 5\}\}$

$\{\{10, -5, 0, 0\}, \{-5, 10, -5, 0\}, \{0, -5, 10, -5\}, \{0, 0, -5, 5\}\}$

$k // \text{MatrixForm}$

$$\begin{pmatrix} 10 & -5 & 0 & 0 \\ -5 & 10 & -5 & 0 \\ 0 & -5 & 10 & -5 \\ 0 & 0 & -5 & 5 \end{pmatrix}$$

$M^{-1/2}$

$m1 = \{\{0.5, 0, 0, 0\}, \{0, 0.5, 0, 0\}, \{0, 0, 0.5, 0\}, \{0, 0, 0, 0.5\}\}$

$\{\{0.5, 0, 0, 0\}, \{0, 0.5, 0, 0\}, \{0, 0, 0.5, 0\}, \{0, 0, 0, 0.5\}\}$

$m1 // \text{MatrixForm}$

$$\begin{pmatrix} 0.5 & 0 & 0 & 0 \\ 0 & 0.5 & 0 & 0 \\ 0 & 0 & 0.5 & 0 \\ 0 & 0 & 0 & 0.5 \end{pmatrix}$$

So that, K^* ,

$$\text{MatrixForm [m1.k.m1]>(*Obtention of k*)}$$

$$\begin{pmatrix} 2.5 & -1.25 & 0. & 0. \\ -1.25 & 2.5 & -1.25 & 0. \\ 0. & -1.25 & 2.5 & -1.25 \\ 0. & 0. & -1.25 & 1.25 \end{pmatrix}$$

- 4) Calculate through Mathematica, the symmetric eigenvalues and eigenvectors for k^* in order to get natural frequencies (W_i) and mode shapes (V_i).

$$\det (\lambda I - k^*) = 0$$

$$(k^* - \lambda I) v = 0$$

$$\begin{pmatrix} 2.5 - \lambda & -1.25 & 0 & 0 \\ -1.25 & 2.5 - \lambda & -1.25 & 0 \\ 0 & -1.25 & 2.5 - \lambda & -1.25 \\ 0 & 0 & -1.25 & 1.25 - \lambda \end{pmatrix} v = 0$$

$$\text{Eigenvalues[u]}$$

$$\{4.41511, 2.93412, 1.25, 0.150768\}$$

$$\text{Eigenvectors[u]}$$

$$\{\{-0.42852507312435956, 0.6565385020081387, -0.5773502691896257, 0.22801342888377912\},$$

$$\{0.6565385020081387, -0.22801342888377918, -0.5773502691896257, 0.42852507312435956\},$$

$$\{0.5773502691896257, 0.5773502691896257, 0., -0.5773502691896257\},$$

$$\{0.2280134288837792, 0.42852507312435956, 0.5773502691896258, 0.6565385020081387\}\}$$

$$v1 = \{0.2280134288837792, 0.42852507312435956, 0.5773502691896258, 0.6565385020081387\} // \text{MatrixForm}$$

$$\begin{pmatrix} 0.228013 \\ 0.428525 \\ 0.57735 \\ 0.656539 \end{pmatrix}$$

$$v2 = \{0.5773502691896257, 0.5773502691896257, 0., -0.5773502691896257\} // \text{MatrixForm}$$

$$\begin{pmatrix} 0.57735 \\ 0.57735 \\ 0. \\ -0.57735 \end{pmatrix}$$

$$v_3 = \{0.6565385020081387, -0.22801342888377918, -0.5773502691896257, 0.42852507312435956\} // \text{MatrixForm}$$

$$\begin{pmatrix} 0.656539 \\ -0.228013 \\ -0.57735 \\ 0.428525 \end{pmatrix}$$

$$v_4 = \{-0.42852507312435956, 0.6565385020081387, -0.5773502691896257, 0.22801342888377912\} // \text{MatrixForm}$$

$$\begin{pmatrix} -0.428525 \\ 0.656539 \\ -0.57735 \\ 0.228013 \end{pmatrix}$$

5) Calculate natural frequencies (rad/s):

$$W_i = \sqrt{\lambda_i}$$

$\lambda_1 = \sqrt{0.150768}$	$\lambda_3 = \sqrt{2.93412}$
0.388289	1.71293
$\lambda_2 = \sqrt{1.25}$	$\lambda_4 = \sqrt{4.41511}$
1.11803	2.10122

$$W_1 = 0.388289 \quad W_2 = 1.11803 \quad W_3 = 1.71293 \quad W_4 = 2.10122$$

6) Calculate mode shapes:

$$u_i = M^{-1/2} v_i$$

$$e = m \cdot v$$

{{-0.214263, 0.328269, -0.288675, 0.114007}, {0.328269, -0.114007, -0.288675, 0.214263}, {0.288675, 0.288675, 0., -0.288675}, {0.114007, 0.214263, 0.288675, 0.328269}}

$$u_1 = \{0.1140067144418896, 0.21426253656217978, 0.2886751345948129, 0.32826925100406934\} // \text{MatrixForm}$$

$$\begin{pmatrix} 0.114007 \\ 0.214263 \\ 0.288675 \\ 0.328269 \end{pmatrix}$$

$$u_2 = \{0.28867513459481287, 0.28867513459481287, 0., -0.28867513459481287\} // \text{MatrixForm}$$

$$\begin{pmatrix} 0.288675 \\ 0.288675 \\ 0. \\ -0.288675 \end{pmatrix}$$

```

u3 = {0.32826925100406934, -0.11400671444188959, -0.28867513459481287, 0.21426253656217978} // MatrixForm


$$\begin{pmatrix} 0.328269 \\ -0.114007 \\ -0.288675 \\ 0.214263 \end{pmatrix}$$


u4 = {-0.21426253656217978, 0.32826925100406934, -0.28867513459481287, 0.11400671444188956} // MatrixForm


$$\begin{pmatrix} -0.214263 \\ 0.328269 \\ -0.288675 \\ 0.114007 \end{pmatrix}$$


```

7) In the process of calculation, the use of the mode summation method is necessary. The modal participation factors are determined by:

$$d_i = \frac{v_i^T q(0)}{\sin \theta}$$

Calculate initial conditions:

$$x(0) = \begin{pmatrix} 0.025 \\ 0.02 \\ 0.0010 \\ 0.001 \end{pmatrix} \quad \dot{x}(0) = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \quad \theta = \frac{\pi}{2}$$

$q(0) = M^{1/2} X(0)$	$\dot{q}(0) = M^{1/2} \dot{x}(0)$
$y = \{0.025, 0.020, 0.010, 0.001\}$ (*Initial conditions x(0)*)	$y1 = \{0, 0, 0, 0\}$ (*Initial conditions $\dot{x}(0)$ *)
MatrixForm[m2.y](*Obtention of q in x(0)*)	MatrixForm[m2.y1]
$\begin{pmatrix} 0.05 \\ 0.04 \\ 0.02 \\ 0.002 \end{pmatrix}$	$\begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$
$q(0) = \{0.05, 0.04, 0.02, 0.002\}$	$\dot{q}(0) = 0$

So that, modal participation factors are:

$$d_i = \frac{v_i^T q(0)}{\sin\left(\frac{\pi}{2}\right)} = v_i^T q(0)$$

$$d_1 = v_1 \cdot q = 0.0414$$

$$d_2 = v_2 \cdot q = 0.0508068$$

$$d_3 = v_3 \cdot q = 0.0130164$$

$$d_4 = v_4 \cdot q = -0.00625569$$

Modal participation factors d_3 and d_4 are much smaller than the factors d_1 and d_2 . Thus mode one (w_1) and mode two (w_2) will dominate the response.

- 8) Throw $x(t)$ equation is possible to illustrate how each mode shape contributes to forming the total response of the system.

$$x(t) = \sum_{i=1}^n d_i \sin(w_i t + \theta) u_i$$

The solutions given by the equation for the 4 floors are:

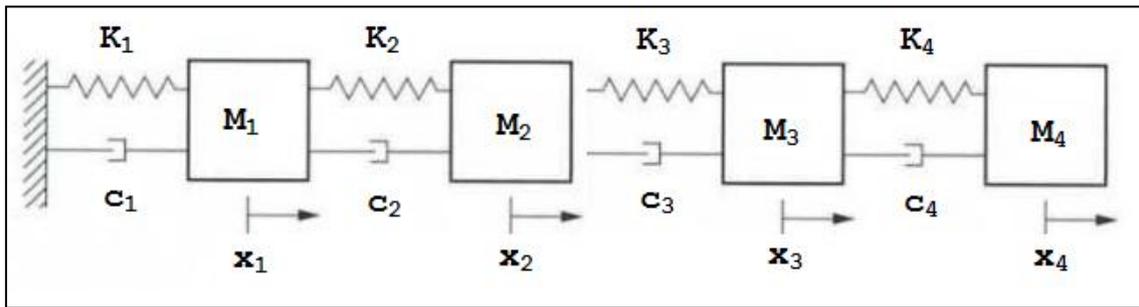
$$x_1(t) = 0.0047 \cos(0.3883t) + 0.0147 \cos(1.1180t) + 0.0043 \cos(1.7129t) + 0.0013 \cos(2.1012t)$$

$$x_2(t) = 0.0089 \cos(0.3883t) + 0.0147 \cos(1.1180t) - 0.0015 \cos(1.7129t) - 0.0021 \cos(2.1012t)$$

$$x_3(t) = 0.012 \cos(0.3883t) + 0 \cos(1.1180t) - 0.0038 \cos(1.7129t) + 0.0018 \cos(2.1012t)$$

$$x_4(t) = 0.0136 \cos(0.3883t) - 0.0147 \cos(1.1180t) + 0.0028 \cos(1.7129t) - 0.0007 \cos(2.1012t)$$

1.2. Calculation of a multi story building with modal damping



In this section, the building is going to be calculated in three times, taking into account that the damping ratio in the different cases are $\zeta = 0.01$, $\zeta = 0.03$ and $\zeta = 0.05$.

1.2.1. Calculation of a building with modal damping ($\zeta = 0.01$)

By using the mode summation method, the undamped equations of motion are going to be transformed into “q” coordinate system.

$$q(\tau) = \sum_{i=1}^n d_i e^{(-\zeta \omega_i \tau)} \sin(\omega_{di} \tau + \theta_i) v_i$$

1) Calculate initial conditions.

$$x(0) = \begin{pmatrix} 0.025 \\ 0.02 \\ 0.0010 \\ 0.001 \end{pmatrix} \quad \dot{x}(0) = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

$q(0) = M^{1/2} X(0)$	$\dot{q}(0) = M^{1/2} \dot{x}(0)$
$y = \{0.025, 0.020, 0.010, 0.001\}$ (*Initial conditions x(0)*)	$y1 = \{0, 0, 0, 0\}$ (*Initial conditions $\dot{x}(0)$ *)
MatrixForm[m2.y](*Obtention of q in x(0)*)	MatrixForm[m2.y1]
$\begin{pmatrix} 0.05 \\ 0.04 \\ 0.02 \\ 0.002 \end{pmatrix}$	$\begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$
$q(0) = \{0.05, 0.04, 0.02, 0.002\}$	$\dot{q}(0) = 0$

2) For any value of damping ratio, modal shapes are unchanged.

As $\zeta = 0.01$ ($W_{di} = 0.99995$), natural frequencies (rad/s) are still the same as the problem before.

$$W_{di} = W_i \sqrt{1 - \zeta^2}$$

$$W_1 = 0.388289 \quad W_2 = 1.11803 \quad W_3 = 1.71293 \quad W_4 = 2.10122$$

3) Calculate phase angle, θ_i :

$$\theta_i = \tan^{-1} \frac{W_{di} v_i^T q(0)}{v_i^T q(0) + \zeta_i W_i v_i^T q(0)}$$

$$W_{di} = W_i \sqrt{1 - \zeta^2}$$

$$\theta_1 = \tan^{-1} \frac{W_{d1} v_1^T q(0)}{v_1^T q(0) + \zeta_1 W_1 v_1^T q(0)} = \tan^{-1} \frac{W_{d1}}{\zeta_1 W_1} = \tan^{-1} \frac{W_i \sqrt{1 - \zeta^2}}{\zeta_i W_i} = \tan^{-1} \frac{\sqrt{1 - \zeta^2}}{\zeta_i} = \tan^{-1} \frac{\sqrt{1 - (0.01)^2}}{0.01} = 89.427^\circ$$

$\theta_1 = \theta_2 = \theta_3 = \theta_4 = 89.427^\circ \rightarrow 1.56 \text{ rad}$

4) Calculate modal participation factors. As $1/\sin(89.427^\circ) = 1.00005 \approx 1$, modal participation factors still the same as the problem before:

$$d_i = \frac{v_i^T q(0)}{\sin \theta}$$

$$\begin{aligned} d_1 &= v_1 \cdot q = 0.0414 \\ d_2 &= v_2 \cdot q = 0.0508068 \\ d_3 &= v_3 \cdot q = 0.0130164 \\ d_4 &= v_4 \cdot q = -0.00625569 \end{aligned}$$

5) Once $q(t)$ is computed, transform back to the physical coordinate system by:

$$\begin{aligned} x(t) &= M^{-1/2} q(t) \\ x(t) &= \sum_{i=1}^n d_i e^{(-\zeta W_i t)} \sin(W_{di} t + \theta_i) u_i \end{aligned}$$

The solutions given by the equation for the 4 floors are:

$$x_1(t) = 0.0047 e^{-0.00388t} \sin(0.3883t + 1.56) + 0.0147 e^{-0.01118t} \sin(1.1180t + 1.56) \\ + 0.0043 e^{-0.01713t} \sin(1.7129t + 1.56) + 0.0013 e^{-0.02109t} \sin(2.1012t + 1.56)$$

$$x_2(t) = 0.0089 e^{-0.00388t} \sin(0.3883t + 1.56) + 0.0147 e^{-0.01118t} \sin(1.1180t + 1.56) \\ - 0.0015 e^{-0.01713t} \sin(1.7129t + 1.56) - 0.0021 e^{-0.02109t} \sin(2.1012t + 1.56)$$

$$x_3(t) = 0.012 e^{-0.00388t} \sin(0.3883t + 1.56) + 0 e^{-0.01118t} \sin(1.1180t + 1.56) \\ - 0.0038 e^{-0.01713t} \sin(1.7129t + 1.56) + 0.0018 e^{-0.02109t} \sin(2.1012t + 1.56)$$

$$x_4(t) = 0.0136 e^{-0.00388t} \sin(0.3883t + 1.56) - 0.0147 e^{-0.01118t} \sin(1.1180t + 1.56) \\ + 0.0028 e^{-0.01713t} \sin(1.7129t + 1.56) - 0.0007 e^{-0.02109t} \sin(2.1012t + 1.56)$$

1.2.2. Calculation of a building with modal damping ($\zeta = 0.03$)

By using the mode summation method, the undamped equations of motion are going to be transformed into “q” coordinate system.

$$q(t) = \sum_{i=1}^n d_i e^{(-\xi \omega_i t)} \sin(\omega_{di} t + \theta_i) v_i$$

1) Calculate initial conditions.

$$x(0) = \begin{pmatrix} 0.025 \\ 0.02 \\ 0.0010 \\ 0.001 \end{pmatrix} \quad \dot{x}(0) = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

$q(0) = M^{1/2} X(0)$	$\dot{q}(0) = M^{1/2} \dot{x}(0)$
$y = \{0.025, 0.020, 0.010, 0.001\}$ (*Initial conditions x(0)*)	$y1 = \{0, 0, 0, 0\}$ (*Initial conditions $\dot{x}(0)$ *)
MatrixForm[m2.y](*Obtention of q in x(0)*)	MatrixForm[m2.y1]
$\begin{pmatrix} 0.05 \\ 0.04 \\ 0.02 \\ 0.002 \end{pmatrix}$	$\begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$
$q(0) = \{0.05, 0.04, 0.02, 0.002\}$	$\dot{q}(0) = 0$

2) For any value of damping ratio, modal shapes are unchanged.

The natural frequencies (rad/s) for $\zeta = 0.03$ are the following:

$$\omega_{di} = \omega_i \sqrt{1 - \zeta^2}$$

$$\omega_1 = 0.38809 \quad \omega_2 = 1.11753 \quad \omega_3 = 1.71216 \quad \omega_4 = 2.10027$$

3) Calculate phase angle, θ_i :

$$\theta_i = \tan^{-1} \frac{\omega_{di} v_i^T q(0)}{v_i^T q(0) + \zeta_i \omega_i v_i^T q(0)}$$

$$\omega_{di} = \omega_i \sqrt{1 - \zeta^2}$$

$$\theta_1 = \tan^{-1} \frac{w_{d1} v_1^T q(0)}{v_1^T q(0) + \xi_1 w_1 v_1^T q(0)} = \tan^{-1} \frac{w_{d1}}{\xi_1 w_1} = \tan^{-1} \frac{w_1 \sqrt{1-\xi^2}}{\xi_1 w_1} = \tan^{-1} \frac{\sqrt{1-\xi^2}}{\xi_1} = \tan^{-1} \frac{\sqrt{1-(0.03)^2}}{0.03} = 88.28^\circ$$

$\theta_1 = \theta_2 = \theta_3 = \theta_4 = 88.28^\circ \rightarrow 1.54 \text{ rad}$

- 4) Calculate modal participation factors. As $1/\sin(88.28^\circ) = 1.00045 \approx 1$, modal participation factors still the same as the problem before:

$$d_i = \frac{v_i^T q(0)}{\sin \theta}$$

$$\begin{aligned} d_1 &= v_1 \cdot q = 0.0414 \\ d_2 &= v_2 \cdot q = 0.0508068 \\ d_3 &= v_3 \cdot q = 0.0130164 \\ d_4 &= v_4 \cdot q = -0.00625569 \end{aligned}$$

- 5) Once $q(t)$ is computed, transform back to the physical coordinate system by:

$$\begin{aligned} x(t) &= M^{-1/2} q(t) \\ x(t) &= \sum_{i=1}^n d_i e^{(-\xi w_i t)} \sin(w_{d_i} t + \theta_i) u_i \end{aligned}$$

The solutions given by the equation for the 4 floors are:

$$\begin{aligned} x_1(t) &= 0.0047 e^{-0.011648t} \sin(0.3883t + 1.54) + 0.0147 e^{-0.0335409t} \sin(1.11753t + 1.54) \\ &\quad + 0.0043 e^{-0.0513879t} \sin(1.71216t + 1.54) + 0.0013 e^{-0.0630366t} \sin(2.10027t + 1.54) \\ x_2(t) &= 0.0089 e^{-0.011648t} \sin(0.3883t + 1.54) + 0.0147 e^{-0.0335409t} \sin(1.11753t + 1.54) \\ &\quad - 0.0015 e^{-0.0513879t} \sin(1.71216t + 1.54) - 0.0021 e^{-0.0630366t} \sin(2.10027t + 1.54) \\ x_3(t) &= 0.012 e^{-0.011648t} \sin(0.3883t + 1.54) + 0 e^{-0.0335409t} \sin(1.11753t + 1.54) \\ &\quad - 0.0038 e^{-0.0513879t} \sin(1.71216t + 1.54) + 0.0018 e^{-0.0630366t} \sin(2.10027t + 1.54) \\ x_4(t) &= 0.0136 e^{-0.011648t} \sin(0.3883t + 1.54) - 0.0147 e^{-0.0335409t} \sin(1.11753t + 1.54) \\ &\quad + 0.0028 e^{-0.0513879t} \sin(1.71216t + 1.54) - 0.0007 e^{-0.0630366t} \sin(2.10027t + 1.54) \end{aligned}$$

1.2.3. Calculation of a building with modal damping ($\zeta = 0.05$)

By using the mode summation method, the undamped equations of motion are going to be transformed into “q” coordinate system.

$$q(t) = \sum_{i=1}^n d_i e^{(-\zeta \omega_i t)} \sin(\omega_{di} t + \theta_i) v_i$$

1) Calculate initial conditions.

$$x(0) = \begin{pmatrix} 0.025 \\ 0.02 \\ 0.0010 \\ 0.001 \end{pmatrix} \quad \dot{x}(0) = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

$q(0) = M^{1/2} x(0)$	$\dot{q}(0) = M^{1/2} \dot{x}(0)$
$y = \{0.025, 0.020, 0.010, 0.001\}$ (*Initial conditions x(0)*)	$y1 = \{0, 0, 0, 0\}$ (*Initial conditions $\dot{x}(0)$ *)
MatrixForm[m2.y](*Obtention of q in x(0)*)	MatrixForm[m2.y1]
$\begin{pmatrix} 0.05 \\ 0.04 \\ 0.02 \\ 0.002 \end{pmatrix}$	$\begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$
$q(0) = \{0.05, 0.04, 0.02, 0.002\}$	$\dot{q}(0) = 0$

2) For any value of damping ratio, modal shapes are unchanged.

The natural frequencies (rad/s) for $\zeta = 0.05$ are the following:

$$\omega_{di} = \omega_i \sqrt{1 - \zeta^2}$$

$$\omega_1 = 0.3878 \quad \omega_2 = 1.11663 \quad \omega_3 = 1.71078 \quad \omega_4 = 2.09859$$

3) Calculate phase angle, θ_i :

$$\theta_i = \tan^{-1} \frac{\omega_{di} v_i^T q(0)}{v_i^T q(0) + \zeta_i \omega_i v_i^T q(0)}$$

$$\omega_{di} = \omega_i \sqrt{1 - \zeta^2}$$

$$\theta_1 = \tan^{-1} \frac{w_{d1} v_1^T q(0)}{v_1^T q(0) + \xi_1 w_1 v_1^T q(0)} = \tan^{-1} \frac{w_{d1}}{\xi_1 w_1} = \tan^{-1} \frac{w_1 \sqrt{1-\xi^2}}{\xi_1 w_1} = \tan^{-1} \frac{\sqrt{1-\xi^2}}{\xi_1} = \tan^{-1} \frac{\sqrt{1-(0.05)^2}}{0.05} = 87.134^\circ$$

$$\theta_1 = \theta_2 = \theta_3 = \theta_4 = 87.134^\circ \rightarrow 1.52 \text{ rad}$$

4) Calculate modal participation factors. As $1/\sin(87.134^\circ) = 1.00125 \approx 1$, modal participation factors still the same as the problem before:

$$d_i = \frac{v_i^T q(0)}{\sin \theta}$$

$$\begin{aligned} d_1 &= v_1 \cdot q = 0.0414 \\ d_2 &= v_2 \cdot q = 0.0508068 \\ d_3 &= v_3 \cdot q = 0.0130164 \\ d_4 &= v_4 \cdot q = -0.00625569 \end{aligned}$$

5) Once $q(t)$ is computed, transform back to the physical coordinate system by:

$$x(t) = M^{-1/2} q(t)$$

$$x(t) = \sum_{i=1}^n d_i e^{(-\xi w_i t)} \sin(w_{di} t + \theta_i) u_i$$

The solutions given by the equation for the 4 floors are:

$$\begin{aligned} x_1(t) &= 0.0047 e^{-0.01941 t} \sin(0.3878 t + 1.52) + 0.0147 e^{-0.0559 t} \sin(1.11663 t + 1.52) \\ &\quad + 0.0043 e^{-0.085646 t} \sin(1.71078 t + 1.52) + 0.0013 e^{-0.105081 t} \sin(2.09859 t + 1.52) \\ x_2(t) &= 0.0089 e^{-0.01941 t} \sin(0.3878 t + 1.52) + 0.0147 e^{-0.0559 t} \sin(1.11663 t + 1.52) \\ &\quad - 0.0015 e^{-0.085646 t} \sin(1.71078 t + 1.52) - 0.0021 e^{-0.105081 t} \sin(2.09859 t + 1.52) \\ x_3(t) &= 0.012 e^{-0.01941 t} \sin(0.3878 t + 1.52) + 0 e^{-0.0559 t} \sin(1.11663 t + 1.52) \\ &\quad - 0.0038 e^{-0.085646 t} \sin(1.71078 t + 1.52) + 0.0018 e^{-0.105081 t} \sin(2.09859 t + 1.52) \\ x_4(t) &= 0.0136 e^{-0.01941 t} \sin(0.3878 t + 1.52) - 0.0147 e^{-0.0559 t} \sin(1.11663 t + 1.52) \\ &\quad + 0.0028 e^{-0.085646 t} \sin(1.71078 t + 1.52) - 0.0007 e^{-0.105081 t} \sin(2.09859 t + 1.52) \end{aligned}$$

ANNEX 2: GRAPHICS

